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The development and current status of wireless communication systems for train-to-ground and train-to-train in urban rail transit

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Abstract. This paper explores in depth the development history, current status, challenges, and future trends of wireless communication systems for train-to-ground and train-to-train in urban rail transit. The train-to-ground communication system enables real-time data transmission between trains and the control center through the collaboration of onboard and ground devices, ensuring safe train operation; the train-to-train communication system focuses on direct information exchange between trains, optimizing operational efficiency. Communication systems have evolved from early dedicated channels, analog clusters, to modern WLAN, LTE-M, and the introduction of 5G technology, continuously upgrading to meet the growing operational demands. However, issues such as limited spectrum resources, multi-mode compatibility, anti-jamming capability, system reliability, network security, and construction and maintenance costs remain to be addressed. In the future, the deeper application of 5G technology, multi-mode integration, intelligent operation and maintenance, network slicing, and the integration of cloud platforms and big data technologies will drive the system toward greater efficiency and intelligence, providing strong support for the modernization of rail transit.

Keywords: urban rail transit, train-to-ground communication, train-to-train communication, wireless communication technology

1. Introduction

With the acceleration of urbanization, urban rail transit has increasingly become a key method to alleviate traffic congestion and enhance urban operational efficiency, and its importance continues to grow. The train-to-ground and train-to-train communication systems, as core structures of urban rail transit, undertake critical tasks such as train operation control, passenger information services, and emergency communications. In recent years, wireless communication technology has rapidly evolved from analog to digital and from narrowband to broadband, greatly enhancing the operational efficiency and safety of urban rail transit. However, as rail transit networks continue to expand and the demand for intelligence increases, existing wireless communication systems still face numerous technical challenges, such as limited spectrum resources, multi-mode compatibility issues, and insufficient anti-jamming capabilities. This paper will review the development history of train-to-ground and train-to-train wireless communication systems, analyze the current technological status, explore the challenges faced, and look ahead to future trends, with the aim of providing references for the further development of wireless communication systems in urban rail transit.

2. Definition and distinction of train-to-ground and train-to-train wireless communication systems in urban rail transit

The train-to-ground communication system typically consists of onboard communication devices (such as onboard antennas, wireless modules, etc.) and ground communication devices (such as base stations, antennas, etc.), used to achieve real-time bidirectional data transmission between trains and the ground control center. It can transmit real-time train speed and location information accurately to the ground control center and can also send braking information and real-time passenger information system data from the ground control center to the train. Key technologies include WLAN (Wireless Local Area Network), LTE-M, and 5G communication technologies. This system is an essential component of modern urban rail transit and a key technological support for ensuring safe train operation and improving operational efficiency [1].

The train-to-train communication system typically consists of onboard communication devices, ground communication devices, and transmission networks. Onboard communication devices include internal communication devices (such as passenger call buttons, broadcasting systems, etc.) and inter-train communication devices, which are used to enable data exchange between trains. Ground communication devices include station communication and control center equipment, which are used to receive and process information transmitted between trains. The system is designed to transmit train safety information, scheduling instructions, and operational data between trains, enabling real-time monitoring of train position, speed, and braking distance, thus optimizing the safety distance and operational efficiency between trains. This enhances rail transit operational efficiency, ensures safe train operation, and improves service quality. The technological foundation of the system primarily includes WLAN, WiMAX, LTE, and other wireless communication technologies. The introduction of 5G technology has significantly improved communication speed and real-time capabilities, creating infinite possibilities for further enhancing the intelligence of urban rail transit.

Both train-to-ground and train-to-train wireless communication systems play crucial roles in the field of urban rail transit. The core differences primarily lie in the communication objects, network architecture, and application scenarios. The train-to-ground communication system is primarily used for data exchange between trains and ground facilities, while the train-to-train communication system is mainly used for information exchange between trains. The train-to-ground communication system relies on the interaction of onboard devices, ground base stations, and control centers, whereas the train-to-train communication system focuses more on direct communication and autonomous collaboration between onboard devices. The train-to-ground communication system emphasizes ensuring safe train operation and global scheduling, while the train-to-train communication system is mainly used to achieve coordinated operation between trains and make real-time dynamic adjustments.

3. Development history of train-to-ground wireless communication system technology

3.1. Dedicated channel method

In the early days of urban rail transit in China, wireless communication was primarily based on the railway's train dispatch communication method—dedicated channel communication. This included point-to-point shortwave, ultrahigh-frequency radios, and conventional walkie-talkies. This communication method transmitted analog signals, with fixed channel allocation as the main approach. It was primarily used for train dispatch wireless communication and combined both wired and wireless methods to facilitate voice communication between trains and dispatch centers. However, this method had poor anti-jamming capabilities, limited bandwidth, and could not support data transmission. The quality of communication was also greatly affected by the environment.

3.2. Analog cluster method

With technological advancements, the analog cluster method began to be adopted in the 1980s. The cluster communication system enables frequency resource sharing and supports users sharing channels, offering high wireless channel utilization, fault tolerance, and flexibility, making it efficient and effective. This method was mainly applied to train dispatching, emergency communications, and voice communication between stations and trains. However, this method was still based on analog signals, making the cluster system vulnerable to interference. As a result, communication quality was unstable, and high-speed data transmission was difficult to achieve.

3.3. Digital cluster method

In the 1990s, the digital cluster method gradually replaced the analog method, marking the evolution of wireless communication technology from analog to digital. The application of digital communication technology has enhanced communication stability and reliability, improved anti-interference capabilities, increased bandwidth, and supported more data transmission requirements. It is mainly used in train dispatching, vehicle-mounted video surveillance, passenger information systems, etc. However, the bandwidth of this mode remains limited, making it difficult to meet the needs of large-scale data transmission, thus requiring a gradual transition to broadband systems.

3.4. Introduction of WLAN technology

In the 21st century, WLAN technology was introduced and widely applied in train-to-ground wireless communication for urban rail transit. WLAN is a wireless local area network technology based on the IEEE 802.11 standard, which enables data transmission and sharing through wireless connections between access points and wireless terminals. It supports high-speed data transmission and has a wide coverage area, mainly used in Passenger Information Systems (PIS), onboard video surveillance, and train status monitoring. However, the coverage of a single WLAN network AP is limited, requiring dense deployment, which makes maintenance in tunnels difficult and affects the stability of data transmission when trains are moving at high speeds. This technology operates on public frequency bands (2.4GHz or 5.8GHz), which are susceptible to interference from external devices such as mobile hotspots, and has weak anti-interference capabilities [2]. Furthermore, as the demand for urban rail informatization increases, the existing bandwidth is insufficient to meet the high-bandwidth requirements of services such as PIS and CCTV. Since WLAN uses public electromagnetic waves to transmit data, there are security risks such as data leakage or eavesdropping, making security and confidentiality issues in WLAN technology particularly prominent.

3.5. Widespread adoption of LTE-M technology

LTE (Long Term Evolution) technology, as a key stage in the evolution from 3G to 4G, has been widely applied in the field of rail transit wireless communication. Among these, LTE-M (LTE for Metro) is a dedicated communication system based on LTE technology. With the maturation of LTE-M technology, it has gradually become the mainstream technology for train-to-ground wireless communication in urban rail transit. It uses dedicated frequency bands and an optimized network architecture to address the issue of open frequency band interference, enhancing communication bandwidth and reliability to achieve high-speed, stable, and reliable communication between trains. LTE-M is primarily applied in CBTC (Communications-Based Train Control), PIS, onboard video surveillance, train status monitoring, and other areas. However, LTE-M technology has relatively high construction costs and requires dedicated spectrum resources.

3.6. Introduction and application of 5G technology

5G communication technology is the latest technological innovation in the field of communications. With the widespread adoption of 5G technology, train-to-ground wireless communication has entered a new stage of development. By using advanced technologies such as massive MIMO and edge computing, 5G achieves higher communication speeds, lower latency, greater capacity, and stronger anti-jamming capabilities [3]. It is primarily applied in CBTC, PIS, autonomous metro systems, and provides strong technical support for the construction of smart metro systems, such as train automatic monitoring and real-time data transmission, thus supporting the modernization of rail transit. However, the construction costs of 5G networks are relatively high, and the technical complexity is also significant. Issues related to compatibility with existing systems still need to be addressed.

4. Development history of train-to-train wireless communication system technology

4.1. Early CBTC systems based on train-to-ground communication and the introduction of train-to-train communication

The urban rail transit signaling system initially relied on fixed block and quasi-moving block systems. Later, it evolved into a CBTC system. The structure of the CBTC system is shown in Figure 1. The CBTC system uses wireless communication technology to enable information exchange between trains and ground equipment, including target speed, position, and track circuit status. It employs moving block technology to achieve precise train control and operational management. Key technologies in CBTC include wireless communication technologies (such as WLAN, LTE-M), and a combination of distributed control and centralized scheduling. However, traditional CBTC systems have some challenges, such as high system complexity, strong coupling, and a large number of devices, leading to numerous practical challenges [4]. For example, the system's strong dependence on the ground control center, the vulnerability of its internal wireless communication network to external interference, and the need for improved reliability. To optimize the CBTC system, researchers have proposed a train operation control system based on train-to-train communication to enable direct information exchange between trains, thus reducing complexity and coupling [5].

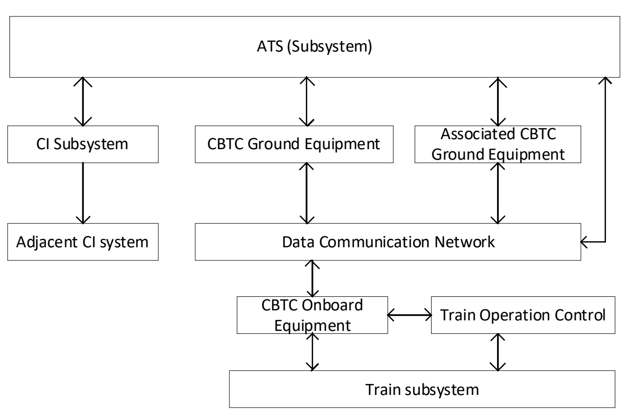

Figure 1. CBTC system block diagram

4.2. The rise of train-to-train communication technology

The concept of VBTC (Vehicle-Based Train Control) was introduced in the early 21st century, and related research has already been conducted. It can be said that the VBTC system is an upgraded version of the CBTC system. Its basic architecture is shown in Figure 2. The VBTC system is based on train-to-train communication technology, enabling real-time exchange of information such as position, speed, and operational status between trains, thus achieving precise control of train operations. This allows for more efficient coordination between trains and improves overall transportation capacity. At the same time, the VBTC system integrates static-dynamic safety protection strategies, providing comprehensive protection for security risks at four layers: perception, network, collaborative processing, and application. For example, at the perception layer, Petri net modeling is used to identify high-risk states; at the application layer, reachable identification is used to locate high-risk states and develop corresponding safety measures [6]. Compared to the traditional CBTC system based on ground control, the VBTC system offers significant improvements in flexibility and real-time performance, making it better suited to adapt to the complex urban rail transit environment.

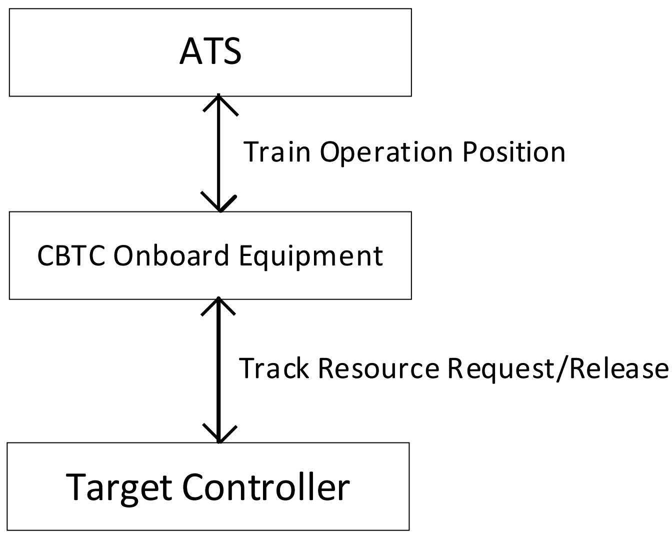

Figure 2. CBTC framework based on train-to-train communication

4.3. Development of train-to-train communication technology

By 2010, the Train Autonomous Control System (TACS), based on train-to-train communication, emerged as a next-generation urban rail signaling control system. Unlike the traditional CBTC system, TACS enables autonomous collaborative operation of trains through direct train-to-train communication, shifting the core functions originally performed by trackside equipment to the trains themselves. In TACS, trains exchange real-time operational status information and can independently perform functions such as positioning, speed measurement, and protection, greatly improving the system's response speed and operational flexibility. As shown in Figure 3, the simplified system architecture significantly reduces dependence on trackside equipment, thereby reducing construction costs and facilitating later maintenance [7]. Furthermore, the decentralized control approach allows trains to dynamically adjust their operating strategies based on real-time operational conditions, optimizing the use of line resources and shortening train station stop times. In terms of safety, TACS adopts multiple safety mechanisms. The system not only supports smooth degraded operation in case of failures but also integrates radar, visual, and other multi-source sensor data to ensure safe operation under various abnormal conditions [8]. The technological advantages of TACS make it suitable not only for urban rail transit but also hold promise for expansion to medium-capacity railways, intercity railways, and even high-speed rail in the future. This technology undoubtedly provides a new solution for the development of smart rail transit, showcasing vast potential for future growth [9].

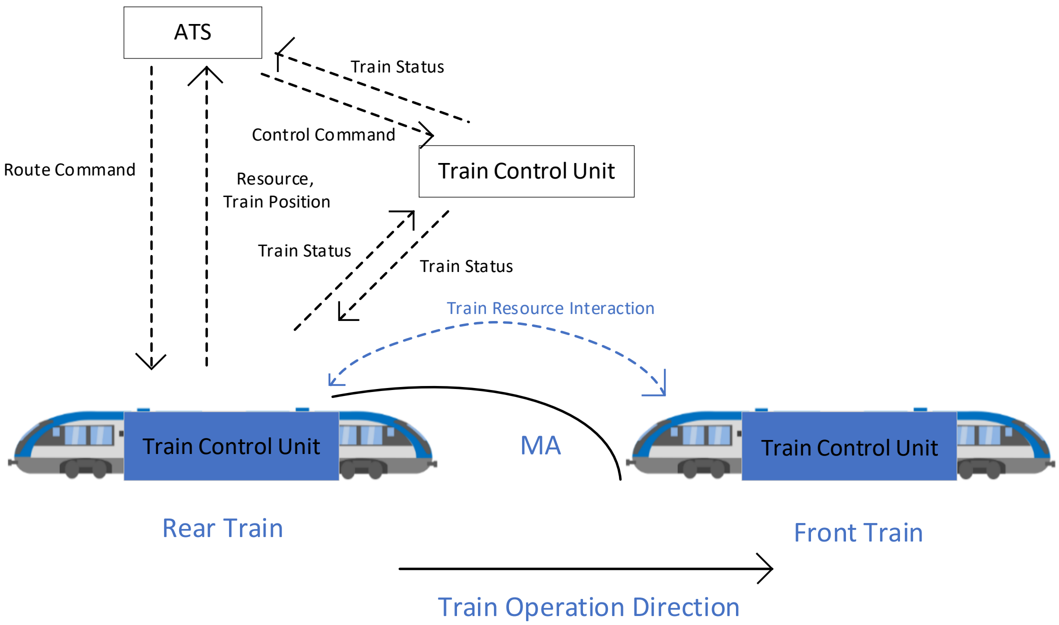

Figure 3. TACS framework based on train-to-train communication

5. Key technologies of train-to-ground communication system in urban rail transit

5.1. WLAN technology

In the train-to-ground communication system of urban rail transit, the architecture of WLAN technology mainly consists of ground wired communication networks, train-to-ground wireless communication networks, and onboard wired communication networks. The ground wired communication network serves as the backbone of the system, responsible for connecting trackside equipment and station devices, using Ethernet technology to ensure efficient data transmission. The train-to-ground wireless communication network utilizes wireless Access Points (APs) arranged along the rail lines, employing the IEEE 802.11 standards to facilitate wireless data transmission between trains and ground equipment. To improve the reliability and anti-interference capability of the system, a typical approach is to use cross-dual network coverage, where two independent wireless networks are alternately arranged, with each network operating on different channels to avoid channel interference. The onboard wired communication network connects various devices on the train, ensuring seamless data transmission and collaboration between onboard devices [10].

In terms of data transmission flow, control instructions or train operation information generated by ground equipment are transmitted via the ground wired communication network to the trackside access point. The AP then sends the data to the onboard wireless radio (MR) on the train via wireless signals. After the onboard MR receives the signal, it transmits the data to the onboard controller (CC) or other onboard devices. Conversely, information generated by onboard devices, such as train position and speed, is sent from the onboard MR to the trackside AP, ultimately reaching the ground equipment. This process not only ensures real-time data transmission but also improves the system's reliability and fault tolerance through redundant design [11].

The application of WLAN technology in the train-to-ground communication system of urban rail transit effectively addresses the high-bandwidth requirements for train operation control, passenger information display, and video surveillance. By adopting dual-network redundancy design and intelligent switching mechanisms, this technology enhances the system's reliability while also ensuring operational cost-effectiveness. It can be said that WLAN technology not only provides crucial technical support for the safe and efficient operation of urban rail transit but also accumulates valuable experience for the future upgrade and development of rail transit communication systems.

5.2. LTE-M technology

LTE-M technology is based on the mature LTE network architecture and uses dedicated frequency bands such as 1.8 GHz or 2.3 GHz to provide stable and reliable wireless communication between trains and the ground control center. Compared to traditional WLAN technology, it avoids interference issues caused by shared frequency bands, significantly improving communication quality. The entire system consists of three parts: the core network of the ground control center, the wireless access network deployed along the rail tracks, and the onboard terminals on the train, together forming an efficient train-to-ground communication network. The core network is responsible for data processing and user management, the trackside wireless access network consists of the baseband processing unit, remote radio unit, and dual-polarization leaky cables, ensuring efficient signal transmission and wide coverage. The onboard unit includes the train access unit, onboard switches, and other devices, enabling seamless connectivity for the train's internal communication equipment [12].

At the key technical level, LTE-M significantly enhances the system's anti-interference capability by using dedicated frequency bands, dual-polarization leaky cables, and band-pass filters. Additionally, the optimization of wireless link budgets and the application of small cell technology further expand the signal coverage and improve transmission efficiency. Moreover, the introduction of Power Saving Mode and Extended Discontinuous Reception technology effectively reduces the power consumption of terminal devices and extends battery life [13].

With its advantages of high reliability, fast transmission, and wide coverage, LTE-M technology is becoming the ideal choice for train-to-ground communication systems in urban rail transit. As this technology continues to improve and optimize, it will not only better ensure the safe and efficient operation of rail transit but also drive the entire industry toward a more intelligent future.

The architecture of the vehicle-mounted communication system based on LTE-M and WiFi technologies is shown in Figure 4.

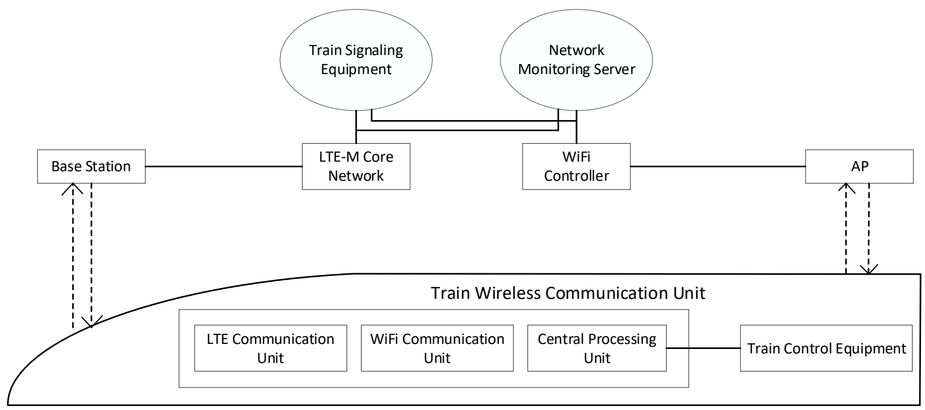

Figure 4. System architecture diagram of train communication based on LTE-M and WiFi technologies

5.3. 5G technology

The 5G train-to-ground wireless communication system typically uses a layered architecture that includes a core network, wireless access network, and terminal devices. In the core network, the 5G Core Network (5GC) architecture supports network slicing, which enables customized services based on different business needs [14]. The wireless access network achieves high-density coverage and high-bandwidth transmission by deploying small base stations and using massive antenna technology (Massive MIMO). Terminal devices primarily include onboard terminals (such as the Train Access Unit) and ground station equipment. Network slicing, a key technology in 5G, divides the physical network into multiple logically isolated virtual networks, providing dedicated network services for different applications such as train operation control, video surveillance, and PIS [15]. For instance, latency-sensitive CBTC operations can be allocated to the URLLC slice, while high-bandwidth applications like video surveillance and PIS systems can use the eMBB slice. This flexible resource allocation method significantly improves network utilization efficiency.

At the technical implementation level, Massive MIMO technology enhances spectrum efficiency and data transmission rates by deploying a large number of antennas at the base station. It also supports more simultaneous users, effectively increasing the bandwidth and stability of train-to-ground communication [16]. Mobile Edge Computing technology pushes computing and storage resources to the network edge, significantly reducing data transmission latency, which is particularly suitable for real-time applications such as train control [17]. Additionally, 5G networks can flexibly allocate spectrum resources based on actual business needs, further improving overall spectrum utilization efficiency. The collaborative application of these technologies not only enhances system performance but also lays a foundation for innovative applications such as intelligent operation and maintenance.

The architecture of the urban rail wireless communication system based on 5G technology is shown in Figure 5.

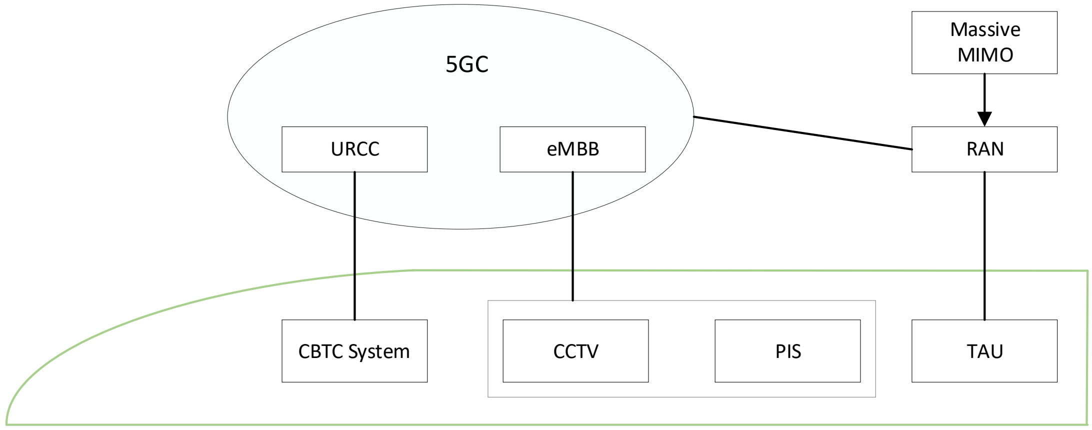

Figure 5. Schematic diagram of urban rail wireless communication system based on 5G technology

From a practical business perspective, the low latency and high reliability required by the CBTC system can be met through 5G networks with end-to-end latency of less than 10 milliseconds [18]. At the same time, the high bandwidth characteristics of 5G can support data transmission rates of up to 1 Gbps, perfectly catering to the real-time transmission requirements of high-definition video for video surveillance and PIS systems. More importantly, 5G technology also supports the implementation of intelligent operation and maintenance systems by transmitting real-time train status and sensor data, enabling remote monitoring and fault diagnosis. This will significantly enhance the operational safety and efficiency of rail transit.

6. Key technologies of train-to-train communication system in urban rail transit

6.1. Communication technologies based on logical and physical point-to-point methods

Currently, communication technologies based on logical point-to-point and physical point-to-point methods are the two main technical solutions in train-to-train communication systems. The logical point-to-point communication technology relies on existing wireless communication network architectures, where the core mechanism involves indirect data exchange between trains through base stations and the core network. Specifically, trains periodically send their operational status information (including but not limited to train ID, real-time position, speed, acceleration, and direction of travel) to nearby trackside base stations via the onboard communication unit. After processing at the base station access layer, the data is transmitted to the core network's data gateway via the backbone transmission network, and routing is determined based on the target train's network identifier. Finally, data is delivered through the base station in the target train's region [19]. As shown in Figure 6, the system architecture of this technology can be decomposed into terminal layer (onboard devices), access layer (base stations), core layer (mobile core network), and application layer (train control systems). Its advantage lies in the ability to reuse existing network infrastructure, ensuring stable communication coverage over a wide area. However, the communication performance of this model is limited by factors such as the density of base station deployment, the quality of wireless channels, and core network transmission delays. Especially during high network loads or base station handovers, additional delays may occur. Furthermore, in the case of base station failures or network congestion, the transmission of critical safety information may be interrupted. Therefore, in practical deployment, it is necessary to combine redundant base station configurations, QoS priority scheduling, and backup communication links (such as satellite or mesh networks) to enhance the system's robustness.

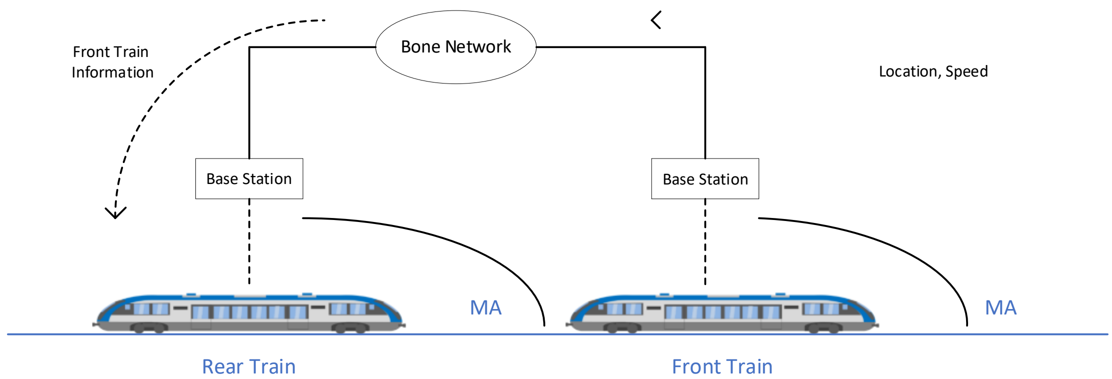

Figure 6. Schematic diagram of point-to-point communication technology based on remote control

In contrast, the physical point-to-point communication technology is based on the Device-to-Device (D2D/V2V) communication mechanism, where trains directly establish wireless links without relying on base stations for data relay. As shown in Figure 7. The technical implementation of this method depends on physical layer waveform design, resource allocation algorithms, and high-precision time synchronization to ensure end-to-end latency as low as milliseconds. In typical applications, trains broadcast basic safety messages in real time via onboard sensors and communication modules, allowing adjacent trains to parse the message content for coordinated collision avoidance or speed adjustment. The core advantage of this technology lies in its decentralized architecture, which helps avoid the inherent delays introduced by base station forwarding. It also allows coverage expansion through relay nodes in environments with significant multipath effects, such as tunnels [19]. However, its limitations cannot be ignored. Free space path loss and obstruction from physical barriers (such as buildings) restrict the communication range, typically to less than 1 km. In high-density train groups (e.g., at hubs), channel competition may lead to data collisions. Therefore, further research and optimization of wireless signal propagation technologies are required to improve its applicability in complex environments.

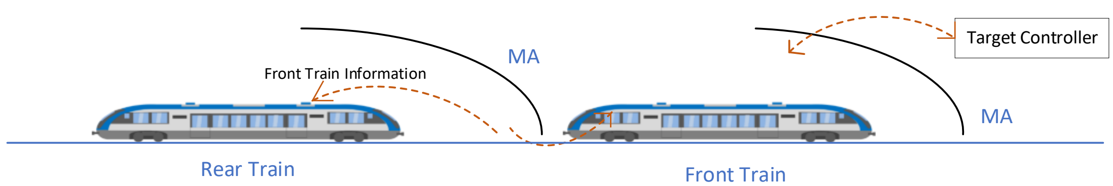

Figure 7. Schematic diagram of point-to-point communication technology

6.2. Wireless resource management technology based on soft frequency reuse

In the train-to-train communication system of urban rail transit, Soft Frequency Reuse (SFR) technology has gained significant attention as an efficient wireless resource management solution due to its remarkable advantages in interference coordination and spectrum efficiency improvement. The core principle of this technology involves dividing the cell into a central area and an edge area, and applying differentiated frequency reuse factors. The central area is allowed to use the full frequency band resources, while the edge area adopts a partial frequency reuse strategy. This zoning resource allocation mechanism effectively reduces inter-cell interference by introducing spatial domain frequency reuse differences, particularly improving the signal quality for edge users. From a technical implementation perspective, the application of SFR in rail transit scenarios mainly involves three key aspects: first, frequency planning based on geographic location, which requires optimizing the frequency reuse pattern according to train operating trajectories and base station deployment; second, dynamic power control, which adjusts transmission power in different areas to balance system capacity and interference levels; and finally, adaptive resource scheduling, which allocates resource blocks based on real-time channel state information. Research indicates that in typical urban rail transit environments, using SFR technology can increase edge user throughput by 30%-50%, while improving overall system spectrum efficiency by over 20% [20].

In summary, the application of SFR technology in the train-to-train communication system of urban rail transit not only effectively addresses the issue of inter-cell interference but also significantly enhances the system's spectrum efficiency and the throughput of edge users. Future research could further explore the integration of SFR technology with other advanced technologies to better meet the complex demands of urban rail transit.

6.3. Train-to-train communication based on 5G technology

5G technology is profoundly transforming the train-to-train communication system in urban rail transit, bringing unprecedented technological breakthroughs to this field. From a system architecture perspective, the train-to-train communication system includes several key components such as cloud network platforms, data centers, operation scheduling centers, logistics maintenance centers, onboard units, and intelligent trackside units [21]. By constructing a complete 5G network architecture that covers critical nodes such as the urban rail transit control center, depot, and parking lots, 5G technology provides strong technical support for train operation control and scheduling [22]. This comprehensive system design not only enhances communication efficiency but also lays a solid foundation for future intelligent expansion.

The advantages of 5G technology, including high speed, low latency, large capacity, and high reliability, make it the ideal choice for urban rail transit communication. Its network transmission speed far exceeds that of 4G technology, with latency as low as 1 millisecond, while providing tens of times more network connections than 4G, greatly enhancing communication efficiency and service quality [22]. Additionally, the full-duplex communication and signal enhancement technologies employed by 5G significantly improve resource utilization and anti-interference capabilities, providing reliable support for the real-time transmission of audio, video, and various technical parameters.

In practical applications, 5G technology further enhances the performance of train-to-train communication systems by optimizing frequency band resource allocation, signal coverage design, interval signal handover strategies, and application development. For example, in terms of signal coverage, 5G networks achieve comprehensive coverage through a combination of antennas and coaxial cables, while also addressing signal loss in special environments such as tunnels and issues with train body shielding [22]. Furthermore, the ultra-dense heterogeneous network structure of 5G can meet the data transmission requirements for high capacity, high reliability, and low latency in train-to-train communication, ensuring the safe and continuous operation of trains.

5G technology supports direct communication between trains, simplifying the communication process and improving communication efficiency. Through technologies such as data encryption, the security of communications can be enhanced. Additionally, 5G technology is compatible with existing 4G systems, preventing system crashes in emergency situations and ensuring the stable operation of the system. This compatibility and flexibility are crucial for the smooth transition and long-term development of urban rail transit systems.

The application of 5G technology in the train-to-train communication system of urban rail transit not only improves communication efficiency and operational safety but also drives the intelligent transformation of rail transit systems. By integrating 5G technology, urban rail transit systems can achieve more flexible train operation mode configurations, resource reservation and sharing, and optimize emergency response capabilities, providing passengers with more efficient and safer travel services. With continuous technological advancements, the application prospects of 5G technology in urban rail transit will become even broader.

7. Typical application scenarios of train-to-ground communication systems in urban rail transit

In urban rail transit train-to-ground communication systems, LTE-M technology serves as a comprehensive bearer platform, effectively supporting multi-service transmission for train operation control, video surveillance, and cluster scheduling through its high capacity and reliable bidirectional communication capability [23]. For example, the successful implementation of LTE-M on Kunming Metro Lines 4 and 5 has demonstrated its exceptional performance in complex hub environments, providing valuable experience for subsequent line construction. The CBTC system relies on wireless spatial waves or leaky cables as transmission mediums to establish a safe and reliable bidirectional information exchange channel between trains and the ground. Its optimized channel modeling technology significantly improves communication stability in complex environments such as tunnels and elevated tracks [23]. I believe that with the deeper application of 5G technology in the future, the real-time performance and reliability of the CBTC system will be further enhanced, providing stronger technical support for high-density train operations. Additionally, the train-to-ground communication system integrates passenger information services, enabling real-time video streaming and monitoring image transmission between trains and stations via wireless networks, thereby providing passengers with high-quality information services [11]. Notably, this design concept, which deeply integrates operational control with passenger services, embodies the "passenger-centered" approach in the development of modern rail transit. These three typical application scenarios together form the integrated "control-monitoring-service" communication system architecture of modern urban rail transit.

8. Typical application scenarios of train-to-train communication systems in urban rail transit

Train-to-train communication systems are driving a new paradigm in the intelligent development of rail transit. Their value is not only reflected in the technological advancements but also in the innovation of operational concepts. In train automatic control, the biggest breakthrough of train-to-train communication lies in achieving true distributed collaborative control—each train is no longer an isolated entity but a dynamic node within an intelligent network. This architecture is more flexible and reliable than traditional centralized control systems [24]. A particularly noteworthy development is the introduction of machine learning algorithms in the next-generation systems. By deeply learning from historical operation data, these systems can predictively optimize the overall operation strategy of train fleets. This intelligent collaborative control represents the future direction of development. In the realm of safety and emergency response, the transformation brought by train-to-train communication is even more profound. The traditional "train-ground-train" information transmission model has inherent delays, whereas direct train-to-train communication establishes a mesh-based early warning system. The latest systems can now achieve millisecond-level hazard information broadcasting, combined with rapid decision-making by onboard AI, reducing emergency response time by over 60% [24]. This real-time protection network is redefining the safety standards of rail transit. In terms of intelligent operation and maintenance, the most forward-thinking aspect is its predictive maintenance capability. By analyzing subtle characteristic data such as vibrations and currents generated during train interactions, the system can identify potential failures in key components, such as the bogie, weeks in advance [25]. This data-driven, preventive maintenance model will fundamentally change the traditional passive "post-failure repair" approach.

These three dimensions of innovation mutually promote each other, together constructing the intelligent system of rail transit. Train-to-train communication technology enables train fleets to have collaborative decision-making capabilities, driving the industry's leap from mechanization to intelligence. This transformation not only optimizes operational efficiency but also reshapes the service model. With the integration of new technologies such as 5G, this transformation is accelerating, signaling that rail transit is heading toward a smarter future.

9. Current maturity and application cases of wireless communication systems in urban rail transit

The wireless communication systems in urban rail transit are currently undergoing a critical period of technological upgrades and optimization. Various wireless communication technologies demonstrate different levels of maturity and effectiveness in practical applications. WLAN technology, with its relatively low deployment costs and broad coverage, has become an important means of enhancing passenger travel experiences, particularly excelling in providing wireless internet services. However, its stability and security in high-speed environments are insufficient, which limits its application in more critical train-to-ground communication areas. For example, Guangzhou Metro uses WLAN technology to provide wireless internet services to passengers, significantly enhancing the passenger travel experience. However, its application in key services, such as train operation monitoring, still requires further improvement [26].

LTE-M technology is widely applied in urban rail transit and can meet the current demands for most train-to-ground communication and passenger information services. Its high data transmission rate and excellent mobility support make it one of the mainstream choices for urban rail transit communication systems. For example, Shanghai Metro Line 1 uses LTE technology to achieve data communication and control information transfer between trains and the ground control center, supporting real-time scheduling and management of train operations [26].

The emergence of 5G technology has brought a qualitative leap to urban rail transit wireless communication systems. With its advantages of high speed, low latency, and high reliability, 5G technology shows immense potential in both train-to-ground and train-to-train communication. 5G technology not only supports critical services such as real-time train control and high-definition video surveillance but also provides powerful technical support for smart station services. For example, the high bandwidth of 5G technology enables the real-time transmission of high-definition video surveillance systems, significantly improving emergency response capabilities. Its low-latency feature provides reliable communication support for autonomous trains [27].

The communication solution adopted by Lijiang Tram Line 1 combines LTE private networks and 5G public networks through a redundant integration approach. This solution achieves efficient data transmission and enhances operational efficiency and safety through proper equipment deployment [28]. This integrated solution not only fully utilizes the maturity of LTE technology and the advanced features of 5G technology but also improves system reliability through redundancy design. The application of 5G millimeter-wave technology in the depot and parking areas, using multi-antenna and beamforming technologies, enables efficient data backhaul when trains are parked, supporting a variety of service requirements [29].

10. Technical challenges and development trends of urban rail transit wireless communication systems

10.1. Technical challenges

Urban rail transit wireless communication systems face numerous technical challenges in practical applications. One of the key factors limiting system development is the limited availability of spectrum resources. For example, the 1785-1805 MHz frequency band used by LTE-M technology has varying bandwidth allocations across different regions, resulting in limitations in system functionality and performance [30]. The issue of multi-mode compatibility adds complexity to system construction and maintenance, with technical barriers preventing seamless interconnection between different wireless communication technologies. For instance, Line 1 and Line 5 of Dalian Metro use the TETRA and LTE-M standards, respectively, which cannot directly interconnect [30]. Additionally, the complex operating environment poses significant challenges to the system's anti-interference capabilities, as signal transmission stability and reliability are affected by various sources of interference. The CBTC system, operating on the 2.4 GHz frequency band, is particularly susceptible to interference from other wireless devices, impacting signal transmission stability and reliability [31]. Insufficient system reliability could lead to train operation interruptions, while network security issues may result in data breaches and system paralysis, severely affecting the normal operation of rail transit [32].

10.2. Development trends

Although urban rail transit wireless communication systems face numerous technical challenges, their development prospects remain highly optimistic. With its high speed, low latency, and high reliability, 5G technology has already become the key development direction for future wireless communication systems. In both train-to-ground and train-to-train communication, the application of 5G technology has greatly enhanced the overall performance and reliability of these systems. Multi-mode integration, through reasonable architectural design and key technological applications, has successfully achieved compatibility and coordinated operation between different communication standards, significantly enhancing the overall performance of the system [30]. As the process of intelligence and automation continues, intelligent operation and maintenance platforms, supported by big data analysis and artificial intelligence technologies, have enabled real-time monitoring of train operation statuses and fault prediction, effectively improving operational efficiency [15]. The widespread use of network slicing technology has provided tailored network services for various communication needs, further optimizing resource allocation. The deep integration of cloud platforms and big data technologies has provided powerful technical support for centralized management and optimization of wireless communication systems, significantly reducing construction and operational costs. Additionally, the implementation of segmented commissioning and co-line operation plans [32] has effectively reduced technical risks and construction costs, paving the way for the efficient construction and operation of rail transit systems.

In the future, urban rail transit wireless communication systems will experience a wave of technological innovation and upgrades. With the widespread application of 5G and even 6G technologies, data transmission rates will significantly increase, and latency will be greatly reduced, thereby driving the system towards a more intelligent and integrated direction. At the same time, the deep integration of advanced technologies such as the Internet of Things, cloud computing, and artificial intelligence will make system functions more diverse and robust, providing reliable support for the intelligent operation of rail transit. This series of innovations will bring more efficient and intelligent operation methods to future rail transit systems, offering passengers a more comfortable and convenient travel experience.

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