Postprint: Broadband Wireless Communication Systems for High-Speed Railways

Authors: Zhou Yiqing, Zhou En, Tian Lin, Shi Jinglin

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Abstract

With the development of high-speed railway and broadband wireless communication technologies in China, the demand for providing broadband wireless communication in high-speed rail environments has grown increasingly urgent. The narrowband GSM-R (Global System for Mobile Communications on Railways) currently employed by high-speed rail systems can only support data transmission rates below 200kbps, which is insufficient to meet the requirements of emerging services such as video surveillance and passenger multimedia for future high-speed rail applications. It is imperative to develop broadband wireless communication systems optimized for high-speed rail scenarios to deliver stable, reliable, and high-quality broadband wireless communication services for train operations, control systems, and passenger services. This paper analyzes the challenges confronting broadband wireless communication systems for high-speed rail in core technologies including network architecture, resource management, and physical layer air interfaces, by considering the distinctive characteristics of high-speed mobility and predictable location of high-speed rail, and proposes solution approaches to address these challenges.

Full Text

Broadband Wireless Communication Systems for High-Speed Railways

Yiqing Zhou, En Zhou, Lin Tian, Jinglin Shi

Abstract

With the rapid development of high-speed railways and broadband wireless communication technologies in China, the demand for providing broadband wireless communication services in high-speed rail environments has become increasingly urgent. Currently, the narrowband GSM-R (Global System for Mobile Communications on Railways) system used in high-speed railways can only provide data transmission rates below 200kbps, which cannot meet future requirements for new services such as video surveillance and passenger multimedia applications. To deliver stable, reliable, and high-quality broadband wireless communication services for railway operations, control, and passengers, it is essential to develop optimized broadband wireless communication systems specifically designed for high-speed rail environments. This paper analyzes the challenges faced by broadband wireless communication systems for high-speed railways in three core technical areas—network architecture, resource management, and physical layer air interface—considering the characteristics of high-speed mobility and predictable trajectories, and proposes approaches to address these challenges.

Keywords: high-speed railway; broadband wireless; network architecture; resource management; physical layer air interface

1 Background

In recent years, high-speed railways have experienced rapid development worldwide. Compared with other transportation modes, high-speed railways offer large carrying capacity, high operating speeds, and efficient transportation, while also aligning with global green development trends. Consequently, they have received increasing attention and application worldwide. Following large-scale construction in Japan and Europe, the United States proposed a plan in 2009 to build 10 high-speed railway lines across 10 regions with a total investment of $13 billion, which will become major inland transportation corridors in the future. By the end of 2009, the Wuhan-Guangzhou high-speed railway—the world' s fastest at 350 km/h—was put into operation in China. According to China' s Medium- and Long-Term Railway Development Plan, by 2020, the country will have completed a "four vertical and four horizontal" high-speed passenger railway network spanning 13,000 kilometers, including 5,000 kilometers of lines operating at 250 km/h and 8,000 kilometers at 350 km/h. This rapid development has driven growth across numerous industries including construction, manufacturing, materials, and tourism, establishing high-speed rail as a major artery of the national economy and China' s primary future public transportation method.

The world' s fastest Wuhan-Guangzhou high-speed railway

Within such a massive integrated system, every component relies on communication, particularly wireless communication. The three core technologies in dedicated passenger railway systems are rolling stock, train control, and civil engineering. As the sole communication means between trains and operation management authorities, wireless communication technology is a key component of train control systems, bearing the critical mission of improving operational efficiency and ensuring the safety of train operations and passenger lives. Wireless communication systems in high-speed railways must feature high reliability

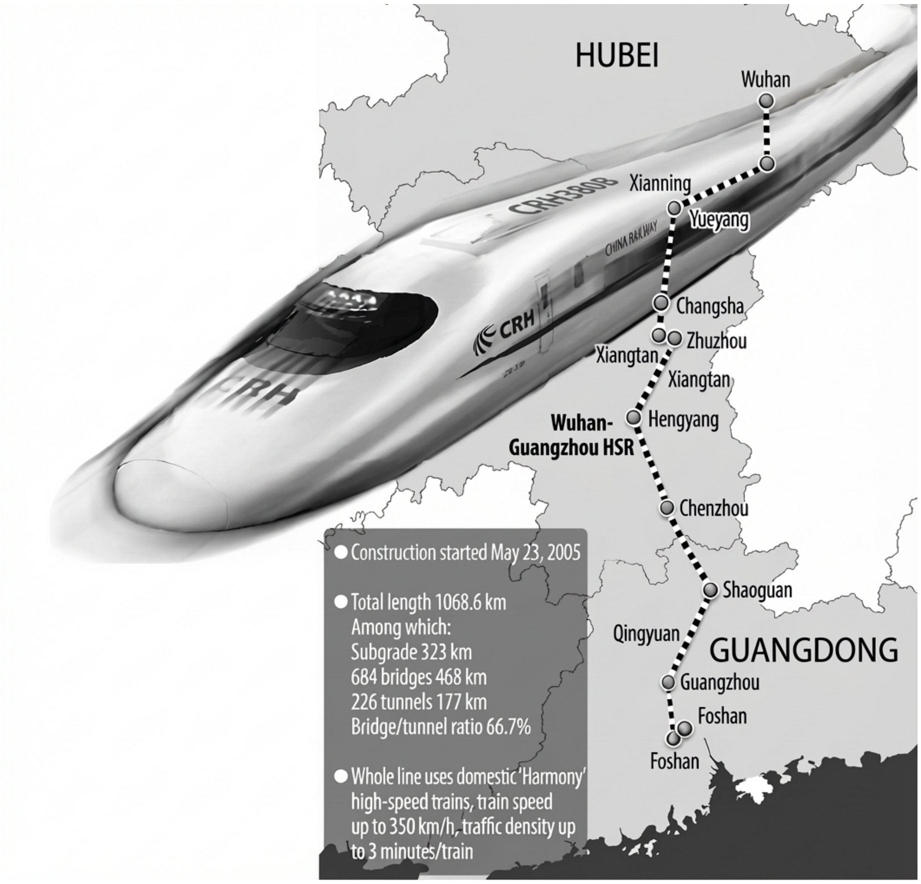

Figure 1: Figure 1

and a complete architecture to guarantee rapid and accurate transmission of various dispatching commands for train operation control, while also providing comprehensive services for equipment maintenance, operation management, and passenger communications.

China’ s railway system began using radio for locomotive dispatching communications in the 1950s. These early systems were simple point-to-point simplex analog wireless communication systems that could meet basic service requirements such as train dispatching, emergency rescue, and maintenance operations. In the early 1980s, radio dispatching command systems were established using walkie-talkies or vehicle/fixed stations. During the 1990s, analog trunking systems were introduced, providing not only dispatching services but also communication between private network users and between private and public networks. However, analog communication technology suffered from low spectrum efficiency and severe co-channel interference, hindering the deployment of new services. Therefore, after 2000, analog trunking systems gradually evolved into digital trunking communication systems with the development of digital communication technologies. Existing digital dedicated mobile communication systems capable of providing dispatching services include Europe’ s TETRA system, Motorola’ s iDEN system, Israel’ s FHMA system, and Europe’ s GSM-R system. Currently, China’ s high-speed railways use the narrowband GSM-R system, which can basically meet traditional train operation and control requirements. However, since GSM-R can only provide transmission rates of several tens of kbps, it cannot support advanced services such as automatic train control, video surveillance, or dynamic container management, let alone satisfy the increasingly strong demand for passenger broadband multimedia services.

China’ s high-speed railways lag significantly behind other countries in broadband wireless communication development. For instance, Chinese high-speed railways rarely provide broadband wireless data services, while NTTBP (NTT Broadband Platform) launched commercial wireless data services on Japan’ s Tsukuba Express in August 2006, French TGV Line EST provided network services to train passengers via satellite technology in December 2007, and Japan’ s Shinkansen offered passenger data services using WLAN technology in March 2009.

Communication has now become an indispensable social function, and broadband wireless communication is an essential technology for the progression from today’ s E-society to tomorrow’ s U-society. Since the 1980s, mobile communication technology has advanced rapidly due to technological development and improved living standards. The first- and second-generation mobile cellular systems initially provided convenient wireless voice services anytime and anywhere. In the 1990s, with the emergence of the Internet, demand for wireless data communication grew, leading third-generation (3G) systems to introduce mobile multimedia services including data communication. However, people have become dissatisfied with 3G’ s rate limit of 2Mbps, prompting the development of the so-called “3.9 generation” LTE (Long Term Evolution) system, which can provide transmission rates up to 300Mbps. Future fourth-generation IMT-A (International Mobile Telecommunications-Advanced) systems aim to provide high-speed communication up to 1Gbps, comparable to wired communication systems. Developing broadband wireless communication technology is crucial for improving national technological levels, promoting economic development, and enhancing people’ s living standards. Starting from 3G, China has actively participated in the development and standardization of mobile communication technologies, proposing the TD-SCDMA (Time Division-Synchronous Code Division Multiple Access) standard with independent intellectual property rights, which has further evolved into the 3.9G international standard TDD-LTE. The currently standardizing fourth-generation broadband wireless IMT-A system has become a key national technology project for the next decade. Based on global 3G network operations, high-speed data services have become the fastest-growing value-added business. Streaming media, mobile online gaming, online music, and large-capacity downloads represent the development trend of 3G services. It is foreseeable that as high-speed rail becomes China’ s primary transportation method, demands for broadband wireless communication on trains will continue to increase.

Developed countries have proposed several solutions for high-speed railway broadband wireless communication. Japan employs leaky cable technology, which can provide stable and reliable 2Mbps transmission rates but suffers from small coverage, high cost, and demanding installation requirements. France uses satellite communication technology with rates below 1Mbps, which is susceptible to interference and expensive. Australia adopts WiMAX (Worldwide Interoperability for Microwave Access) technology, which can provide 6Mbps rates at speeds up to 90km/h but remains in its initial stages. These existing solutions suffer from high costs, limited bandwidth, large delays, and other issues that fail to adequately meet high-speed railway broadband wireless communication needs. The fundamental reason is that existing wireless communication systems are optimized for low-speed environments (below 15km/h), and system performance degrades sharply in high-speed mobile environments. In the long term, to meet broadband wireless communication needs for high-speed railways, we must design optimized broadband wireless communication systems that address characteristics such as high-speed mobility and fixed operating routes, providing stable, reliable, and high-quality wireless communication services for railway operations, control, and passengers.

2 Current Status of Broadband Wireless Communication for High-Speed Railways

High-speed data communication in special scenarios such as high-speed railways has long been a research focus. The key to wireless broadband communication in high-speed vehicle scenarios is supporting high data transmission rates and high mobility in vehicle-to-ground wireless transmission. Uhlirz proposed a concept for high-speed train communication systems based on GSM cellular mobile communication systems as early as 1994 [1]. GSM-R was identified by China’ s Ministry of Railways as a solution for railway scenario mobile communications by the end of 2000 and has developed into a dedicated wireless dispatching command communication system covering all railway trunk lines. However, GSM narrowband communication systems cannot meet broadband service requirements. China’ s GSM-R communication system has only 4MHz of frequency bandwidth, with transmission rate being one of the main factors restricting GSM-R’ s ability to provide broadband data services. In 2004, Ohta et al. adopted 5GHz wireless LAN technology to provide mobile wireless access services for users on high-speed moving trains [2], but the roaming-based network handover lacked support for high mobility. Additionally, Knoerzer et al. established a wireless channel model for high-speed railway train scenarios, demonstrating that OFDM (orthogonal frequency division multiplexing) is a potentially viable technical solution [3]. Greve et al. proposed a network architecture called FAMOUS to provide broadband services for fast-moving users [4], dividing train broadband wireless Internet application systems into access and aggregation networks. Based on WiMAX standards and products, they designed a fast network recovery algorithm for passenger train access that enhanced WiMAX technology’s support for high mobility in passenger train access. In February 2005, the Nomad Digital Rail (NDR) system developed by UK’ s Nomad Digital company could provide up to 32Mbit/s bidirectional broadband data transmission rates between vehicle and ground, with stable data transmission rates maintained at 6Mbit/s, supporting large file transfers and online audio/video entertainment services for passengers [5]. Based on NDR’ s excellent performance, cellular mobile operator T-Mobile installed and configured NDR systems on 14 trains on the London-Brighton line to provide commercial broadband WiFi hotspot services for passengers.

In China, GSM-R cellular mobile communication systems are currently used primarily for train dispatching and control. In most scenarios, passengers on trains mainly use their mobile phones to directly access base stations outside the train, utilizing 2G and 3G networks provided by cellular mobile operators for necessary voice communications. Data services remain in the preliminary stage, with main difficulties being transmission rate and quality issues. To address broadband data service problems on high-speed trains, Chinese companies have begun proposing solutions. For example, China Railway Yipin Media Co., Ltd. has launched a train digital television system that provides online wireless connections and interactive video information services for passengers, which has been officially recognized by the Ministry of Railways as a railway passenger information service system. Overall, broadband mobile communication in ground ultra-high-speed mobile environments such as high-speed railways remains in the early stages of development, and no efficient, reliable, or performance-optimized solution has yet emerged. Many issues in core technologies such as network architecture, resource management, and physical layer technologies still require discussion and resolution.

3.1 Broadband System Network Architecture

Broadband wireless communication for high-speed railways typically employs two architectures: single-link and dual-link. In the single-link architecture, base stations communicate directly with passengers' portable terminals. Under this approach, portable terminals must handle Doppler shift issues, and wireless signals must penetrate the train carriage walls, resulting in significant transmission loss.

In the dual-link architecture, mobile communication on vehicles is completed in two steps: first, communication between the external network and the vehicle-mounted base station; second, communication between user portable terminals and the vehicle-mounted base station. In this case, the vehicle-mounted base station can employ complex algorithms or hardware circuits to address channel fading and Doppler shift problems, allowing passenger terminal equipment to remain as simple as possible. The key to wireless broadband communication in high-speed vehicle scenarios is supporting high data transmission rates and high mobility in vehicle-to-ground wireless transmission.

For high-speed railway application scenarios, we believe belt-shaped network coverage should be adopted. One feasible technology is smart array antenna tracking. Antenna arrays can automatically adjust direction to maintain alignment between the strongest signal direction of access point array antennas built along the high-speed railway and the strongest direction of array antennas on the train, thereby providing significant antenna gain, forming long belt-shaped coverage, reducing the deployment quantity and handover frequency of such dedicated access equipment, and providing high-quality, high-capacity high-speed wireless access. Meanwhile, to avoid significant signal attenuation caused by penetration through carriage walls, a heterogeneous collaborative two-layer network architecture should be adopted: the first layer employs the physical layer and medium access control layer protocols proposed in this paper to achieve long-distance high-speed communication in high-speed mobile scenarios; the second layer is communication inside the high-speed moving vehicle, such as short-range high-speed access communication between passengers and relatively stationary access points (APs) in high-speed trains. To address rate and capacity mismatch issues between long-distance communication and short-range high-speed access communication, multiple receiving nodes can be used to obtain spatial diversity gains and improve transmission performance of long-distance high-speed communication. Key issues in networking technology for this heterogeneous collaborative scenario must also be studied, including corresponding node selection, resource allocation, and power allocation, while theoretically analyzing heterogeneous collaborative communication theory.

[FIGURE:2] Smart antenna tracking [FIGURE:3] Belt-shaped coverage

3.2 Novel MAC Layer Wireless Resource Management Algorithms

Several important medium access control (MAC) layer mechanisms in existing broadband wireless communication systems cannot be effectively applied to high-speed railway environments. First are random access control and cell handover algorithms. Due to their long processing delays, the channel changes significantly during ultra-high-speed movement, making processing based on pre-operation channel information completely unable to meet post-operation channel requirements, resulting in random access control and cell handover failures that greatly degrade user experience and system performance. Second, existing MAC layer scheduling algorithms are mostly based on accurate channel information. In ultra-high-speed mobile scenarios, accurate channel information is difficult to obtain, and due to processing delays, obtained channel information no longer accurately reflects channel conditions during signal transmission. Consequently, traditional scheduling algorithms inevitably suffer significant performance degradation in ultra-high-speed environments.

Therefore, in terms of MAC layer resource management, high-speed railway broadband wireless communication systems should focus on research into fast and reliable random access control algorithms and cell handover algorithms, specifically addressing quality-of-service-differentiated random access algorithms, collision resolution mechanisms, seamless handover mechanisms, and macro-diversity handover algorithms in ultra-high-speed mobile scenarios, while providing specific design schemes for handover triggering, decision, and execution. It is particularly necessary to introduce channel prediction technology to reduce the impact of feedback errors on transmission performance in practical systems and improve system robustness [6-7]. Based on this, research should investigate scheduling mechanisms for feedback errors and multi-user interference cancellation mechanisms caused by feedback errors to further reduce feedback error impact. Simultaneously, feedback mechanisms in specific wireless channels must be studied to effectively utilize feedback channel resources, reduce feedback overhead and errors, and improve system performance.

3.3 Physical Layer Air Interface Technology for Ultra-High-Speed Mobile Broadband Wireless Systems

High-speed movement in high-speed railways causes rapid channel fading, posing tremendous challenges for reliable communication. For a long time, extensive research has been conducted on wireless communication systems under fast fading and frequency-selective channels. Addressing the difficulty of obtaining high-speed mobile channel estimates, establishing robust channel estimation algorithms has become a hot topic in fast fading channel system research [8]. Additionally, non-coherent techniques that do not require channel information, such as non-coherent coded modulation and non-coherent MIMO (Multiple Input and

Multiple Output) [9], are also popular physical layer technologies for ultra-high-speed mobility. On the other hand, existing broadband wireless systems mostly employ OFDM-based air interfaces, whose anti-multipath interference characteristics are crucial in broadband systems. However, OFDM has stringent synchronization requirements, including time-domain and frequency-domain synchronization. With accurate time-domain synchronization, OFDM systems can avoid inter-symbol interference (ISI); in the frequency domain, OFDM is highly sensitive to frequency offset, which originates from carrier frequency deviation at the transmitter and receiver and Doppler shift caused by high-speed movement, resulting in inter-carrier interference (ICI) or inter-channel interference that affects system performance [10]. Additionally, inter-carrier interference cancellation methods can be adopted to overcome frequency offset effects [11]. Inter-carrier interference causes error floors that limit OFDM performance. Therefore, the analysis of inter-carrier interference caused by ultra-high-speed movement and the design of anti-interference mechanisms have always been research priorities in OFDM systems.

Analysis of the above research content reveals that traditional research on physical layer air interface technology for ultra-high-speed mobile broadband wireless systems has generally focused on physical layer performance alone, rarely considering the impact of physical layer technology on other layers, particularly MAC algorithms. However, physical layer air interface technology selection significantly impacts MAC layer algorithms. For example, cell handover mechanisms are completely different in OFDM-based versus CDMA (Code Division Multiple Access) systems. In researching broadband wireless communication systems for high-speed railways, to provide reliable broadband wireless communication under ultra-high-speed mobility, physical layer air interface technology design must not only ensure reliable communication at its own layer but also comprehensively consider impacts on upper-layer algorithms. Following this approach and considering overall system performance, we propose a complementary coded OFDM (CC-OFDM) air interface technology based on code division multiplexing using complementary codes. On one hand, OFDM' s advantages in broadband wireless communication have been proven in practical systems, including LTE broadband mobile communication systems designed for medium-low speed mobility. LTE is considered the most promising future broadband wireless system, but it was not designed for ultra-high-speed mobility. When designing ultra-high-speed mobile broadband wireless communication systems, compatibility with existing broadband wireless communication systems should be considered to simplify user mobile terminal design, reduce mobile terminal complexity and cost, and thereby facilitate the development of ultra-high-speed mobile broadband wireless communication systems. On the other hand, code division multiplexing allows system soft handover between cells, bringing macro-diversity effects that can significantly improve cell handover performance under ultra-high-speed mobility. Furthermore, research on complementary codes shows that due to their ideal correlation properties, code division multiplexing based on complementary codes has anti-multiple access interference characteristics and outperforms code division multiplexing systems based on orthogonal Walsh codes. Introducing complementary code-based code division multiplexing can utilize the ideal correlation properties of complementary codes at the physical layer to cancel partial frequency-domain inter-carrier interference, while at the MAC layer, complementary code-based random access can be adopted to reduce congestion. Therefore, CC-OFDM is an effective solution suitable for ultra-high-speed mobile broadband wireless communication.

Current research on air interface technology combining code division multiplexing and OFDM mainly focuses on VSF-OFDM and BR-OFDM schemes based on orthogonal Walsh codes [12]. Since broadband wireless communication has primarily focused on system performance under low-medium speeds, most existing research has been conducted under slow fading channels. Research on CC-OFDM performance under fast fading remains insufficient.

4 Conclusion

In summary, high-speed movement in high-speed railways introduces a series of technical challenges including handover between cells, Doppler shift, and rapid wireless channel variation. To design broadband wireless communication systems suitable for high-speed railway environments, we must first propose a linear heterogeneous collaborative network architecture applicable to ground ultra-high-speed mobile environments at the network layer. Simultaneously, addressing the characteristics of ultra-high-speed mobility, we must provide solutions for core MAC layer wireless resource management mechanisms, particularly random access, cell handover, and resource allocation. From an overall system performance perspective and considering MAC layer requirements, we should apply novel multiple access technologies at the physical layer to better meet the special scenario requirements of high-speed railway mobility.

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Author Biographies:

Yiqing Zhou: Researcher, Wireless Communication Technology Research Center, Institute of Computing Technology, Chinese Academy of Sciences, zhouyiqing@ict.ac.cn

En Zhou: Assistant Researcher, Wireless Communication Technology Research Center, Institute of Computing Technology, Chinese Academy of Sciences

Lin Tian: Assistant Researcher, Wireless Communication Technology Research Center, Institute of Computing Technology, Chinese Academy of Sciences

Jinglin Shi: Researcher, Wireless Communication Technology Research Center, Institute of Computing Technology, Chinese Academy of Sciences

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