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Mobile Internet Access Optimization for High-Speed Rail Systems

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Abstract

As high-speed railways continue to expand and the speed of trains increases, the wireless transmission of train control signals and mobile internet access needs to be done in a reliable and timely manner. The demands for these needs, along with other requirements, are causing the mobile communication systems for railways to evolve from the traditional GSM-R-based narrow-band systems to more advanced broadband options. The narrow band systems like GSM-R do not include newer real-time features offered by LTE-R and 5 G-R systems, such as multimedia video surveillance, dispatching IoT-enabled railways, and multimedia support. The paper starts by explaining the existing GSM-R system, which is straightforward, but highlights the shortcomings of the system. The focus is drawn to new user requirements of enabling data services and further evolving user demands to outline the most important benchmarks for future railway communication systems. The developments in wireless technologies and network structures suitable for railway mobile communication systems are also studied. Then, advanced systems are analyzed to meet the challenges of future technology and mobile communication needs. The paper covers all these points and provides a conclusion based on the findings, which the readers can access directly.

Keywords: Speed, Railways, LTE-R, GSM-R, IoT, Structures, and 5G-R.

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1 Introduction

The development of high-speed railway HSR as a new mode of transport is being adopted in the world because of its safety, speed, and efficiency. HSR transport has been built in Austria, Belgium, China, France, Germany, Italy, Japan, the Netherlands, Poland, Portugal, Russia, South Korea, Spain, Sweden, Turkey, the United Kingdom, the United States, and Uzbekistan, connecting the major cities of these countries. Europe is the only region where HSR lines cross international borders. In December 2017, China had built 25,000 kilometers of HSR, accounting for 2/3 of the total in the world, and had a capacity of more than 1.4 billion passengers annually (Lu, 2017). Bullet trains that run between Beijing and Shanghai had their maximum speed increased to 350 km/h in September 2017 (Zhen, 2017).

Table 1 contains the overview of the HSR systems of the countries under discussion and is based on the information provided by the International Union of Railways UIC and several other online sources (International Union of Railways, 2018). With the expansion of HSR throughout the globe and an increase in train speeds, the reliability and promptness of wireless transmission systems for sending control signals on the train and internet access for passengers are increasingly critical (Khoeurt et al., 2023; Liu & Yuan, 2010; Ayesh, 2024).

The mobile communication system is a bridge between the ground infrastructure and the trains, essential for the safe and efficient operation of HSR networks. Mobile communication standards have been developed over the years. The first international mobile communication standard for railways, the Global System for Mobile Communications-Railway (GSM-R), facilitates reliable two-way communication to transfer movement authority, speed restrictions, control signals, etc (Sniady & Soler, 2012; Sniady et al., 2015). Although widely accepted and proven reliable, it has a slow adoption rate due to the increasing demand in the railway industry. As mobile systems shift towards 4G and 5G, railway telecommunication systems must evolve as well (Aguado et al., 2011).

Table 1: Development of High-Speed Railways (HSR) Worldwide by 2017

Country	HSR in Operation (km)	Maximum Operating Speed (km/h)	Population Coverage (%)
China	25,000	350	10.70
Spain	3,100	320	12.69
Germany	3,038	320	18.28
Japan	2,765	320	36.55
France	2,647	320	12.96
Sweden	1,706	200	21.41
United Kingdom	1,377	300	11.99
South Korea	1,104.5	300	44.57
Italy	999	200	18.47
Russia	845	250	12.22
Turkey	802	250	7.00
Finland	609.5	220	1.89
Uzbekistan	600	250	9.01
Austria	352	230	27.55
Belgium	326	300	7.83
Netherlands	175	300	11.99
Poland	143	200	12.57
Norway	64	210	12.44
United States	54.6	240	3.73

LTE-R has become a topic of interest over the years due to the commercial success of LTE. Nokia deployed the first LTE-R production network in South Korea in 2016 (Nokia, 2016). LTE-R utilizes advanced physical-layer technologies such as Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO) alongside all-IP packet switching and flat network architecture at the network layer. All these components allow LTE-R to provide data transmission speeds up to 100 Mbps with a 20 MHz bandwidth and latency as low as 100 ms at high speeds (Sniady & Soler, 2013). Video surveillance and multimedia dispatching while on a timeline boost the range of services LTE-R covers compared to tri-VR, making it a more comprehensive framework.

Under 4G systems, LTE Advanced (LTE-A) seems to leave a gap in supporting primitive railway operations like autonomous train functionalities or massive-scale RIoT connectivity. Although we already possess full-fledged automatic train operation systems, they cannot handle complex or emergency scenarios. In these scenarios, the International Telecommunication Union (ITU) suggests 5G as the mobile network technology for autonomous driving with its massive RIoT connections and high-speed internet for passengers (Malarvizhi et al., 2020; International Telecommunication Union, 2003). It is estimated that 5G will provide extremely high data rates (around 1 Gbps) and significant network capacity advancement (up to 1,000x). Also, the lag time is anticipated to range between 1-5 ms.

According to ITU, by the end of 2015, 5G will have three main application scenarios: enhanced mobile broadband (eMBB), which will be served by eMTC, and ultra-reliable low-latency communication (LLC). The framework of high-speed railways comes with an abundance of passengers, swift speeds, and many sensors, making it ideal for the three domains. In 2019, China announced the world's largest 5G test network, with expectations of commercial use in 2020 (Wang, 2017). With the global rollout of 5G, it is expected that railway mobile communication systems across the world will possess greater functionality with the development of 5G-Railway (5G-R) systems (Muralidharan, 2024).

While there has been an increasing amount of research done on GSM-R, LTE-R and even 5G technologies, there are very few studies focused on the 5G-based communication systems designed specifically for railway applications (Booch et al., 2025) (Trisiana, 2024). This paper seeks to bridge that gap by discussing in detail the existing railway mobile communication systems and studying their prospective developments along with the technical obstacles they present.

The rest of this paper is organized as follows. Section II analyzes the GSM-R system and describes its shortcomings. Section III deals with new user expectations and emerging data services, introducing relevant KPIs for new systems. Section IV examines new wireless technologies and network designs for next-generation railway communications, outlining the associated technical challenges. Finally, Section V concludes with the overarching insights and recommendations compiled during the research process.

2 Mobile Communications Systems for Railways

GSM-R, or Global System for Mobile Communications-Railway, is the first mobile communication system explicitly dedicated to international driving and controlling train operations (Shao & Jiang, 2015). By IEEE standards, it was developed by the Union International des Chemins de Fer (UIC), which built upon the committed compatibility of services (CoCS) framework. The system is based on analog systems and cable-bound interfaces with GSM technology. It exploits the benefits of commercial wireless infrastructure while dismantling older, incompatible analog and cable-bound systems, which relieves patchwork networks. Specialized base stations are usually installed in remote areas along the railway tracks. GSM-R is mostly deployed using fixed base stations bordering the railway lines, and increased coverage solutions, directional antennas, and leaky feeders are utilized for tunnels and difficult-to-reach areas.

Different regions have varied allocations for GSM-R. It works in specific frequency bands, supports data transmission of 9.6 kbit/s, and accommodates up to a maximum speed of 500 km/h trains. For example, Europe uses the 876–880 MHz (uplink) and 921–925 MHz (downlink) bands, while other countries, including China, use slightly different allocations. GSM-R in China uses 19 effective channels with 21 available, each channel consisting of 0.2 MHz bandwidth while maintaining a base station distance of 3 to 5 kilometers to provide strong and resilient coverage.

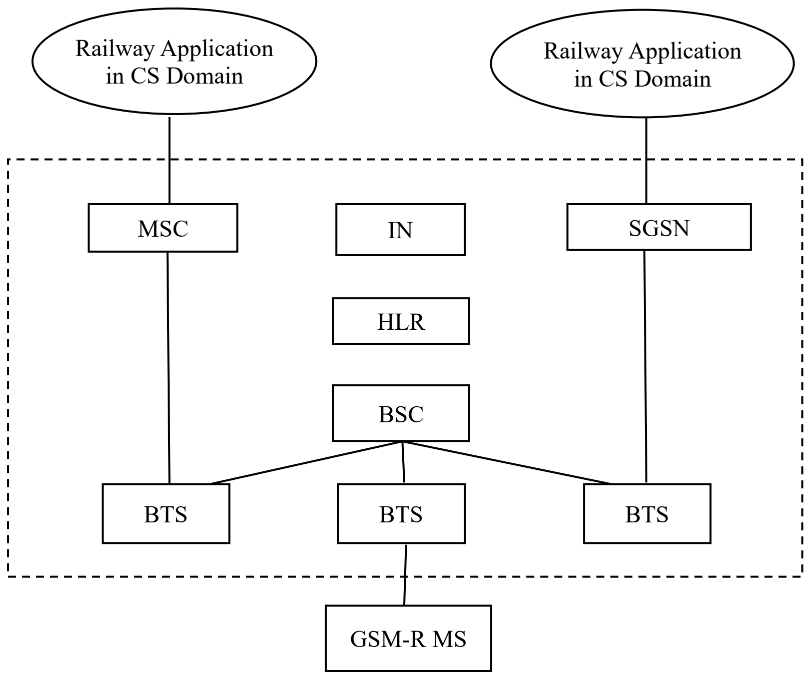

Figure 1: The Network Structure for Network Structure of GSM-R

On a functional level, GSM-R comprises the core services of GSM, augmenting it with railway-specific features like Enhanced Multilevel Precedence and Preemption (eMLPP), Voice Broadcast Service (VBS), and Voice Group Call Service (VGCS). These services facilitate mission-critical activities, including dispatching, train control communications, and enumeration. Nevertheless, despite these efforts, operators face significant shortcomings in modern railways (Figure 1). The system's latency, approximately 400 ms, in conjunction with a low data rate, makes it inapt for new emerging applications such as real-time video services or low-latency interactive services. Moreover, the system's capacity is severely limited by a spectrum of 4 MHz because adjacent frequency bands are heavily utilized, complicating expansion. Equally important, passenger connectivity, or the lack of it, is another major drawback as the system does not accommodate mobile internet, forcing passengers to rely on poorly performing public networks.

With the growth of high-speed rail travel and mobile internet, railway systems require modernization. According to UIC estimates, its lifecycle will end by 2025. To solve some of GSM-R's difficulties, such as frequent handovers in high-speed environments, loose limits have been developed due to high-speed RoF technology (Figure 2). RoF moves complex signal processing from the base station to a centralized control unit with Remote Antenna Units (RAUs) connected by optical fiber. This technology has been implemented with the Shanghai Transrapid MAGLEV system, which maintains reliable communication up to 500 km/h.

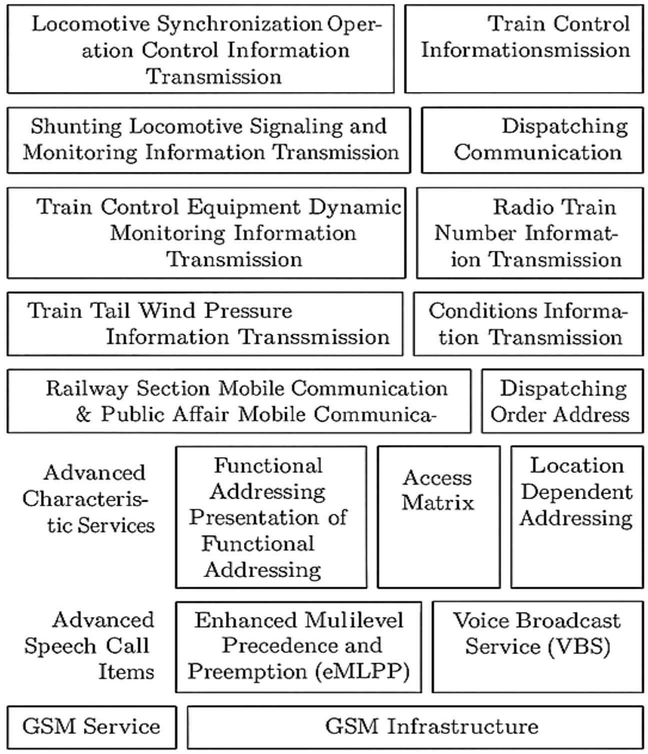

Figure 2: Service Model Structure for GSM-R

3 A Business Report on Future Railway Mobile Communication Systems

Real-time and all-encompassing communications are critical to ensure the reliability of railway operations with the sustained increase in train speed and reduced frequency intervals. Like other modes of transportation, railways are under pressure to meet excellent high-speed internet and communication system services for operational functions and customer satisfaction.

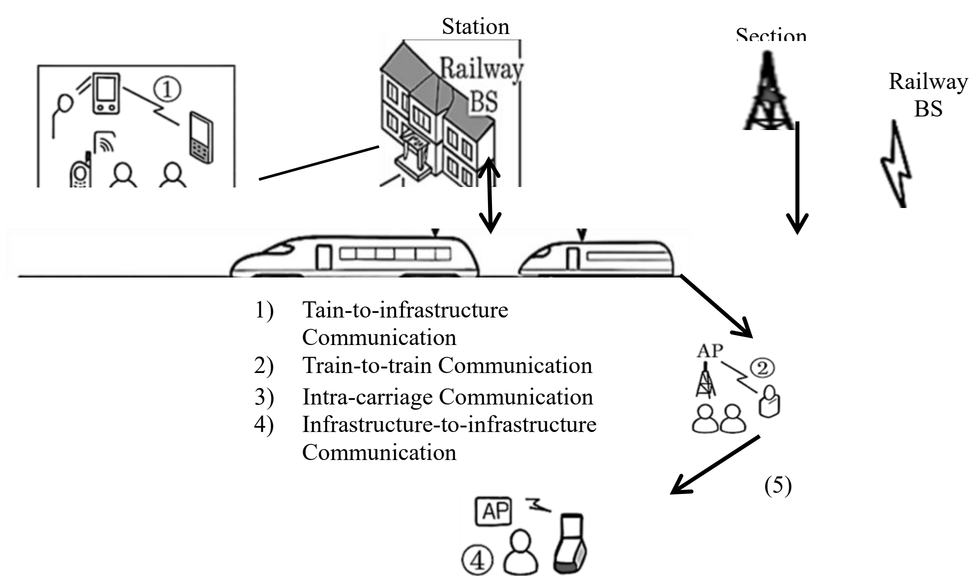

Figure 3: Five Representative Scenarios of Communication

Emerging services for the future railway mobile communication systems include real-time video surveillance and high-definition cameras along the tracks, which would enable transmitting real-time footage to permit drivers to detect possible hazards better. These video feeds will also assist in meeting various operational requirements, like multimedia dispatching. Further, vital services include train-to-train (T2T) direct communication. Unlike existing systems that rely solely on train-to-infrastructure (T2I) link systems, T2T communication allows the sharing of the location and status of the trains in real-time. This communication is crucial for the enhancement of safety measures as passengers would reduce the chances of rear-end collision ensuing due to infrastructure failure and redundancy in the pre-existing system.

In cutting-edge train communication systems, train multimedia dispatching should also be facilitated. Current systems are restricted to data and voice communication, which most likely does not allow dispatchers to interpret ground conditions accurately. Adding text data, images, and live video feeds will enhance situational awareness and efficiency, especially in emergency responses. Furthermore, developing the Railway Internet of Things (RIoT) is equally essential. Bridge and tunnel sensors will remotely send health and maintenance data to control centers, enabling remote inspections using safety checks and predictive maintenance algorithms.

A less studied but equally important criterion is passenger connectivity. As internet use continues to expand, providing high-speed, consistent internet access throughout all train stations is a growing need. Passengers expect the ability to browse the web, watch high-definition videos, and conduct work during travel, necessitating expansive wireless coverage and bandwidth (Masson & Berbineau, 2017).

To respond to these challenges, forthcoming railway communication systems must incorporate high data rate capabilities (from several Gbps to tens of Mbps). For example, advanced broadband train control systems have been proposed for the CRH3A EMU. These concepts show that with average usage rates, user penetration, and equipment capacity, a train with 1,114 passengers could theoretically require over 160 Mbps in passenger throughput. This number is orders of magnitude above the limits of existing narrowband systems such as GSM-R. As a result, a shift from narrowband to broadband mobile communication systems is imperative. Increased bandwidth will require accurate real-time monitoring, IoT applications, harsh passenger internet access, and extensive multimedia dispatching in the high-speed rail domain (Lannoo et al., 2007; Shi et al., 2011).

4 Future Railway-dedicated Mobile Communication Systems

For integrated support of railway activities, five representative scenarios of communication have been identified: Train to Infrastructure (T2I) communication, direct Train to Train (T2T) communication, Internet access within the carriages, communication within the station, and Infrastructure to Infrastructure (I2I) communication (Ai et al., 2015), as shown in Figure 3. Considering that wired communications are usually implemented for infrastructure-to-infrastructure links, which are less technically demanding, this subsection will concentrate on the first four wireless communications scenarios. Because of the variety of services and operational contexts, the future design of mobile communication systems for railways is heterogeneous at one or several frequency bands and multiple access technologies will be required.

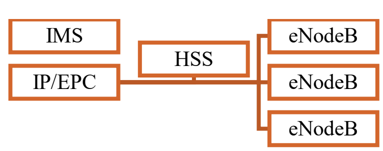

Figure 4: The Overall Structure of LTE-R

A. T2I Communication Systems

Fulfilling the requirements of future high-speed rail (HSR) systems will include services like video streaming and transmission of live images, which will require changing T2I communication systems.

Following the adoption of LTE for commercial purposes, LTE-R (Long-Term Evolution for Railways) is undergoing development as a successor to GSM-R. While both structures have similarities, LTE-R employs a flatter network topology (refer to Figure 4). This means eNodeBs and network routers are directly interconnected, reducing system latency (Gao & Sun, 2010). LTE-R integrates sophisticated technologies such as Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO). With MIMO, the transmission of multiple independent data streams becomes possible, thus increasing the data rate without the need for additional bandwidth. Furthermore, OFDM reduces the chances of interference during the processing of MIMO signals by breaking broadband channels into orthogonal flat sub-channels. Comparisons between LTE-R and GSM-R can be found, proving that LTE-R indeed provides enhanced performance and user experience. LTE-R has advanced capabilities for railway services such as video monitoring of critical regions (tunnels, bridges) and multimedia dispatching (He et al., 2016). Along with this, LTE-R advances legacy railway services such as eMLPP, VGCS, and VBS, ensuring backward compatibility via its Evolved Packet Core (EPC), enabling smooth migration to the newer system.

However useful LTE-A is, there are certain services where it falls short. One of the essential services for autonomous train operations is pervasive real-time video surveillance, but an LTE-A network does not have the bandwidth to support it. Additionally, longitudinal monitoring of railway assets through the Internet of Things (RIoT) may also place high requirements on connectivity, coverage, and energy consumption, where LTE-A falls short. Therefore, there is a need for 5G integration into T2I communications.

5 G-R is a standard 5G network specialized for railways and is anticipated to provide ultra-low latency of 1-5 ms alongside high peak data rates reaching up to 1 Gb/s. 5G systems are projected to offer 1000 times an increase in system capacity, 10 times better spectral efficiency, and 25 times higher average cell throughput compared to LTE systems. While LTE has some limitations, the new 5G network is backward compatible, meaning that it is more efficient at supporting existing railway services and also able to introduce new features. Massive MIMO is one challenger enabling this innovation, increasing spatial resolution, data throughput, and energy efficiency (James et al., 2025; El-Saadawi et al., 2024). Users with access to high-speed connections are aided through the low-level MAC architecture of the joint beamforming cloud processor (Liu et al., 2013).

Aside from incorporating MIMO, 5G may use Filter-Bank Multicarrier (FBMC) modulation instead of OFDM. FBMC helps accommodate band gaps, making it ideal for data-centric services (Winter et al., 2009). This also means 5 G-R will be able to provide real-time monitoring, multimedia services, and large-scale IoT-enabling infrastructures, which will facilitate predictive maintenance and autonomous driving.

In addition to cellular systems, the possibility of using IEEE 802.11-based WiFi in train environments has also been evaluated. The University of Nebraska conducted studies, sponsored by the Federal Railroad Administration (FRA), which showed that WiFi 802.11a/b/g could sustain mobile train communication with appropriate coverage. Further work by SNCF and Orange Labs in France proved that over a 13 km track segment, 802.11b/g can be used, and later tests achieved tens of Mbps through 802.11n. More recently, ACKSYS released a rugged AP system supporting 802.11ac with over 900 Mbps per stream. This makes it possible to set up wireless trackside backbones. Future 802.11ax WiFi systems will increase the throughput eight times compared to the previous version because of the cost-efficient real-time T2I communication for passengers, crew, and maintenance staff.

Efficient resource management continues to be challenging because of overlap, bandwidth contention, and unpredictable usage behaviors. Cognitive Radio (CR) resolves this problem dynamically with real-time spectrum sensing, aggregation, and adaptive replanning. Since railway environments are more systemic and predictable, CR can keep track of wireless conditions and optimize frequency selection and transmission settings during the train's course.

Optical Wireless Communication technology, or Free Space Optics, is a new field worth exploring. Research carried out in Japan and the UK under the umbrella of laser tracking systems showed OWC potential with a throughput of up to 400 Mbps. OWC also has immunity to electromagnetic interference and abundant unlicensed bandwidth. For this reason, it is an excellent candidate for T2I links.

In remote or infrastructure-light areas, satellite remains a valued alternative. GEO satellites have broad coverage but suffer from high latency (>250 ms) and signal degradation owing to terrain and weather conditions. However, Ka-band satellites are said to have greater capacity at a better cost. Thus, satellites are considered add-ons for earthbound T2I systems. LTE-R and 5G-R are expected to become the backbone of future T2I systems, while WiFi, CR, OWC, and satellites will augment T2I depending on the operational scenario and context in which they are used.

B. T2T Direct Communication Systems

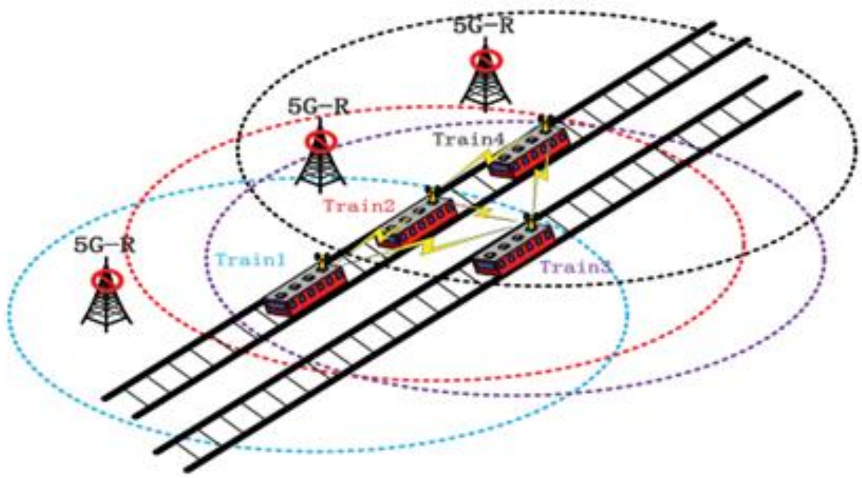

Figure 5: T2T Communication Systems

T2T communication will serve when T2I connectivity becomes dysfunctional. It allows communication between trains via onboard equipment even where non-sightline (NLOS) conditions apply. Therefore, some atmospheric bands should have deep diffraction characteristic potential. Increasing train speed and traffic density will demand higher transmission rates and delay tolerance for T2T systems, explaining why these systems are becoming more stringent.

5G cellular networks have a new two-layer architecture of microcell and device layer. The device layer consists of D2D-capable subsystems that permit communication between units without network reliance. Thanks to 5G's flexible spectrum, T2T communication becomes simplistic because of its low latency, ultra-reliable high-performance metrics, and throughput. Communication needs these attributes to be efficient.

Figure 5 shows a T2T scenario in 5 G-R systems. In the case of infrastructure failure, T2T emergency D2D networks can be quickly established. Trains on the same track, such as Train 1 and Train 2, communicate directly, while cross-track trains, such as Train 1 and Train 4, may serve as relays to increase the communication distance.

C. Intra-Carriage Communication Systems

During high-speed train journeys, passengers often need continuous Internet connectivity. However, mobile Internet delivery is problematic due to the high attenuation of carriage materials, frequent handovers, and high Doppler shifts. Even LTE-R cannot completely support intra-carriage Internet access because of spectral limitations.

The most efficient solution is to install wireless LANs (e.g., Wi-Fi) inside the carriages. These APs are connected to external antennas that interface with trackside infrastructure. Research also focuses on high-frequency standards such as IEEE 802.11ad/WiGig (60 GHz) and optical technologies like Li-Fi. Preliminary studies into the design of massive MIMO systems for intra-carriage applications offered promising access strategies and designs for maintaining constant connection.

5 Challenges of 5 G-R

The emergence of 5 G-R is expected to strengthen mobile communication systems for railways. Nonetheless, being an underdeveloped area of research, 5 G-R has many overarching issues to contend with, especially problems related to the characteristic propagation issues and channel modeling within different railway contexts. These issues are elucidated below.

1. Network Coverage Along Railway Tracks

Perhaps one of the more frontier issues facing 5 G-R is the uninterrupted coverage of the network along the expansive stretches of railway lines. 5G as a heterogeneous network facilitates spectrum access using high and low-frequency bands. Thus, enabling the 5 G-R deployment over multiple frequency ranges is feasible. For example, mid-quality low-band access could serve as an access layer, such as the 450–470 MHz spectrum proposed for use by next-generation railway communications in China. The underutilized spectrum between 6 GHz and 100 GHz can also support low-cost, high-data-rate transmission. However, realizing any access to the entire spectrum is associated with various challenges, like accurate channel measurement and modeling, single-point access mergers for low/high-frequency bands, and the intricate design of RF components.

2. Propagation Characteristics in T2T Communication

The 5 G-based train-to-train (T2T) networks have distinct features, T2T propagation characteristics, and channel models based on the operational environment. Sustained distance communication links are highly susceptible to environmental fluctuations, hostile weather conditions, and extensive external system interference. Developing reliable and all-encompassing channel models continues to be a significant challenge. Effective disruption mitigation at multiple levels of T2T links is necessary to avoid interference from different T2T links. Furthermore, T2T communication faces severe regulatory issues, which make security critical. Research done on M2M communication security, such as trusted environment-based connections and secrecy-based access control methods, may offer strategies that can be built upon to resolve these issues.

3. Synchronization in C/U-Plane Decoupled Architectures

In the C/U-plane decoupled architecture used in 5 G-R, the control plane (C-plane) and user plane (U-plane) run on distinct physical nodes. This division creates problems for the alignment of user data and control information. In high mobility cases, trains move into overlapping registration areas at such a high speed that the handover process does not finish in time, leading to service disruptions. Providing solutions to the problem of soft and rapid handovers is especially attractive to researchers. New approaches concerning staggered handovers in C/U-plane architecture have been investigated recently, offering new possibilities for overcoming these challenges.

4. Massive MIMO Under High Mobility

New lines of research on massive multiple-input, multiple-output (MIMO) systems focus on under-studied areas, such as channel conditions with mobility. Significantly, few jobs have addressed the challenges of high mobility performing massive MIMOs. For example, to facilitate 5 G-R system deployment, specific propagation models and channel attributes relative to the high mobility (T2I) Train-To-Infrastructure communication need to be developed. Furthermore, Internet access via Intra-Carriage broadband in trains necessitates these models. Additionally, the infrastructure soars and passenger ovate in train cars dictate shadow fading. This has a substantial impact on the deployment of array antennas. Advanced design problems arise from these facts with optimal counts, shapes, and orientations for antennas whose spatial and loading scenarios are highly variable.

5. Coexistence with Public Networks in Stations

At railway stations, 5 G-R must interact with public mobile networks. While 5 G-R caters to mission-critical railway communication needs, most networks are readily available and employed to surf the web for leisure activities by passengers. A fundamental problem is preventing adjacent channel interference between these systems. Another problem is the spatial design of stationary structures. Semi-closed spaces that contain high user density and are complex in architecture pose a distinct challenge to the performance of massive MIMO. Therefore, the development of targeted massive MIMO antenna arrays for railway stations is a compelling area of research.

6 Conclusion

This work analyzes the anticipated growth in demand for railway services and discusses the prospects of 5 G-R for better mobile communication systems in high-speed railways (HSRs). The first generation standard, the Global System for Mobile Communications-Railway (GSM-R), which is used today, is already outdated with modern rotary train operations and services. Although LTE-R is an improvement and does offer more services when compared to GSM-R, it still does not support forthcoming applications like autonomous train operation, RIoT (Railway Internet of Things) with massive connectivity, and high-speed internet access for the traveling populace. 5 G-R is projected to offer a radical shift in communication capabilities in overcoming these restrictions. These advanced railway applications with stringent requirements, such as ultra-reliable, low-latency, and high-capacity communication, are possible through 5 G-R and beyond what LTE-R can support. This extends to advanced train-to-infrastructure (T2I) and train-to-train (T2T) communications, intra-carriage, and intra-station communication networks working under a single heterogeneous umbrella.

Whether it is a slow transition through GSM-R to LTE-R and then 5 G-R, or 5 G-R is implemented directly, the progress of the 5G technologies, their commercial feasibility, and the policies set by governing bodies will play crucial roles. This paper has analyzed the significant challenges regarding 5 G-R deployment while equally highlighting the opportunities. These challenges include network coverage, high mobility channel modeling, synchronization issues in C/U-plane decoupled architectures, massive MIMO deployment, and coexistence with public networks. Solving these issues will be essential for leveraging the full capabilities of 5 G-R in future railway communication systems.

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