Innovation in Key Technologies of 5G-R System

LIN Wei, WANG Fang, GAO Shangyong, SHI Bo

Signal & Communication Research Institute, China Academy of Railway Sciences Corporation Limited

Abstract: This paper analyzes the communication business needs and application characteristics based on China's railway operation scenarios. Focusing on the specific needs of railways, the 5G-Railway (5G-R) system adds railway-specific functional network elements on the basis of general architecture. In terms of system networking, it focuses on the innovative key technologies of 5G-R core network and wireless network networking to adapt to the railway management mechanism and reliability requirements. It analyzes the technical optimization and innovation of 5G-R railway common equipment in terms of redundancy mode, function sinking, fault detection and reversal mechanism, etc.; 5G-R wireless network adopts the same-site equipment redundancy mode, and the paper analyzes the technological innovation of RRU redundancy, BBU redundancy and PCI planning, etc.; it also highlights the benefits of the train-ground integrated transmission system, including reduced roof antennas, decoupling of services and communication, unified spatial and temporal benchmarks, and cost savings.

Keywords: intelligent HSR; railway mobile communication; 5G-R; system architecture; networking technology; terminal application; train-ground integrated transmission

(This paper is selected from *China Railway*)

1 Introductions

In June 2019, the 5G system was officially launched for commercial operations in China. Following the large-scale deployment and application of public networks, the equipment becomes more sophisticated, which has laid a solid foundation for industry applications. In the future, railway intelligent communication will primarily manifest in intelligent network operation, resource management, system maintenance, and service application [1]. The 5G-R system is a critical base for railway to achieve intelligent communication.

The philosophy behind the 5G-R system development is to establish a private 5G-R network technology system by leveraging the experience in construction and operation of the GSM-R system based on railway business needs and application characteristics. To date, a preliminary standard architecture for the 5G-R system has been established, and the core network, wireless network, application terminals, and other equipment have been developed and tested for their system function, performance, and interfaces on the loop line of Railway Laboratory for 5G Innovation. Currently, dynamic field tests are being conducted on the loop line to verify system networking and service quality. In the next phase, key service testing, including high speed adaptability, train operation control and dispatching communication will be carried out on high speed test line. This work aims to establish a solid foundation for the engineering application of 5G-R.

2 Railway Business Needs and Application Characteristics

2.1 Application Scenarios

From a management perspective, railway communication in China is managed in a two-level structure: national railways and China Railway (CR) group companies. The first-level system is responsible for the management and monitoring of the operational status of the whole railway communication system and the organization and coordination of the business crossing different CR group companies; the second-level system is responsible for the operation and maintenance of the system and business management within the CR group companies.

Based on the categories of application scenarios, railway mobile communication can be broadly categorized into four scenarios: continuous wide coverage along main railway lines, hotspot areas within stations and yards, status awareness of fixed facilities along the lines, and intelligent mobile communication [2]. The requirements for relative speed, service bandwidth, reliability, and the number of connections demanded by communication agents vary significantly across these scenarios, thereby imposing distinct requirements on communication systems.

2.2 Business Needs

The primary task of the 5G-R system is to deliver reliable communication capabilities for train-ground train operation control and dispatch command services [3]. It will play a crucial supporting role in ensuring orderly transportation operations, enhancing train operation safety protection, and improving transportation productivity [4].

The railway 5G private network primarily facilitates train operation-related services, which are categorized into two main areas: train operation command and control, and operation and maintenance. In total, there are 90 services available [5]. These services can be further classified into voice, data, and video services. The calling modes encompass individual calling, group calling, and point-to-multipoint communication. Railway-specific services include function addressing, location addressing, and call restrictions, among others. These services require innovative customization based on the existing service logic of the GSM-R system.

Technological innovation centered on the railway management system, application scenarios, and service functional requirements is crucial for addressing key challenges in 5G-R technology. This involves aspects such as 5G-R system architecture, networking, functionalities, interfaces, and comprehensive business bearing.

3 System Architecture Innovation

Building on the 5G core (5GC) network, the 5G-R system primarily incorporates railway broadband trunking communication equipment (MCx), intelligent network (IN) equipment, a domain name server (DNS), remote authentication dial-in user service (RADIUS) equipment, equipment identity register (EIR), 5G-R home subscriber server (5G-GROS), 5G-R interface server (5G-GRIS), operation and maintenance service forwarding interface server for the onboard wireless communication equipment operation and maintenance management system (RMS-I), a connection management platform (CMP), among other application interfaces/access management devices [6].

Additionally, by introducing the service communication proxy (SCP) to aggregate signaling links, the number of signaling links between the CR group company 5GC core networks has been reduced from over 6,000 to over 300. This separation of service and signaling flows enhances maintenance and management efficiency. The 5G-R system has improved the call detail record (CDR) feature based on 3GPP specifications according to the actual needs of the railways and has eliminated interoperability with the 4G system.

4 Networking Technology Innovation

4.1 Two-level networking for core network

To align with the management

framework of two levels (national railways and CR group companies), the 5G-R core networks are structured into two-level networks: equipment shared nationwide and core networks within CR group companies.

4.1.1 Technical advantages of two-level networking

(1) Compared to one-level networking, two-level networking efficiently simplifies the signaling links between CR group companies (see Figure 1 for an example with the core networks of 5 CR group companies). The link requirements, network architecture, and routing organization are streamlined, facilitating operation and maintenance. Furthermore, the advantages become more pronounced as the number of nodes increases. With the implementation of two signaling links for load distribution among the core networks of 18 CR group companies, there are 306 signaling links in place with one-level networking and 36 signaling links with two-level networking. Thus, the number of signaling links is reduced by 88%.

(2) During operation, if a one-level networking is adopted, adjustment of signaling points by any of the CR group companies will require synchronous adjustments of link parameters of the remaining 17 CR group companies. If two-level networking is implemented, it is only necessary to adjust the relevant configuration of the local equipment and the equipment shared nationwide.

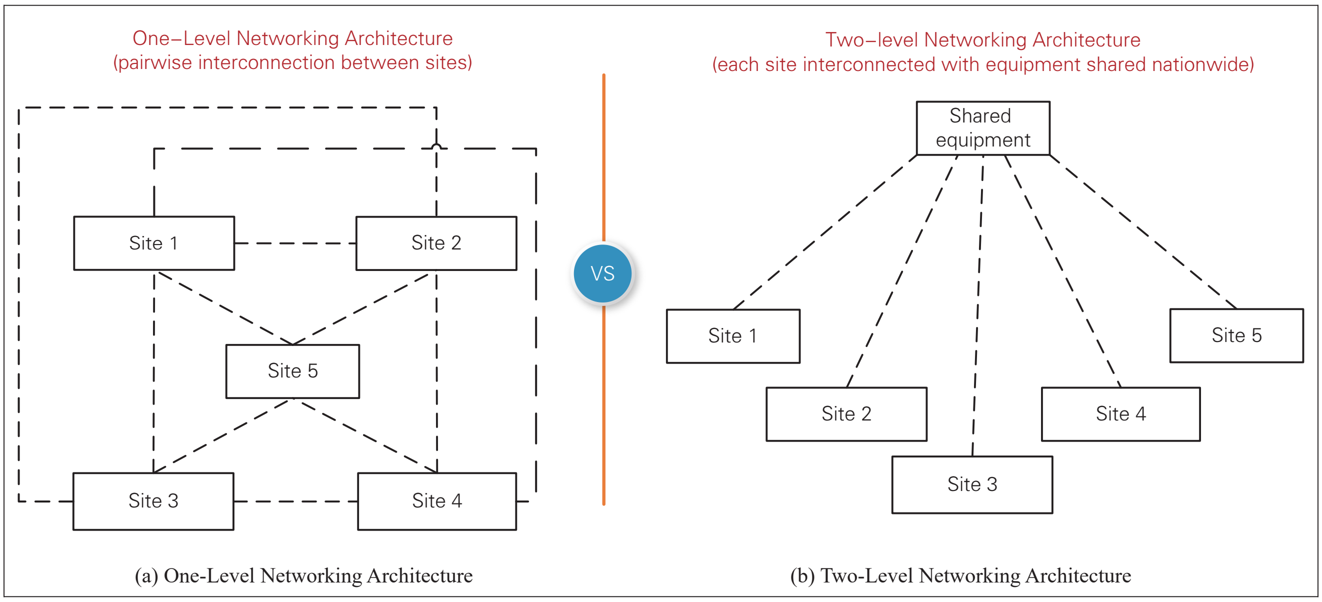

Figure 1 Comparison of One-Level and Two-Level Networking Architectures

According to the above analysis, compared with one-level networking, two-level networking has the advantages of simplified signaling links and a small correlation range for modifying core network link configuration. A disadvantage is that the one-level equipment is shared nationwide, meaning that any fault can impact services across the CR group companies. Therefore, on the one hand, it is necessary to strengthen the redundant configuration of equipment shared nationwide; on the other hand, it is necessary to simplify the functions of network elements shared nationwide as much as possible and deploy the service functions that can be handled locally at the 5G core networks of CR group companies. Building on the experience gained from GSM-R, the 5G-R system will implement a more optimized solution for the deployment of equipment that is shared nationwide.

4.1.2 Deployment principles of equipment shared nationwide

(1) Further strengthening the redundant configuration of equipment shared nationwide. As for the GSM-R equipment shared nationwide, one equipment center is deployed each for two CR group companies, for example group company A and group company B; while as for the 5G-R, four equipment centers will be deployed. This configuration offers greater redundancy and enhances resilience against force majeure events, such as natural disasters (see Figure 2).

(2) Reducing the equipment shared nationwide and deploying it at the core networks of CR group companies as far as possible. Compared to GSM-R, the 5G-R equipment shared nationwide eliminates servers for storing user subscription data and user authentication. Instead, these functions are integrated into the core networks of CR group companies. The 5G-R system reserves the intelligent network, the level 1 domain name servers, home interface servers, signaling forwarding equipment, and other equipment related to services across CR group companies. For the key equipment that supports services nationwide, corresponding level 2 equipment is deployed within CR group companies to perform the relevant service functions. The failure of the level 1 equipment does not affect normal operation of services within CR group companies, which reduces the impact

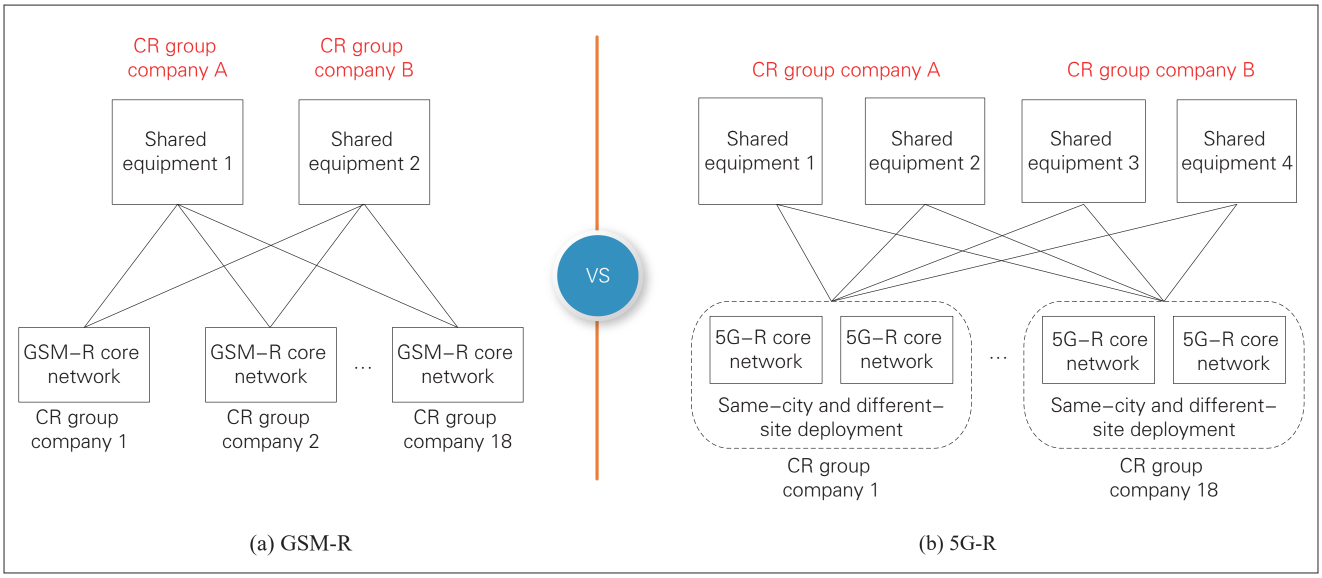

Figure 2 GSM-R, 5G-R Shared Equipment and Core Network Redundancy Configuration Networking

range of equipment faults. See Table 1 for the comparison of GSM-R and 5G-R equipment shared nationwide.

(3) Further improving the switching mechanism between active and backup equipment. The equipment shared nationwide is provided with both local redundancy and remote disaster recovery backup. Redundant backup utilizes various strategies, including load sharing, active and backup redundancy, floating IP redundancy, and pooling group redundancy. Regardless of the redundancy mode, effective fault detection is essential for initiating equipment switching. See Figure 3 for the link inspection and switching mechanisms between GSM-R and 5G-R equipment.

GSM-R adopts circuit switching mode, and when the equipment judges the status of the peer equipment, it only detects the link status, but not the status of the service application layer. In some extreme conditions, the application layer of the equipment has a hidden fault, that is, it cannot normally process the service and does not trigger the alarm, at this time, the link layer works normally, and will not trigger the automatic switch of the equipment, and the fault state cannot be automatically recovered.

Different from GSM-R, 5G-R adopts full IP switching mode to jointly inspect the status of both the link layer and the application layer. In the event of an unalarmed hidden fault of the equipment, when the originating equipment continuously sends service requests to the active equipment for several times in a row, and when the access time reaches the specified number or duration and there is no response from the service layer, the originating equipment can automatically initiate a service request to the backup equipment. This mechanism allows the service initiator to actively switch to redundant equipment, thereby enhancing overall system reliability.

4.2 Equipment redundancy networking for wireless network

To enhance the redundancy of wireless coverage, GSM-R utilizes interleaved redundancy and same-site redundant coverage [7], with interleaved redundancy primarily used along HSR lines. Given that the 5G-R system employs same-frequency networking approach, interleaved coverage will exacerbate same-frequency interference between cells. In urban rail transit, to improve the reliable train-ground data transmission of the communication-based train control (CBTC) system, the metro LTE-M system utilizes two inter-frequency wireless networks for same-site redundant coverage [8]. Both GSM-R and LTE-M achieve wireless network redundancy through frequency segmentation. With limited frequency resources in private networks, frequency resource segmentation will further reduce the system's capacity. Considering these factors, a key innovation for 5G-R wireless networks is to achieve same-site redundant networking without frequency segmentation.

Baseband unit (BBU) is an indoor device with low failure rate, which is generally installed in machine rooms at station or in section with easy access; RF remote unit (RRU) is generally an outdoor device with relatively high failure rate, which is installed on the towers along railway line, and is relatively inconvenient to maintain, so the demand for RRU redundancy configuration is more prominent.

For different classes of lines, BBU and RRU adopt differentiated networking methods. For 5G-R lines carrying train control services, redundant BBUs and redundant RRUs are adopted to ensure the requirements of service self-healing in case of single-point failure; for other lines, single BBUs and redundant RRUs are adopted.

4.2.1 RRU redundant coverage

Two RRUs with the same site are set up as a location group, adopting the cell merging mode of operation, and the two RRUs constitute the redundant coverage of the same logi-

Table 1 Comparison of GSM-R and 5G-R Equipment Shared Nationwide

Equipment	GSM-R	5G-R	Remarks
User subscription data server	●	△	In the GSM-R system, the home location register (HLR) is a device shared nationwide, which uniformly stores and manages user subscription data; In the 5G-R system, unified data management (UDM) is integrated into core networks of CR group companies that manage their respective user subscription data
Intelligent network	●	○	In GSM-R system, intelligent network equipment handles function addressing and location-based addressing nationwide; In the 5G-R system, intelligent network equipment mainly handles functions crossing CR group companies. Calling services, including location addressing and function addressing within CR group companies, have been transitioned to the core networks of these group companies and are handled by MCx
Authentication server	●	△	In the GSM-R system, the Radius equipment is shared nationwide. It is responsible for the unified authentication of terminal equipment's network access validity and static IP address allocation; In the 5G-R system, the Radius equipment is integrated into the core networks of CR group companies. It handles the authentication of terminal equipment's network access validity under its jurisdiction and dynamically assigns IP addresses, facilitating easier core network maintenance
Domain name server	●	●	In the GSM-R system, DNS is shared nationwide and it is not deployed within CR group companies; In the 5G-R system, the core networks of CR group companies are provided with Level 2 DNS to perform the domain name query function within CR group companies. The Level 1 DNS is only responsible for forwarding requests and responses for domain name queries crossing these group companies
Home interface server (GROS)	●	○	In the GSM-R system, the GRISs deployed within CR group companies do not offer IP address inquiry and update functions for onboard equipment. If the GROS fails, it will disrupt the normal updating of GRIS IP addresses for onboard equipment across national railways; In the 5G-R system, the GRISs deployed within CR group companies are responsible for the IP address inquiry and update functions for both local and adjacent CR group companies. If the GROS fails, it will not impact the normal updating of IP addresses for these group companies
SMS Center	●	●	The equipment has limited applications and operates independently. It does not interfere with other services
Terminal equipment identification server		●	In the GSM-R system, EIR is not enabled. After the existing IMEI data is collected and a database is established, it will be enabled in due course; In the 5G-R system, the EIR is shared nationwide. It checks and authenticates the validity of terminal equipment IMEISV to further enhance terminal access security. If the EIR fails and the relevant message times out without response, the end device will automatically enter the subsequent process

● Equipment shared nationwide; ○ Equipment shared nationwide with certain functions deployed at lower level; △ Equipment deployed within CR group companies.

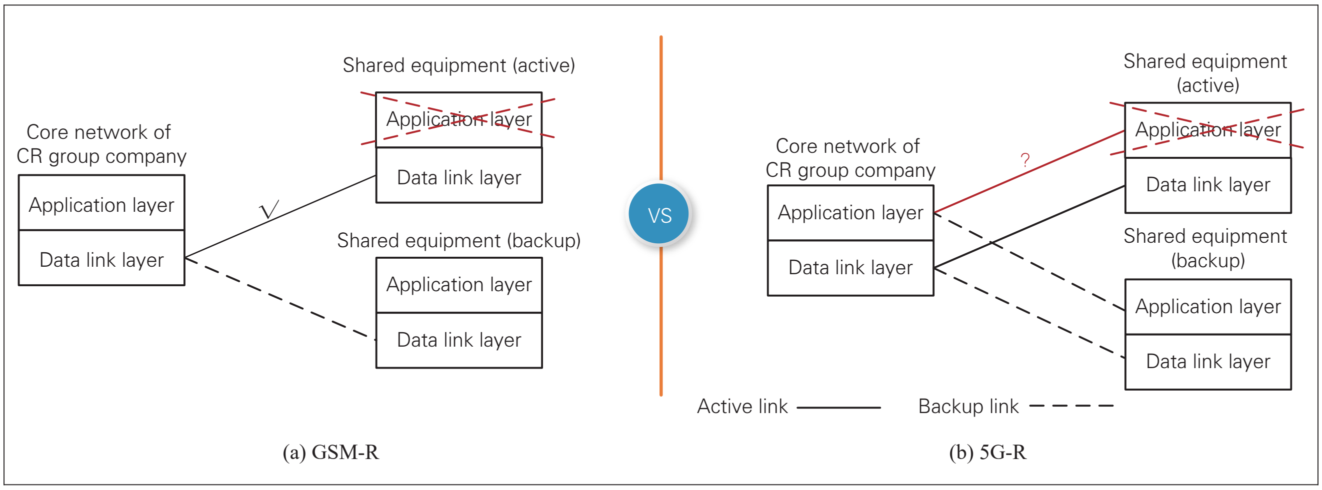

Figure 3 Status Inspection and Switching Mechanisms of GSM-R and 5G-R Equipment

cal cell. The two RRUs use the complete frequency band to work simultaneously, and if either RRU fails, the other RRU can still ensure continuous coverage.

Two RRUs in the same location group share multiple antennas for coverage of the railway line. In order to reduce the power loss and avoid the use of power splitters, the connection relationship between RRUs and antennas is shown in Figure 4 [9].

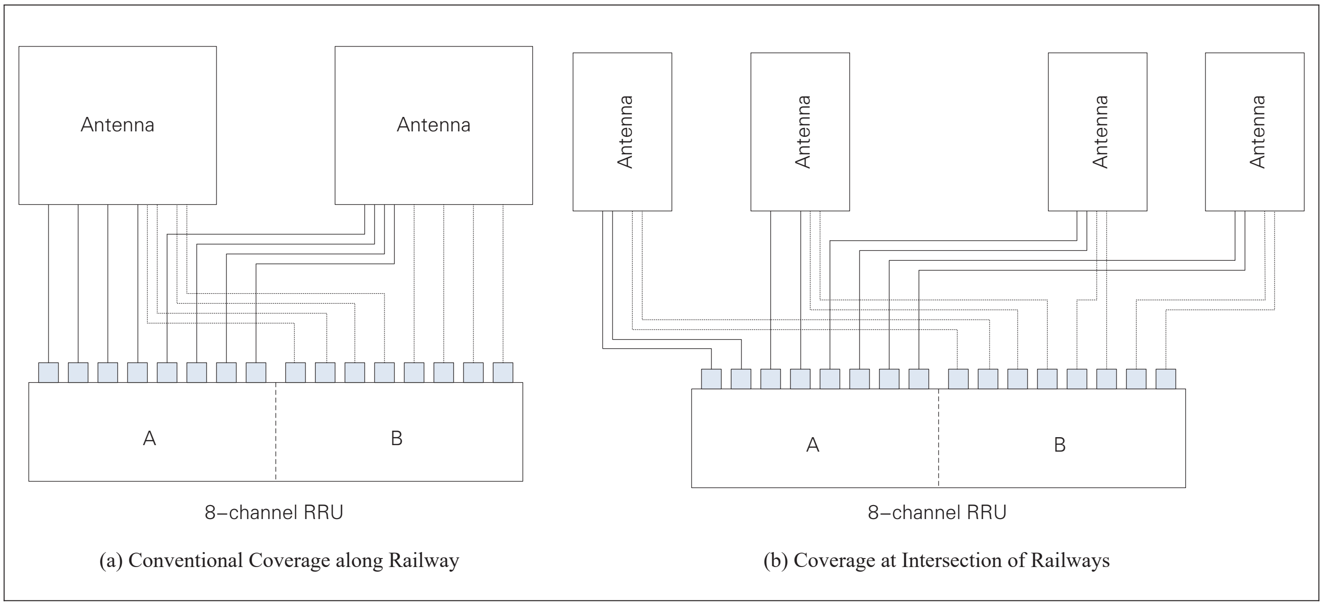

Figure 4 Schematic Diagram of RRU and Antenna Connections (8-channel RRU as an example)

Conventional coverage along the railway line can adopt the connection method in Fig. 4(a), where two RRUs in the same location group share 2 pairs of antennas, constituting the same logical cell and the transmission mode is 8T8R. If one RRU fails, the transmission mode will be automatically downgraded to 4T4R.

Coverage at intersection of railways can adopt the connection method in Fig. 4(b), where two RRUs in the same location group share 4 pairs of antennas to form the same logical cell and the transmission mode is 4T4R. If one RRU fails, the transmission mode is automatically downgraded to 2T2R.

4.2.2 Wireless networking with a single BBU

In the configuration of one BBU and two same-site redundant RRUs, ring, star, or chain networking can be adopted between the BBU and RRUs (see Figure 5)[9].

The two redundant RRUs at the same site should be connected to different baseband processing units of BBU to further enhance reliability.

4.2.3 Wireless networking with two redundant BBUs

In the configuration of redundant BBUs and same-site redundant RRUs, chain or star networking can be adopted between BBUs and RRUs (see Figure 6)[9].

The BBUs adopt the main and standby redundancy operation mode, the active BBU works and the backup

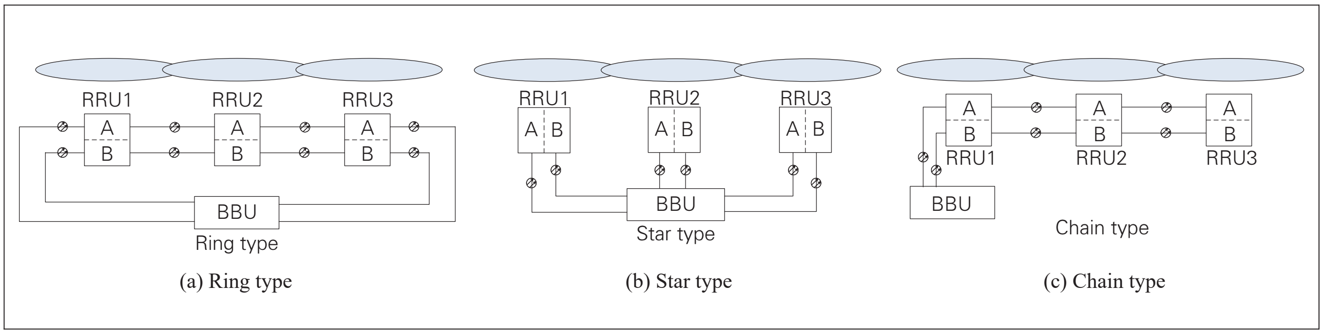

Figure 5 Wireless Networking with a Single BBU

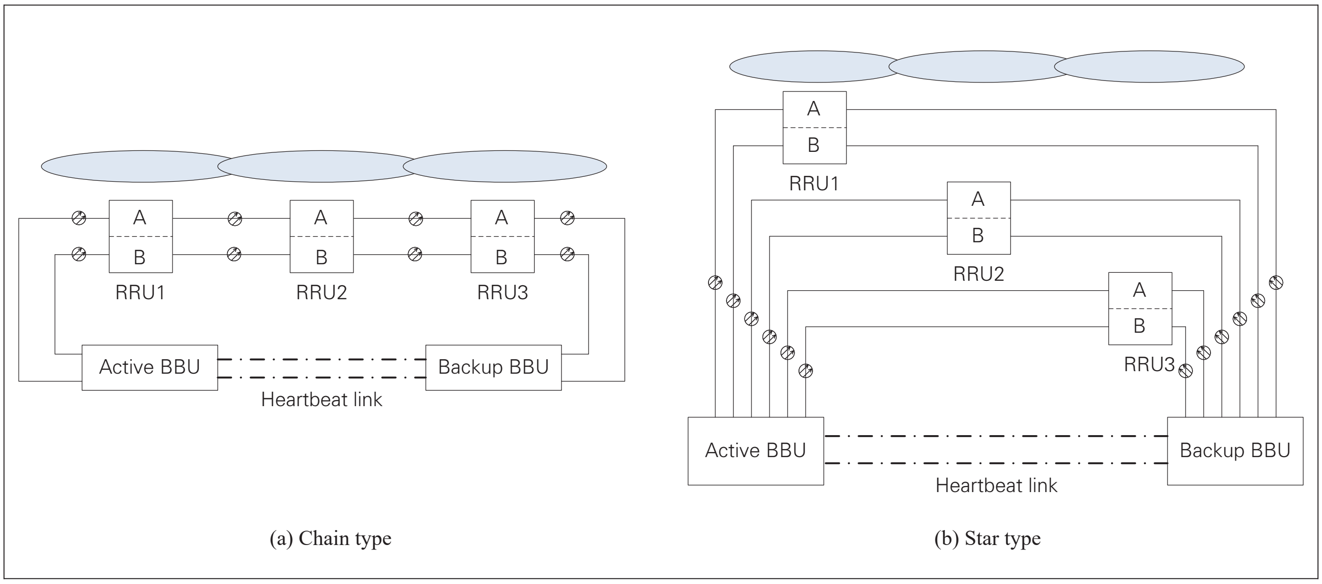

Figure 6 Wireless Networking with Two Redundant BBUs

BBU only powers up and does not work. A heartbeat detection mechanism is adopted between BBUs, when the backup BBU detects the failure of the active BBU, the backup BBU takes over the RRU work with switching time no more than 18 s [6]. Thus, in most cases, only one BBU is working. For specific failure scenarios, such as in Fig. 6, where the fiber between the chain-connected RRU2 and the primary BBU is interrupted, RRU2 and the subsequent RRU3 will be switched to the standby RRU, and the failure will be automatically recovered, and this is when the two sets of BBUs are working at the same time.

4.2.4 Planning for physical cell ID (PCI)

Since 5G-R cells are networked with the same frequency, the PCI between adjacent cells must ensure that there is no mode 3 identical situation in order to avoid the occurrence of interference [10]. In the case of dual BBU redundant wireless networking, since each BBU needs to plan its own PCI, the demand for PCI is high, so avoiding mode3 interference between neighboring cells presents a challenge to PCI planning. In the following, the PCI planning scheme is proposed according to three typical scenarios of setting RRU location groups governed by dual redundant BBUs as different cells, one logical cell and two logical cells.

(1) When RRU location groups managed by BBUs are configured as different cells, both the active and backup BBUs use the same PCI for the same location group (see Figure 7).

Regardless of whether the active BBU operates alone, or the backup BBU operates alone, or both the active and backup BBUs operate in different RRU location groups simultaneously, the PCIs of adjacent cells will not cause mode 3 interference.

(2) See Figure 8 for PCI planning when the RRU location groups managed by BBUs are configured as one logical cell.

The active BBU uses cell PCI mode 3 followed by 0 and 1, respectively, and the backup BBU uses cell PCI mode 3 followed by 2. This scheme gives priority to guaranteeing that there is no mode 3 interference with adjacent cell PCI when the active BBU operates normally.

For abnormal conditions such as non-consecutive active BBU equipment failure or NG interface interruption, all RRU location groups under this BBU are switched to work in the backup BBU. The backup BBU is configured with a cell PCI mode 3 followed by 2, and the adjacent active BBU is configured with a cell PCI mode 3 followed by 0 and 1. No mode

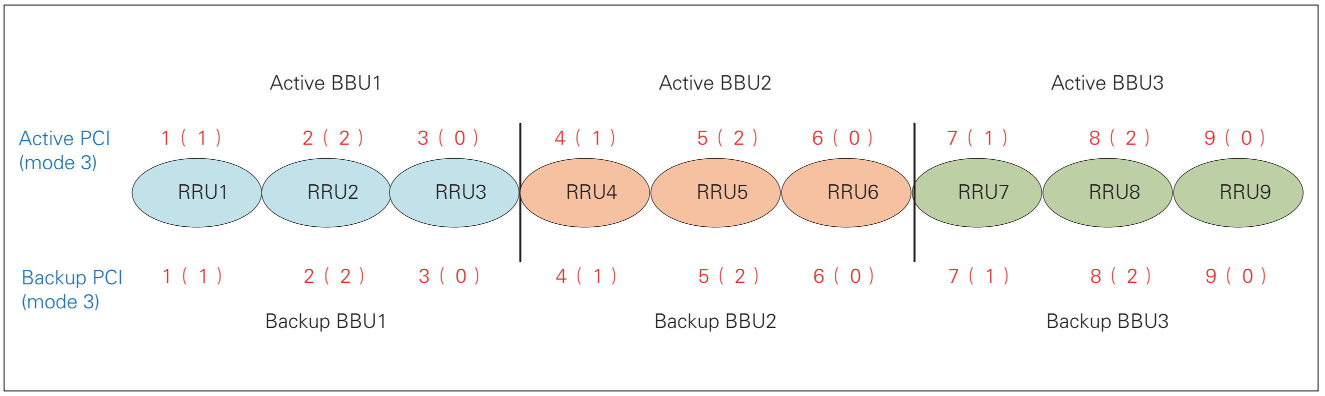

Figure 7 PCI Planning in the Case Where RRU Location Groups are Configured as Different Cells with Two Redundant BBUs

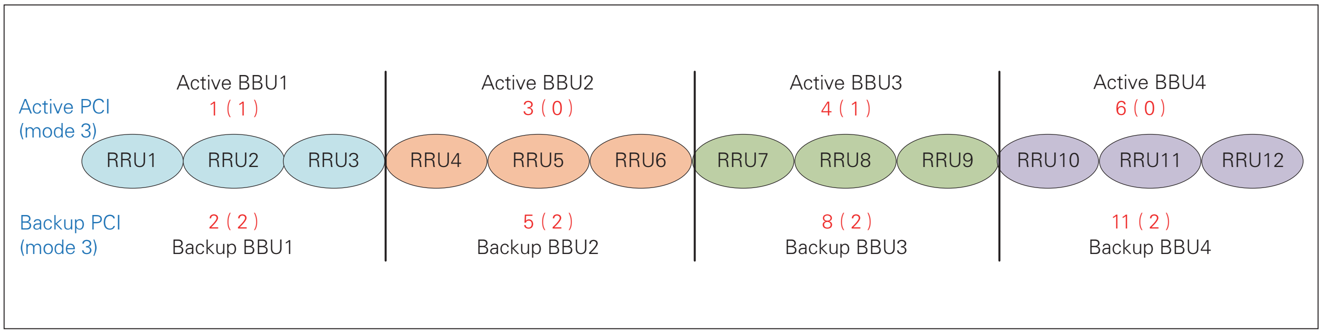

Figure 8 PCI Planning in the Case Where RRU Location Groups are Configured as One Logic Cell with Two Redundant BBUs

3 interference is formed between adjacent cells.

Under abnormal conditions such as link interruption between the RRU location group located in the middle and the active BBU, the backup BBU takes over the subsequent RRU location group, and the active BBU and the backup BBU work at the same time, and one logical cell splits into two. The active BBU is configured with a cell PCI mode 3 followed by 1 or 0, and the backup BBU is configured with a cell PCI mode 3 followed by 2. PCI mode 3 interference will not be formed between adjacent cells.

For two or more consecutive active BBU devices or link failures, standby BBU is switched on. The consecutive standby BBUs adopt cell PCI mode 3 followed by 2, which will form mode 3 interference. Considering that neighboring active BBUs are set up at different sites during engineering planning, the probability of two or more consecutive active BBU failures is very low.

(3) See Figure 9 for PCI planning when the RRU location groups managed by BBUs are configured as two logical cells.

The cell PCI adopted by the active BBU is 1 and 2 after mode 3. The standby BBU is configured with two sets of cell PCI parameters, one set is the same as the cell PCI adopted by the active BBU, and the other set of PCI parameters are 0 after mode 3.

When the active BBU operates normally, cell PCI mode 3 is followed by 1 and 2, and adjacent cell PCIs do not form mode3 interference.

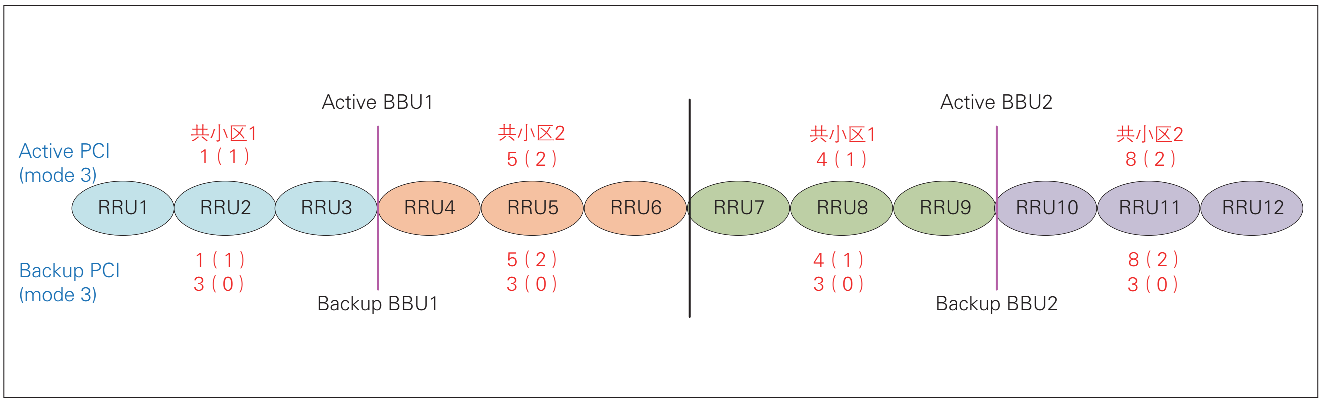

Figure 9 PCI Planning in the Case Where RRU Location Groups are Configured as two Logic Cells in Wireless Networking with Two Redundant BBUs

When all RRU location groups or all location groups of a logical cell as a whole are switched to work in the standby BBU, the standby BBU adopts the same cell PCI planning as that of the active BBU, with modes 1 and 2 after mode 3, and the PCI of the neighboring cells does not form mode 3 interference.

When part of the RRU location group of a logical cell is switched to the standby BBU, cell splitting occurs and PCI adopts 3 (0); the other RRU location groups still work in the active BBU, and the cell PCI modulo 3 is followed by 1 and 2, and no mode 3 interference will be formed by the PCI of the neighboring cells.

For some RRU location groups switched to backup BBU in two or more consecutive logical cells, consecutive cell splits occur, PCI adopts mode 3 (0), and mode 3 interference occurs between these consecutive split cells. The probability of this failure scenario is low.

5 Terminal Application Innovation

The primary task of the 5G-R system is to provide high-quality train-ground communication, which includes services related to train operation and various onboard monitoring services. Since GSM-R is a narrowband system, the train-ground communication for various onboard services is independently managed by each specialty. In 2020, the International Union of Railways (UIC) proposed establishing a unified communication gateway onboard to facilitate the integrated support of various services. The 5G-R system significantly enhances service bearing capacity compared to the GSM-R system. As 5G-R applications continue to grow, leveraging onboard communication equipment to comprehensively manage train-ground services has emerged as an innovative direction for terminal applications.

5.1 Problems and Challenges

In the application of 5G-R, if each specialty adheres to decentralized and independent communication access, the following issues will arise:

(1) Limited installation space for roof antennas. Unlike the GSM-R system, where each terminal module is connected to a single antenna, the 5G system employs a Multiple Input Multiple Output (MIMO) transmission mode, requiring each terminal module to connect to at least two antennas. Statistics show that the antenna positions on existing EMU trains and locomotives are predetermined at the time of manufacture. For instance, each EMU train is equipped with 9 roof antennas. Existing antennas have already occupied the roof space, and increasing the 5G-R antenna positions is not possible, especially because it is extremely difficult to remodel the existing car body.

Without roof antenna integration, when accessing the 5G-R system, it is necessary to add 13 more roof antennas on top of the existing 9 roof antennas, i.e. at least 22 roof antennas. Moreover, new demand for train-ground service in the future will lead to more roof antennas, which does not support train-ground communication expansion capabilities. Obviously, the communication access method and the communication roof antenna need to be integrated to meet the needs of 5G-R service development.

(2) Limited installation space inside trains. If 5G-R communication units are equipped for each specialty independently, it requires a certain expansion of space. Considering the limited space inside the vehicle, it is difficult to provide installation space for 5G-R communication units for each specialty.

(3) Repeated investment and high cost. 5G-R is a broadband mobile communication technology with strong data transmission capability and comprehensive bearing capacity. If each specialty is independently configured with 5G-R communication units, it will result in repeated configuration and repeated investment in the communication units of each specialty. In addition, each specialized device rents its own 5G channel on the public network, and the overall traffic cost is high compared to the integrated bearing.

(4) Not conductive to management and data collection. The repeated setup of onboard access points and ground gateways is not conducive to centralized and unified management and big data collection.

5.2 Construction of train-ground integrated wireless transmission system

With the advancement in railway broadband communication technology, unified train-ground service transmission has increasingly become a common practice in railway industry both domestically and internationally. During the research and development of 5G-R technology, a train-ground integrated wireless transmission system has been developed to facilitate train-ground services.

5.2.1 System architecture

The onboard integrated wireless transmission system primarily consists of three parts: new integrated antennas, an onboard transmission platform, and ground railway mobile transmission equipment (see Figure 10).

5.2.2 System functions

The onboard transmission platform provides a unified train-ground communication channel for onboard services. Its primary functions include: (1) supporting 5G-R, public networks, Wi-Fi, with millimeter wave reserved; (2) offering multiple Ethernet, serial port, and other service interfaces; (3) supporting BDS satellite positioning and time synchronization; (4) providing unified authentication and management; (5) conducting statistics and analysis of service traffic.

5.2.3 Advantage analysis

(1) Reduced roof antennas. Calculations indicate that integrated transmission leads to a reduction in the number of roof antennas from 22 to 8, compared to independent transmission. For EMU trains, the existing roof antenna layout can be retained, allowing 5G signal access without modifications to the carbody. The antenna integration scheme is presented in Table 2.

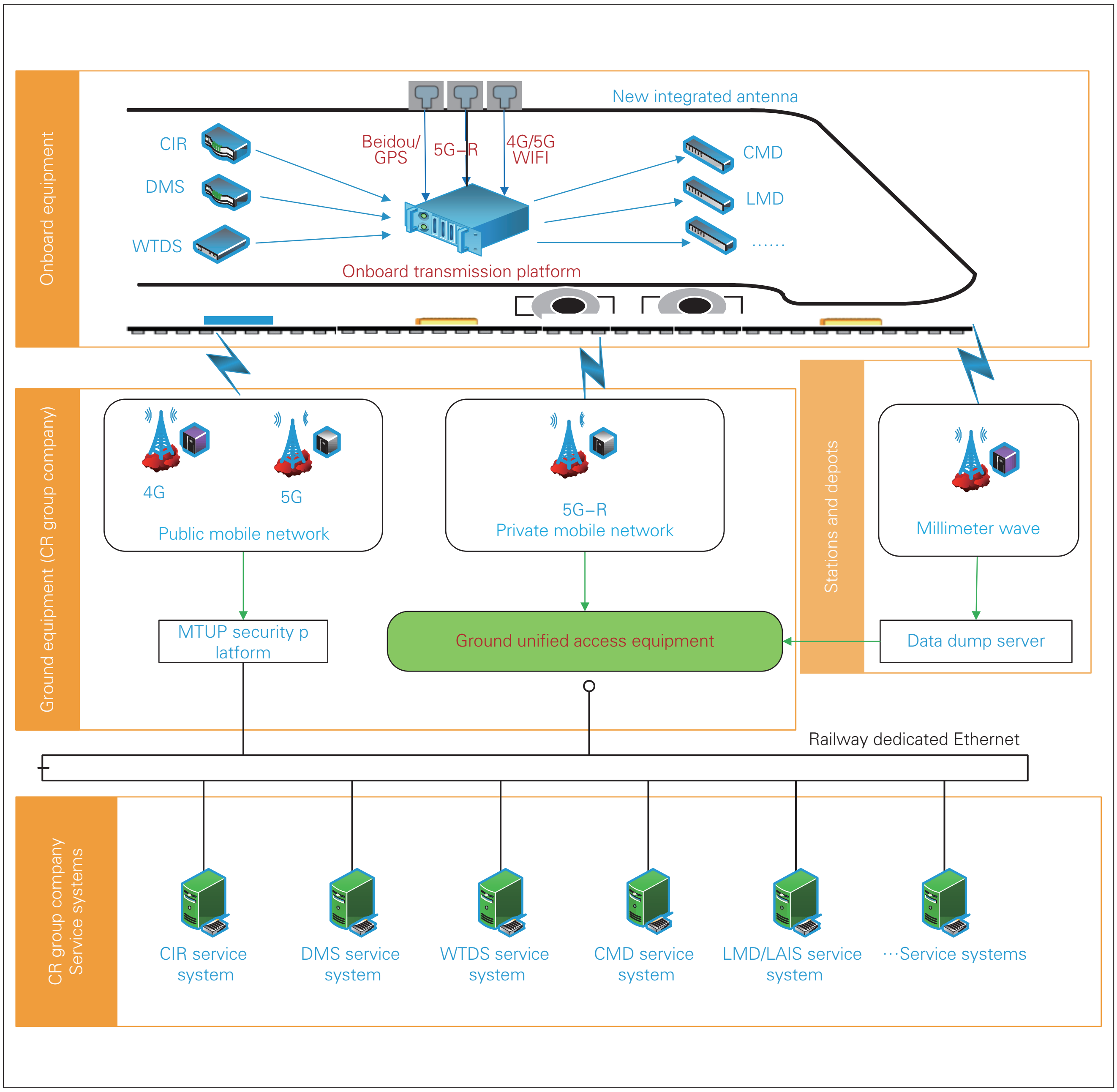

Figure 10 Architecture of the Train-ground Integrated Transmission System

(2) Decoupling of services and communication. Each service system connects to the train-ground integrated transmission system through standard interfaces. The services and communication systems are decoupled, allowing for independent technological evolution and upgrades without mutual constraints.

(3) Unified temporal and spatial benchmarks. It provides time and geographical coordinate information to onboard service systems to achieve temporal and spatial synchronization.

(4) Investment savings. Onboard communication equipment is integrated to decrease redundant construction and investment. When the public network is used, unified access can help reduce communication charges.

6 Conclusion

Meeting the needs of railroad business functions and system application is the core of 5G-R innovation work. Up to now, a series of research results have been achieved in 5G-R technology research. This paper systematically expounds the innovation work in 5G-R system architecture, networking and on-board terminal application, etc. In addition, the 5G-R technology innovation needs to be followed up continuously, and the research work on operation and maintenance technology, IoT application and other aspects is still deepening, which will achieve more innovative results.

(Translated by CHEN Min)

Table 2 Antenna Integration Scheme

Equipment	Services supported	Type of communication services	Number of antennas
ATO	ATO service	GSM-R system	1
		5G-R system	
ATP	ATP service	GSM-R system	2
		5G-R system	
Integrated transmission platform	CIR service, BLOS transmission service, vehicle-vehicle communication service, DMS service, HGDJ service, AMS service, EOAS service, and WTDS service	5G-R system	5
		Operator's public network system	
		WLAN system	
		GNSS system	
		Beidou short message	
CIR	CIR service	GSM-R system	
		450 MHz train dispatching system	
		800 MHz early warning system	
DMS	DMS service	GSM-R system	
CRES	CRES service	GSM-R system	
		5G-R system	
Total			8

References

[1] YANG Yin, QIU Ping, DENG Yefei, et al. White Paper on Railway Intelligent Communication [R]. Beijing: China Railway Society, 2021.
[2] WANG Tongjun. Key railway 5G technology analysis and development route [J]. *China Railway*, 2020 (11): 1-9.
[3] JIANG Yongfu. Discussion on priorities of railway 5G-R research and development [J]. *China Railway*, 2022 (9): 8-11.
[4] LIN Wei. Research on the transmission power parameter of 5G-R mobile terminal [J]. *China Railway Science*, 2023 (3): 153-161.
[5] China State Railway Group Co., Ltd. *Interim Specification for Service and Function Requirements of 5G Private Network for Railway: TJ/DW 239-2021* [S]. Beijing, 2021.
[6] China State Railway Group Co., Ltd. *Interim General Technical Specification for Railway 5G Private Mobile Communication (5G-R): TJ/DW 246-2022* [S]. Beijing, 2022.
[7] National Railway Administration. *Code for Design of Railway Digital Mobile Communication System (GSM-R): TB 10088-2015* [S]. Beijing: China Railway Publishing House, 2016.
[8] China Association of Metros. *Long Term Evolution for Metro (LTEM) - Design and Engineering Specification Part 1: Engineering Design: T/CAMET 04009.1-2018* [S]. Beijing: China Railway Publishing House, 2018.
[9] China State Railway Group Co., Ltd. *Interim Technical Specification for Railway 5G Private Mobile Communication (5G-R) Base Station Equipment: TJ/DW 256-2023* [S]. Beijing, 2023.
[10] WANG Qiang, LIU Hailin, HUANG Jie, et al. *5G Wireless Network Optimization* [M]. Beijing: Posts & Telecom Press, 2021.