5G for Railways: Next Generation Railway Dedicated Communications

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ABSTRACT
To overcome increasing traffic, provide various new services, further ensure safety and security, and significantly improve travel comfort, a new communication system for railways is required. Since 2019, public networks have been evolving to fifth generation (5G) communication worldwide, whereas the main railway communication system is still based on second generation (2G) communication. It is thus necessary for railways to replace the current 2G-based technology with the next generation railway dedicated communication system with improved capacity and capability, and the 5G for railways (5G-R) technology is a promising solution for further intelligent railways. This article gives a review of the current developments of next generation railway communications, followed by a discussion of the typical services that 5G-R can provide to intelligent railways. Then the main application scenarios of 5G-R are summarized, and system configurations are compared. Some key technologies of 5G-R such as network architecture, massive MIMO, millimeter-wave, multiple access scheme, and ultra-reliable low-latency communication are presented and analyzed. Finally, some challenges of 5G-R are highlighted.

INTRODUCTION
The railway has been an important mode of transportation during the development of human society. Tracing back to the first industrial revolution, human industrial technology has experienced mechanical revolution, electric power revolution, and information technology revolution. Nowadays, we are going through intelligent technology revolution, due to the fast developments of artificial intelligence, big data, cloud computing, and fifth generation (5G) communication. Meanwhile, the railway is about to move from the information era to the intelligent era. The intelligent railway will apply 5G, artificial intelligence, big data, cloud computing, the Internet of Things (IoT), satellite navigation, and other new-generation information technologies. Through comprehensive and efficient use of resources, intelligent railways can realize comprehensive sensing, ubiquitous interconnection, and fusion processing of railway equipment, infrastructure, and environmental information. The railway system will enter a period of safer, more efficient, greener, more comfortable, and faster development.

The International Union of Railways (UIC) has been advocating railway digital and intelligent transformation and developing a new platform. The Future Railway Mobile Communication System (FRMCS) [1] is proposed by UIC as a key enabler for railway digitalization. UIC has further released the FRMCS User Requirements Specification (URS) [2], which includes 72 use cases for future railway communications. Such huge amounts of new services and business needs cannot be supported by the current Global System for Mobile Communications — Railways (GSM-R). In [3], several radio access technologies in FRMCS including WiFi, LTE, and satellite are tested using an emulation platform in railway scenarios. After UIC released FRMCS, the 3rd Generation Partnership Project (3GPP) made a study to determine the working requirements of FRMCS and analyze the differences between it and the existing functions in 3GPP TS 22.289. Since 3GPP Release 15 only includes enhanced mobile broadband, most of the requirements of FRMCS can only be well considered and implemented in Releases 16 and 17. Therefore, an intelligent railway communication system should be based on Release 16 and have the ability to smoothly evolve to Release 17.

Meanwhile, many countries have actively formulated their own development strategies of intelligent railways to enhance integration and innovative application of intelligent technologies and railways. The European Union (EU) proposed the 5GRAIL project [4], which is organized by UIC and other companies such as the European Rail Industry, Nokia, Siemens, and Alstom. 5GRAIL will establish a partnership with EU Shift2Rail to meet changing EU transport needs by using advanced and intelligent technologies. Germany proposed an Industry 4.0 and Strong Rail strategy, which copes with massive railway technological changes, such as intelligent railway production, operation, and maintenance. Switzerland proposed SmartRail 4.0 to modernize the railway intelligent system with the aim of ensuring robustness of future services, increasing capacity of the existing infrastructure, and increasing safety of employees in the track area. Cyber-Rail proposed by Japan is committed to providing real-time passenger information service and making train operation more flexible, safer, more reliable, and more competitive. NTT DOCOMO and East Japan Railway Company have verified stable operation of typical 5G communication capabilities, including handover between base stations and transmission of high-definition video data. Korea Railroad Research Institute has tested 5G-based autonomous train control technology. It has been a common consensus among countries to apply digital technology to the future railway systems and make better use of the advantages of intelligent railways.

Nowadays, the existing GSM-R, as a narrowband communication system with low bandwidth and data...
rate, cannot meet the requirements of smart railway services including train multimedia dispatching communication (which provides train dispatching services with a combination of text, voice, image, and video communications), intelligent operation and maintenance, and so on [5]. GSM-R also faces the problem of insufficient industrial chain support, and it urgently needs to evolve to a new generation of railway communication system [6]. LTE-Railways (LTE-R) was considered for railway communication system evolution at the beginning of the 2010s [7]; however, it was found that LTE system cannot meet the requirements of ultra-reliable communication and massive connectivity for future railways. It also cannot support the smart services and intelligent applications in future railways [6]. LTE-R is currently being deployed in a few high-speed railway lines and subway lines in China, India, Korea, and Spain [8]. It generally supports a 5G-oriented evolution and interconnectivity with GSM-R. To satisfy high data rate and massive connectivity requirements, 5G for railways (5G-R) has attracted much attention nowadays. The high-data-rate, low-latency, and high-access-density characteristics of 5G can provide high-quality services for intelligent railway applications. In Europe, the GSM-R system is obsolete and will be replaced by FRMCS, and the developments are ongoing. FRMCS will be a critical enabler for it to take the operations into the digital age [9]. In [10, 11], 5G New Radio performance is tested for FRMCS, and it is found that 5G New Radio can well satisfy the requirements of FRMCS. China has issued a strategy to strengthen national transportation, and promote the digital and intelligent railway development based on 5G technologies.

In summary, 5G-R is a promising solution for future intelligent railways, and this article aims to review and analyze the features and key challenges of 5G-R. The rest of the article is organized as follows. The next section presents the typical services that 5G-R can provide to intelligent railways. Then the main application scenarios of 5G-R are summarized. Following that, we discuss some key technologies of 5G-R. Finally, some challenges of 5G-R are highlighted.

**Services of 5G-R**

The existing railway dedicated communication system such as GSM-R only provides data transmission for control signals, and mainly covers train-to-ground communication environments. The services of 5G-R are diverse, and the future railway communications should provide reliable wireless coverage in more cases including continuous wide area coverage along railway lines, railway yards and hot spots coverage, monitoring of railway ground infrastructure, and broadband smart applications for intelligent trains. The services of 5G-R-based intelligent railways can generally divide into four categories, which are presented in detail as follows:

1. **Train Operation Related Service:** It includes multimedia scheduling, railway dispatching command, automatic train operation, locomotive synchronous control, train number information checking, warning of train approaching, shunting train protection, and so on. Such services are especially important to the safety of train operation.

2. **Maintenance Service:** It includes emergency communications, intelligent maintenance communications, data update of onboard equipment, railway freight information transmission, passenger services, and so on. These services are helpful to improve railway intelligent operation and maintenance.

3. **Monitoring Related Service:** It includes real-time monitoring of train status and onboard equipment, power safety monitoring, locomotive driver monitoring, overhead power line monitoring, construction vehicle monitoring, railway cables monitoring, and so on. Such services can improve the safety of a railway system.

4. **Passenger-Oriented Service:** It includes high-speed Internet on train and on platform, a real-time and intelligent passenger information system, multimedia personal infotainment (i.e., information and entertainment) in railway environments, visual/audio public address information, and so on. Such services can improve passenger comfort and travel efficiency.

Various services and wireless coverage environments put forward higher requirements on the bandwidth, delay, reliability, and security of communication systems. They also put forward new requirements for information sharing, and a unified information and communication platform is thus needed to connect various devices in railway environments. 5G-R should support such comprehensive services, and provide complete coverage and wireless access in railway lines, tunnels, stations, railway yards and depots, carriages, and so on. Figure 1 shows a fully connected 5G-R network architecture and the corresponding services, where comprehensive connectivity is supported including train-to-ground link, train-to-train link, and IoT, for all the railway-related devices. In addition, it is challenging to offer all the services with limited bands and low deployment cost for 5G-R.

**Application Scenarios of 5G-R**

5G-R motivates new applications in future intelligent railways by providing rich wireless services and improved coverage. Application scenarios of 5G-R can generally be divided into four categories: intelligent construction, intelligent equipment, intelligent operation and maintenance, and smart travel. Each application scenario and the corresponding information and communication requirements are shown in Table 1. The situation of the supported communication systems are also compared in Table 1, and it is found that only 5G-R can support all the intelligent application scenarios in future railway systems.

1. **Intelligent Construction:** It unifies railway design and construction stages and adopts new tech-
Technologies such as building information modeling (BIM), digital design and management, IoT environment monitoring, and high-precision staff and equipment positioning, among others. Intelligent construction can improve the efficiency of railway architectural design and construction, realize sustainable development of railway construction industry, and efficiently unify the various stages of architectural design, building component production, and on-site construction. Such applications require high-precision positioning, low end-to-end delay, low packet loss rate, large bandwidth, and high data rate. This application scenario has been adopted by the development strategies of EU 5GRAIL and Korea Railroad BIM 2030.

2. Intelligent Equipment: It refers to railway equipment based on advanced technologies, such as intelligent technology, sensor technology, automation technology, and information technology. Intelligent equipment has the characteristics of ubiquitous perception, intelligent fusion, and analysis and decision making. Intelligent equipment in 5G-R mainly includes intelligent multiple-unit trains and the next generation train control system. The former involves onboard IoT, security and surveillance system, entertainment, passenger information system, and more. The latter requires a 5G network to provide highly reliable communications with low latency and high data rate. This application scenario has been adopted by the development strategies of EU 5GRAIL and Switzerland SmartRail 4.0.

3. Intelligent Operation and Maintenance: It mainly includes railway intelligent maintenance, multimedia dispatch communication, and emergency command. 5G-R will use low-power wireless sensors and wireless charging technology to lighten trackside equipment and realize green monitoring along railway lines. For railway intelligent maintenance, intelligent analysis of equipment status data and historical information, and on-site augmented reality assistance will be employed to realize the prediction of equipment failures, and further realize visualized digital twin operation and maintenance of railways. Moreover, 5G-R will support more intelligent and convenient multimedia dispatch communication and emergency command, and realize real-time audio and video dispatch command, and safety control of all elements in the railway operation process [6]. The 5G-R system needs to provide large connection and wide coverage in railway environments to support the large-scale sensing and interconnection required by the applications. This application scenario has been adopted by the development strategies of EU 5GRAIL, Germany Industry 4.0, and Switzerland SmartRail 4.0.

4. Smart Travel: In the future, 5G-R will provide widely covered communications with high data rate for the scenarios of railway station service and train passenger service to realize smart travel. 5G-R supports the building of the smart railway station to better meet the needs of passengers in station for multimedia communication, station navigation, and smart feeder transportation. In future smart stations, passengers entering the station will be assisted by more intelligent systems and guided more efficiently. Face recognition technology, smart security for

| Application scenario       | Technical requirement & system support | Technical requirements |
|---------------------------|----------------------------------------|------------------------|
|                           | Audio and video reliable transmission | IoT data collection    |
|                           |                                        | IoT real-time control   |
|                           |                                        | Precise positioning    |
|                           |                                        | High speed video stream |
|                           |                                        | Offloading with large bandwidth |
|                           |                                        | Augmented reality      |
| Intelligent construction  | Intelligent survey and design          |                       |
|                           | Dispatch communication                 | ✓                      |
|                           |                                        | ✓                      |
|                           | Intelligent multiple-unit train        |                         |
|                           | Train control system                  | ✓                      |
|                           |                                        | ✓                      |
|                           | On-board equipment monitoring          | ✓                      |
|                           | Ground infrastructure monitoring       | ✓                      |
|                           | Multimedia dispatch communications     | ✓                      |
|                           | Emergency communications               |                         |
|                           | Safety-related perception and protection| ✓                      |
|                           | Intelligent video surveillance         | ✓                      |
|智能设备                  | Multimedia entertainment               | ✓                      |
|                           | Station navigation                    | ✓                      |
|                           | Smart logistic                        | ✓                      |

TABLE 1. Typical 5G-R application scenarios.
and it is found that 5G-R has improved performance compared to the existing railway communication systems. The 5G-R system is expected to support the above-mentioned services and applications with various key technologies.

1. **Novel Network Architecture and Network Slicing:** Considering the complex and diverse railway applications, 5G-R can introduce a cell-free wireless access topology to provide more flexible wireless control, service monitoring, and protocol stack customization capabilities. Simultaneously, the novel network architecture can provide highly customizable network services for different users and applications, and establish a resource-sharing integrated information platform. The 5G-R network can implement multiple network slices on the same physical infrastructure platform and provide comprehensive slice division for applications with different requirements such as high-definition video surveillance, automatic train operation, and railway IoT, and finally realize the end-to-end slicing deployment of the railway dedicated communication network. It is noteworthy that 5G-R should guarantee safety services' cohabitation with other services if a public 5G network is used [6]. Another approach is to use a private 5G network with possible sharing of infrastructure or hybridization with other safety applications.

2. **Massive MIMO:** Centralized massive multiple-input multiple-output (MIMO) can generate narrow beams with large gain to high-speed trains and greatly improve system capacity. Moreover, distributed massive MIMO technology is expected to be a promising solution to deal with the communication quality degradation problem caused by users' rapid movement and frequent handover. A distributed massive MIMO system

### Key Technologies of 5G-R

The future railway system will develop in the direction of networking, intelligence, and automation. The next generation railway dedicated communication system should realize comprehensive perception, interconnection, and information interaction among all railway users and infrastructures. Typical intelligent railway applications, such as video-based track monitoring, ultra-high-reliability train control, and intensive access of massive users and sensors, correspond to the three typical 5G scenarios, respectively: enhanced mobile broadband, ultra-reliable low-latency communication, and massive machine-type communication. Therefore, the development of railway dedicated communications supported by 5G has been widely expected. Table 2 summarizes some key parameters of GSM-R, LTE-R, 5G, and 5G-R, and it is found that 5G-R has improved performance compared to the existing railway communication systems.

### TABLE 2: System configurations of GSM-R, LTE-R, 5G, and 5G-R.

| Parameter | System          | GSM-R                       | LTE-R                          | 5G                               | 5G-R                           |
|-----------|-----------------|-----------------------------|--------------------------------|---------------------------------|--------------------------------|
| Frequency |                 | Uplink: 876–880 MHz         | 450 MHz, 800 MHz                | Sub-6GHz: 410–7125 MHz          | 900 MHz, 1.9 GHz, 2.1 GHz, 5.9 GHz |
|           |                 | Downlink: 921–925 MHz       | 1.4 GHz, 1.8 GHz                | Millimeter-wave: 24.25–71 GHz   |                                |
| Bandwidth |                 | 0.2 MHz                     | 1.4–10 MHz                      | Sub-6GHz: 5–100 MHz             | 10–20 MHz; possible ≥100 MHz at higher frequency bands |
| Modulation|                 | GMSK                        | QPSK, 16-QAM                    | 256-QAM, OFDM, FBMC, UFMC, OFDM, F-OFDM | QPSK, 16-QAM, 64-QAM, 256- QAM, OFDM |
| Typical cell range |              | 8 km                        | 4–12 km                        | tens of meters to several kilometers | 1–6 km                         |
| MIMO      |                 | No                          | 2 × 2                           |                                 |                                |
| Average data rate |            | <10 Kb/s                    | 1–10 Mb/s                      | 50–100 Mb/s                     | 5G-R 10–50 Mb/s                |
| Peak data rate |              | 172 Kb/s                    | Uplink: 10 Mb/s Downlink: 50 Mb/s | Uplink: 15 Gb/s Downlink: 20 Gb/s | Uplink: 50 Mb/s Downlink: 200 Gb/s |
| Peak spectral efficiency |        | 0.33 bps/Hz                  | 2.55 bps/Hz                     | Uplink: 15 bps/Hz Downlink: 30 bps/Hz | Uplink: 8 bps/Hz Downlink: 15 bps/Hz |
| Mobility  |                 | Max. 500 km/h               | Max. 500 km/h                   | Max. 500 km/h                   | Max. 500 km/h                  |
| Reliability |               | 99.99%                      | 99.99%                          | 99.99%                          | 99.999%                        |
| Connection loss rate |          | ≤ 10⁻²/h                     | ≤ 10⁻²/h                        | NA                              | Voice related: ≤ 10⁻²/h Video related: ≤ 10⁻⁵/h |
| End-to-end latency |         | 500 ms                      | 200–500 ms                      | 1–10 ms                         | 50–500 ms                      |
| Handover success rate |       | ≥ 99.5%                     | ≥ 99.5%                         | 90–99.5%                        | ≥ 99.9%                        |
| 4K video  |                 | No                          | No                             | Support                          | Possible support with increased bandwidth |

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service monitoring, and procedures, 5G-R can introduce a cell-free wireless access and diverse railway protocol stack customization capabilities.

3. Railways IoT: Millimeter-Wave: Millimeter-wave technology can use abundant bandwidth resource well and support transmission data rate up to the gigabit-per-second level for massive 5G-R applications. To combat the huge penetration loss and propagation attenuation in millimeter-wave bands, beamforming technique is utilized, thereby realizing high-gain millimeter-wave transmission, and the repeater nodes on top of the train can also be used to improve signal transmission as suggested in 3GPP TR 38.854. The key challenges faced with its practical implementation mainly include the rapidly time-varying channel in high-mobility scenarios and random blockage events in complicated scenarios. With the known route and measurable position of trains, dynamic beam tracking is guided by prediction, and hybrid beamforming is efficiently developed. It is shown in Fig. 3 that efficient beamforming can achieve tens of gigabits per second level sum data rate in train-to-ground millimeter-wave communications, and data rate generally decreases with moving speed due to the Doppler effect [13]. Considering realistic deployments such as the large-scale antenna system and the non-stationary channel condition, efficient beamforming design deserves more attention for single- and multiple-user scenarios.

4. Railway IoT: In the near future, railway IoT will be equipped with massive sensors to enable comprehensive situation awareness. Generally, the massive IoT devices have low power and low cost, so grant-free random access can be used to reduce signaling overhead. Also, due to the scarce radio resource, reliable grant-free random access for massive users cannot be supported with conventional multiple access schemes. Thus, non-orthogonal multiple access (NOMA) is used to achieve larger user access numbers. Among the NOMA schemes, tandem spreading multiple access (TSMA) can effectively realize reliable grant-free random access for massive railway IoT user devices [14].

5. Ultra-Reliable Low Latency Communication: According to 3GPP TS 22.289, the future railway needs to guarantee less than 100 ms end-to-end latency for operation related voice and data communications, and support 99.9999 percent reliability for critical data communication, both at 500 km/h. Ultra-reliable low-latency communication mainly guarantees railway communication performance from two aspects:

- Highly reliable transmission under incomplete channel state information. Considering the impact of channel state information error, the transmission delay and packet error rate can be reduced by increasing transmission power and balancing inter-cell interference to ensure end-to-end transmission performance.
- Highly reliable transmission with hybrid automatic repeat request. Considering the spectrum efficiency and energy efficiency of the 5G-R system, as well as the small packet feature of ultra-reliable low-latency services, the finite block length coding theory can be adopted to characterize the transmission performance, and thus the system can be optimized with a unified framework to guarantee the requirements of railways.

**CHALLENGES**

**Frequency Resource**

Future railway communications should provide reliable data transmission for different applications such as train control, station and yard coverage, ground
Reliable Big Data Transmission

A high-speed train generally includes many users and devices, and instantaneous big data transmission with high reliability leads to significant challenges to 5G-R due to the following reasons.

Non-Stationary Channel: The channel of a high-speed railway has been generally considered to be non-stationary due to the dynamic evolution of multipath components caused by motion. Non-stationary channel characterization has many advantages such as improving accuracy of channel simulation and system evaluation, pre-conditioning the waveform to match the expected fading profile, and more, which are important to guarantee reliable big data transmission. The dynamic behaviors should be included in high-speed railway channel modeling and channel estimation.

Carriage Penetration Loss: The average carriage penetration loss of a typical high-speed train is about 25–35 dB for sub-6 GHz. Such high penetration loss significantly reduces signal-to-noise ratio (SNR) for onboard passengers, and the performance of onboard broadband service is thus affected. The condition may be even worse if millimeter-wave is used for data transmission. The penetration loss is also affected by the incidence angle of signal from base station to train. The link budget of 5G-R should be carefully conducted. A possible solution is to use mobile femtocells technology to enhance QoS [15], where a carriage is considered as a femtocell, and signals inside the train are forwarded from the outside by cables.

Doppler Frequency Offset and Spread: 5G-R should support mobility up to 500 km/h. The corresponding Doppler frequency offset and spread affect demodulation performance of receivers in dynamic railway environments. For 2.1 GHz, the uplink Doppler frequency offset would be larger than 680 Hz for 350 km/h, and it would be much higher for millimeter-wave bands. The solution is mainly to use algorithms to adjust frequency of users and to eliminate the influence of Doppler offset.

Multi-User Group Handover: 5G-R base station spacing is reduced compared to GSM-R because of higher carrier frequency, and frequent group handover exists, which causes network congestion and performance degradation. Wireless network planning is required to achieve faster cell re-selection and reasonable cell overlap to satisfy inter-cell handover requirements. At the same time, cell merging can reduce the number of inter-cell handovers and improve performance and reliability. Moreover, new schemes are required to reduce the number of handover blockings, and a femtocell-based network mobility scheme can be designed to support seamless handover in 5G-R scenarios.

Intelligent Perception and Decision Making Platform

The future railway system needs to establish a complete intelligent perception and decision making platform to support full-element and full-status perception and decision making of the intelligent railway. A proposed vision of the platform is illustrated in Fig. 4. On this platform, railway systems, communication systems, IoT, big data, and artificial intelligence technologies will be deeply integrated to realize perception, transmission, and processing of different types, dimensions, and volumes of data. Artificial intelligence can enable the network to process large amounts of data, dynamically identify and adapt to complex scenarios, and satisfy the requirements for high-speed and real-time signal processing capabilities. Moreover, based on networking integrated cloud-edge-end, the intelligent perception and decision making platform will support railway intelligent decision making and signal control, and comprehensively improve intelligence levels of railway disaster prevention, operation
and maintenance, monitoring, and dispatching. Such a platform can be used for railway digital twin and motivate the evolution of 5G-R to the 6G railways era with higher network intelligence.

**Integration of Advanced Technologies and Systems**

**Broadband and Narrowband Coexistence:** GSM-R and 5G-R networks will still have a long time to coexist, and many issues need to be solved as follows: interconnection between GSM-R and 5G-R networks, cohabitation between GSM-R and 5G-R, overlapping coverage of GSM-R and 5G-R networks, collaboration of multimedia dispatch communications for GSM-R and 5G-R, updates of onboard terminal module to support both GSM-R and 5G-R, antenna updates and deployments for new frequency bands, and more. In addition, future railway communications should be adaptable and able to support multiple access technologies with bearer independence.

**Integration of Advanced Technologies:** It involves the integration and cooperation of 5G-R and different advanced technologies such as LTE, WiFi6, fixed 5G (F5G), satellite communications, IEEE 802.11 bd next generation vehicle-to-everything, millimeter-wave/terahertz communications, and IoT. 5G New Radio and LTE offer natural integration via the radio interface. WiFi6 achieves 9.6 Gb/s data rate, which is an effective supplement for 5G New Radio networks in low-speed scenarios. It can be applied to 5G-R scenarios such as virtual reality, augmented reality, and video surveillance. F5G, based on the passive optical network, is a fixed network supplement to 5G New Radio networks. With F5G, 5G-R can support massive connectivity and high capacity, and establish railway Internet of Everything. Satellite communications such as low orbit satellite Internet and high-throughput satellites can be integrated with 5G-R to develop the air-space-ground integrated railway communication network, which provides comprehensive and seamless coverage for different 5G-R scenarios. Together with IEEE 802.11 bd vehicle-to-everything technology, it supports the development of a fully connected and integrated intelligent transport system. Moreover, a satellite navigation system combined with 5G-based positioning can realize high-precision positioning for various railway environments such as open areas and tunnels. Millimeter-wave/terahertz communications can realize ultra-high-speed transmission of onboard data and high-speed video data delivery of a passenger information system. IoT can be used to realize the interconnection and perception of railway infrastructure, devices, equipment, and so on.

**Conclusion**

This article has introduced 5G-R technology, which could lead to fundamental changes in future railway systems. 5G-R offers highly competitive performance, supports many railway services, and can be applied in various railway application scenarios. In addition, intelligence will play a crucial role for 5G-R in increasing performance and improving services of the network. 5G-R system configurations are compared and discussed. Some key 5G-based technologies such as network architecture, massive MIMO, millimeter-wave, multiple access, and ultra-reliable low-latency communication are discussed for railway applications, and a suite of these solutions will form the basis of 5G-R to satisfy the expected performance requirements. Finally, some technical challenges of 5G-R research and implementation are discussed.

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**References**

[1] Int’l. Union of Railways, “Future Railway Mobile Communication System,” 2019, http://uic.org/frms.

[2] “Future Railway Mobile Communication System User Requirements Specification,” FRMC5 Functional Working Group & Architecture and Technology Group, 2019, pp. 1–521.

[3] M. Berbénue-Leiva et al., “Zero On Site Testing of Railway Wireless Systems: The Emulator-on-Rail Platforms,” Proc. VTC-Spring, 2021.

[4] 5G-Rail, European Union Horizon 2020 Research and Innovation Programme, 2020, https://5grail.eu.

[5] A. Gonzalez-Plaza et al., “5G Communications in High Speed and Metropolitan Railways,” Proc. EuCAP, 2017.

[6] B. Ai et al., “5G Key Technologies for Smart Railways,” Proc. IEEE, vol. 108, no. 6, 2020, pp. 836–93.

[7] R. He et al., “High-Speed Railway Communications: From GSM-R to LTE-R,” IEEE Vehic. Tech. Mag., vol. 11, no. 3, 2016, pp. 49–58.

[8] L. Zhang et al., “Propagating Model for Outdoor-to-Indoor and Indoor-to-Indoor Wireless Links in High-Speed Train,” Measurement, vol. 110, no. 1, 2017, pp. 41–52.

[9] B. Allen et al., “Defining an Adaptable Communications System for All Railways,” Proc. Veh. Tech., 2018, pp. 1–11.

[10] M. H. M. Sambas et al., “5G Key Technologies for Smart Railways,” Proc. IEEE, vol. 112, no. 5, 2022, pp. 591–96.

[11] S. Adhikari et al., “5G-Powered FRMCs,” Ericsson White Paper 2022, pp. 1–20.

[12] J. Zhang et al., “Cell-Free Massive MIMO-OFDM for High-Speed Train Communications,” IEEE JSAC, to appear.

[13] M. Gao et al., “Efficient Hybrid Beamforming With Anti-Blockage Design for High-Speed Railway Communications,” IEEE Trans. Vehic. Tech., vol. 69, no. 9, 2020, pp. 9643–55.

[14] Y. Ma et al., “OTFS-TDMA for Massive Internet of Things in High-Speed Railway,” IEEE Trans. Wireless Commun., vol. 21, no. 1, 2022, pp. 519–31.

[15] R. Rahiem et al., “Cooperative and Coordinated Mobile Femtocells Technology in High-Speed Vehicular Environments,” Proc. ICAINA, 2021, pp. 653–66.

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