Computers and Artificial Intelligence; Vol.3, No.6; 2026
E-ISSN: 3006-3728 P-ISSN: 3006-371X
DOI: https://doi.org/10.70267/cai.v3n6.5160
Published by: Zeus Press

A Review of the Application of Optical Communication in High-Speed Railway Systems

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Abstract

This paper mainly introduces the applications of optical communication technology in high-speed railway systems. It generally presents and analyzes the evolution of basic technologies from the early plesiochronous digital hierarchy (PDH) and synchronous digital hierarchy (SDH) to dense wavelength-division multiplexing (DWDM) and the optical transport network (OTN), the carriage of core high-speed railway services supported by optical communication, and current frontier innovations related to high-speed railway systems. Finally, it discusses the current shortcomings of this technology in adapting to external factors and the future technical direction and application prospects of deep integration between optical communication and the fifth-generation railway mobile communication system (5G-R). The analysis shows that optical communication is the core transmission foundation supporting the construction of intelligent high-speed railways and has very important application value and development potential in high-speed railway systems.

Keywords

optical communication, high-speed railway, high-speed railway communication, railway system

1. Introduction

Optical communication is a high-speed communication technology that uses optical signals as information carriers and optical fiber as the main transmission medium. At the transmitting end, electrical signals such as text, sound, and images are loaded onto light waves through modulation technology and converted into optical signals carrying information. The optical signals propagate forward inside the optical fiber according to the principle of total internal reflection. At the photoelectric receiving end, the received optical signals are decoded and restored to electrical signals that can be recognized by equipment, thereby completing information transmission. Optical communication has advantages including ultra-large bandwidth capacity, low-loss long-distance transmission, strong resistance to interference, high speed and low latency, and economical energy consumption. It therefore has an irreplaceable and important role in the large and complex high-speed railway system, which has extremely high requirements for information accuracy. Since the Daqin Heavy-Haul Railway first introduced a plesiochronous digital hierarchy (PDH) optical fiber transmission system in the 1980s, China's railway optical communication technology has undergone four generations of technological iteration: PDH, synchronous digital hierarchy (SDH), dense wavelength-division multiplexing (DWDM), and optical transport network (OTN). Each technological upgrade has directly improved the safety level of high-speed railway train control, transportation dispatching efficiency, and intelligent service capabilities.

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Following the development of these four generations of railway optical communication technology in China, this paper analyzes the core principles, engineering application characteristics, and scenario-adaptation boundaries of the technologies at each stage and, in combination with the current service requirements of intelligent high-speed railway transformation, provides a technical path for the subsequent planning, construction, operation, and maintenance of high-speed railway optical transmission systems.

2. Evolution of Basic Technologies

Optical communication technology has also undergone a series of technological iterations in high-speed railway systems. Its development history is briefly introduced below.

2.1 PDH

PDH was mainly used from the end of the last century to the beginning of this century as a transmission technology during the transition from conventional-speed railways to high-speed railways. Its core principle is that each station along the line uses its own clock with a very small error to package low-rate small signals into high-rate signals for point-to-point transmission along the railway, without a unified global timing rule. In the 1980s, the Daqin Heavy-Haul Railway first adopted PDH technology, laid an eight-core single-mode optical cable, and established multiple communication stations, opening a new era of optical fiber communication on China's main railway lines [1]. It was mainly used to carry low-bandwidth services at small stations along the railway. A single optical fiber link supported a maximum transmission rate of only 140 Mbit/s and used direct signal transmission. Its safety protection mechanism for trains running at high speed was insufficient, and it had problems such as poor compatibility and insufficient bandwidth capacity. It was therefore unable to handle information transmission for high-speed railways and was no longer constructed as a mainstream solution in high-speed railway projects after 2010.

2.2 SDH

Compared with the PDH, the significant change introduced by the SDH is that all stations along the line share the same accurate clock, and the signal packaging rules are globally unified. Low-rate tributaries can be flexibly extracted from a high-rate stream. SDH is also equipped with an innovative self-healing ring protection switching mechanism; through ring networking, it can automatically switch to a backup link within 50 ms after a line failure. In 2009, the Ganzhou-Shaoguan Railway took the lead in adopting SDH technology and laid a 20-core communication optical cable. At present, the 2,500-km-long 20-core optical cable on the Beijing-Kowloon Railway is China's longest SDH communication optical cable [1]. SDH uses the rectangular block frame structure of Synchronous Transport Module level 1 (STM-1) as the basic information transmission module, at a rate of 155.520 Mbit/s [2]. The capacity of a single link was also increased to 10 Gbit/s. SDH became the mainstream communication technology for the first generation of high-speed railways and supported the early use of the Chinese Train Control System Level 2 and Level 3 (CTCS-2/CTCS-3), representing a major advance in early high-speed railway communication. However, it still has problems such as insufficient bandwidth utilization and cannot support equipment such as the high-definition monitoring systems required by high-speed railways, so it has gradually been phased out.

2.3 DWDM

DWDM followed the synchronous digital hierarchy. Its core principle is to use an optical multiplexer to couple and transmit multiple optical signals of different wavelengths within the low-loss window of a single optical fiber, so that the signals are independent and do not interfere with one another. This increases the total capacity of a single optical fiber from the 10 Gbit/s or 40 Gbit/s level of SDH to the Tbit/s level, an increase of more than one hundred times. The bandwidth of a single-mode optical fiber is almost unlimited, whereas traditional PDH and SDH technologies both use light of a single wavelength as the signal carrier for transmission in optical fiber. They therefore do not fully use the enormous bandwidth of optical fiber and waste network resources, which led to the development of DWDM technology [3]. DWDM uses existing optical cable resources to allow more channels of signals to be transmitted on each fiber, greatly increasing communication capacity and reducing communication construction and operating costs [4]. It is better suited to the broadband transmission requirements of high-speed railways. In addition, on an SDH network, optical-

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layer power balancing and redundant deployment of multi-station optical amplifiers have successfully enabled ultra-long-distance unrepeated transmission over more than 700 km, making the technology better suited to the long-distance communication requirements of long high-speed railway sections. Its shortcoming is that it supports only point-to-point direct signal transmission, and it is difficult to locate fault points and carry out refined management and control.

2.4 OTN

OTN is currently one of the important optical communication technologies in high-speed railway networks. It is equivalent to adding the intelligent traffic management and control system of SDH to the multi-lane expressway of DWDM and combines the technical advantages of the preceding three generations. The current rate per wavelength supports 800 Gbit/s to 1.2 Tbit/s. OTN retains the advantage of ultra-large bandwidth while allowing flexible scheduling of services on each optical path. It supports fifth-generation railway mobile communication system (5G-R) and various future broadband services for high-speed railways and ensures the timely transmission of signals while trains are running at high speed. In addition, OTN technology has a complete optical-layer and electrical-layer architecture. Each network layer has a corresponding management and monitoring mechanism, and both the optical and electrical layers have network survivability mechanisms. OTN technology can provide powerful operation, administration, and maintenance (OAM) functions and can implement up to six levels of tandem connection monitoring (TCM), providing comprehensive performance and fault monitoring functions [5].

Fault location and detection in railway optical transport networks have a prominent role and clearly affect the operating quality of the network, so they require attention in practical work. At present, railway optical transport networks have different types of faults, and the detection and location technologies are also relatively specialized. From an application perspective, the technologies lack comprehensiveness and specificity, location is relatively slow, and detection depends excessively on manual work [6]. Intelligent algorithms in some complex scenarios still require further optimization.

2.5 Summary

A comparison of the different technologies used in high-speed railways is shown in Table 1 below.

Table 1: Comparison of Different Technologies Used in High-Speed Railways

Technology Type	PDH	SDH	DWDM	OTN
Core Mechanism	Independent high-precision clock at each station, without unified global timing	All stations share a unified high-precision clock, and signal packaging rules are globally unified	Independent transmission based on individual wavelengths, combined with the SDH synchronization mechanism	Unified dual-layer management and control of the optical and electrical layers, integrating the synchronization advantages of SDH
Maximum Rate per Link	140 Mbit/s	10 Gbit/s	Tbit/s level	800 Gbit/s to 1.2 Tbit/s per wavelength
First or Typical Application	Daqin Heavy-Haul Railway in the 1980s	Ganzhou-Shaoguan Railway in 2009; 2,500-km ultra-long SDH optical cable on the Beijing-Kowloon Railway	Capacity expansion of trunk lines in long high-speed railway sections	Current core carriage technology on mainstream domestic high-speed railway trunk lines
Core Networking Characteristic	Point-to-point direct-transmission networking	Ring networking with self-healing ring protection switching within 50 ms	Multi-wavelength coupled transmission over a single optical fiber, supporting ultra-long unrepeated transmission over more than 700 km	Flexible wavelength-level scheduling and support for six levels of tandem connection monitoring (TCM)

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Technology Type	PDH	SDH	DWDM	OTN
Core Advantage	Simple deployment, suitable for early low-bandwidth services at small stations	Flexible tributary scheduling and a mature protection mechanism	More than one hundred times higher optical fiber capacity, greatly reducing construction, operation, and maintenance costs	Combination of ultra-large bandwidth and intelligent management and control, with comprehensive OAM fault-monitoring capability
Main Shortcoming	Poor compatibility and an incomplete safety protection mechanism	Insufficient bandwidth utilization and difficulty carrying high-bandwidth services such as high-definition monitoring	Only point-to-point direct transmission is supported; fault points are difficult to locate and refined management and control capability is weak	Intelligent fault-location algorithms in complex scenarios still require optimization, and detection in some scenarios depends on manual work
Application Positioning	Mainstream technology during the transition from conventional-speed railways to high-speed railways; no longer used in high-speed railway construction after 2010	Mainstream communication technology for the first generation of high-speed railways, supporting early application of CTCS-2/CTCS-3	Transitional technology for high-bandwidth high-speed railway transmission, fully using the potential of existing optical cable resources	Current core high-speed railway optical communication technology, fully supporting 5G-R and various future broadband services

In recent years, the rapid iteration of railway communication transmission hardware has enabled the coexistence of PDH, SDH, data networks, and OTN, forming diverse transmission methods. This has not only increased transmission rates but has also allowed transmission methods, transmission stability, and transmission confidentiality to be combined according to different service requirements, using a three-in-one approach to ensure higher-quality and more efficient railway operation [7]. At the same time, as science and technology continue to develop, a new generation of technologies will also emerge in the future and jointly serve China's high-speed railway services.

3. Carriage of Core Services

From within the railway operating system, train dispatching, train operating status, and train location all require support from the railway communication system. This requirement is directly related to the safety and stability of the entire railway system. Therefore, a communication system in a railway environment must first provide timely and stable communication. Only such a communication system can fully ensure the normal operation of the entire railway system [8]. Optical communication can meet these requirements well and plays an important role in ensuring the stable operation of high-speed railways.

3.1 Automatic Optical Cable Monitoring System

Because optical cable lines extend along the entire high-speed railway, traditional detection methods are inefficient. High-speed railway communication concerns the safety of the entire high-speed railway system, so an automatic monitoring system has been developed.

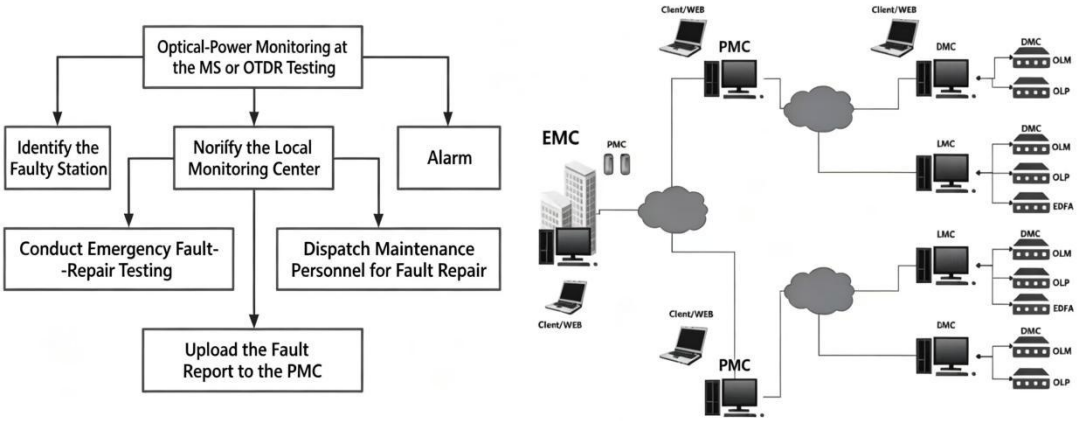
The system consists of a monitoring center, a remote optical fiber monitoring system, and a communication network that connects the local monitoring center and the remote optical fiber monitoring system [9]. Optical-power monitoring at the monitoring station (MS) or testing with an optical time-domain reflectometer (OTDR) is used to determine whether a railway line has a fault, and the detection results are sent to the monitoring center in real time. After receiving a warning, the monitoring center quickly responds to verify and repair the fault, ensuring the stable operation of the railway system, and uploads the fault to the provincial monitoring center (PMC). The PMC has a data memory function for fault maintenance and can accumulate historical

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experience so that repairs can be made quickly when a fault occurs again. (The basic principle of the system is shown in Figure 1 below.)

In an optical fiber communication system, the optical signals generated by Brillouin scattering are effectively used through a backward-transmission mechanism. By integrating a circulator and fiber Bragg grating technology, an optical detector can be accurately located, thereby optimizing the data acquisition process [9]. The core of this monitoring system is the collection, by the online monitoring system, of optical signals transmitted from each line. If the external environment changes at a certain location, such as through temperature changes or human factors, the Brillouin scattering signal of that optical communication section changes. Analysis of the frequency shift of the Brillouin scattering spectrum can then accurately locate the fault point and ensure traffic safety along the entire line. In addition, when line intrusion causes an optical cable to shake, the highly sensitive detection system can rapidly capture and locate the event and interconnect with nearby stations and dispatching rooms, thereby greatly improving the efficiency of information transmission.

Figure 1: Basic Principle of the Automatic Optical Cable Monitoring System [9]



3.2 Optical Protection System

This system provides a dual-fiber testing function for the active and standby cables, that is, it simultaneously monitors the optical power of the transmit and receive fibers of the active and standby cables. It can fully monitor the quality of the optical cables on the active and standby routes, predict the service life of the optical cables, and effectively avoid the possibility that the fibers on both routes will be blocked at the same time. The active fiber uses a 97:3 optical-splitting online monitoring scheme, whereas the standby fiber uses a light source provided by the equipment itself to implement all-optical monitoring [10].

The active and standby links of ordinary public-network optical protection can share part of an optical cable duct route, whereas the optical protection system of a high-speed railway requires the two paths to be laid completely independently to ensure operation. The key to system operation is optical-power measurement in optical communication. If optical communication on one line is interrupted, the detected optical communication power changes rapidly. The system automatically switches to another communication line within 50 ms and identifies possible causes of the fault according to the optical-power data detected in real time. This narrows the fault range for technicians and accelerates repair work.

In addition, optical communication also plays an important role in ensuring the normal operation of traction power supply lines. Through a dedicated optical fiber channel, electrical quantities at both ends of the line are measured, and the measured current, voltage, and other data are transmitted directly through the optical fiber. The data synchronization error between the two ends is controlled within 1 μs. According to the settings of the internal program, differential protection can accurately distinguish faults within the protected zone from normal operating conditions outside the zone. This fundamentally avoids incorrect operations and failures to operate caused by traditional power-line carrier transmission and ensures rapid fault removal on high-speed railway traction power supply lines.

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3.3 Voice Communication and Video Monitoring Systems

According to the requirements of the railway authorities, all lines, especially high-speed railway lines, need to be equipped with an integrated video system. However, traditional video monitoring systems have the following problems. On the one hand, the monitoring points are relatively dispersed, and construction costs are relatively high. On the other hand, stable and reliable transmission directly affects the success of the integrated video monitoring system [11]. The deployment requirements for monitoring points on China's high-speed railways specify one high-definition camera with artificial-intelligence track-intrusion recognition every 200 m along the main line. On key line sections, such as tunnels, the interval is reduced to one camera every 100 m. High-elevation pan-tilt-zoom cameras are additionally installed in risk sections such as tunnel portals, subgrade slopes, and under overpasses. In station areas, full monitoring coverage is required at important locations such as platform-door gaps, turnouts, and equipment rooms.

By connecting a telephone directly to the section optical communication equipment deployed along the railway, the system can provide clear, high-quality voice services. It is fully compatible with the user terminals and methods of cable telephone posts and implements voice services such as section telephones, automatic telephones, and rescue telephones [11].

The system connects all voice nodes along the line to a closed ring optical fiber through an optical add-drop multiplexer (OADM). The same voice optical signal is transmitted simultaneously in the active and standby directions. If an optical cable breaks or a node fails at any location, the optical cross-connect equipment completes route switching directly in the optical domain within 50 ms. In addition, based on the standardized frame structure of SDH, precise time-slot multiplexing of multiple voice services is implemented through a virtual container (VC), and forward error correction (FEC) is used to automatically correct signal bit errors caused by optical fiber bending and interference, ensuring distortion-free transmission of voice signals for dispatching telephones and emergency call posts.

Within the same physical optical fiber, optical transponder units (OTUs) modulate the video signals from different stations onto optical carriers of different wavelengths. An optical multiplexer unit (OMU) combines dozens of optical signals and sends them into the fiber for transmission. The total capacity of a single fiber can reach 8 Tbit/s, which is equivalent to simultaneously carrying two million high-definition video streams. The dedicated wavelengths for different video services are physically independent, and the bandwidth contention found in traditional Internet Protocol (IP) networks does not occur. Even if some non-core video traffic increases sharply, the dedicated wavelengths for key video services, such as station security checks and foreign-object monitoring along the line, still have exclusive use of 100 Gbit/s bandwidth, completely avoiding image freezing. An erbium-doped fiber amplifier (EDFA) simultaneously provides relay amplification for the entire group of wavelength optical signals. Signal gain is compensated every 80 km, ensuring that the optical signal-to-noise ratio remains above 18 dB after long-distance transmission and that end-to-end video transmission latency is controlled within 7 ms, thereby meeting the real-time video delivery requirements of the train beyond-line-of-sight system.

4. Frontier Innovations

4.1 Free-Space Optical (FSO) Communication Technology

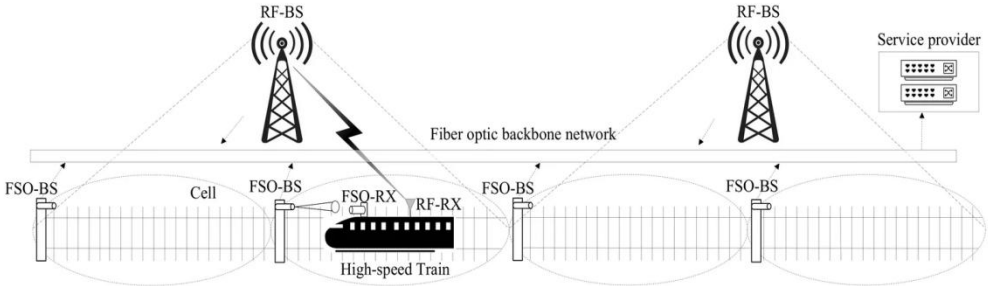
As train operating speeds continue to increase and communication traffic demand grows, traditional radio-frequency communication faces problems such as limited spectrum resources and a complex electromagnetic environment, creating major challenges in transmission capacity and coverage performance. With advantages including high bandwidth, license-free operation, and strong resistance to interference, free-space optical (FSO) communication technology has gradually become an ideal choice for addressing high-speed railway communication problems and has shown great potential for high-speed communication in high-speed railway environments [12].

Free-space optical base stations (FSO-BSs) and radio-frequency base stations (RF-BSs) are deployed on both sides of a high-speed railway and share an optical backbone network. Relying on the low-loss transmission window at 1,550 nm, the network enables millisecond-level low-latency interaction over hundreds of kilometers, supports real-time reporting of train locations and delivery of base-station pre-

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activation instructions, provides reliable transmission support for predictive train-ground communication scheduling, and connects base stations along the line to the control center. The train periodically reports location information obtained from its onboard positioning device to the control center. Based on the train location, railway track, and preset base-station deployment locations, the control center determines the area that will soon provide service and sends activation commands to the corresponding FSO/RF base stations before the train enters their coverage. The optical fiber backbone network carries the Institute of Electrical and Electronics Engineers (IEEE) 1588 version 2 Precision Time Protocol. Hardware timestamp calibration implements sub-microsecond frame synchronization among base stations along the entire line, without complex phase alignment between heterogeneous links. This supports completion, within microseconds, of FSO/RF link-quality evaluation and optimal-path switching by the onboard selection combining (SC) strategy and is suitable for highly dynamic high-speed railway (HSR) channel scenarios above 350 km/h. After receiving the signal, the receiver uses the SC strategy to continuously evaluate the signal quality of the two links and selects the better link for real-time data transmission. As an extension of free-space optical communication, FSO provides Gbit/s-level broadband train-ground transmission, resists electromagnetic interference, and has no spectrum constraints. Ground optical backhaul uses a multi-service optical transport network (MS-OTN) platform to implement self-healing switching within 50 ms, ensuring uninterrupted forwarding of service data to the train communication network and forming a complete optical communication technology loop. Because the FSO and RF links use different transmission mechanisms, SC does not require direct signal-level fusion between the heterogeneous links and provides a low-complexity reception strategy for highly mobile HSR scenarios. In addition, using SC at the receiving end eliminates the requirement for strict phase synchronization between the two heterogeneous links. The FSO/RF base stations implement time synchronization over the shared optical fiber backbone network through a standard synchronization protocol, such as the IEEE 1588 Precision Time Protocol. Packet- or frame-level synchronization is sufficient for the coordinated operation of heterogeneous access nodes. The demodulated data are then forwarded to the train communication network [12], completing end-to-end information transmission. (The basic principle of this technology is shown in Figure 2 below.)

Figure 2: Basic Principle of FSO Communication Technology [12]



4.2 Laser Interferometry for High-Speed Railway Health Inspection Using Trackside Telecommunication Fiber

Health inspection of the extensive high-speed railway network is essential for maintaining normal transportation. The CR450 high-speed train, whose operating speed can reach 450 km/h, is currently undergoing trial operation. As operating speeds continue to increase, the safety requirements for high-speed railway trains are also increasing. To shorten the long inspection cycle of the current track recording vehicle method, this study implemented a laser interferometer sensing system that converts existing optical fiber cables in high-speed railway cable ducts into effective sensing elements. Based on distributed vibration sensing of trains in daily operation, an average power spectral density indicator is used to evaluate the health condition of high-speed railway infrastructure [13].

In recent years, distributed vibration sensing based on existing optical fiber networks has become a highly attractive method. Instead of using dedicated optical fiber sensors such as fiber Bragg grating (FBG) sensors, this method uses the telecommunication fiber itself as the sensing element to capture real-time vibrations caused by human activities and natural events [13]. The method has an important role in geological detection, structural imaging, and other fields and can also be applied to high-speed railways. With the aid of a distributed sensing system, existing optical cables in high-speed railway cable ducts can be used as sensing elements. This

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enables dual-service reuse of the existing high-speed railway optical communication network for communication transmission and condition sensing, eliminates the need to lay additional dedicated sensing fibers such as FBGs, and greatly improves the utilization of current optical communication network resources. Each passing train induces vibrations coupled with the train-track-bridge (TTB) system, from which the health condition of the high-speed railway system can be extracted. This optical-fiber-based sensing method can supplement existing inspection methods represented by the track recording vehicle (TRV) and provide real-time health monitoring for long-distance high-speed railways [13].

This technology has completed more than 14 months of continuous observation tests on a 12-km test section of the Beijing-Guangzhou High-Speed Railway and experienced changes in various environmental factors. The system did not cause any interference to core transmission services such as train control and dispatching on the original high-speed railway optical communication network, and it accurately identified millimeter-level rail creep deformation. As an effective supplement to traditional periodic inspection methods, this frontier innovation relies entirely on existing high-speed railway optical communication infrastructure to achieve real-time monitoring of the entire line without blind spots and provides a core technical model for constructing an integrated all-optical information system for transmission, sensing, and maintenance in the next generation of intelligent high-speed railways.

5. Current Shortcomings and Future Prospects

5.1 Current Shortcomings

At present, China's railway section telephone network system mainly uses copper-core cables for communication and has shortcomings including narrow bandwidth, small capacity, high loss, poor resistance to interference, and difficult maintenance. With China's economic development, demand for copper has increased and the price of copper-core cables has continued to rise, increasing construction investment costs [14]. Their suitability is currently low.

China has diverse terrain, and high-speed railway lines must cover most parts of the country to meet people's travel needs. Some lines are located on plateaus and in severely cold conditions. Optical fibers age faster under these conditions, and efficient fault investigation cannot currently be ensured in some remote high-altitude areas. The capabilities of intelligent algorithms in current optical networks and the transmission performance of optical fibers under extreme conditions need to be improved to meet future high-speed railway optical communication requirements.

Optical communication itself also currently has some problems, including susceptibility to atmospheric media, the contradiction between signal quality and transmission distance, laser safety, and alignment at the transmitting and receiving ends [15]. The technology requires continuous improvement.

In addition, although China is now a global leader in equipment such as optical fibers and optical cables, bottlenecks remain in core components such as high-rate optical chips. For China's high-speed railways to develop steadily, these technical difficulties must be overcome.

5.2 Future Prospects

5.2.1 5G-R Technology

With the continuous development of fifth-generation (5G) communication technology in China, the Global System for Mobile Communications-Railway (GSM-R), a second-generation narrowband communication system that has been in service for many years and is widely used on China's high-speed railways, is moving toward 5G-R. However, this technological transition will require a long period of future testing and adjustment. A key issue is how to ensure compatibility between the stable operation of the existing high-speed railway communication system and 5G-R system trials in some regions. Through a unified carriage architecture and the high-bandwidth characteristics of optical communication, optical communication can both ensure the stable operation of existing high-speed railway communication and provide a path for 5G-R information transmission, avoiding large-scale reconstruction of the communication system. In addition, China's fastest high-speed train currently in operation, the Fuxing CR400, has entered service on multiple lines and has a maximum operating speed of 350 km/h. Speeds will continue to increase in the future, and the next-generation

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CR450 high-speed electric multiple unit will reach 400 km/h, creating greater demands for response speed during operation. The optical communication network can provide high-bandwidth backhaul channels through 5G-R base stations along the line and handle the enormous transmission pressure caused by problems such as Doppler frequency-shift compensation and seamless signal switching in high-speed operating scenarios, thereby ensuring uninterrupted and smooth train-ground communication throughout high-speed railway operation.

As the population increases and science and technology continue to develop, high-speed railway digital services will grow geometrically in the future. Relying on wavelength-division multiplexing (WDM) technology, optical communication will break through the bandwidth bottleneck of traditional transmission networks and allow a single optical fiber to simultaneously carry the combined requirements of office services at various stations, Internet access, offline ticket sales, communication along the railway, and Wi-Fi use by high-speed railway passengers, thereby forming an ultra-large platform for unified carriage of all services.

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Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

This paper is an output of the science project.

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