FRMCS: Enabling smarter and safer railway operations

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CONTENTS

KEY TAKEAWAYS

- Railways must evolve into highly connected ecosystems, to strengthen safety, enhance efficiency of operations, increase rail network capacity and resiliency, change the train experience, and to optimize their costs. This is a radical transformation for railways, as it is not just about modernizing legacy systems, but it is also about unlocking new possibilities for sustainable and intelligent transportation.
- FRMCS builds on 3GPP-based 5G standalone and mission-critical (MCX) architectures to support the new European train control systems (ETCS) as a replacement for GSM-R. GSM-R is a technology that is moving towards its end of life which is expected within the next decade. It is a narrowband technology, and therefore it cannot support the new needs of railways such as high-speed data transmission for instance by real-time video monitoring or support for larger number of devices as well as the integrated use of AI in areas such as automation.
- To support the railway operators' higher performance requirements in terms of bandwidth, latency, or number of devices, the International Union of Railways (UIC) in collaboration with various stakeholders such as ETSI and 3GPP, initiated the development of the Future Railway Mobile Communication System (FRMCS), which in its FRMCS V3 is expected to be completed by 2027.
- FRMCS brings an architectural shift to railways operators. GSM-R was created as a vertically integrated system including connectivity and applications. This meant that any changes in the application layer required a change in the GSM-R core, nearly impossible due to its imminent obsolescence. Instead, with 5G at the foundation of FRMCS the new standard is not tied to specific vertical applications and consequently, it enables more flexibility in deployment and application adoption.

RECOMMENDATIONS

1. **Leverage FRMCS for broader transformation.** Railways should plan their FRMCS investments to support core use cases like Automatic Train Operation (ATO), emergency calls, trackside alarms, voice communications, and signaling. The 5G foundation also enables smart station initiatives such as digital kiosks and enhanced passenger connectivity.

2. **Stage the FRMCS transition.** Railways should adopt a phased transition to ensure continuous operations. Because FRMCS uses 5G technology, operators can begin deploying connectivity immediately, enabling incremental investments rather than requiring a single, large-scale commitment.

3. **Plan early for FRMCS-GSM-R interoperability.** Railways should prepare now for gradual FRMCS adoption beginning around 2027, ensuring interoperability between FRMCS and GSM-R. This careful approach will allow gradual migration of existing applications and the phased introduction of new services, with both networks operating concurrently for several years.

Introduction to the railway industry

Railway transportation has been a cornerstone of global mobility and economic progress for over two centuries. It remains one of the most efficient, sustainable, and reliable means of moving people and goods across vast distances. As the backbone of modern infrastructure, railways play a pivotal role in reducing road congestion, lowering carbon emissions, and enhancing trade connectivity. Today, the growing importance of railway transportation is underscored by the increasing urbanization, climate-conscious policies, and rising demand for fast and seamless travel experiences.

Railways are at the forefront of governments' focus, with governments investing heavily in expanding and modernizing railway networks to meet these demands. These ambitious initiatives aim to create a sustainable, safe, and modern transport industry. The perfect example of this global trend is the European Union's ambitious plan to double passenger transport by 2030 and freight transport by 2050, highlighted in its official "European Year of Rail" program strategy in 2021. Other initiatives are unfolding across the globe, including India's Dedicated Freight Corridor, and China's Belt and Road, and similar initiatives in North Africa and Latin America that highlighting the universal recognition of railways as a basis of future transportation systems.

TRENDS IN RAILWAYS: THE EVOLUTION OF RAILWAY COMMUNICATIONS

The railway industry is on the cusp of undergoing a profound technological transformation, driven by the advancements in connectivity, digitalization, and automation. Traditional systems, supported by multiple disjointed technologies and manual processes, are being replaced by cutting-edge solutions that leverage broadband connectivity. As railways evolve into highly connected ecosystems, this transformation is not just modernizing legacy systems but also unlocking new possibilities for sustainable and intelligent transportation, setting the stage for a future where railways become faster, safer, and more passenger-centric than ever before.

This transformation is laying the foundation for the intelligent railway systems of tomorrow, promising a complete paradigm shift in how railway networks are conceived and operated.

Figure 1: Signals for change – technology transformation of railways

1. **Operational Digitalization** (from 2G GSM-R to 5G FRMCS)
2. **Advanced signaling**
3. **Connected drivers & on-board staff**
4. **Connected passengers**
5. **Connected stations** (staff, IoT, CCTV, infotainment, etc...)
6. **Efficient asset tracking**

SOURCE: OMDIA

The motivation behind this technological shift is multifaceted. The modernization of railway communication systems is driven by the growing need to enhance safety, optimize operations, and provide compelling passenger services. Below is the vision propelling this transformation:

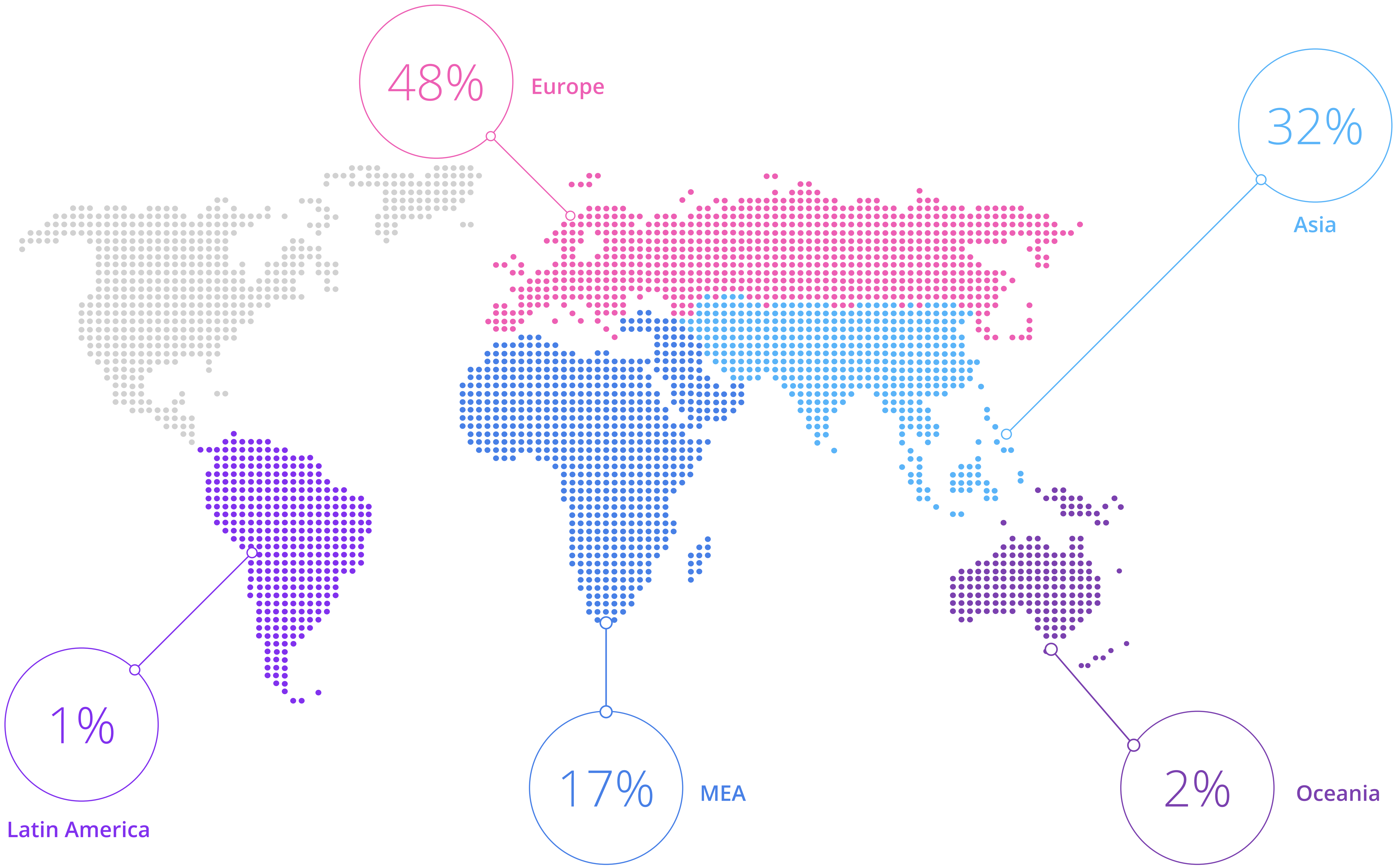
- **Strengthened safety:** Safety remains the foremost priority in railway operations. Advanced communication systems are pivotal in achieving safer operations for passengers, staff, and infrastructure.
- **Enhanced efficiency:** Boosting the reliability of operations and maintenance procedures and ultimately supporting fully automatic train operations (ATO). Efficiency is crucial for railways to maximize capacity and deliver reliable services.
- **Increased rail network capacity:** Advanced communication technologies facilitate the minimization of headway between trains, improving track utilization and throughput. Seamlessly integrating these factors ensures higher capacity, fewer bottlenecks, and a more sustainable railway network addressing rising demand in urban, regional, and high-speed railway corridors.
- **Improved capabilities:** FRMCS enables higher cruising speeds, supports fully driverless operation, and helps identify faults early using onboard analytics. It also provides stronger protection against failures and cyber threats—making railway operations smoother, safer, and more reliable beyond just increased track capacity.
- **Cost optimization:** The modernization of railway communication systems allows operators to streamline expenses while simultaneously improving service quality. Digitalization enables predictive maintenance, reduces downtime, and enhances energy efficiency: ensuring that railway networks can operate more cost-effectively while delivering superior performance.
- **Passenger-centric approach:** To remain competitive and attract passengers, railways must offer innovative services and an enhanced travel experience. Although FRMCS doesn't directly address passenger communications, it is based on a 5G SA private wireless network that can be extended on its own to guaranteeing comfort and an enhanced experience for railway users.

APPROACHING THE END OF LINE: GSM-R SYSTEMS OBSOLESCENCE

Achieving these ambitious goals is only possible with reliable rail traffic management systems and effective train control systems (TCS). For decades, the railway industry has relied on robust and specialized communication systems to ensure safe and efficient operations. Dominating among these is the European TCS (ETCS), which relies on the Global System for Mobile Communications-Railway (GSM-R), a dedicated communication standard designed specifically for railways.

GSM-R has been instrumental in supporting critical functions like voice communication, signaling, and train control for more than three decades. However , its technological limitations are becoming increasingly apparent in the face of modern operational demands. As the demands of evolving railway operations increase, it has become apparent that more advanced communication technology is required.

Figure 2: Regional share of the total deployed ETCS railway systems worldwide



SOURCE: OMDIA **NOTE:** EUROPEAN RAIL TRAFFIC MANAGEMENT SYSTEM, IS A SYSTEM OF STANDARDS FOR MANAGING AND CONTROLLING RAILWAY SIGNALING ACROSS EUROPE AND OTHER GLOBAL REGIONS.

KEY CHALLENGES OF GSM-R SYSTEMS:

Limited bandwidth: GSM-R operates on narrowband technology, which cannot support the growing demand for high-speed data transmission required by advanced applications such as real-time video monitoring and predictive maintenance.

Incompatibility with emerging technologies: GSM-R is based on 2G GSM circuit-switching technology to enable voice communications and limited data transmissions. As the Internet of Things (IoT), artificial intelligence (AI), and automation gain traction in railway operations, legacy systems lack the capability to integrate seamlessly with these technologies, hindering innovation.

Vertical integration by design: GSM-R tightly couples its hardware, software, and applications which limits flexibility. As a consequence, introducing upgrades or modifying existing functionalities often requires deep-level changes to the underlying communication platform, making upgrades costly and time-consuming for railway operators.

Cybersecurity vulnerabilities: Older communication systems are increasingly susceptible to cyber threats, posing risks to both operational safety and passenger security.

Inability to meet passenger expectations: Modern passengers expect reliable connectivity and real-time information during their journeys. Legacy systems could not deliver these services effectively.

End-of-life risk: GSM-R uses 2G cellular technology, which is globally being phased out. Declining vendor support will make spare parts and expertise increasingly scarce and costly, jeopardizing maintenance and the reliability of critical train control and signaling systems.

GSM-R is rapidly approaching the end of its lifecycle, and the railway industry has already acknowledged GSM-R's obsolescence, no longer capable of supporting the long-term objectives of railway operators. Omdia has observed GSM-R technology well in its maintenance stage and predicts it will reach its end-of-life in the new decade.

While the primary drivers toward this digitalization upgrade are the significant operational improvements enabled by modern technology, this impending sunset of GSM-R acts as a forcing function, compelling railways to transition towards next-generation communication systems that align with the broader vision of smarter, more efficient, and future-proof railway networks.

FRMCS – Future Railway Mobile Communication System

DEFINING THE FUTURE RAILWAY MOBILE COMMUNICATION SYSTEM

The International Union of Railways (UIC) initiated the Future Railway Mobile Communication System (FRMCS) program as a GSM-R replacement. FRMCS was initially led and developed for European railway networks, but it has soon captured the interest of global railway operators beyond Europe (e.g., Australia). FRMCS was set up to provide railways with a standardized, future-proof communication solution capable of supporting advanced rail operations and services.

FRMCS builds on 3GPP-based 5G standalone and mission-critical (MCX) architectures to support the new ETCS as a replacement for GSM-R. Additionally, FRMCS aims to converge railway operators' different wireless communication needs under a single technology. This includes, among other services, multimedia agile dispatch, video and multimedia services, operating data management, predictive maintenance for enhanced efficiencies. FRMCS aims to create a comprehensive, integrated communication platform for modern railway networks.

FRMCS's key performance highlights include the decoupling of its network and service, the use of standard IP interfaces for rapid new service deployments, and a modular foundation design for wireless technology to facilitate its evolution path. It also offers multiservice capability and stable RF coverage in high-speed scenarios. These features ensure that FRMCS can adapt to future technological advancements and meet diverse railway communication needs.

The development of FRMCS is a testament to the power of collaboration among diverse stakeholders across the railway ecosystem. Recognizing the need for a next-generation communication standard and embracing the capabilities of broadband and 5G technologies, industry players, governments, and international organizations have come together to shape the future of railway communications.

Figure 3: Success in cooperation: FRMCS stakeholders and their contributions

Railway Operators

Railway operators worldwide are at the forefront of driving FRMCS development, providing critical insights into operational challenges, user requirements, and infrastructure needs. Their involvement ensures that the system is tailored to real-world scenarios, delivering enhanced safety, efficiency, and passenger services.

Standardization Bodies

Organizations like the International Union of Railways (UIC) and the European Telecommunications Standards Institute (ETSI) in collaboration with 3GPP have played pivotal roles in defining FRMCS standards. By establishing a unified framework, these bodies ensure global interoperability and compatibility, enabling seamless adoption across borders.

Technology Vendors and Manufacturers

Leading technology providers, including telecom equipment manufacturers, software developers, and network integrators, are actively contributing to FRMCS development. Their expertise in 5G, IoT, and edge computing is instrumental in designing and testing the advanced features of the new communication system.

Government and Regulatory Authorities

Governments and regulatory bodies support FRMCS through policy frameworks, spectrum allocation, and funding initiatives. Their involvement is crucial in facilitating the smooth transition from legacy systems like GSM-R to FRMCS while ensuring compliance with safety and security regulations.

Research Institutions and Academia

Research institutions and academic organizations contribute to FRMCS by conducting studies, prototyping innovative solutions, and testing new technologies. Their work lays the groundwork for addressing technical challenges and optimizing the system's performance.

Telecommunications Providers

Telecommunications providers bring their expertise in 5G infrastructure and network deployment to the table, enabling the high-speed, low-latency connectivity required for FRMCS applications.

SOURCE: OMDIA

THE ROLE OF 5G IN FRMCS

While GSM-R has been a cornerstone of train operations for many decades, the standard was created as a vertically integrated system including connectivity and applications. This meant that any changes in the application layer required a change in the GSM-R standard.

Instead, 5G is the foundation of FRMCS and is not tied to the specific vertical applications. This enables more flexibility in deployment and application adoption. FRMCS will include GSM-R features, but because of the flexibility of 5G and its eMBB, uRLLC, and mMTC capabilities, FRMCS will be able to support new use cases including cameras and videos and smart stations.

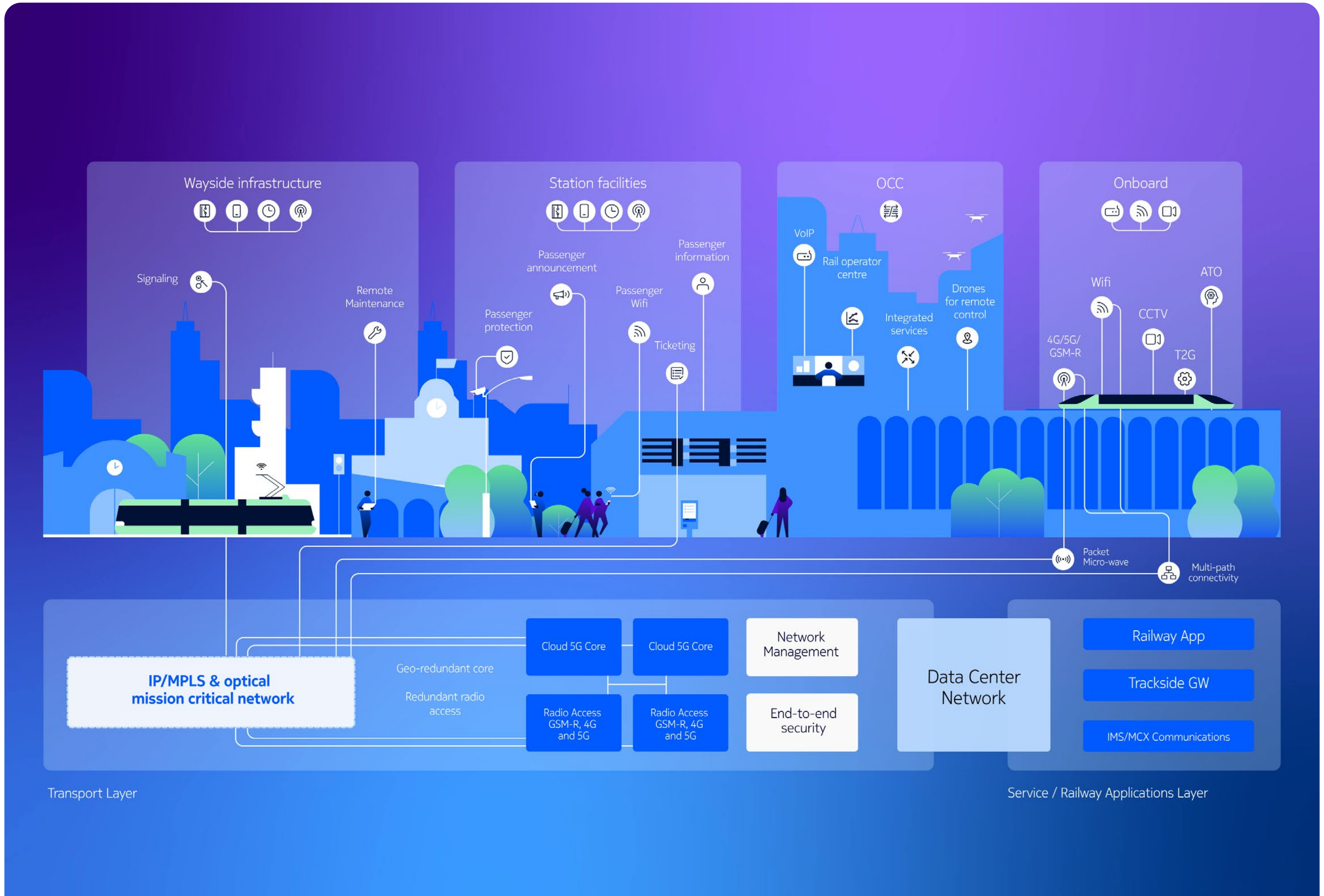
Railways will benefit from a layered architecture designed to specifically support their digital transformation. 5G effectively becomes a platform to support innovative applications:

1. At the bottom there is the transport and network communication layer which includes IP/MPLS fiber backbone but also the 5G core and RAN. This is the communication layer on which FRMCS and other applications can be built. Since this is standard-based, this is the foundational layer that can be started even today by the railway customer.
2. Alongside this communication foundation, there is the railway service application layer including security, IMS and MCX communications.
3. At the top is another application layer solving new use case challenges in areas such as wayside infrastructure, stations facility, operator control center, and onboard services.

From a performance perspective, 5G brings high capacity, performance and reliability, ultra-reliable, low-latency mission-critical communications with latency as low as 1ms, as well as massive MTC capabilities enabling the connection of millions of IoT devices with one cell. 5G brings more spectrum options beyond the currently used 900 MHz band used for GSM-R, and therefore offers more flexibility.

5G has also a more flexible architecture compared to GSM-R. The 5G network is built using a service-based architecture. Among other benefits, this enables the network with the capability to distribute network functions such as the UPF to support URLLC applications. 5G also brings end to end cyber-security with multi-layer encryption.

With the ability to operate at higher frequencies and larger carrier bandwidths, 5G can transmit larger amount of data in real-time. This is something that was heavily limited with GSM-R. Real-time data capability will deliver operational awareness supporting automated systems.



SOURCE: NOKIA

FRMCS – The development journey

FRMCS MILESTONES

The FRMCS timeline shows steady progress. FRMCS V1 specifications were published in late 2023 and tested and validated in high-profile trials. FRMCS V2 specifications are being finalized for publication by 2025. FRMCS V3, the final specification and validation phase, is expected to be completed by 2027. The FRMCS 1st Edition should then be ready for European deployments, marking a significant milestone in railway communication evolution.

Figure 4: FRMCS timeline – a journey to success

FRMCS 1.0
(COMPLETED STAGE)

- Started in 2019
- Completed in March 2023
- Validated through 5GRail project trials

FRMCS 2.0
(2025)

- To be validated through Mobile Radio for Railways Networks in Europe Project 2 (MORANE 2)

In 2024 FRMCS–T (LTE-based) became avalible, making deployments possible

FRMCS 3.0
(2027)

- First commercially deployed 5G standards
- Coexistence of technologies

COMMERCIAL FRMCS
(GSM-R END-OF-LIFE)

- Mass FRMCS deployments
- End-of-life for GSM-R around 2030+

SOURCE: OMDIA

Railway operators should recognize the critical importance of starting their transition programs as soon as possible. Given that GSM-R market support is nearing its end, postponing the inevitable evolution toward FRMCS systems could result in significant downtime and enormous costs for infrastructure overhauls.

Omdia strongly advocates that proactive planning and the implementation of a staged transition toward FRMCS are crucial to ensure continuous, efficient railway operations. In other words, although the commercial edition of the FRMCS standard is expected to be ready for European deployments by 2027, the transition to this next-generation communication system does not have to wait. Deployment can be carried out in a modular, staged manner, allowing railway operators to begin implementing initial components and capabilities today. By taking these early steps, operators can start reaping the benefits of enhanced connectivity and digitalization while ensuring a smoother and more cost-effective transition to full-scale FRMCS deployment in the future.

KEY DRIVERS FOR FRMCS ADOPTION

There are several drivers in the railway systems which underpin the need to adopt FRMCS and which cannot be served by using GSM-R:

- **Autonomous operations:** FRMCS enables critical autonomous train control systems through reliable, low-latency communication, precise positioning, and real-time signaling. FRMCS provides high-bandwidth support for supplementary safety applications like high-resolution cameras and video analytics. These are important use cases like monitoring stations, tracks, and surroundings but exceed GSM-R's narrow channel capacity.
- **Security:** With cybersecurity threats becoming ever increasing across a network which has assets and devices across the whole national territory, it is essential for railways operators to continue improving their cybersecurity posture for their network and operations.
- **Efficient operations:** These are both cost, and revenue related. Railway operators need to maintain outstanding levels of punctuality, scheduling, and minimal safe headway in order to accommodate for larger container capacity, reduce congestion, and optimize the movement of goods. Better use of train infrastructure can also help with sustainability goals, since a more efficient use of the railway network can reduce car and truck-based traffic on the roads.
- **Changing the train experience:** Besides improving the capacity and regularity of trains, delivering a superior digital experience both in the station via automated and digital ticketing and in the train with high-bandwidth connectivity is key to improving the travelers' perception of the train jouney. Pleased passengers are more likely to travel by train, increasing top line revenue for operators.

CHALLENGES IN FRMCS IMPLEMENTATION

Challenges to FRMCS implementation are of three main types: Operational, business, and technical.

OPERATIONAL

With the FRMCS timeline from early tests to full adoption expected to cover a time period of roughly a decade, interoperability with legacy GSM-R systems is a challenge. Choosing the optimal migration path and the right partners to engage with in these long-term processes are also new challenges to the realization of FRMCS. Cross-border interoperability between different networks or interoperability with public 5G networks, and spectrum alignment and regulations are all significant operational challenges.

BUSINESS

With FRMCS being a significant undertaking because of the scale of deploying a new network infrastructure across entire nations, high cost is a challenge that needs to be taken into account. Additionally, using FRMCS to create an improved traveler digital journey experience, may require railways operators to embrace new technologies and processes.

TECHNICAL

FRMCS requires the railway operator to deploy, integrate, and optimize new infrastructure. This requires for instance to upgrade backhaul from SDH technology to an IP/based backbone. The deployment of the core network of part of it in distributed servers or even in the cloud also present a significant change to the current core network deployment modes. Spectrum acquisition and management, and potentially the need to lease spectrum from third parties are also technical challenges.

FRMCS BENEFITS DRIVE THE DIGITALIZATION OF RAILWAYS

FRMCS is the key enabler supporting the digital transformation sweeping through the railway industry. FRMCS is not just a technological upgrade; it is the foundation for a fully digitalized railway ecosystem. By leveraging 5G broadband, it addresses the diverse requirements of critical, operational, and business communications while enabling the evolution to smarter, more sustainable railway networks.

DRIVING DIGITALIZATION ACROSS RAILWAY FUNCTIONS

- **For critical communications:** FRMCS ensures ultra-reliable, low-latency connectivity for vital safety applications like train control, automated train operations (ATO), and critical machine-to-machine (M2M), and telemetry. Its capabilities enable real-time decision-making and enhance the overall safety and reliability of railway operations.
- **For operational excellence:** FRMCS empowers digitalized operations by supporting data-driven processes such as AI, predictive maintenance, remote diagnostics, and continuous monitoring. Its high-bandwidth capacity allows the integration of data-intensive applications like CCTV, real-time passenger information systems, and lineside communications, optimizing traffic management and reducing downtime.
- **For passenger-centric innovation:** As a consequence of the high-speeds and reliable connectivity enabled by its underlying 5G SA infrastructure, FRMCS also facilitates advanced business communications such as real-time ticketing, personalized journey updates, and seamless onboard entertainment. These features redefine the passenger experience and , as a result, make railways a more attractive and competitive mode of transportation.

A UNIFIED PLATFORM FOR THE FUTURE

FRMCS is designed to be the enabler of digitalization, unifying the disparate communication needs of railways under a single, scalable, and future-proof platform. Its ability to integrate emerging technologies like IoT, edge computing, and AI makes it the backbone of a connected, intelligent railway network. Moreover, its inherent flexibility supports the deployment of new services and innovations as industry demands evolve, ensuring long-term value for railway operators.

As railways strive to meet the challenges of the 21st century, the 5G-powered communications benefits of FRMCS are the key to unlocking the full potential of digitalization. By enabling safer operations, efficient management, and enhanced passenger services, FRMCS positions railways as the backbone of sustainable, intelligent, and connected transportation systems.

FRMCS USE CASES AND APPLICATIONS

FRMCS and its associated 5G transport network can support applications across the whole train experience, from station operations to on-board security and situational awareness. Additionally, because 5G is a standard-based technology which is also widely deployed by telecoms operators for their own nationwide networks, there is an opportunity for railway operators to leverage additional resources such as additional RAN or other capabilities tested and used in the telecoms operators' world. This could be done in order to support particularly demanding use cases or to optimize investment patterns.

IMPROVE TRAIN OPERATIONS (GROUND AND ON THE TRAIN)

- Railway emergency call
- Train dispatch and emergency voice communication
- Train control and running safety data services
- Data transfer
- O&M remote data update on train and O&M operation guide
- Video services
  - *Intrusion alarm*
  - *Trackside disaster alarm*
  - *Maintenance assistant*
  - *Driver behavior*
- Monitoring and control
- Telemetry
- Ground-to-ground voice call
- Trackside maintenance
- Remote equipment control
- Railways control and signaling
- Passengers' information systems

IMPROVE STATION OPERATIONS

- Data transfer
- Smart ticketing
- Autonomous operations
- Infrastructure monitoring and sensing
- Digital kiosks
- Digital twins
- Employees communication
- Passengers' information systems
- Video services
  - *Video surveillance*
  - *Crowd management*

IMPROVE CUSTOMER TRAVEL EXPERIENCE

- Data transfer
- Always-on connectivity
- Voice services
- High bandwidth services
- Smartphone centered experience
- Passengers' information systems

FRMCS – A technical overview

FRMCS ARCHITECTURE AND COMPONENTS

Network Infrastructure

The Future Railway Mobile Communication System (FRMCS) is the planned successor to GSM-R, using modern 5G technology to support existing railway communications and enable new digital services.

FRMCS architecture follows a clear, layered model:

- **Communication Infrastructure:** Includes the radio access network (RAN) along railway tracks and the core network managing connectivity. The trackside RAN uses 5G New Radio (NR) base stations, optimized for rail operations. FRMCS operates in two main European frequency bands dedicated for railway use. The primary rollout will likely begin using the 1900 MHz TDD (time-division duplex) band (n101), as this band offers high data capacity and avoids initial interference with GSM-R operations. Later, the 900 MHz FDD (frequency-division duplex) band (n100: 874.4–880 MHz uplink and 919.4–925 MHz downlink) will supplement coverage.

  The core network adopts the standard 5G Core (5GC) architecture, built with software-based network functions. These functions handle connectivity, mobility, session management, and security. The core supports virtual deployment, either centralized or distributed near the network edge for performance.

- **Onboard System:** Trains will use a modular onboard architecture (Telecom Onboard Architecture - TOBA). TOBA manages connectivity across different wireless technologies, enabling seamless handovers and redundancy. An onboard gateway integrates train applications such as signaling systems and operational communications with the network, managing multiple connections automatically.
- **Mission-critical Services Layer:** FRMCS includes specialized communication services essential for railway safety and operations. These services, defined by the 3GPP standards, include mission-critical push-to-talk voice (MCPTT), mission-critical data, and video communication (MCData, MCVideo). These services support functions like group communication, emergency broadcasting, priority handling, and automatic location-based call routing.

The FRMCS infrastructure is fully IP-based, allowing railways to simplify their communications by combining multiple older systems onto one modern platform. Its flexible design supports both traditional and advanced rail applications, including real-time video feeds and automation systems, while maintaining the reliability and low latency required for critical railway operations.

HOW THE SOLUTION PROVIDERS WILL DELIVER ON THE FRMCS' REQUIREMENTS

Railways will benefit from private networks technologies to deliver the use cases discussed in the previous section, however, the solution provider must ensure it can deliver on five key delivery areas, such as trust, interoperability, simple operations, long-lived and evergreen and optimized.

Trust

Stakeholder trust is of utmost importance to the railway organizations. Some of their stakeholders include the regulatory organizations and the end customers and hence the railways must ensure that the solution provider can meet all their requirements. Further, other requirements include having a secure and proven solution that will serve the industry vertical's both today and in the long term, supporting the railways over its lengthy deployment and innovative cycles. Others include:

- Having a roadmap to 5G and beyond.
- Solution vendor should deliver the same level of trust and security as it does to the large service providers.

Interoperability

Railways are a brownfield of different IT, OT, and connectivity technologies including GSM-R. It is critical that any new solution can interoperate with existing technology but also this will remain open throughout the whole lifespan of the private network. For this reason, the core network solution provider must ensure adequate backward compatibility to ensure it can connect the next-generation network with legacy systems.

Simple operations

Simplicity of operations is essential to ease the workload of railways' networking teams. It is further essential that the network solution functions without errors and avoids service interruptions. Modern networks have thousands of parameters to maintain. Once these were optimized using manual activities, but in the smart networking era, the number of parameters will be several orders of magnitude higher, and manual changes to parameters will no longer scale given the complexity of the problem. Further:

- A FRMCS solution should leverage the state-of-the-art automation processes that come with modern cloud-native solutions to reduce not only repetitive manual intensive tasks but also operational costs.
- The solution will need to have a small footprint to save on both cabinet space and power usage requirements.

Long-lived and evergreen

The trends shaping the railways are starting now, but it should be remembered that the assets are expected to last more than 10 years. Furthermore, the railways' communications network needs to be able to continue support and evolve alongside the growth of these trends.

Future-proofing investments is a major concern of railways' organizations, given the long-expected lifespan of these networks. While cloud native technologies will facilitate improved agility and scalability of resources, it also requires new operation models. In particular the network is disaggregated compared to previous generations, requiring ongoing effort to keep all software up to date. In particular, it will be important to ensure all 3GPP specifications between the network and devices are maintained and the latest features that 5G or, later, 6G will bring are delivered, but also to ensure the of platform's security is not compromised.

Optimized

Railways' organizations have very specific needs in terms of devices, coverage, resilience, reliability, cost, and scalability. It needs a solution fully tailored to its business, which is forward looking in a highly competitive and regulated markets. In addition, to deliver on size, capabilities and ability to upgrade on a regular basis to deliver new technologies as they emerge, the solution must leverage cloud native technologies.

In today's world, management of the total cost of ownership (TCO) is at the top of most service provider organizations' requirements: vendors must leverage standardized tools to drive economies of scale and better manage the platform's resource requirements.

Network and resource scalability is an important feature of 5G networks, for example, when the devices require higher bandwidth for a specific time, for example in the cluster where the train is passing, the core network must scale the necessary resources dynamically to deliver those requirements and then scale them down when no longer required, releasing the resources to another region. Only today's cloud-native-based networks are capable of such agility and resource usage optimization.

The railways will also benefit from cloud native technologies to easily add or remove the network functions present (mutability) and ensure the right network function elements are instantiated to deliver the necessary functionalities.

NOKIA'S CORE ENTERPRISE SOLUTIONS HELP MEET THE UNIQUE NEEDS OF RAILWAYS

To address railway operators' needs, Nokia has developed a comprehensive FRMCS solution featuring Nokia's Core Enterprise Solutions at its heart. Built around a flexible, cloud-native 5G core architecture, this approach provides railway operators a straightforward upgrade path to FRMCS. Operators can confidently begin their journey today by deploying Nokia's 5G SA transport network as the future-proof foundation for FRMCS.

The Nokia's Core Enterprise Solutions deliver proven trust, global interoperability, simplified operations through lifecycle automation, evergreen software capability, and robust security based on zero-trust principles. With deep railway-specific optimizations and seamless migration from GSM-R, Nokia ensures railways remain reliable, agile, and ready for the future.

FRMCS – Implementation and Deployment

MIGRATION STRATEGIES

Railway operators have two requirements for smooth FRMCS migration: a realistic adoption timeline and guaranteed GSM-R/FRMCS interoperability.

Operators must deploy FRMCS well before GSM-R reaches its end-of-life, allowing both networks to coexist initially. As FRMCS coverage expands, workloads and applications will gradually transition from GSM-R, with trains potentially using both technologies across different segments during the extended parallel operation period. During transition, interoperability, security, and high-performance communications must be maintained across both networks. Telecom operators may support railways by offering specific resources or network slices regionally—an approach still being explored that could simplify initial deployment.

To optimize investment cycles and avoid potential last-minute cost and supply-chain pressures caused from the impending GSM-R obsolescence, railway operators can implement standard-based infrastructure before FRMCS specifications are finalized. Early spectrum acquisition is essential for concurrent network operation, while an IP-based backbone infrastructure is needed to support FRMCS's increased high-demand use cases. Initial FRMCS deployments will be limited testing projects, potentially supported by government incentives like Europe's MORANE-2. These tests will help operators evaluate new applications, identify key use cases, and gain valuable insights that will inform broader implementation.

As deployments expand, operators will need equipment supporting EU-reserved bands for FRMCS: Band n101 (1900-1910 MHz, TDD) and Band n100 (874.4-880 MHz uplink / 919.4-925 MHz downlink, FDD). Because Band n100 will initially coexist closely with GSM-R frequencies, many operators plan to start FRMCS deployments in the 1900 MHz Band n101 adding Band n100 for redundancy and coverage after GSM-R phases out.

With trials beginning now and broader network deployments set to follow shortly, the main migration period is expected from 2027 (following the completion of the first full FRMCS specification) until GSM-R's end-of-life around 2035.

Case study: NCRTC Delhi–Meerut RRTS

PIONEERING MISSION-CRITICAL BROADBAND FOR HIGH-SPEED RAIL IN INDIA

OVERVIEW

The Delhi–Ghaziabad–Meerut Regional Rapid Transit System (RRTS), India's first high-speed regional rail, represents a transformative approach to urban mobility. Spanning 82 km with 25 stations, this new rail corridor was designed to reduce travel time from 90+ to just 60 minutes. To safely enable speeds up to 160 km/h and support high-frequency operations, the National Capital Region Transport Corporation (NCRTC) adopted a cutting-edge communication solution, leveraging a private LTE-based mission-critical broadband network.

KEY CHALLENGES AND GOALS

The NCRTC Delhi–Meerut RRTS project was envisioned to deliver high-speed, high-frequency regional rail transit. To achieve this, the communications system had to overcome several unprecedented challenges:

- **Replace legacy GSM-R systems with a future-ready, broadband communication network:** a 3GPP-standard LTE/4.9G wireless infrastructure
- **Enable safe operation at 160 km/h under ETCS Level 2,** making it the first global deployment of ETCS Level 2 with Automatic Train Operation (ATO) over LTE radio.
- **Ensure real-time, uninterrupted wireless connectivity** between trains and the control center.
- **Achieve full regulatory compliance and spectrum allocation for private LTE use:** as the original 700 MHz allotment was under regulatory process, India's Department of Telecom (DoT) temporarily provided 900 MHz spectrum to commence trial operations on the first segment
- **Ensure compliance with 'Make in India' manufacturing guidelines** and deliver the solution on a compressed timeline aligned with infrastructure rollout.

STAKEHOLDERS AND THEIR ROLES

The successful implementation of the mission critical private cellular communications network involved coordinated efforts from several key stakeholders:

- **NCRTC:** Project owner and strategic driver, responsible for planning, procurement, and operational oversight.
- **Indian Railways/Railway Board:** Approved the shift to LTE for RRTS and aligned it with national signaling strategies.
- **DB International Operations:** O&M contractor responsible for operations, staff training, and real-time system use.
- **Department of Telecom (DoT) & TRAI:** Facilitated dedicated spectrum allocation and regulatory compliance.
- **Ministry of Housing and Urban Affairs (MoHUA):** Provided policy guidance and helped coordinate spectrum approvals.
- **Nokia:** Supplier of the end-to-end private LTE system, including EPC, radio, and mission-critical services.
- **Alstom:** Lead integrator for signaling and telecom systems, supplying ETCS L2 and integrating LTE with train control.
- **Validation of Critical Broadband Deployment:** The PoC successfully demonstrated the deployment of a reliable broadband network tailored to the unique needs of public safety users, ensuring secure, prioritized, and mission-critical connectivity.

WHY PRIVATE MISSION-CRITICAL BROADBAND?

NCRTC's primary problem was to enable fast, safe, and reliable commuter rail service in a dense urban region. This required adopting a cutting-edge mission-critical communications system to support advanced signaling, radio-dispatch voice and data connectivity. Traditional rail communication systems lacked the flexibility, scalability, and low-latency performance needed for the modern high-speed rail goals. By shifting to a private cellular network, NCRTC ensured:

- **Real-time ETCS signaling for train control**
- **Mission-Critical Push-to-Talk (MCPTT) for dispatch and operations**
- **Redundant and resilient architecture, including backup control centers**
- **Support for video, IoT, and automated diagnostics**
- **Future readiness for 5G and FRMCS migration**

The private LTE network offers greater control, consistent quality of service (QoS), and superior bandwidth, enabling a unified platform for voice, data, and video communication, all integral for efficient and safe rail operations.

SOLUTION ARCHITECTURE OVERVIEW

The solution is based on a 3GPP-standard private LTE network deployed in the 700 MHz band. Nokia provided the end-to-end LTE network including the radio access network, Evolved Packet Core (EPC), and network management systems. This LTE backbone enables ETCS Level 2 signaling with ATO, and supports mission-critical services like MCPTT voice, mission critical data for signaling and control, video, and IoT.

Alstom integrated this telecom layer with its ETCS onboard and trackside equipment, ensuring seamless operation between the train, Radio Block Centre (RBC), and control centers. Redundancy was built in through multiple control centers and a backup EPC. The system is FRMCS-ready, allowing a future migration path to 5G-based rail communications.

Future-Readiness (FRMCS): A notable aspect is that this LTE network is seen as a precursor to the Future Railway Mobile Communication System (FRMCS). The network can be upgraded or expanded toward 5G in the future, and the use of standard MCX interfaces means it could interoperate with other networks. In essence, NCRTC's system is one of the first FRMCS-aligned implementations in the world, and lessons from it are informing other railways.

CUSTOMER NEEDS AND HOW THEY WERE MET

NCRTC identified eight key technical and operational requirements, each addressed by the LTE-based solution:

1. **Fast Deployment:** The LTE system was deployed in sync with infrastructure works, enabling the priority section to go live within tight deadlines despite COVID-era supply constraints.
2. **High Availability with Redundancy:** Redundant LTE core sites and robust radio coverage ensure uninterrupted operations even in failure scenarios.
3. **Low Latency:** LTE's sub-100ms latency supports real-time ETCS data exchange at 160+ km/h, ensuring immediate response for safety-critical commands.
4. **Reliable QoS for Critical Services:** 3GPP-standard QoS Class Identifiers (QCI) prioritize ETCS, MCPTT, and operational data, guaranteeing availability even under high network load.
5. **Same Features as TETRA:** Push-to-Talk voice groups, emergency calls, dispatcher control, and broadcast capabilities replicate and enhance the functionality of legacy TETRA systems.
6. **RF Tuning for Safety and Coverage:** Optimized 700 MHz spectrum ensures strong, continuous coverage, even in tunnels, to minimize the need for additional cell sites.
7. **Stable Train Comms:** Seamless LTE handovers and rugged onboard modems guarantee uninterrupted train-ground communication, vital for breaking and switching.
8. **Clear Voice Quality:** High-quality codecs and MCX prioritization ensure crisp audio for staff and public announcements.

RESULTS AND IMPACT

The system was successfully validated during dynamic tests and is now operational on the first corridor stretch. Benefits realized include:

- **Improved Safety through Automatic Train Protection**
- **Enhanced Passenger Information with real-time location and arrival data**
- **Higher Train Frequencies and Reliability using ATO over LTE**
- **Future-Proof Investment aligned with FRMCS standards.**
- **Reduced Delays and Maintenance with digital signaling and fewer trackside components**

CONCLUSION

NCRTC's LTE-based mission-critical network exemplifies how broadband transformation can enable a modern, efficient, and safe railway system. It marks a critical shift from legacy systems to digital, resilient infrastructure and delivers long-term value, future readiness, and world-first innovation in passenger rail.

Appendix

About

Nokia

At Nokia, we create technology that helps the world act together.

As a trusted partner for critical networks, we are committed to innovation and technology leadership across mobile, fixed and cloud networks. We create value with intellectual property and long-term research, led by the award-winning Nokia Bell Labs.

Adhering to the highest standards of integrity and security, we help build the capabilities needed for a more productive, sustainable and inclusive world.

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