

Integrating FRMCS: Enhancing rail communications with 5G technology

Content

Introduction	3
GSM-R - FRMCS coexistence challenge in 900 MHz	5
Leveraging 5G key features for efficient rail track coverage	8
Sharing radio with CSPs to Optimize Deployments	11
Key takeaways	13
Glossary	14
References	16
Authors	17

Introduction

Countries worldwide are strategizing to increase the share of rail in transporting people and goods to develop more sustainable transportation systems. They recognize that rail is the most sustainable, innovative, and secure mode of transportation today and will remain so in the foreseeable future. For passengers, rail travel is the safest option, as indicated by the extremely low fatalities per billion passenger-kilometers (km) compared to those suffered by road travelers. With more than 200,000 km of railway lines in the USA, about 150,000 km in Europe, and more than 100,000 km in India, businesses and freight carriers can benefit from low-cost and increasingly competitive transportation solutions while reducing their carbon footprint.

High-speed train travel is possible only with automatic train control. A train driver without such control would lose situational awareness and not react fast enough at speeds above 180 km/h. In Europe, the standard railway control-command and traffic management system is the European Train Control System (ETCS). This system is currently enabled by the global system for mobile communications–railway (GSM-R), and its standardization has been primarily driven by the International Union of Railways (UIC). Despite the success of GSM-R, it is becoming obsolete [\[1\]](#) due to the technological advances in mobile communications, the widespread use of broadband services, and the rapid deployment of 5G cellular networks. Recognizing the need to gradually replace GSM-R with modern technology, the UIC has decided to lay the foundation of the 5G future railway mobile communication system (FRMCS). [\[2\]](#) The main goal of FRMCS is to fully digitalize railway operations, support increasingly automated train operations (ATO), and embrace the possibilities offered by 5G, without creating a railway-specific cellular network technology. Additionally, FRMCS is also designed to be cost-effective and future-ready, ensuring compatibility and enabling an effortless migration from GSM-R.

FRMCS trials are scheduled for 2026 with parts of the system mature enough for initial deployment. The FRMCS European testing and validation program (MORANE 2) is set to conclude in 2027, which will also mark the finalization of the first edition of FRMCS, also known as FRMCS V3. This milestone will verify the maturity of the specifications, including dedicated rail spectrum band specifications and the sharing of communication service provider (CSP) bands, as well as demonstrate product interoperability of FRMCS components. MORANE 2 is not only relevant for standardization efforts but also signifies the beginning of the FRMCS rollout, starting the large transformation from GSM-R to FRMCS for automatic train control, as illustrated in Figure 1.

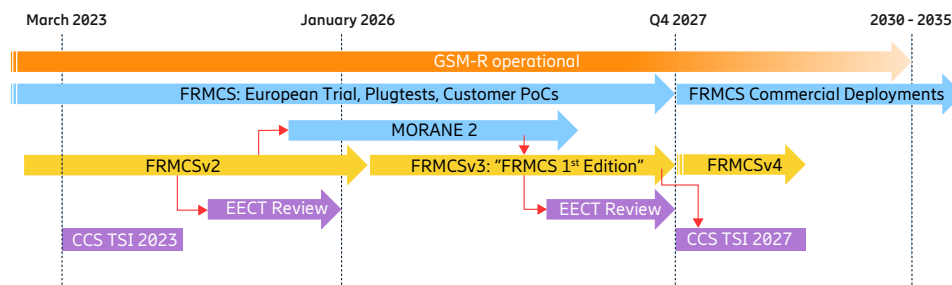


Figure 1: Timeline of FRMCS and GSM-R deployment, trials, and standardization [3]

Deploying the mission-critical FRMCS is a challenging and costly undertaking. There are several options for doing so, especially since it needs to be implemented while GSM-R remains operational and occupies part of the 900 MHz spectrum band that will eventually be used for FRMCS. Leveraging the extensive features of 5G NR effectively in the new, unoccupied 1900 MHz railway spectrum band, and collaborating with CSPs as necessary, provides a cost-effective and future-proof way to begin deploying FRMCS alongside GSM-R and expanding it in the long run.

GSM-R - FRMCS coexistence challenge in 900 MHz

Many rail applications, such as the European train control system (ETCS) and automatic train operation (ATO), are essential to the future operation of rail transportation. Therefore, mobile networks must provide sufficient capacity along the entire rail route where these applications are used, particularly at cell edges. Furthermore, a mobile network failure would be detrimental to modern, digitized rail traffic (as seen with GSM-R failures). It is therefore essential to incorporate redundancy and failover mechanisms into the mobile network design, including redundant coverage and network components of FRMCS.

Considering the extensive amount and length of rail tracks and the achievable inter-site distance (ISD) with the given spectrum, deploying FRMCS is both challenging and costly for railway infrastructure managers. These challenges get more complicated with stringent resilience requirements and the corresponding need for redundant deployments.

With two spectrum bands (n100 and n101, see Figure 2) allocated to the railways by the ECC [\[4\]](#), FRMCS can be deployed redundantly using these bands. However, GSM-R is currently using parts of the n100 spectrum. While there are solutions for FRMCS and GSM-R to coexist in the same spectrum, this will always result in a less efficient use of the spectrum compared to having only a full NR carrier for FRMCS.

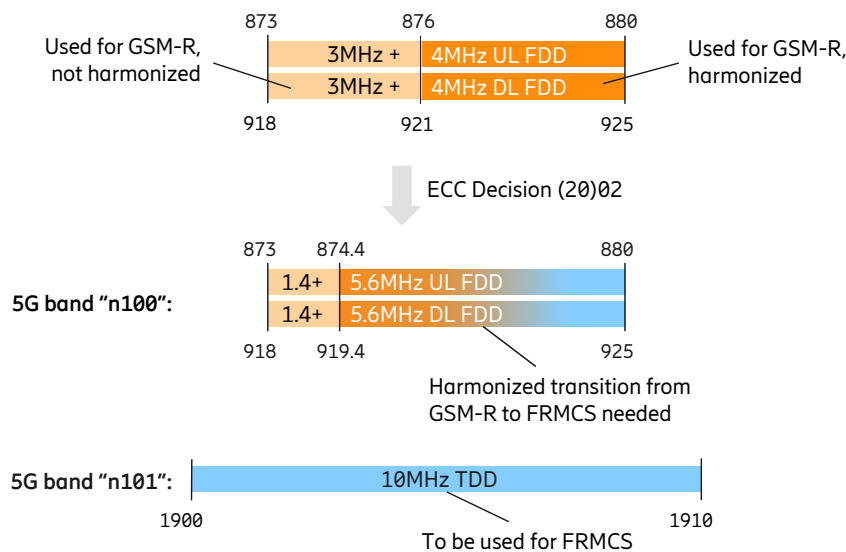


Figure 2: Rail spectrum allocation in Europe

With all these challenges, the performance requirements, including load and latency, are moderate for the basic services that FRMCS must support, which aim to replace GSM-R. However, FRMCS provides significant potential to enhance rail operations. Higher grades of automation and remote train operation require critical video and sensor communication. Additionally, video surveillance as well as other complementary applications can be enabled when more capacity is available, such as by using public networks outside the railway-owned spectrum.

FRMCS deployment strategies: A proper preliminary radio-network design is essential to identify an optimal FRMCS deployment approach. Generally, initial FRMCS deployment coexisting with legacy GSM-R coverage should focus on using the full n101 band for initial coverage, while in regions where GSM-R is not implemented, n100 allows for a more cost-effective deployment. More specifically, band n101 should be deployed as a full 10 MHz TDD carrier with 30 kHz subcarrier spacing (SCS) to achieve improved performance at high train speeds compared to 15 kHz SCS. For redundancy, existing GSM-R coverage should be prioritized where available and later replaced by a full 2x5 MHz FDD carrier in n100 when GSM-R phases out and n100 products gain market traction. Deploying multi band antennas that already support n100 and n101 reduces effort, since n100 can be added later with minimal additional work.

Where GSM-R is not available and the n100 band does not allow cost-effective FRMCS deployment, collaboration with CSPs should be pursued to provide redundant connectivity over one or more public networks. Collaborating with CSPs to that end enables more advanced architectures that integrate well into the dedicated railway 5G Core network, as opposed to using public networks as normal subscribers. Furthermore, working with CSPs to provide seamless coverage along rail tracks with their spectrum not only benefits the resilience of FRMCS but also provides the throughput needed for video-based applications. Many railways are also planning CSP-based FRMCS coverage for regional lines where the volume of traffic does not make dedicated coverage economically feasible. The ubiquitous connectivity to train passengers and hybrid deployment models promise to enable a more cost-effective deployment compared to two separate stand-alone networks.

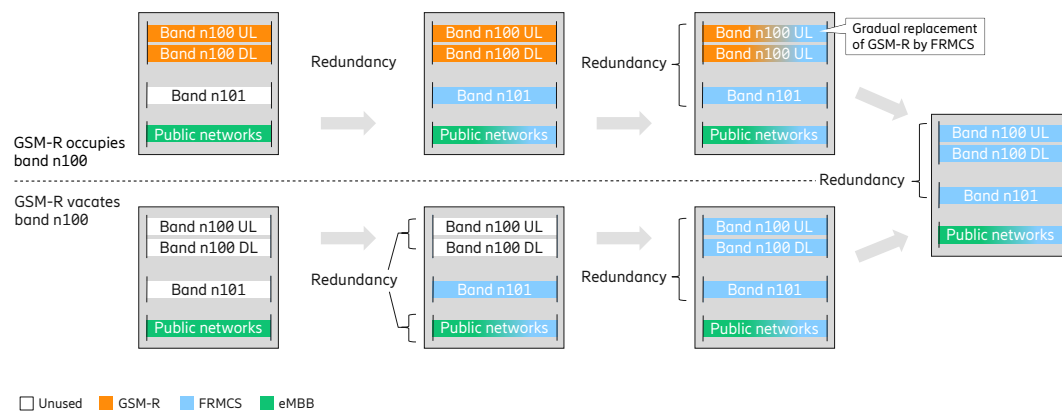


Figure 3: Recommended sequence of FRMCS deployment with GSM-R, various bands, and public networks

To reduce the significant cost pressure for FRMCS deployments, existing infrastructure can be reused in many cases—particularly the radio sites from GSM-R deployments. Although band n101 exhibits greater path loss than the spectrum used by GSM-R, which might suggest a need for a shorter ISD and thus additional radio sites, the advanced features of NR mitigate this effect. Depending on the specific deployment, only a few additional sites on top of reused GSM-R sites are typically needed to achieve full coverage along the rail tracks. As a result, deploying FRMCS in band n101 can be approximately as cost effective as deploying it in band n100 on an existing GSM-R grid.

Leveraging 5G key features for efficient rail track coverage

The choice of base station configuration plays an important role in determining ISD: a larger ISD reduces both build and operational costs. Choosing the appropriate antennas for FRMCS will be important to maximize coverage and capacity. For track coverage, highly directional antennas with narrow horizontal beamwidths can maximize signal levels along the track and control interference to and from other FRMCS cells or networks. Antennas can be configured back to back with two separate radios or with a single radio serving both directions. In large station deployments where multiple tracks converge, wider beam antennas can be used, with careful attention to site placement and antenna design to meet higher traffic demands. Tunnel coverage can be achieved either with leaky feeder (fed by radio units) or with radio units using lower profile antennas that fit within tunnel constraints. Ideally, leaky feeders should support MIMO to maximize bit rates.

Additional antenna ports can be used to maximize coverage and site spacing. It is expected that 2-, 4- and 8-port antenna will be used for FRMCS. Usually, all antennas will be contained in a single package. Using 4- or 8-port antennas also offers benefits such as beamforming and uplink interference rejection combining.

Figure 4 provides an example of the ISD for different base station configuration choices with moderate loading. ISD was calculated assuming a required cell-edge uplink bitrate of three Mbps. This target was chosen based on two trains passing at the cell edge using one Mbps each, with additional capacity available for trains closer to the cell site.

The first three results show the benefits of using more base-station antennas in a suburban environment. The last three results show the same base-station configurations in a rural environment. For each case, the achievable downlink cell-edge bitrate is also shown. ISD increases over 2T2R by 20 to 25 percent per doubling of base-station antennas.

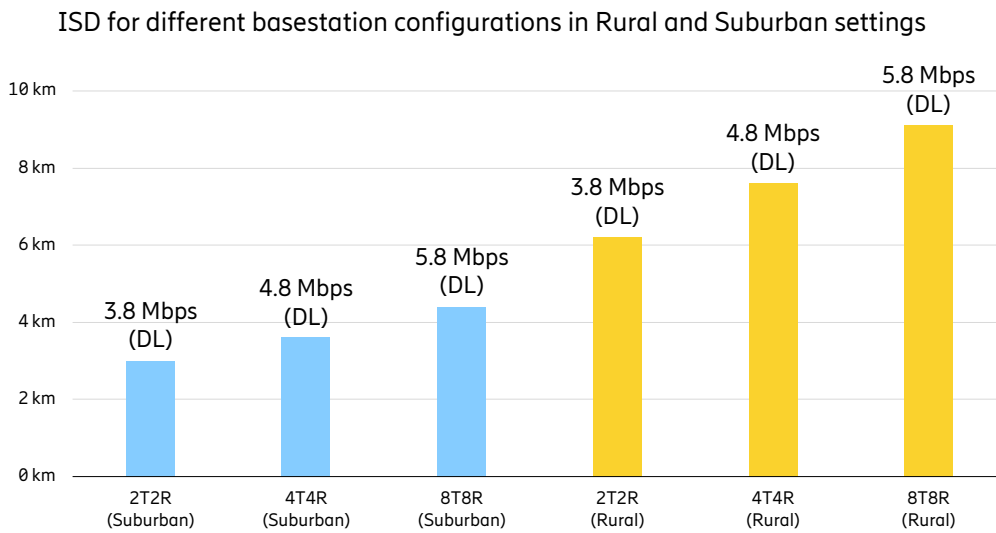


Figure 4: Required ISD to achieve three Mbps UL throughput and given DL throughput for different antenna capabilities and in different environments.

For GSM-R, radio equipment was typically housed in shelters at the base of towers. For FRMCS, however, placing radio units at the top of the mast, close to the antenna, has advantages. This placement reduces the feeder loss (by 2-4dB) and ultimately optimizes the RF performance enabling larger inter-site distance (approximately 20 percent larger). Although maintenance costs for radios at the mast top may be higher, this is largely offset by the lower site density required.

The FRMCS 5G RAN architecture also allows deployment of a centralized RAN (C-RAN), as shown in Figure 5. In this model, a baseband unit (BBU) is deployed centrally for each 30 km section of track. Each BBU is connected to the radio sites in its section using optical fronthaul, minimizing the number of BBUs and backhaul connections needed in the network. Furthermore, this facilitates advanced interconnection between BBUs for features that enhance mobility and improve cell-edge coverage.

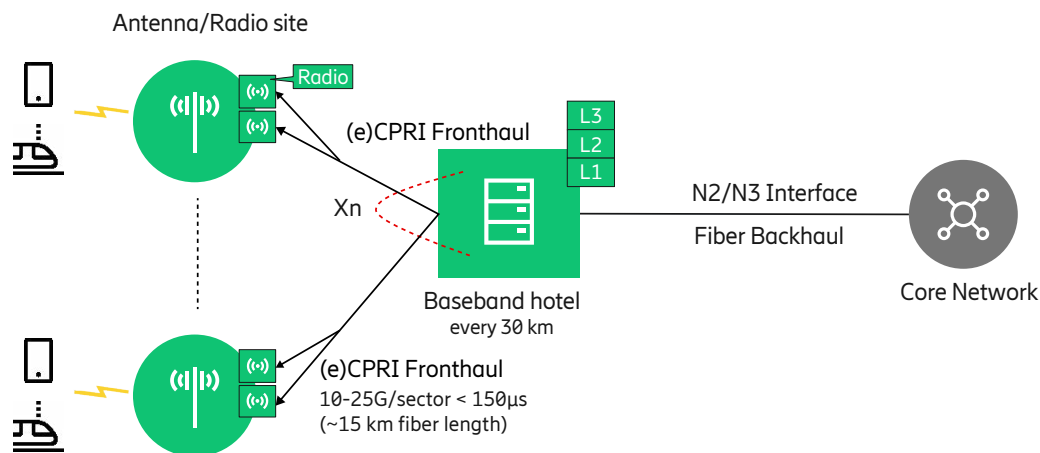


Figure 5: Centralized RAN architecture

For the potential railway deployments described above, 5G NR supports a wide range of configurations and features to enable efficient and reliable FRMCS. Below are a few examples:

1. 30 kHz subcarrier spacing in 5G is an ideal match for the high-speed railway deployment in the n101 band, and generally in the mid band, due to the shorter slot duration.
2. Support for three and four DMRS symbols in a slot enables accurate channel estimation in high-speed railway scenarios.
3. NR supports flexible TDD patterns and allows for the optimization of a TDD pattern for band n101 that achieves the desired UL and DL performance.
4. 5G supports mobility features such as lower-layer mobility (e.g., dynamic point selection) and conditional handover, which can be utilized in railway deployments to minimize service interruptions.
5. 5G offers a rich set of on-demand and flexibly configurable reference signals, CSI feedback modes, and MIMO schemes to maximize spectrum utilization in different railway scenarios.
6. UL-CoMP/joint reception for improved UL coverage.

Sharing radio with CSPs to Optimize Deployments

While railway infrastructure managers will primarily rely on a dedicated 5G system using the dedicated rail spectrum, there are two reasons to collaborate with CSPs for a hybrid network deployment:

1. integration of public networks for redundancy and additional capacity, and
2. cost sharing

While redundancy can also be achieved using only dedicated network components, leveraging CSPs' existing infrastructure is much more cost-effective, especially when integration is driven by the need to increase the capacity available to trains.

For cost sharing, the primary focus is on sharing passive infrastructure such as towers, fiber, and power, although active components can be shared in some cases.

Generally, there are three ways to integrate a public network into the dedicated railway network [5]:

1. Multi-operator core network (MOCN): a radio site is shared between the core networks of both the railway-dedicated network and the CSP's public network [6]. This requires a dedicated backhaul from each shared BBU site to the FRMCS core, but it avoids dependency on the CSP core network and is therefore more resilient and secure. In MOCN, the UE can build neighbor lists based on the railway-dedicated radio sites and the CSP sites, facilitating seamless handover between them.
2. National roaming: this allows a train to move between networks that provide radio coverage in the train's current location while remaining connected throughout the journey, with only short interruptions during transitions. This follows the home-routed roaming model, where data is routed via the CSP's core network. Only the core networks need to be integrated; however, this involves many control interfaces and is not a simple task. Using the public networks is fully dependent on the CSPs' core network being operational.
3. Subscriber model: a second UE connects to the public network with a separate SIM card, fully independent of the dedicated rail network. While there is no integration effort between the dedicated and public networks, mobility between the networks must be facilitated by a function that treats both networks as separate IP paths. Integrating mission-critical services with both core networks is necessary, which increases complexity outside the networks.

Irrespective of the option used, it is possible to utilize both the railway dedicated network and the CSP's network simultaneously by using more than one UE on the train, each with its own SIM card and subscriber profile. FRMCS multipath can leverage these connections to provide additional enhancements to the train's connectivity, such as the ability to dynamically switch an application's connection from one UE to another if the connection through one UE fails or experiences degraded quality. Using multiple UEs simultaneously can also increase the overall capacity of the train's connectivity by aggregating the available capacity of the individual UE connections.

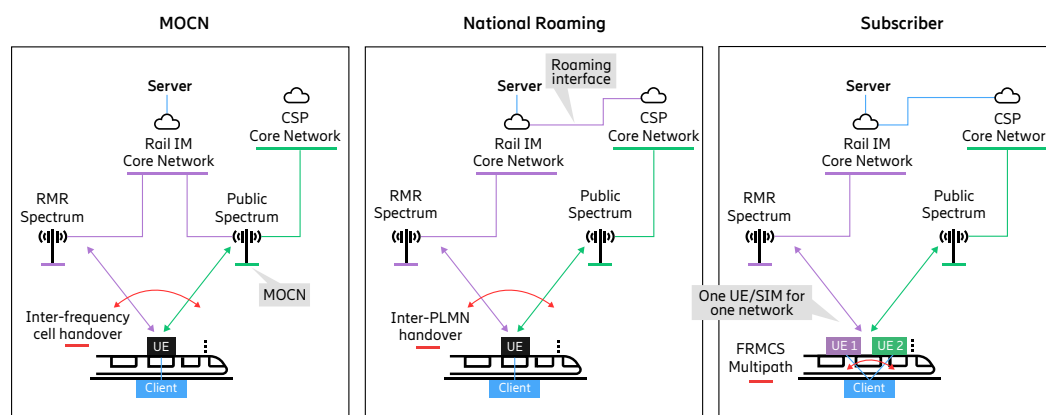


Figure 6: Architecture of deployment options for integrating public network access

Key takeaways

FRMCS deployment strategy: Start with a proper preliminary radio network design to evaluate the best FRMCS deployment approach. Except for specific greenfield tracks, initiate roll out of band n101 equipment—where GSM-R is present and n100 cannot provide a cost effective solution—using the right features to provide the required connectivity along rail tracks. For redundancy, continue using GSM-R and public networks where feasible. Avoid deploying n100 with less than 5 MHz bandwidth adjacent to GSM-R. To optimize cost, collaborate with CSPs to improve coverage for passenger connectivity, which can also support FRMCS. Reuse existing GSM-R infrastructure wherever possible.

5G key features: A set of key features, particularly in the 5G RAN can significantly enhance the coverage on long rail tracks when used effectively. Such as: multi-TRP, beamforming, MIMO, doppler compensation, conditional handover, access barring, and QoS mechanisms.

Integration with public networks: While railway infrastructure managers must build parts of a dedicated 5G system for mission critical rail operations, it is beneficial to leverage CSP networks for higher resilience and additional capacity. Options include MOCN integration for straightforward failover scenarios or FRMCS multipath for more flexible use of multiple UEs and networks.

Reuse and share infrastructure: Many countries already have infrastructure from GSM-R and other networks—masts, fiber, and power. Reusing these assets wherever possible reduces the investment needed to deploy FRMCS. Collaboration with CSPs (and among CSPs) to extend coverage along rail tracks—for FRMCS or passenger services—will further lower the required investments.

Glossary

ATO	Automatic train operations
BBU	Baseband unit
BS	Base station
CCS	Command control and signaling
CEPT	European conference of postal and telecommunications administration
CPRI	Common public radio interface
C-RAN	Centralized RAN
CoMP	Coordinated multi-point
CSI	Channel state information
CSP	Communication service provider
dB	Decibel
DL	Downlink
DMRS	Demodulation reference signal
ECC	Electronic communications committee
EECT	ERA extended core team
eMBB	Enhanced Mobile Broadband
ERA	European union Agency for railways
ETCS	European Train Control System
FDD	Frequency division duplex
FRMCS	Future rail mobile communication system
GSM-R	Global system for mobile communications – Railway

IM	Infrastructure manager
IP	Internet protocol
ISD	Inter-site distance
Mbps	Megabits per second
MC	Mission critical
MIMO	Multiple Input Multiple Output
MOCN	Multi operator core network
MORANE	Mobile radio for railways networks in Europe
NR	New radio
PLMN	Public Land Mobile Network
PoC	Proof of concept
QoS	Quality of service
RAN	Radio Access Network
RF	Radio frequency
RMR	Railway mobile radio
SCS	Subcarrier spacing
SIM	Subscriber identity module
TDD	Time division duplex
TRP	Transmission and reception point
TSI	Technical specification of interworking
UE	User equipment
UIC	International Union of Railways
UL	Uplink

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