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5G for Future Railway Communications

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Executive Summary

The present White Paper focuses on standardization of Future Railway Mobile Communication System (FRMCS) and intends to explore capabilities of 3GPP 5G System (5GS) and Mission Critical Services (MCX), being the technical foundation of FRMCS.

FRMCS is the future worldwide telecommunication system designed by International Union of Railways (UIC), the Worldwide Railway Organization, in close and permanent cooperation with the different stakeholders from the rail sector, as the successor of GSM-R, which has an estimated end-of-life around 2035, but also as a key enabler for rail transport digitalization. With FRMCS enabling a scalable and future-proof system for the railway operators, apart from ensuring a continuation of railway operation when GSM-R will be stopped, they can benefit from new and enhanced use cases such as automatic train protection, automatic train operation, improved voice & video services, enhanced rail traffic management and enhanced performance. UIC and the rail supply industry are actively working in 3GPP to create the necessary enhancements to the 5GS and MCX standards.

In this perspective, this White Paper provides an overview of a list of 3GPP Release 18 5GS features which is also complemented by a description of MCX capabilities of interest for the rail sector.

This first edition of this White Paper is then a must-read for all ecosystem stakeholders who are unfamiliar with FRMCS as its adoption is approaching. Providing the necessary clarifications in this White Paper is a means to further encourage the worldwide adoption of FRMCS.

1. Introduction

1.1. Necessity of a next generation system for railway communications

Economy requires movement of goods and people, and this implies that the modes of mobility and infrastructure sustaining them are indispensable to economic growth. Of these mobility modes, railway presents an interesting and appealing choice, as it does not only provide timely transport but is also relatively low on carbon footprint. According to UIC, railway represents 8% of global passenger and freight transport activity, but only account for 2% of transport sector emissions [1]. In the era of climate change, railway is an effective mobility mode to maintain economic growth while reducing carbon footprint.

The railway services and infrastructure require communications technology for operation, performance and for maintenance. Precise and well-coordinated train operation are essential for timely and safe transport of passengers and cargos, making communications technology crucial. Indeed, this is the reason behind the success of GSM-R, the railway adaptation of the second-generation GSM technology. GSM-R is deployed on more than 130 000 kilometers of track in Europe and 210 000 kilometers worldwide. GSM-R is an interoperable system introducing nationwide connectivity based on 3GPP standards, enabling voice, signalling and limited data capabilities. In Europe, this connectivity is extended at the continent level.

However, as GSM-R is a second-generation mobile communications technology, its data capability is approximately four to six orders of magnitude less than that of the latest mobile communication generation [2]. This limitation hinders the adoption of potential digital applications and advanced connectivity, which are compulsory to digitalize the railway industry. Digitalization of railway can bring three key benefits: smart mobility, smart operations, and smart employees [2]. Passengers can enjoy more efficient and engaging railways with digitalization, while the employees can benefit from enhanced productivity. Furthermore, the suppliers of GSM-R have committed to supporting the system until 2035[1], making its maintenance beyond that date highly challenging and costly. This makes the transition to advanced connectivity for rail transport digitalization even more attractive and necessary.

This is why the UIC[2], with the support of the Railways and the Rail Supply industry, is designing the FRMCS, the next generation telecommunications system for railway communications, as a response to the two elements of strategic importance for the future of the railways, namely obsolescence and digitalization. With FRMCS enabling a scalable and future-proof infrastructure for the railway operators, apart from ensuring a continuation of railway operation when GSM-R will be stopped, they can benefit from new and enhanced use cases such as automatic train protection, automatic train operation, improved voice & video services, enhanced rail traffic management and enhanced performance. UIC has decided to base FRMCS on the 3rd Generation Partnership Project (3GPP) 5G technology and is actively working with 3GPP to create the necessary enhancements to the 5G standards.

[1] Some suppliers will support beyond 2035 on a contract basis with long-term GSM-R maintenance agreements.
[2] The global association representing the railway sector and promoting rail transport [22].

Like 5G, the FRMCS is also designed to be flexible, as the railway functions are separated from the network and the radio technology used [3]. It can utilize different 5G networks, other than the ones dedicated to railway networks. The 3GPP-developed technologies successfully align with the requirements of UIC. For example, FRMCS supports application centric communications [4].

1.2. Envisioned services of future railway communications system

Understanding the FRMCS specification and evolution requires understanding the potential services envisioned and enabled by the FRMCS. This section provides an overview of such applications envisioned by the UIC with FRMCS.

The UIC distinguishes the applications of FRMCS based on two axes of type and use [2]. The type refers to whether the application is communications application (Comms) or the supporting application for communications application(s) (Support). The use refers to the three different uses of the applications as follows:

- Critical: applications that are essential for train movements and safety or a legal obligation.
- Performance: applications that help to improve the performance of the railway operation.
- Business: applications that support the railway business operation in general.

The selected FRMCS applications can therefore be visualized and mapped as shown in Table 1 [2]. It should be highlighted that the applications shown in the table are not exhaustive, and the details of the applications are explained further below Table 1.

Table 1: FRMCS Applications Framework and Mapping

	Critical	Performance	Business
Comms	• Automatic Train Protection (ATP) • Automatic Train Operation (ATO) • Railway Emergency Communications (REC) • Voice communications	• Voice communications • Train Control and Monitoring Systems (TCMS), including e.g. telemetry • Public address • Transfer of data	• Help point for information / emergency • Wireless internet services for train and platform
Support	• Assured voice communications • Multi-user talk control • Role management and presence • Location services		• Billing information

Under critical communication application, ATP refers to Automatic Train Protection, where the speed of train is checked against the permitted speed allowed by the system (e.g., signalling) and emergency brakes are automatically applied if this is not the case. ATO refers to Automatic Train Operation and requires reliable communications technology to ensure efficient and reliable transfer of data between different elements of the railway system. Furthermore, REC, refers to the case where railway emergency communication can be setup with groups of users (for the case when driver initiates the REC, the list of participants is determined based on originator's location and participants roles). Finally, voice communications for critical comms provide communications among railway staffs/operators in various cases including multiple trains, banking, shunting, and trackside maintenance.

For performance communication application, there are various types of voice communications applications. For example, train staff can interact with ground users of the railway communications system. The train staff can also make public address to inform the passengers. Mobile communications may be used to transfer data or video (CCTV offload or live streaming) from the train to the ground system automatically for monitoring and archiving purposes.

Under Business communication application, help point for information/emergency refers to the ability for the public (passengers) to set up a voice communication with the appropriate ground train staff or driver for information/emergency purposes. Wireless internet services for the train and the platform also belong to his category.

For critical support, assured voice communications allow the users to be indicated as soon as the end-to-end voice communication link is broken. Multi-user talker control limits the number of simultaneous talkers in a multi-user voice communication. The role management and presence allow a user of FRMCS to possess one or more roles (e.g., train lead driver, train staff, primary controller, etc.) within a specific organization, and enables the user to select a role depending on the context. Roles are used both for routing purposes, and to identify participants in a communication. Location services refer to the ability of the FRMCS system to store and provide the location of the user/device for multiple usage e.g., Railway Emergency Call, train driver to controller call where the controller is selected based on location of the train driver.

1.3. Overview of the White Paper

Since the FRMCS specifications are highly dependent on the 3GPP 5G specifications, it is necessary to understand the 3GPP technologies that form the basis of FRMCS to gain technical understanding of FRMCS. This whitepaper therefore provides a description of the second version of FRMCS (FRMCS v2), which is based on the 5G 3GPP Release 18 features.

The whitepaper is structured as follows. Following this section, section 2 will describe the legacy technologies addressing railway communications and the collaboration among three key organizations to drive evolution towards FRMCS. Then, various 3GPP technologies used for FRMCS will be explained in section 3, ranging from the 5G architecture to innovation in the 5G radio technology and then to support for mission critical services. Finally, section 4 will provide high-level benefits of FRMCS based on the 3GPP technological features and concluding remarks.

2. Legacy technologies for railway communications and evolution towards FRMCS

2.1. General

In addition to the use cases and rationale for the FRMCS, it is also important to understand the context of change behind FRMCS. For example, one should be aware of the legacy technologies that FRMCS is trying to replace and how different organizations/standards are evolving to bring FRMCS to reality. Hence, this section provides an overview of the legacy technologies that the railway industry has adopted, including the GSM-R that was mentioned in the introduction. Then, FRMCS is described in more detail with outlining of relevant organizations and how they fit together to develop FRMCS.

2.2. Legacy technologies

The creation of a pan-European system for railway telecommunications was initiated in the 1990s by the UIC, where GSM-R was selected as the interoperable radio system for Railways and was mandated by a European Decision in 1997. The first implementation of GSM-R in Europe was in 2001. GPRS was introduced in 2016, bringing a native IP bearer to the GSM-R. Since 2001, GSM-R has achieved a great success both in Europe and outside Europe. GSM-R is deployed on more than 130 000 kilometres of track in Europe and 210 000 kilometres worldwide [5].

GSM-R, as mentioned previously, is an adaptation of GSM for use in railway communication systems. GSM is the second-generation cellular communications system that uses a combination of time division multiple access (TDMA) and frequency division multiple access (FDMA) to provide voice and data services to mobile devices. GSM-R uses GSM to provide voice and data communication between trains, stations, and control centres. GSM-R, unlike GSM, operates on 873 MHz to 880 MHz for uplink, and on 918 MHz to 925 MHz for the downlink in Europe. Some other bands that are used include 885 MHz to 889 MHz for uplink and 930 to 934 MHz for downlink in China, and 1 770-1 785 MHz for uplink and 1 865-1 880 MHz for downlink in Australia. GSM, on the other hand, operates in various bands from 890 MHz up to 1 990 MHz worldwide.
GSM-R adoption was a gradual process. The European Union mandated GSM-R as part of the EU Directive on the interoperability of the rail system (i.e., every new railway telecommunication system in Europe is mandated to adopt GSM-R). Note that FRMCS has already been introduced in EU regulation in 2023 [6].

Other non-interoperable radio systems for railways are rolled out, mostly outside Europe. There is a wide range of communication standards worldwide, indicating varied approaches and developmental stages in railways, with a significant reliance on analogue systems (UHF, HF), limited number of narrowband digital radio systems (DMR, TETRA and GSM-R), and very limited number of broadband digital radio systems (LTE, WiMAX). This heterogeneity reflects the individual railway operational needs and historical contexts.

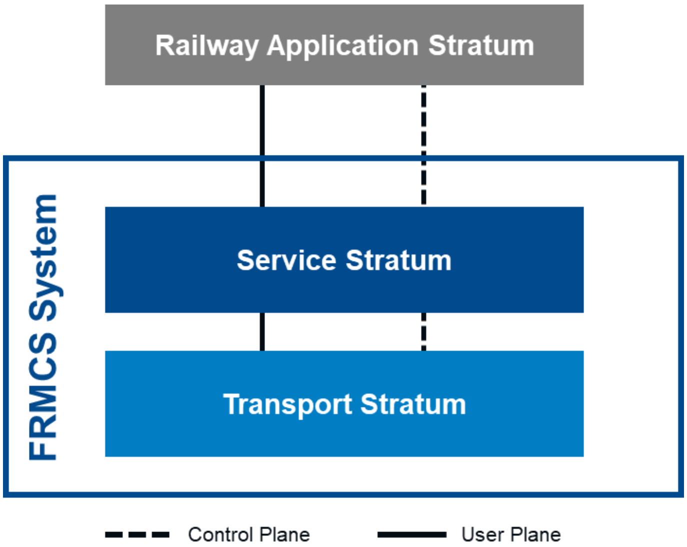
2.3. Evolution towards FRMCS

2.3.1. FRMCS Overview

The FRMCS is a system that consists of three strata as shown in Figure 1 [7].

To enable independence between Railway Applications and the necessary physical transmission, a Service Stratum is introduced as an abstraction layer, that acts as separation and adaptation layer between Railway Applications and Transport stratum. Therefore, in principle, the FRMCS Architecture consists of three major Strata, of which only two strictly belong to the FRMCS System, Service and Transport.

Figure 1: Three Strata of FRMCS [7]



In terms of the solutions adopted by the FRMCS system, the Transport Stratum will be the 5G System. For the Service Stratum, 3GPP-defined Mission Critical Services for voice, video and data are adopted. The Railway Application Stratum will consist of various applications that utilize the Service Stratum to operate.

It may already be apparent to the readers that the applications and services are the subset of what was covered in the section 1.2. Indeed, FRMCS is developed not by a single organization, but thanks to the collaboration among different organizations. The services envisioned and corresponding requirements are specified by the UIC, which are then developed into ETSI standards (Technical Committee (TC) Rail Telecommunications (RT)) for solutions that are based on 3GPP technical specifications. The subsequent sections will provide the standardization efforts of these key organizations and the macroscopic view of the relationship among the three organizations.

2.3.2. UIC Activities overview

The UIC has been providing guidance on the railway communications technology since the inception of GSM-R. Specific to FRMCS, the UIC has seven working groups (see UIC extranet for details [8]):

- The FRMCS steering group steers and manages the development of FRMCS by leading the global FRMCS strategy and planning.
- The FRMCS Functionality Working Group (FWG) focuses on the match between system functionalities and railway needs, ensuring that the system meets the demand of the railway industry. FWG delivers FRMCS Functional Requirements Specification (FRMCS FRS [2]).

- The FRMCS Architecture and Technology Group Working Group (ATWG) defines the FRMCS architecture and the system requirements. ATWG delivers FRMCS System Requirements Specification (FRMCS SRS [3]).
- The FRMCS Telecom On-Board Architecture (TOBA) focuses on the On-Board FRMCS (hence TOBA) and its functional requirements. TOBA WG delivers TOBA FRS [9].
- The UIC Group for Frequency Aspects (UGFA) studies and identifies the expected needs for spectrum, the basic component of mobile radio systems. This is particularly useful and critical in transition scenarios. UGFA delivers studies and spectrum recommendations to ATWG as inputs to FRMCS SRS.
- FRMCS Functional Interface Specifications (FIS) defines the call flows to determine any gaps or inconsistencies [10].
- FRMCS Form-Fit-Functional Interface Specification (FFFIS) defines the On Board and Track Side Applications interface [11].

2.3.3. ETSI TC RT

ETSI TC RT was created along with the adoption of GSM-R, where the committee was dedicated to GSM-R. The committee therefore was focused on maintaining the specifications for the use of GSM to meet the requirement of the railways, and to update and develop these existing standards based on the relevant European directives. The development of GSM-R was mostly done by submitting Change Requests to 3GPP directly with three dedicated ETSI specifications on GSM-R to cover the "gaps".

The TC RT committee started work on FRMCS in 2015, while the 3GPP started to study the FRMCS to identify corresponding service requirements on the mobile communications system from Release 15. While the 5G system per se is defined by 3GPP, the ETSI RT committee oversees the following aspects of FRMCS standardization:

- Study the next generation end-to-end system architecture for rail transportation supporting multiple access technologies.
- Cooperate with UIC for use cases and user requirements for FRMCS.
- Participate in standardization of Mission Critical Communications within 3GPP, especially in the normative aspects related to FRMCS.
- Develop pan-European FRMCS technical specifications including interworking between GSM-R and FRMCS.

2.3.4. 3GPP

While 3GPP's Release 18 5G and mission critical communications standards are adopted for FRMCS, the 3GPP role in railway communications dates to GSM-R. Since GSM has been transferred to 3GPP from ETSI, 3GPP has been the home for the mobile communications technology, and GSM-R was not an exception.

Release 13 is an important milestone of 3GPP as this was the release where Mission Critical Push To Talk (MCPTT[3]) was introduced in LTE with the partnership of The Critical Communications Association (TCCA). TCCA became a market representative partner of 3GPP, working closely to define the next generation critical communications system based on LTE and beyond. In Release 14, the MCPTT was enhanced with data communications (MCData) and video communications (MCVideo). Release 15 was focused on the definition of 5G system and hence mostly consisted of basic functionalities of the mobile communications system. Since Release 15, the work on railways has resumed and Release 18 specifications provide the baseline for FRMCS system.

2.3.5. How UIC, ETSI and 3GPP fit together

To realize FRMCS, UIC is responsible for the creation of a complete set of specifications, from user requirements via architecture to system requirements specifications, etc. Part of these requirements are provided to 3GPP as inputs.

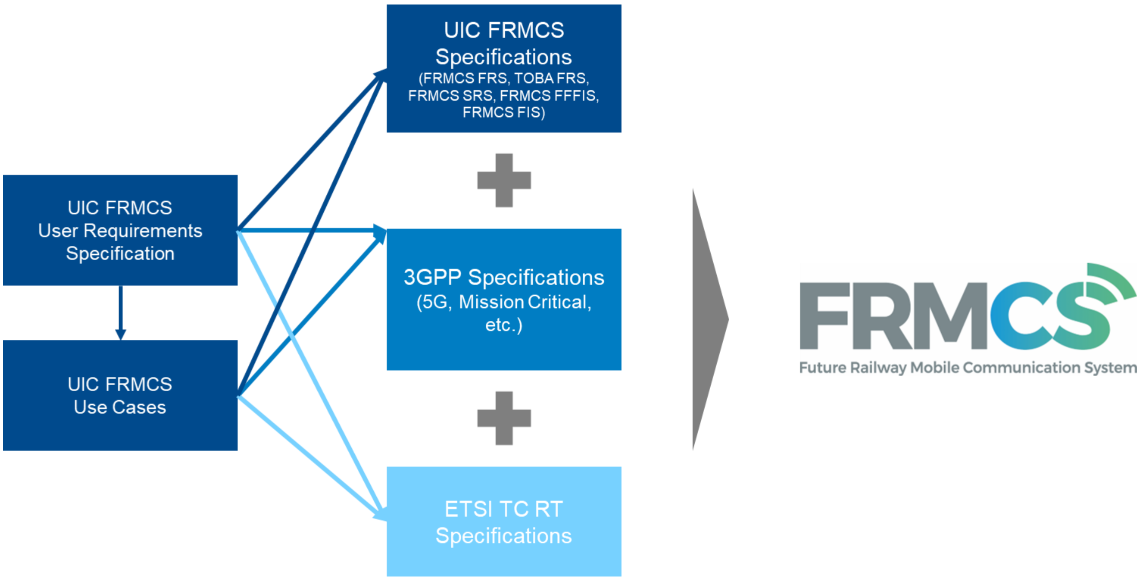
The UIC contributes to the technical work of FRMCS within ETSI and 3GPP [12]. The basic building blocks are provided by 3GPP and hence the UIC participates directly in 3GPP as Individual Member together with Railway Industry to define the additional features and functionalities in 3GPP specifications necessary for FRMCS. UIC participates in the following 3GPP working groups, where the FRMCS contributions are described in the below list per working group:

- RAN1: Physical layer for the railway mobile radio.
- RAN4: Radio performance aspects for the railway mobile radio.
- RAN5: Conformance testing for the railway mission critical systems and UEs.
- SA1: Service requirements of railways mission critical systems.
- SA6: Architecture and the necessary procedures for the railways mission critical systems overall.
- CT1: Detailed protocols of railways mission critical systems and MC UEs.

In addition, any remaining gaps between the 3GPP and FRMCS specifications are addressed by ETSI TC RT as was the case in GSM-R. The graphical representation of these relationships is shown in Figure 2.

[3] Note that abbreviation MC is used when it is used as 3GPP terminology (e.g., MCPTT, MC UE, MC gateway, MC service server), whereas mission critical will be used to indicate the nature of being mission critical per se.

Figure 2: Relationships among three key organizations



3GPP and UIC will continue collaborating to enhance FRMCS system in Release 19 and beyond [5], by adding more services including enhancement of ad-hoc group calls and emergency alerts, enhancement of location-based services, enhancements in security for railway communications, support of NR channel bandwidth less than 5MHz, and support of carrier aggregation and dual connectivity. Interested readers are encouraged to look into Annex A for more details on FRMCS work in 3GPP.

3. 3GPP Technologies for Future Railway Communications

3.1. Overview

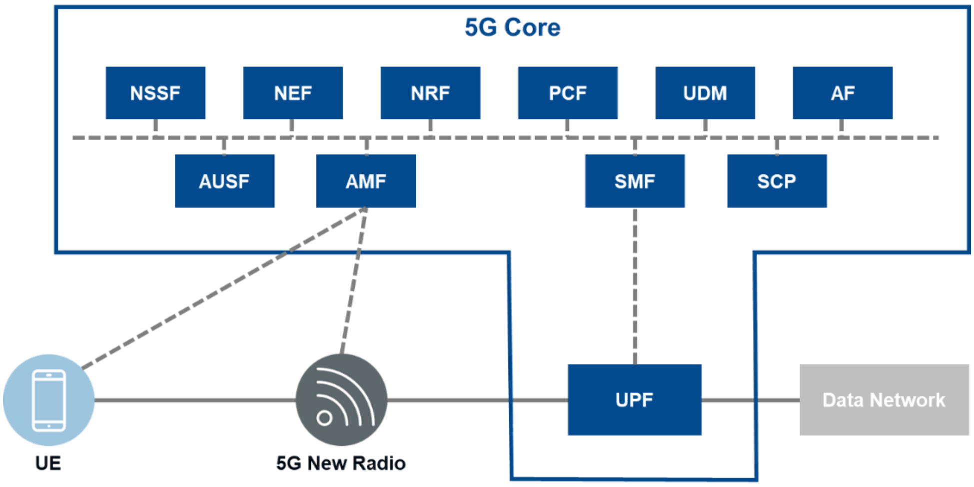
Given that the 2nd version of FRMCS system (FRMCS v2) will be based on 3GPP Release 18 standalone 5G System, it is important to understand 3GPP technologies if one is going to study FRMCS. The 5G System, however, is an intricate system that guarantees carrier-grade reliability and performance and consists of numerous specifications, which is not easy to decipher. In this context, this section provides a high-level summary of 3GPP technologies relevant for FRMCS to facilitate understanding of FRMCS. The standalone (SA) 5G system architecture is described to equip the reader with a basic understanding of 5G System. Then, the innovations in the radio technology that addresses the requirements of FRMCS are outlined. The 3GPP defined mission critical communications is described next so that the reader can understand the Service Stratum solution of FRMCS. Finally, the end-to-end architecture of FRMCS is provided to illustrate how different standards fit together into one FRMCS system.

3.2. 5G Architecture

The 5G SA architecture refers to the Option 2 architecture, where 5G New Radio (NR) base stations are connected to the 5G Core (5GC). The architecture is straightforward in single network case (i.e. the subscriber stays within the coverage of its home operator - Public Land Mobile Network) as shown in Figure 3.

The distinct characteristic of 5G SA compared to previous generations is that it employs SBI (Service Based Interfaces). This facilitates addition of functionalities by not employing traditional point-to-point reference points, and exposure of network capabilities to the 3rd party (party other than the network operators). For the details of the 5G core functions, the reader is recommended to refer to 3GPP TS 23.501 [13].

Figure 3: 5G Standalone Architecture (Reconstructed from [13])



In addition to the network architecture, the concept of Quality of Service (QoS) flow, control of priority, and assurance of QoS is significantly enhanced in 5G compared to 4G. QoS flow is the finest granularity of QoS differentiation in the 5G core network [13]. If two QoS flows have the same QoS Flow Identifier (QFI), the two are treated in the same manner when forwarding traffic. If the two flows have different QFI, one is prioritised over another. For example, a QoS flow that carries IMS signalling (Mission Critical signalling of FRMCS) is prioritized over a QoS flow that carries video streaming media because the IMS signalling will have QFI[4] that is prioritized.

The QFI can take a dynamically assigned value or can be equal to the standardized value of 5G QoS Identifier (5QI). In any case, the QFI is associated with six QoS attributes:

1. Resource type: determines if network resources need to be dedicated permanently for the duration of the flow.
2. Priority Level: indicates the priority in scheduling resources among QoS flows.
3. Packet Delay Budget: defines the maximum delay that a packet may take between the User Equipment (UE) and the User Plane Function (UPF) of 5GC.
4. Packet Error Rate: defines the maximum rate of error of packets, the ratio of packets that have been processed by the sender but not successfully delivered to the receiver.
5. Averaging window: represents the duration over which the guaranteed flow bit rate (GFBR) and maximum flow bit rate (MFBF) are calculated.

[4] This assumes that standardized 5QI (5G QoS Identifier) is used.

6. Maximum Data Burst Volume: denotes the largest amount of data that the 5G access network is required to serve within its packet delay budget.

Assuming that standardized 5QI is used, the MCPTT voice traffic and MCPTT signalling are treated with higher priority and less delay budget than IMS conversational voice traffic and IMS signalling respectively. Furthermore, the MCPTT traffic and signalling are always prioritized over typical internet traffic (email, chat, FTP, live streaming), assuring the QoS by ensuring sufficient resources are dedicated to mission critical applications even in the event of congestion.

As for the control of priority, the concept of Allocation and Retention Priority (ARP) is used. ARP contains information about the relative importance of a given QoS flow [13]. This enables the network to decide if a given QoS flow can be established or modified based on the available resources. It is also possible to decide which QoS flow to release in case of resource limitations as to free up resources for other "higher priority" QoS flows. Parameters such as the ARP pre-emption capability and the ARP pre-emption vulnerability allows a given QoS to obtain resources from another QoS flow with a lower priority, and a given QoS to give up resources in order to admit another QoS flow with a higher priority.

3.3. Innovation in the Radio

3.3.1. NR spectrum bands

3.3.1.1. General

Every mobile communications generation comes with innovation in radio technology when compared with its predecessor. 5G is no exception and it utilizes a variety of spectrum bands, categorized into two ranges called Frequency Ranges (FR): FR1 and FR2. FR1 deals with the low band and mid-band, where coverage is wider, but data capacity is lower than FR2. The FR2, on the other hand, deals with higher bands also known as millimeter Wave (mmWave) in the industry. Consequently, we have reduced coverage but provided a higher data capacity than FR1. The difference between FR1 and FR2 are listed in Table 2.

Table 2: Comparison of FR1 and FR2

Frequency range	Frequency range	Supported channel bandwidth [MHz]
FR1	410 MHz – 7 125 MHz	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100
FR2	24 250 MHz – 52 600 MHz	50, 100, 200, 400

In the context of FRMCS that needs to interwork with GSM-R and/or need to reuse the spectrum already allocated for GSM-R, FR1 is important because the spectrum bands used by GSM-R are within FR1.

Nevertheless, FR2 will also become important for railways as it enables higher data capacity and ultra-low latency required by some mission critical high bandwidth use cases. Given the importance of the spectrum bands, this section will describe the 3GPP work to support spectrum bands in FR1 and FR2 for the Railways.

3.3.1.2. FR1

The 900 MHz band within FR1 is used by GSM-R In Europe, and hence supporting existing GSM-R bands is essential for FRMCS to be deployed. For FRMCS two FR1 spectrum bands have been harmonized, identified in 3GPP as bands n100 and n101. (see Table 3 for details).

Table 3: Spectrum bands used by FRMCS [14]

3GPP band	Frequency range	Duplex mode & Bandwidth
n100	UL: 874.4 - 880 MHz DL: 919.4 - 925 MHz	FDD: 2 x 5.6 MHz
n101	1 900 – 1 910 MHz	TDD: 10 MHz

For railways it is important to support communication for high-speed train scenarios of up to 500 km/h. For this, 3GPP FR1 specifications have been extended to include additional requirements for Radio Resource Management (RRM) and demodulation performance.

In addition, 3GPP specifications support the 5G NR n100 900 MHz band and n101 1 900 MHz band from Release 18 for both Power Class 3 (23 dBm) and Power Class 1 (31 dBm) vehicular UEs (i.e. high-power UE for Rail Mobile Radio). This is in accordance with the European Commission's assignment of these bands for use by railways in Europe.

An innovation important for the migration from GSM-R to FRMCS in the 900 MHz band is the definition of less than 5 MHz Channel Bandwidth options. This is now being adopted by various MNOs and included in the 3GPP NTN specifications as it enables the use of spectrum that previously was blocked by the 5G NR minimum channel bandwidth definition of 5 MHz.

Other future (Release 19) enhancements relevant for FRMCS are the introduction of carrier aggregation and dual connectivity (CADC) for less than 5MHz channel bandwidths and the use of uplink MIMO in bands n100 and n101.

3GPP work is not confined to standards for requirements but also ensuring conformance of the implementations with the standards. The relevant conformance specifications for the high-speed train scenario (up to 500 km/h) were developed by 3GPP for Release 17 [15], with ongoing additional work for less than 5 MHz channel bandwidths.

3.3.1.3. FR2

The 3GPP work on FR2 focuses on supporting the high-speed train scenarios (up to 350 km/h[5]) for spectrum bands up to 30 GHz. This work is distinct from the one of FR1, because the characteristics of FR2 makes it difficult to penetrate the train and therefore the enhancements for FR1 does not apply. The support of FR2 bands in high-speed train scenarios require a high-powered relay device mounted on the roof of the train for use of 5G by train passengers. The conformance work for the support of high-speed scenario with FR2 is still on-going in Release 18. The work focuses on testing the conformance of the high-powered train roof mounted relay device according to the specifications [16].

3.4. Support for Mission Critical Services

3.4.1. General

The FRMCS system assumes the mission critical communications architecture specified by the 3GPP to provide the service stratum.

[5] Not yet possible to support over 350 km/h with FR2 as of 3GPP Release 18.

It is important to highlight that the purpose of 3GPP defined mission critical communications is to provide mission critical reliability and performance demanded by the use cases such as the railways. In addition, the use of global standards-based generic mission critical services addressing various industries enables economies of scale and functional enhancements, leading to better performance and more economic solutions for railways industry. Indeed, railway systems already come with stringent requirements such as the strict tolerance of communication delay in train control system [4].

This section will be devoted to describing the mission critical communications specified by the 3GPP. First, the common architecture for mission critical services is described as the basis, then various services over the common architecture (e.g., MCPTT) are described. The interworking with GSM-R and interconnection and/or migration with other Mission Critical (MC) systems. Finally, the security of MC systems and prospective features for MC systems (i.e. 3GPP Release 18 or beyond) are covered.

It is to be noted that only a subset of 3GPP-defined mission critical capabilities will be supported by FRMCS.

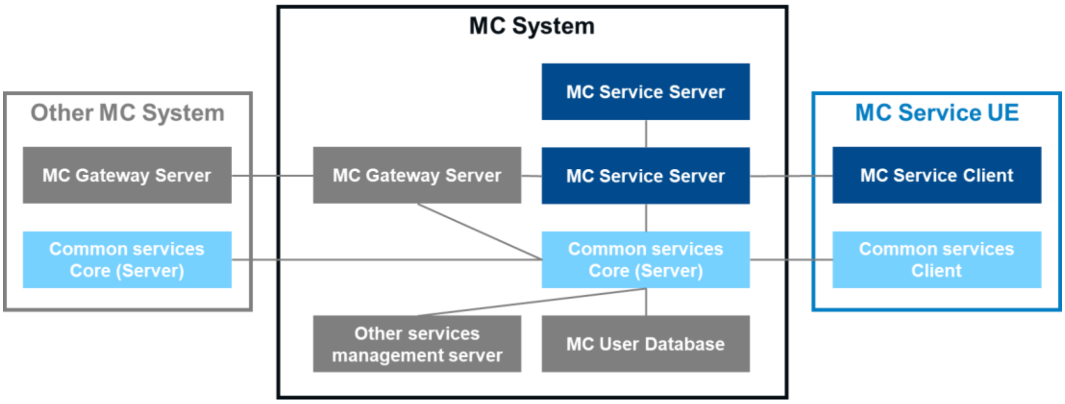
3.4.2. Common Mission Critical Architecture

The 3GPP mission critical communications uses the Session Initiation Protocol (SIP) to support various mission critical services. It is possible to leverage 3GPP's IP Multimedia Subsystem (IMS), also used for operator voice services such as Voice over LTE (VoLTE), or to simply deploy SIP core. The architecture for mission critical services is in 3GPP TS 23.280 [17]. This architecture is the basis for 3GPP mission critical services such as MCPTT, MCData, and MCVideo. The 3GPP mission critical communications architecture consists of the application plane and signalling control plane.

The application plane provides the services required by the user and the necessary functions to support mission critical services. For example, floor control for MCPTT and provision of tones in announcements. The signalling control plane, on the other hand, provides the necessary signalling support to establish the association of users involved in mission critical service. It also controls the access to mission critical services.

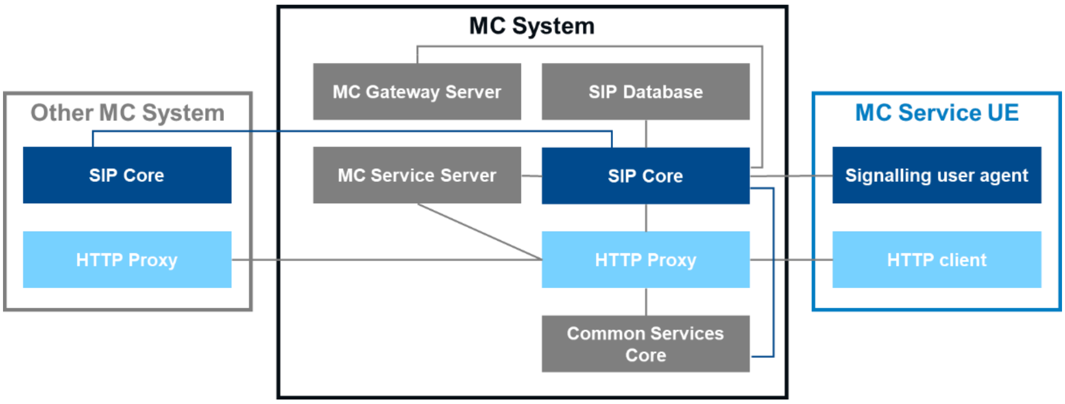
The simplified architecture of the application plane is shown in Figure 4. The MC service server interacts with other MC service servers within the system and with the MC service client in the MC service UE. The common services core deals with features such as group management and identity management, and the server resides in the MC system while the respective clients reside in the MC service UE. The common services core can interact with other services management servers (e.g., group management) and the user database. To connect to other MC systems, the MC service server passes through MC gateway server of the system, which then interacts with the MC gateway server of the other MC system. The common services core can interact directly with the counterparts of the other MC system or access via MC gateway server depending on the type of common services offered. For details, the reader is recommended to consult 3GPP TS 23.280 [17].

Figure 4: Simplified application plane architecture



For the signalling control plane, simplified architecture is shown in Figure 5. The SIP Core (alternatively the core also can be IMS) interacts with the SIP core of other MC systems and Signalling user agent of the MC service UE. Hypertext Transfer Protocol (HTTP) proxies are used in HTTP transactions between the HTTP client and HTTP servers, which are all included in MC service server and common services core but omitted in Figure 5 for simplicity. The SIP core also interacts with SIP database, the MC service & gateway servers, and the common services core. For details, the reader is recommended to consult 3GPP TS 23.280 [17].

Figure 5: Simplified signalling control plane architecture



The common architecture for mission critical service supports various features to meet the requirements of the various mission critical services. First, it supports registration procedures (including authentication and authorization) for MC service users to register to the MC system. The identity management client (abstracted as common services client in Figure 4) communicates to the identity management server (abstracted as common services core in Figure 4) to perform authentication with user credentials (e.g., username and password and biometrics). This can be used for other MC services authorization. Then, the Signalling user agent makes SIP level registration with the SIP core/IMS, completing the registration of the user also on the signalling control plane.

The second feature is group management. It is possible to create a dedicated MC service group of individual MC service users. The group can be used to enable the required communication among these users for one or more MC services. The groups created can be regrouped by authorized users or dispatchers, and it is possible for the changes in group membership to be shared (technically, notified) with the MC service servers and clients. The group management is not restricted within a single MC system but can extend across interconnected MC systems. That is, it is also possible to form MC service group of MC service clients within a partner MC system. For this, the common architecture supports sharing of group configuration information from the primary MC system to the interconnected MC system(s).

Affiliation is a feature related to group management. Whilst affiliation is like groups, it is distinct in that affiliation is an indication of communication interest of the MC service in one or more MC service groups. That is, the user can be affiliated with a group but not necessarily be a member of the group yet. When communication is accepted, the user becomes a (affiliated) group member. The affiliation can be made explicitly and implicitly. In the case of explicit affiliation, the MC service client indicates its interest in one or more MC service groups to the MC service server, either by user's interaction or by an automatic procedure. For implicit affiliation, the user's affiliation is determined through configurations and policies of the MC services and the associated MC service server makes the affiliation.

In mission critical services, it is necessary to manage the role of a particular user. The user may be a general member in a group but may be an authority/dispatcher in another. The different roles in different services/situations need to be managed, and this is achieved using the functional alias feature. Functional alias is a user selectable alias that is tied to the assignment of a task to the user and takes the form of Uniform Resource Identifier (URI). A functional alias can be associated with one or more MC Service IDs (MC service (user) identity), which is a globally unique identifier within the MC service that represents the MC service user. Hence, it is possible for an alias to be associated with one or more MC service users and vice versa. The MC Service ID, then, can be associated with a public user identity (e.g., telephone number - TEL URI, alphanumeric email-like identity - SIP URI), which can be used by another user to request communication with the holder of the identity. In the end, it is possible for MC service users to take different roles on different devices depending on the context setup.

3.4.3. Services over common architecture

Now that the common MC architecture has been covered, the services provided over the architecture should be described. There are three types of services provided over the common architecture. The first is MCPTT, which enables the traditional walky-talky like mission critical voice communications using 3GPP broadband mobile communications technology. Each MC user can request the permission to talk in an arbitrated manner in group calls and it is also possible to engage in private calls between two users [18].

Group communications can be one of the two models. The first is pre-arranged group call, where one of the affiliated group members initiate the call and involve all the group members in the call. The second is the chat group (restricted) call model, where the MCPTT user joins individually a group call without being invited. To participate in the chat group call, the MCPTT user has to explicitly join the call. Other than the two, it is also possible to use group communications for broadcast. The group-broadcast group is defined on MCPTT groups (MC service group in MCPTT context) and allows a user to transmit media one-way (hence broadcast) to the group members.

Note that the group communications can be made off-network (not connected to the MC system) among UEs provided that Proximity Services (ProSe) capability is enabled for the UEs.

Of course, it is possible to setup communications between two MCPTT users. This can be done in automatic commencement mode (does not require receiving user's action) or manual commencement mode (requires receiving user's action). If it is done with manual commencement mode, the floor may be requested by the originator from the start or given to the receiving user from the start without request. Just as in the case of group communications, it is possible to establish off-network private communications between two users, also known as direct mode.

MCPTT comes with the feature of multi-user talker control, where in group communications, the number of simultaneous talkers and the list of users with permission to talk are controlled. This is especially useful in railways in use cases such as shunting. The arbitration is done by the MCPTT server (MC service server for MCPTT) in on-network case and by the currently speaking MCPTT client in off-network case. The latter is delegated to the UE because there is no network connection and hence no MCPTT server to arbitrate.

Just as in conventional voice communications, MCPTT comes with supplementary services such as call forwarding and call transfer. Call forwarding allows incoming private calls to be forwarded to another MCPTT user depending on conditions. For example, the calls can be forwarded only when the caller does not respond. Call transfer allows an existing MCPTT private call to be relocated to another MCPTT user.

While MCPTT comes with more stringent mission critical requirements, calls within MCPTT also have priorities and there are two types of calls that have higher priority than regular MCPTT calls. Emergency communications are communications made to highlight the need for assistance due to a life-threatening situation. It is possible to initiate both private and group emergency communications, where a MCPTT user/group respectively is placed in an emergency state gaining elevated access privilege for MCPTT user's mission critical applications. Note that emergency communications can be made in both on-network and off-network cases. Calls with lower priority than emergency communications but still highlighting the potential of death or serious injury is called imminent peril call. For example, forest fire that is about to encircle campers indicate the event of immediate threat to human lives and hence may require imminent peril call [19]. Private communications, group communications, on-network case, and off-network case are all supported for imminent peril call.

In addition, it is also possible to support ad-hoc group emergency alert and communications. Sometimes, it may be necessary to coordinate the mission critical service users that normally do not work together and do not share any groups in common. For example, there can be a special operation requiring these normally separate users to work together. The ad-hoc group emergency alert and ad-hoc group emergency communications features allow authorized user(s) to combine a set of users into an ad-hoc group satisfying specific criteria to initiate emergency alert and communication within these groups.

Moving on from voice communications, video communications among users (both group and private) is also possible with mission critical services and this is referred to as MCVideo. The MCVideo is, in many cases, a video version of MCPTT. For example, the video group communications take two models of pre-arranged group calls and chat group (restricted) call model. Broadcast group video call, emergency call (private/group), and imminent peril call (private/group) are all supported with MCVideo. There are, however, additional features as MCVideo deals with video media. It is possible to pull/push MCVideo from/to another MCVideo user (can be UE in the field or a video storage server). Finally, it is possible for MCVideo clients to automatically change the video communications parameter with MCVideo adaptation feature. This allows the clients to change parameters such as codec and resolution depending on the network conditions detected through packet loss or packet delay. [20] It is to be noted that FRMCS v2 does not support MCVideo. Video use cases are currently supported using MCData capabilities. It is foreseen to study the technical and economic benefits of MCVideo in later revisions of FRMCS.

Of course, digitalization of mission critical services extends beyond voice and video communications, and transfer of data in a mission critical manner is crucial. MCData service addresses this requirement and enables one-to-one and group data communications between MCData users. Short Data Service capability allows MCData users to exchange messages over the data channel, containing text, binary or hyperlinks. The users can also send a file/data stream or a URL (Uniform Resource Locator) of a file/data stream to another MCData user(s). The delivery can be made in both unicast (one-to-one) and broadcast (one-to-many). The MCData user can track communication messages that are linked to the same topic within group or private data communication with conversation management feature. Using this, the user can view the linked messages in a single thread. It is also possible for MCData users to store their MCData communications permanently in MCData message store. Finally, MCData IP connectivity has been successfully introduced by the Railways to support routing of IP packets in a controlled manner over 5G (to support ATP, ATO and other mission critical data railway applications) [21].

3.4.4. Interconnection and Migration

For FRMCS to work across railway networks, it is necessary for different FRMCS domains or networks to interconnect and be able to migrate respective users from primary to partner FRMCS domains (and vice-versa). The MC systems of 3GPP support such interconnection and migration with partner FRMCS systems.

With MC interconnection, the MC service users from a primary MC system can communicate with other MC service users from the interconnected partner MC system. MC gateway server can be used if network topology needs to be hidden from the partner. For communication, it is possible for the partner MC system to take configuration from the primary MC system to enforce a similar environment as that of the primary MC system. In case where multiple MC systems are involved, the partner MC systems replicate communication media to ensure that MC service group members in these partner MC systems can listen to the MC service users of other MC systems.

With MC migration, it is also possible to migrate MC service users to/from interconnected partner MC system, where migration refers to the MC service user receiving MC service directly from the partner MC system and not from the primary MC system. Of course, it is possible that the 5GS roaming can take place while retaining the primary MC system and therefore migration is not always required in cross-border scenarios. Nevertheless, MC system migration is an important feature when different MC systems are used across the region and continuity of mission critical services need to be maintained.

3.4.5. Interworking with GSM-R

Until the FRMCS system is fully deployed on trackside and in running trains, a migration period has to be considered where both systems – FRMCS and GSM-R – will co-exist. At the end of the migration period, the FRMCS system will replace GSM-R system.

During this migration period, a couple of deployment strategies can be considered. In case where GSM-R only trains run on track sections together with FRMCS only trains (assuming both GSM-R and FRMCS systems coexist on trackside), interworking between FRMCS and GSM-R is required to enable point-to-point calls, group calls, emergency group calls and text messaging services between GSM-R users and FRMCS users. This is realized by means of an InterWorking Function (IWF).

The definition of reference points between the IWF and FRMCS and the interactions between the IWF and FRMCS are specified in 3GPP TS 23.283.

The structure and functionality of the IWF is under drafting by ETSI TC RT.

The IWF acts as an MC service server connecting with the FRMCS MC service server including protocol translation, identity mapping, transcoding, routing and more to be performed by the IWF between the reference points on the FRMCS MC service side and the GSM-R side.

3.4.6. Security

As explained in section 3.4.1, the FRMCS system consists of 3GPP MC services and the underlying 5G transport network.

The 5G System already has relevant security architecture and mechanisms defined in 3GPP and hence these can be followed.

The security model of 3GPP MC systems was primarily designed for Public Safety, with stringent security requirements. The security architecture of Mission Critical Services provides the following signalling and application planes security mechanisms to protect metadata and communications used as part of the MC service (MCPTT, MCData and/or MCVideo):

- Protection of the signalling plane used by the MC Service
- Protection of inter/intra domain interfaces
- Authentication and authorisation of users to the MC Service
- Protection of sensitive application signalling within the MC Service
- Security of RTCP (e.g. floor control, transmission control) within the MC Service
- Security of data signalling within the MCData Service
- End-to-end security of user media within the MC Service

Security mechanisms in the signalling and application planes are independent of each other but may both be required for a secure 3GPP MC system.

FRMCS, on the top of the security mechanisms already foreseen e.g. measures to identify users of the On-Board FRMCS, or TLS encryption, can also inherit from those security protection mechanisms to ensure requested security level.

3.4.7. Prospective features

In Release 19, 3GPP is studying or working on additional features for the mission critical services. First, enhancements to ad hoc group emergency alert and call for group calls such as railway emergency communication is on the way along with location-based services such as mission-critical mobility service based on highly accurate location information. In addition, improving the reliability of mission-critical service and complementing the limited-service mode feature (i.e. the user can use a mission-critical UE without login) are other features that are being worked on. Logging and recording of mission critical communication is also being specified in Release 19. In the RAN domain, 3GPP is working on enabling carrier aggregation and dual connectivity as well as the use of uplink MIMO in the two railway bands n100 and n101 in Release 19.

3GPP has also started studying additional service requirements for railways communication in Release 20. It includes introducing call forwarding for ad-hoc group calls and merging on-going ad-hoc group calls or taking over ad-hoc group calls from another device. Notably, real-time automatic translation of language use cases is being explored in the context of interconnection and migration of mission critical systems. For example, different users of two interconnected mission critical system may engage in conversation without having to speak the same language.

Interested readers are encouraged to explore further details of FRMCS phases and FRMCS SID and WID in 3GPP as described in Annex A.

4. Concluding Remarks

As can be seen from the above, FRMCS is not purely a subsequent generation of GSM-R, but an evolution of GSM-R, enabling digitalization of rail transport by leveraging the 5G system. First of all, FRMCS can exploit the benefits of service-based interfaces in the 5G SA architecture. The 5G QoS flow and control priority mechanisms also ensure that network resources are allocated based on priority to critical communications in the case of network congestion, assuring the mission-critical quality.

The innovations in the radio technology in 5G enables railway operators to keep utilizing also spectrum bands of GSM-R for high-speed trains and ensure coexistence of FRMCS and GSM-R. This is critical as evolution to FRMCS will not happen overnight, and there will be a transitory phase where GSM-R and FRMCS coexist.

3GPP-defined mission critical services provide the necessary solution for FRMCS Service Stratum. The common architecture for mission critical services allows various features such as management of groups, affiliation of users to groups, and the use of functional alias to manage roles of a user. The actual mission critical services supported by the architecture range from voice communications (MCPTT), video communications (MCVideo), and to data communications (MCData). This not only addresses the traditional group voice communications but also extends communications to video media and opens up new data applications in railway communications system.

The FRMCS system can also interwork with legacy GSM-R systems and is able to interconnect with other FRMCS domains/networks to allow communication among users from different FRMCS domains/networks. Moreover, it is possible for a user of a primary MC system to be migrated to another interconnected partner MC system, meaning that the user can receive MC service directly from the partner MC system. As various FRMCS domains/networks are likely to exist (e.g., regionally and nationally), the possibility to interconnect with and connect to other MC systems can address the continuity of MC services in various deployment and cross-border scenarios.

3GPP will continue to work on enhancing the support of FRMCS in the 5G system, and in the subsequent 3GPP technologies such as 6G, in the relevant releases, and these latest advances will contribute even further to improving operational efficiency and performance for railway operators and realizing rail transport digitalisation.

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Annex A. FRMCS Phases and FRMCS SID and WID in 3GPP

As UIC participates directly in 3GPP, works related to FRMCS are separated across releases. This annex provides more details on how FRMCS phases map to different 3GPP releases, and how FRMCS studies and work items in 3GPP are distributed within 3GPP (as of February 2025).

The work on FRMCS started in Release 15, and consequently, phase 1 of FRMCS starts from Release 15. The phase is incremented as the release is incremented. Therefore, FRMCS phase 2 will be in Release 16 of 3GPP, phase 3 in Release 17, and so on. Table 4 shows the mappings more concisely.

Table 4: FRMCS phases and 3GPP releases

FRMCS Phases in 3GPP	3GPP Release
FRMCS_Phase_1	Rel-15
FRMCS_Phase_2	Rel-16
FRMCS_Phase_3	Rel-17
FRMCS_Phase_4	Rel-18
FRMCS_Phase_5	Rel-19
FRMCS_Phase_6	Rel-20

In addition to the mapping, this annex also provides a list of FRMCS related WID and SID that UIC participate in (directly or indirectly). Please see Table 5 for Release 17, Table 6 for Release 18, Table 7 for Release 19, and Table 8 for Release 20.

Table 5: Release 17 SID and WID

WG	Acronym	UID	Title	Rel	WID TDoc
SA6	MCOver5GS	920051	Stage 2 of MCOver5GS	Rel-17	SP-200833
SA6	FS_MCOver5GS	800023	Study on Mission Critical services support over 5G System	Rel-17	SP-200837
RAN4	NR_RAIL_EU_900MHz	911016 (911116) (911216)	Introduction of 900MHz NR band for Europe for Rail Mobile Radio (RMR) (+ core part) (+ perf part)	Rel-17	RP-221768
RAN4	NR_RAIL_EU_1900MHz _TDD	911017 (911117) (911217)	Introduction of 1900MHz NR TDD band for Europe for Rail Mobile Radio (RMR) (+ core part) (+ perf part)	Rel-17	RP-211542
RAN5	NR_lic_bands_BW_R17 -UEConTest	900055	UE Conformance - New Rel-17 NR licensed bands and extension of existing NR bands	Rel-17	RP-202567
RAN5	NR_MBS_5MBS_5MBU SA-UEConTest	950061	UE Conformance - NR Multicast and Broadcast Services including CT and SA aspects	Rel-17	RP-220423
RAN5	NR_HST_FR1_enh-UEConTest	960077	UE Conformance - Enhanced NR support for high-speed train scenario for frequency range 1 (FR1)	Rel-17	RP-221359
RAN5	NR_HST_FR2-UEConTest	960080	UE Conformance - NR support for high-speed train scenario in frequency range 2 (FR2)	Rel-17	RP-221402

Table 6: Release 18 SID and WID

WG	Acronym	UID	Title	Rel	WID TDoc
SA6	IRail	950025	Interconnection and Migration Aspects for Railways	Rel-18	SP-220098
SA6	FS_IRail	880034	Study of Interconnection and Migration Aspects for Railways	Rel-18	SP-200336
CT1	eMCSMI_Irail	980070	Mission critical system migration and interconnection enhancements	Rel-18	CP-223105
SA6	MCGWUE	930017	Gateway UE functions for Mission Critical Communication	Rel-18	SP-210959
SA6	FS_MCGWUE	880033	Study of Gateway UE function for Mission Critical Communication	Rel-18	SP-200335
CT1	MCGWUE	990011	CT aspects of Gateway UE function for Mission Critical Communication	Rel-18	CP-232164
SA1	FS_FRMCS_Ph4	900026	Study on FRMCS Phase 4	Rel-18	SP-220436
SA6	FS_MCAHGC	940022	Study on Mission Critical Ad Hoc Group Communications (AHGC)	Rel-18	SP-211516
SA6	MCAHGC	980051	Mission Critical Ad Hoc Group Communications	Rel-18	SP-221235
CT1	MC_AHGC	1010004	CT1 aspects of Mission Critical ad hoc group communications	Rel-18	CP-232162
SA6	enh4MCPTT	940025	Enhanced Mission Critical Push-to-talk architecture phase 4	Rel-18	SP-211519
CT1	enh4MCPTT	1000020	CT aspects of Enhanced Mission Critical Push-to-talk architecture phase 4	Rel-18	CP-231355
SA6	MCOver5MBS	930016	Stage 2 of Mission Critical Services over 5MBS	Rel-18	SP-210958
CT1	MCOver5MBS	970033	CT aspects of Mission Critical Services over 5MBS	Rel-18	CP-222175
SA6	MCOver5GProSe	940023	Stage 2 of Mission Critical Services over 5GProSe	Rel-18	SP-211517
CT1	MCOver5GProSe	970034	CT aspects of Mission Critical Services over 5GProSe	Rel-18	CP-222176
CT1	MCProtoc18	960009	Protocol enhancements for Mission Critical Services	Rel-18	CP-232163
SA3	MCXSec3	940015	Mission critical security enhancements phase 3	Rel-18	SP-211363
SA6	FS_MCShAC	940020	Study on sharing of administrative configuration between interconnected MC service systems	Rel-18	SP-211514

WG	Acronym	UID	Title	Rel	WID TDoc
RAN4	LTE_NR_HPUE_FWVM_REL18	961012	High-power UE operation for fixed-wireless/vehicle-mounted use cases in LTE bands and NR bands	Rel-18	RP-222872
RAN4	LTE_NR_HPUE_FWVM_REL18	961013	Core part: High Power UE support for NR bands n100 and n101 for Rail Mobile Radio (RMR) in Europe	Rel-18	RP-221878
RAN1	NR_FR1_lessthan_5MHz_BW	941012	NR support for dedicated spectrum less than 5MHz for FR1	Rel-18	RP-231713
RAN4	NR_FR1_lessthan_5MHz_BW	941012	NR support for dedicated spectrum less than 5MHz for FR1	Rel-18	RP-231713
RAN4	NR_FR1_lessthan_5MHz_BW-Core	941112	Core part: NR support for dedicated spectrum less than 5MHz for FR1	Rel-18	RP-231713
RAN4	NR_FR1_lessthan_5MHz_BW-Perf	941212	Perf part: NR support for dedicated spectrum less than 5MHz for FR1	Rel-18	RP-233963
RAN5	LTE_NR_HPUE_FWVM_R18-UEConTest	1000059	UE Conformance - High-power UE operation for fixed-wireless/vehicle-mounted use cases in LTE bands and NR bands (including n100 & n101)	Rel-18	RP-231429
RAN5	NR_FR1_lessthan_5MHz_BW-UEConTest	1030060	UE Conformance - NR support for dedicated spectrum less than 5MHz for FR1	Rel-18	RP-240044

Table 7: Release 19 SID and WID

WG	Acronym	UID	Title	Rel	WID TDoc
SA1	FRMCS_Ph5	1000031	FRMCS Phase 5	Rel-19	SP-230512
SA1	FS_FRMCS_Ph5	950007	Study on FRMCS Phase 5	Rel-19	SP-220437
SA6	enhMC	1000039	Enhanced Mission Critical Architecture for Rel-19	Rel-19	SP-230988
SA6	FRMCS_Ph5	1000038	Railways specific Enhancements to Mission Critical Services	Rel-19	SP-230780
SA6	FS_SensingAPP		New SID for study on Sensing enabler for vertical applications	Rel-19	S6-232777
SA6	FS_AL_ATSSS		Study on application layer support for ATSSS	Rel-19	S6-232538
SA6	FS_5GSAT_Ph3_App	1020053	Study on application enablement for Satellite access enabled 5G Services	Rel-19	S6-232776
CT1	enhMCLoc		Enhanced Mission Critical Location Management	Rel-19	CP-241152
CT1	MCProtoc19		Protocol enhancements for Mission Critical Services	Rel-19	CP-241148
SA3	FS_UIA_Sec	1030032	Study on security aspects of User Identities and Authentication	Rel-19	SP-240507
SA3	MCXSec4	1020035	Mission critical security enhancements for release 19	Rel-19	SP-231783
SA6	MCShAC	1000036	Sharing of administrative configuration between interconnected MC service systems	Rel-19	SP-230692
RAN4	NR_FR1_lessthan_5MHz_BW_Ph2	1030081	NR channel BW less than 5MHz for FR1 Phase 2 - Core part	Rel-19	RP-241495
RAN4	NR_FR1_lessthan_5MHz_BW_Ph2	1030081	NR channel BW less than 5MHz for FR1 Phase 2 - Performance part	Rel-19	RP-241495

Table 8: Release 20 SID and WID

WG	Acronym	UID	Title	Rel	WID TDoc
SA1	FS_FRMCS_Ph6	1030043	Study on FRMCS Phase 6	Rel-20	SP-240199

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