Proceedings of CONF-SEML 2025 Symposium: Machine Learning Theory and Applications
DOI: 10.54254/2755-2721/160/2025.TJ23492

Communication Network Optimization and Signal Enhancement Technology in High-Speed Rail Scenarios

Jianyu Ren

Tianjin University of Technology, Tianjin, China
Renjianyu0127@163.com

Abstract: The high-speed rail communication network has significant characteristics such as high mobility, large signal penetration loss, and sudden traffic volume, and it faces challenges such as the Doppler effect, frequent switching, complex interference, and network capacity bottlenecks. This paper mainly focuses on the communication network in the high-speed rail scenario, comprehensively expounds its characteristics, challenges, optimization and signal enhancement technologies, and conducts an analysis in combination with cases from multiple regions. Through means such as scientific site selection, reasonable layout, algorithm improvement, interference suppression and signal enhancement, many projects have achieved remarkable results. For example, after the optimization of a 500-kilometer high-speed railway line, the signal coverage rate in mountainous areas has been significantly increased, the switching success rate has been significantly improved, and the data rate and traffic processing capacity have been enhanced. The optimization of the Changzhou section of the Beijing-Shanghai High-Speed Railway by China Telecom Changzhou Branch has increased the success rate of parallel section switching, enhanced the network speed and reduced the complaint rate. In the future, high-speed rail communication will develop in the direction of multi-technology integration, intelligent management, green and low-carbon development, and standardized cross-industry collaboration.

Keywords: High-speed rail communication network, Signal enhancement technology, Network optimization, Multi-technology integration, Application case

1. Introduction

With the vigorous development of the global high-speed rail industry, high-speed rail has become an extremely important component of the modern transportation system. High-speed rail not only greatly enhances people's travel efficiency, but also poses unprecedentedly strict requirements for communication networks due to its high-speed and stable operation characteristics. This paper focuses on the research of communication networks in the high-speed rail scenario, deeply analyzes its characteristics and challenges, and comprehensively expounds various optimization and signal enhancement technologies that have emerged to deal with these challenges, as well as related practical application cases. From the global application and continuous evolution of the European GSM-R standard [1,2], to the localized innovations for complex terrains in Southeast Asia; from the forward-looking explorations of Japan and South Korea in 5G + vehicle-road coordination, to the breakthroughs of Europe and the United States in intelligent and green technologies, and to the complete ecological closed loop constructed by China with "safety + experience" as the dual core

DOI: 10.54254/2755-2721/160/2025.TJ23492

goals, the research achievements and practical experiences on a global scale have provided rich materials for the discussion of this article. This paper conducts in-depth research on various aspects such as base station construction and optimization, signal handover technology optimization, network interference suppression technology, and signal enhancement technology. Combined with actual project cases, such as the communication network optimization practice of a 500-kilometer high-speed railway line and the network optimization of the Changzhou section of the Beijing-Shanghai High-Speed Railway by China Telecom Changzhou Branch, it elaborates in detail how to improve the performance of the high-speed railway communication network. It aims to provide comprehensive and in-depth references for the further development of related fields and help high-speed rail communication technology reach new heights.

2. Research status

2.1. Europe: the global application and evolution of GSM-R standards

The GSM-R system led by the International Union of Railways (UIC) has the advantage of a highly reliable and redundant design. The Technical University of Braunschweig in Germany and ZTE jointly developed the "dual-station coverage at the same site" technology. Through the deployment of dual base stations, seamless switching within 100ms of a single base station failure is achieved, ensuring continuous communication at 500km/h. The Alps test increased the success rate of tunnel entrance switching from 82% to 99.6%. The Italian team developed a Kalman filter compensation algorithm for the Doppler frequency offset of GSM-R, reducing the demodulation bit error rate by 60% at 350km/h. The related technology was incorporated into the ETSI standard [1-3].

2.2. Southeast Asia: localized innovation in complex terrain

Beijing Jiaotong University, in collaboration with Bandung Institute of Technology in Indonesia and the University of Birmingham in the UK, has developed a model of a specific tropical climate channel for the complex landforms such as tropical rainforests and volcanoes along the Jakarta-Bandung High-Speed Railway. The analysis using ray-tracing technology [4] reveals that vegetation occlusion leads to a attenuation of millimeter waves of 8-15 dB, and humidity increases the attenuation by 2dB/km. The dynamic beamforming antenna developed by the team has increased the signal coverage in the tunnel by 40%. The semi-physical simulation platform deployed can simulate the communication scenario of a thousand antenna arrays at 500km/h, providing a "parameter localization + equipment lightweight" high-speed rail communication solution for mountainous countries in Southeast Asia.

2.3. Japan and South Korea: forward-looking exploration of 5G + vehicle-road coordination

The JR Company of Eastern Japan has collaborated with Tohoku University to trial a 5G vehicle-road coordination system on the Tohoku Shinkansen. This system uses roadside units (RSU) to transmit real-time information such as track icing and cracks. Combined with an artificial intelligence model, it can issue warnings 20 seconds in advance. In response to the shielding issue in high-speed rail carriages, South Korea's KT Company has developed a "distributed micro base station + millimeter-wave relay" solution. Millimeter-wave antennas are installed on the top of KTX trains, and the signal penetration loss is reduced from 25dB to 12dB by using the 28GHz frequency band, achieving smooth transmission of 4K video inside the train [5]. Teams from Japan and South Korea have both conducted research on satellite-ground integrated networks. For instance, Japan's QZSS satellite has achieved full coverage monitoring of the Tokaido Shinkansen [6].

DOI: 10.54254/2755-2721/160/2025.TJ23492

2.4. Europe and America: breakthroughs in intelligent and green technologies

The "Cognitive Radio + Edge Computing" architecture developed by the University of California, Davis, can dynamically allocate spectrum resources based on train positions, increasing spectrum utilization by 35% in the Northeast Corridor test. The SpaceX collaboration project in Europe utilized Starlink satellites for emergency communication on high-speed rail. During the 2023 Glacier Express accident in Switzerland, the satellite link ensured the real-time transmission of rescue instructions. The "Zero-carbon Base station" project of Deutsche Bahn and Nokia, by leveraging solar energy and artificial intelligence energy efficiency management, has reduced the energy consumption of base stations along the line by 42%, setting an example of green high-speed rail communication.

2.5. China: the path of advancement driven by innovation

The research on high-speed rail communication in China takes "safety + experience" as the dual core goals and forms a complete ecological closed loop of "standard setting - technological innovation - engineering application" under the drive of policies. By independently developing the 5G-R dedicated spectrum (700MHz+3.5GHz) and cross-band aggregation technology, the delay of train control instruction transmission is ensured to be stably controlled within 50 milliseconds, and at the same time, the system reliability reaches the standard of 99.999% [7]. In terms of technological innovation, breakthroughs have been made in the switching algorithm for high-mobility scenarios (with a success rate of 99.8%), deep coverage technology (with a 5G coverage rate of 98.56% in vehicles), and intelligent operation and maintenance systems (with a resource scheduling response time of 3 minutes). In engineering practice, projects such as the tropical climate channel model of the Jakarta-Bandung High-Speed Railway, the interference suppression of the parallel sections of the Beijing-Shanghai High-Speed Railway, and the zero-carbon base station of the Jining-Zhengzhou High-Speed Railway have set global benchmarks. Currently, we are confronted with challenges such as tight spectrum resources and cross-departmental collaboration. In the future, we will focus on the research and development of 6G terahertz communication and integrated vehicle-road-cloud systems, and continue to lead the development of global high-speed rail communication technology [3,8].

3. Characteristics and challenges of communication networks in high-speed rail scenarios

3.1. Characteristics of high-speed rail communication networks

The high-speed railway communication network has remarkable characteristics: First, it has high mobility. The operating speed is mostly between 200 and 350km/h, and some can reach over 400km/h. At 300km/h, the train moves about 83 meters per second, and the time for the terminal to cross the coverage area of the base station is extremely short. If the distance between base stations is 1 kilometer, a train can pass through in just 12 seconds, which places extremely high demands on the switching algorithm. The second issue is the high signal penetration loss. The metal frames of high-speed rail carriages and the metal coatings on the Windows cause signal penetration loss to reach 10-33 dB, resulting in uneven coverage inside the carriages and the formation of signal blind spots in corners, bathrooms and other areas. Thirdly, the traffic volume is highly sudden. An 8-carriage train carries approximately 600 people. If 80% of the users are making video calls simultaneously, the instantaneous traffic at the base stations along the line will increase by more than 500Mbps. When two trains meet, the traffic will overlap. Take the Beijing-Shanghai High-Speed Railway as an example. With an average of 300 pairs of trains per day, the traffic flow in the peak conference area reaches 1.2Gbps, which is prone to cause the base station load to exceed 100% and lead to congestion [9,10].

DOI: 10.54254/2755-2721/160/2025.TJ23492

3.2. Challenges faced by high-speed rail communication networks

The high-speed rail communication network is facing many challenges. First is the Doppler effect. The high-speed movement of the train will cause the frequency of the received signal to change. The formula is $f\_d=(v \cdot f\_c \cdot \cos\theta)/c$ (where v is the train's running speed, f_c is the carrier frequency, θ is the incident angle of the signal, and c is the speed of light). When the speed is 350km/h and the carrier frequency is 2.6GHz, the maximum Doppler frequency shift is approximately 850Hz. This will cause difficulties in signal demodulation, increase the bit error rate by 3 to 5 times, and reduce the data rate by 40%. Secondly, signal switching is frequent. The traditional switching algorithm based on signal strength is prone to causing "ping-pong switching" in the high-speed rail scenario. When a certain line adopts this algorithm, the switching success rate is only 75%, and the interruption time is as long as 200ms. Moreover, in mountainous areas or at tunnel entrances, due to the limited coverage of base stations, it is easy to have missed allocation in adjacent areas, resulting in switching failure. Furthermore, the interference environment is complex, with multipath interference (signals reflected by mountains, Bridges, etc. form multi-path, resulting in intersymbol interference ISI), co-frequency/adjacent frequency interference (the co-frequency interference level of adjacent cells reaches -80 DBM, and the adjacent frequency interference causes demodulation errors due to insufficient filter performance), as well as external interference such as urban area broadcasting and television signals and industrial equipment. All of these lead to the decline of signal quality. Finally, there is a bottleneck in network capacity. The burst traffic volume does not match the static resource allocation of base stations. For instance, during the Spring Festival travel rush, the traffic volume at a certain high-speed railway station during peak hours is ten times that during off-peak hours. The traditional static configuration leads to a congestion rate of 30% during peak hours. Moreover, the dedicated spectrum for high-speed railways is insufficient and needs to be shared with public mobile communications, further exacerbating the interference [10,11].

4. Communication network optimization technology in high-speed rail scenarios

4.1. Base station construction and optimization

The optimization of high-speed railway base station construction takes the continuous signal coverage and capacity improvement as the core, and is achieved through scientific site selection, reasonable layout and equipment selection. In terms of site selection, mountainous areas and tunnel entrances are chosen in places with high terrain and wide views. Combined with leakage coaxial cables (LCX) to expand coverage, for example, in the Wenzhou section of the Hangzhou-Wenzhou High-Speed Railway, "base station + LCX" was used to increase the tunnel signal strength from -110DBM to -90DBM. In urban areas, micro base stations and the like are utilized to address building obstacles. For instance, 5G micro base stations have been deployed around Shanghai Hongqiao Railway Station to achieve full coverage. When optimizing the layout, the straight-line segment is arranged in a quasi-band manner, with a base station spacing of 1.5 to 2 kilometers to ensure overlapping coverage of over 200 meters. The curves and complex terrains adopt chain and honeycomb layouts and use intelligent antennas to adjust the beam. The switching success rate of the curves in the Yunnan section of the Shanghai-Kunming High-Speed Railway has been increased from 85% to 98% through the chain layout. It also combines distributed antenna systems (DAS) and MIMO technologies. In terms of equipment selection and configuration, macro base stations cover large and densely populated areas, micro base stations fill remote blind spots, and radio frequency is used to expand coverage in areas without machine rooms. Signal leakage is reduced by optimizing transmission power and other measures. Zhejiang Mobile deployed 120 macro base stations and 80 micro base stations on the

DOI: 10.54254/2755-2721/160/2025.TJ23492

Hangzhou-Wenzhou High-Speed Railway and combined with LCX technology, increasing the tunnel signal coverage rate from 60% to 95%, becoming a successful example [3,10].

4.2. Signal switching technology optimization

High-speed rail communication is affected by high mobility and is confronted with the problems of frequent switching and failure of traditional algorithms. Now, multiple measures are adopted to deal with them. In terms of the improvement of the switching algorithm, a hybrid algorithm based on speed and signal quality was adopted. By integrating factors such as signal strength (trigger threshold of -95 DBM), train speed (early switching >250km/h), and channel quality (forced switching when signal-to-noise ratio <10dB), the switching success rate of a certain line was increased from 75% to 99.2%. It also combines GIS data with train schedule prediction switching to reduce "ping-pong switching". Meanwhile, the switching parameters are optimized. The switching thresholds in the high-speed and low-speed segments are set to -95 DBM and -100 DBM respectively. The switching hysteresis in the large signal fluctuation and stable regions is set to 3dB and 1dB respectively, and the switching time is reduced to within 80ms. In terms of the planning of surrounding areas, the number of neighboring mountainous areas should be increased (15-20), and the redundant neighboring urban areas should be reduced. The relationship between adjacent areas should be dynamically adjusted by using experimental data and simulation software. For example, the missed allocation rate of the Shanghai-Kunming High-Speed Railway should be reduced from 12% to 3%. In addition, China Telecom has applied the "inter-frequency transition zone" technology in the Changzhou section of the Beijing-Shanghai High-Speed Railway, increasing the success rate of parallel section switching from 85% to 99.8%, effectively solving the communication switching problem of high-speed railways [12].

4.3. Network interference suppression technology

High-speed rail communication is confronted with interference problems such as co-frequency, adjacent frequency and multipath. The countermeasures are as follows: Suppress co-frequency interference, adopt hierarchical and zonal frequency planning, allocate independent frequency groups for high-speed rail (such as the F band 1880-1900 MHZ), use intelligent antenna beamforming technology for directional transmission, and utilize fast frequency hopping in the GSM system to reduce interference. Suppress adjacent frequency interference, optimize the frequency interval to ensure ≥200kHz, and deploy high-performance bandpass filters; When dealing with other interference sources, the self-interference is reduced by grounding the metal casing of the train's electrical equipment, and the subcarrier orthogonality of OFDM technology is utilized to counter multipath interference. Through frequency planning and intelligent antenna adjustment of a certain high-speed railway line, the co-frequency interference was reduced from -80 DBM to below -95 DBM, ensuring the communication quality [8].

5. Signal enhancement technology in high-speed rail scenarios

5.1. Principles of wireless signal enhancement technology

In high-speed rail communication technology, power control, diversity and smart antenna technology are the keys to improving signal quality. Power control technology precisely regulates the transmission power through open-loop preliminary estimation adjustment or closed-loop real-time feedback to compensate for signal attenuation, suppress interference, and ensure signal stability in complex environments. Diversity technology utilizes the fading independence of wireless channels. Through methods such as spatial, time-division, and frequency diversity, it reduces the influence of

DOI: 10.54254/2755-2721/160/2025.TJ23492

fading from the perspectives of multi-antenna reception, delay tolerance, and multi-carrier transmission respectively. For example, spatial diversity can increase the signal strength in mountainous areas by 5-10 dB, and time-division diversity can reduce the bit error rate by 30% - 50%. Smart antenna technology enhances signals and supsupes interference by means of beamforming. The beam-switching smart antenna automatically switches the preset beam, and the adaptive array smart antenna makes real-time dynamic adjustments. Moreover, when combined with diversity technology, the anti-interference ability can be improved by more than 20dB [3,8].

5.2. Application of dedicated signal enhancement technology for high-speed railways

The dedicated signal enhancement technology for high-speed railways has achieved remarkable results in practical applications. The leak-coaxial cable technology allows electromagnetic waves to leak through the grooves of the outer conductors of the cables. It is laid every 200-300 meters in the tunnel and coordinated with the relay station. It can stabilize the signal strength above -85 DBM and also solve the problem of lines of sight obstruction for base stations in mountainous areas. The coverage range is 5-10 kilometers, and it has the advantages of anti-interference and easy maintenance. The Distributed Antenna System (DAS) deploys antennas in a decentralized manner. Within the vehicle compartment, it can increase the signal strength by 15dB and the coverage rate from 60% to 95%. In weak coverage areas such as mountainous regions, it can expand coverage, fill blind spots, and enhance stability in combination with intelligent processing. HyperCell technology optimizes the capacity of private networks by applying dynamic resource allocation and intelligent handover algorithms. Multi-carrier aggregation enables a data rate of up to 200Mbps. Intelligent handover increases the success rate to 99.8% and shortens the interruption time to less than 50ms. After its application on a certain high-speed railway line, peak congestion is reduced by 70% and the user experience rate is improved by 100% [3].

6. Case analysis of communication network optimization and signal enhancement technology in high-speed rail scenarios

6.1. Project background and objectives

A 500-kilometer high-speed railway line passes through many places with complex terrain. Before the implementation of the communication network optimization, this line had many problems. The signal was weak in mountainous areas, the signal disappeared in tunnels, the interference was severe in urban built-up areas, and the traffic volume suddenly increased, causing network congestion during peak hours. To improve these situations, the project goals are set to expand the signal coverage, enhance signal strength, improve signal quality, and optimize the allocation of network resources at the same time to cope with sudden changes in traffic volume.

6.2. Adopted optimization and enhancement technologies

In the optimization of high-speed rail communication networks, multiple methods are comprehensively applied: In terms of base station construction, high-altitude mountain tops are selected for station construction in mountainous areas, and LCX macro base stations are combined at tunnel entrances. The layout is in a chain or honeycomb shape according to the terrain, and the beam is adjusted with smart antennas. Macro and micro base stations are selected according to regional differences. Signal switching optimization adopts a hybrid algorithm of train speed and channel quality, dynamically adjusts the switching threshold and hysteresis, and plans the neighboring areas with the help of road test data and simulation tools. In terms of the application of signal enhancement technology, adaptive array smart antennas are deployed to suppress interference, distributed DAS in

DOI: 10.54254/2755-2721/160/2025.TJ23492

carriages are used to enhance signals, and closed-loop power control is adopted to adjust the transmission power of base stations to reduce signal attenuation in tunnels, jointly improving the performance of high-speed rail communication networks.

6.3. Implementation effect

After optimization, the high-speed railway line has achieved a significant improvement in communication performance. The signal coverage rate in mountainous areas has significantly increased from 60% to 92%, and full coverage has been achieved within the tunnels. The switching success rate has jumped from 75% to 99.2%, and the switching interruption time is less than 50ms. In terms of data rate, the average rate has increased from 1Mbps to 12Mbps, and the packet loss rate has decreased to 2%. The traffic processing capacity has also been significantly enhanced. During peak hours, the base station load has dropped to 60%, and the access failure rate is less than 5%. This has greatly improved the communication quality of high-speed rail and provided a strong guarantee for train operation and passenger experience.

7. Applications of communication network optimization and signal enhancement technology in high-speed rail scenarios

In response to the issues of an average daily passenger flow of over 100,000 on the Changzhou section of the Beijing-Shanghai High-Speed Railway, network congestion during the Spring Festival travel rush, low success rate of parallel section switching (only 85%), insufficient 5G speed, and high user complaint rate, China Telecom Changzhou Branch has set optimization targets such as a parallel section switching success rate of ≥99% and a 5G downlink speed of ≥100Mbps. Through big data analysis to predict traffic, 40 new 5G macro base stations were added and Massive MIMO equipment was upgraded. Self-developed technologies were applied to reduce interference, aggregate carriers and adjust handover strategies. Ultimately, the success rate of parallel segment switching increased to 99.8%, the 5G downlink rate rose from 50Mbps to 120Mbps, the uplink rate rose from 10Mbps to 30Mbps, the complaint rate dropped by 70%, and the high-definition video latency rate decreased from 20% to 3% [3,8].

8. Conclusion

This paper conducts a comprehensive and in-depth study on the communication network in the high-speed rail scenario. High-speed rail is efficient and convenient, but it brings many severe challenges to the communication network. Facing these difficult problems, countries around the world are actively exploring high-speed rail communication technologies. Europe has been continuously evolving based on the GSM-R standard. By leveraging the "dual-station coverage at the same site" technology and the Kalman filter compensation algorithm, it enhances communication continuity and reduces the bit error rate. Southeast Asia has constructed tropical climate channel models for complex terrains, developed dynamic beamforming antennas, and provided localized solutions. Japan and South Korea have achieved results in the research of 5G + vehicle-road coordination and satellite-ground integrated networks. Europe and America have achieved intelligent spectrum allocation and the construction of green and low-carbon base stations. China, with "safety + experience" at its core, has formed a closed loop in standard setting, technological innovation and engineering application, and has achieved remarkable results in many aspects such as spectrum research and development. In terms of technical optimization, through the construction layout of base stations, the improvement of signal switching algorithms, the application of interference suppression and signal enhancement technologies, remarkable achievements have been made. However, there are deficiencies in the research of this paper. In terms of content, targeted research needs to be carried out subsequently to

DOI: 10.54254/2755-2721/160/2025.TJ23492

provide precise technical solutions for different regions. Methodologically, the application effects of some new technologies are only evaluated based on existing data and short-term tests, lacking long-term tracking. In the future, a long-term monitoring system should be established to comprehensively assess the stability and reliability of the technologies. In terms of literature, given the rapid iteration of communication technology, more of the latest academic achievements and industry practice cases need to be included to maintain the timeliness of the research. Looking forward to the future, high-speed rail communication will develop in multiple dimensions. In terms of multi-technology integration, 5G-A introduces new arrays and metasurfaces to enhance spectral efficiency and anti-interference capabilities, while 6G conducts pre-research on emerging communication technologies. Build an integrated space-ground network to achieve the integration of the Internet of Things and the Internet of Vehicles. Intelligent network management optimizes resource allocation with the help of AI, etc. In terms of standardization and cross-industry collaboration, efforts should be made to incorporate Chinese standards into international standards, achieve in-depth coordination between communication and rail transit, comprehensively enhance high-speed rail communication technology, and provide strong support for the development of the high-speed rail industry [13].

References

[1] Watkins M. ERTMS Security Study, Article 4, Identified GSM-R as the New European Railway Communication System [J]. Railway Signal and Communication, 2003, 39 (8): Part of foreign Reference materials.

[2] Jianjia Yao. GSM-R—The Foundation of European Railway Control System (ERTMS /ETCS). China Railway, vol., no. 12, 2001.

[3] Xiaolei Lu, et al. Application of Smart Antenna Technology in Railway 5G-R Networks. Journal of Engineering Science and Technology II, vol. 1001-683X, no. 08, 2024, pp. 47-54.

[4] D. R. Godara, J. S. Purohit, S. Rankawat, and S. K. Modi. Effect of Foliage Length on Signal Attenuation in Millimeter Band at 35GHz Frequency. International Journal of Computer Applications, vol. 84, no. 2, pp., December 2013.

[5] Jie Lv. Research on Key Technologies of Dual-Frequency Cooperative MmWave Vehicular Networks. Doctoral dissertation, School of Information and Communication Engineering, 2024.

[6] Ahao Wang, et al. Improving the performance of BDS single-frequency precise point positioning by integrating QZSS observations in the Asia-Pacific region. Earth, Planets and Space, vol. 76, no. 147, 2024.

[7] Qinlong Wang. Research on Discrete Multi-band Spectrum Aggregation and Resource Scheduling Methods. Thesis, School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, 2018.

[8] Rui Yang, Weijun Zhang, Qingtao Liu. Analysis of Intelligent Antenna Technology for Railway 5G- R Base Stations." Journal of 01-02, vol. 1001-683X, no. 08, 2024, pp. 39-46.

[9] Zhengjie Xiao. The only way for railway informatization, the GSM-R. zte co., LTD website: https://www.zte.com.cn/china/about/magazine/zte-technologies/2011/7/cn_815/244393.html.

[10] Tieli Lin. Research on High-Speed Rail Coverage Solutions in the 5G Era [J]. Post and Telecommunication Design Technology, 2020 (10): 57-62.

[11] Hu, Y. Y. (2012). Research on Radio Resource Allocation Technology in High-speed Railway Mobile Communication System. Engineering field of Radio Management, Research direction of Electronics and Communication Engineering.

[12] Xinyu Wang. Research on Handover Technology Based on OTFS Sensing-Communication Integrated Signals in High-Speed Mobile Scenarios. Thesis, School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, 2024.

[13] Yongfu Jiang. Intelligent Connection Facilitates the Construction of Smart Railway System: Prospects for Railway Communication Development During the 14th Five-Year Plan Period. Railway Signaling & Communication, vol. 57, no. 2, 2021, 01-04.