mathematics

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Review

A Review of Digital Signal Processing Methods for Intelligent Railway Transportation Systems

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Abstract

Digital signal processing plays a central role in intelligent railway communications under high-mobility, strong-multipath, and time-varying-channel conditions. This review surveys representative techniques for multi-carrier modulation, precoding, index modulation, and chaos-inspired physical layer security and highlights their mathematical foundations. Core themes include transform-domain representations typified by time–frequency analysis, linear-algebraic formulations of precoding and equalization, combinatorial structures underlying index mapping and spectral efficiency gains, and nonlinear dynamical systems theory of chaotic encryption. The methods are compared in terms of bit error performance, peak-to-average power ratio, spectral efficiency, computational complexity, and information security, with emphasis on railway-specific deployment constraints. The synergistic application of these methods with intelligent railway transportation systems is expected to enhance the overall performance of railway transportation systems in terms of transmission efficiency, reliability, and security. It provides critical technological support for the efficient and secure operation of next-generation intelligent transportation systems.

Keywords: digital signal processing; intelligent railway communications; transform-domain analysis; precoding matrix; index modulation; chaotic encryption

MSC: 94-02

1. Introduction

As intelligence, automation, and autonomy become the core drivers of modern railway development, railway systems are evolving into data-intensive and information-integrated complex systems [1]. This evolution has placed unprecedented demands on the communication network that supports its operation. It is essential to achieve the real-time collection and interaction of massive data, such as train operation status, track condition monitoring, and environmental perception information. Additionally, in the highly dynamic and time-varying-channel environment, it is crucial to ensure extremely high reliability, ultra-low latency, and absolute security for communication, positioning, sensing, and status monitoring. However, high-speed trains operate in complex communication environments, including tunnels, bridges, and mountainous and urban regions, among others [2]. Signal propagation is susceptible to factors such as multipath fading, Doppler frequency shift, and sudden interference. Under these high-speed mobile transmission conditions,

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achieving reliable and secure data communication has become critical to supporting the stable operation of intelligent railway systems. In this context, traditional narrowband or single-technology communication systems have revealed limitations, including insufficient spectral efficiency, limited anti-interference capability, and difficulties in accommodating the requirements of various services.

In recent years, a series of advanced digital signal processing (DSP) technologies have demonstrated excellent performance in the field of communications, showing potential to meet demands such as high-speed mobility, high spectral efficiency, and enhanced security. If these technologies can be adapted to the specific operational needs and channel environments of railways, they are expected to significantly enhance the overall performance of the system. Table 1 illustrates the challenges in railway communication and the corresponding solutions based on DSP technologies.

Table 1. Comparison of issues in railway communication and DSP solutions.

Questions	Q1: Transmission Reliability in Complex Channel Environments	Q2: Insufficient Spectral Efficiency and System Capacity	Q3: Data Security
Methods	OFDM: mitigate multipath interference; precoding: anti-frequency-selective fading	Index modulation: enhance spectral efficiency	Chaos encryption: enhance physical layer security
Cost	High requirements for synchronization	High complexity in detection	High difficulty in key management and distribution
Applicable scenarios	Vehicle-to-ground communication in complex environments such as tunnels and urban areas; high-speed area switching	Large-capacity monitoring data transmission; passenger information service	Transmission of critical information such as train control instructions and safety alerts

Multi-carrier technology is widely used in modern communication systems due to its significant advantages, including high spectral efficiency, resistance to multipath interference, flexible resource allocation, high data rates, and simplified equalization processing [3]. Compared with single-carrier systems, multi-carrier technology demonstrates obvious advantages in spectrum resource utilization, resistance to complex channel interference, and support for future high-speed communications. It makes it an important foundation for future 6G, the Internet of Things, and intelligent communications. Although multi-carrier transmission systems have multiple advantages in modern communications, they still present some obvious disadvantages. Specifically, the high peak-to-average power ratio (PAPR) requires components with higher power tolerance, which can easily lead to nonlinear distortion in the power amplifier and result in bit error rate (BER) degradation [4,5]. Simple and easily implementable precoding techniques can reduce the PAPR and balance signal-to-noise ratio (SNR) performance without requiring channel state information. On the other hand, the existence of cyclic prefix (CP) causes certain bandwidth overhead, leading to reduced spectral efficiency. Index modulation technology not only transmits information by traditional sub-carriers but also implicitly transmits data by index bits, significantly enhancing the spectral efficiency. Moreover, flexible modulation of the system can be achieved by adjusting scheme parameters, which improves its adaptability.

However, the massive data transmission also poses challenges to the security of information. Traditional encryption methods often face issues such as high computational complexity or key leakage, resulting in reduced security. Chaotic encryption technology

uses the unpredictability and high sensitivity of chaotic systems to effectively enhance the anti-attack capability [6]. It improves signal security and prevents information from being eavesdropped or tampered with. A relationship diagram of several technologies is shown in Figure 1.

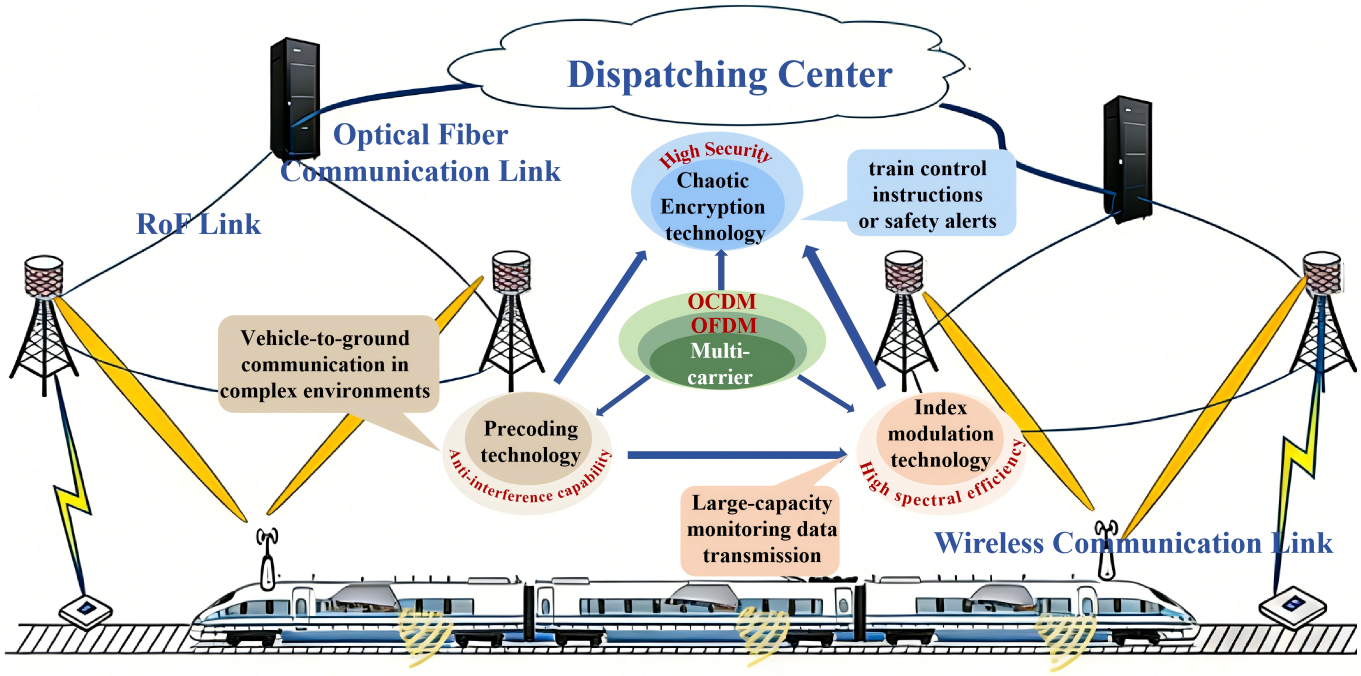


Figure 1. Relationship of four technologies.

Therefore, creatively introducing and adapting advanced digital signal processing technologies—already thoroughly validated in the field of communications—to the specific context of railway transportation has become an inevitable and promising technical pathway to promote its intelligent upgrade.

It is worth noting that with the development of multi-dimensional data, optical communication and intelligent computing are becoming important supports for railway systems. In practical deployments, wireless communication and optical fiber communication form a collaborative and complementary heterogeneous integrated network based on the characteristics of the scenarios and the requirements of the services. Wireless communication, with its flexibility and mobility, mainly carries out real-time interactions of dynamic links such as vehicle to ground and vehicle to vehicle, meeting the requirements of train control instructions, status synchronization, etc. Optical fiber communication, leveraging its high bandwidth and anti-electromagnetic interference capabilities, has established a backbone transmission network connecting base stations, stations and dispatch centers. It also provides stable and reliable signal coverage for special scenarios such as tunnels.

Therefore, this paper focuses on a comprehensive review of advanced DSP technologies for intelligent railways, systematically summarizing the research progress of OFDM, precoding, index modulation, and chaotic encryption technologies. The combination of advanced DSP technology with optical transmission media can achieve high-reliability, low-latency, and high-security transmission in complex railway environments. This study aims to provide a clear technical development summary and a framework for integration and innovation for scholars in related fields. It offers theoretical support and technical path references for the evolution of intelligent railway systems.

The main structure of this review is as follows: Section 2 mainly introduces the methodology used in this review. Section 3 details the latest research findings and development trends of these advanced digital signal processing technologies. Section 4 elaborates on the

principles of these technologies. Section 5 summarizes the application of these technologies in the field of communication systems. Section 6 systematically explores the innovative application prospects of these digital signal processing methods in intelligent railway transportation and provides ideas for future research directions. Finally, Section 7 summarizes the main findings of this paper.

2. Research Methodology

To ensure the systematicity, comprehensiveness and representativeness of this review, we followed the basic principles of systematic literature reviews and established clear processes for literature search, screening and analysis. The search strategy aimed to cover the research status and applications of four DSP technologies: multi-carrier technology, precoding technology, index modulation technology and chaotic encryption technology.

2.1. Database Selection

To ensure the systematicity and currency of the search, this study focuses on the key developments and applied research of four DSP technologies in recent years and conducts a comprehensive literature search across the following academic databases:

- IEEE Xplore Digital Library: The most authoritative literature database in the fields of electronic engineering, computer science, and communications, it contains the majority of the top conference and journal papers related to this subject.
- Web of Science: It utilizes its authoritative citation indexing function to retrieve high-impact academic journal studies and supports citation analysis (such as forward and backward searches).
- To closely track the latest advancements in the application of DSP technologies within optical transmission systems, we directly search the official websites of authoritative journals such as *Optics Express*, *Optics Letters*, and *Journal of Lightwave Technology*. This approach aims to directly acquire the most cutting-edge and high-quality research outcomes and to compensate for the update delay of general databases.

2.2. Keyword Search

This review employed multiple keywords to retrieve the relevant literature:

ALL ((“OFDM” OR “OCDM”) AND (“Precoding”) AND (“Index Modulation”) AND (“Chaotic encryption” OR “Physical layer security”) AND (“signal processing”)).

2.3. Literature Evaluation

Literature inclusion criteria:

- The publications were published in journals ranked above Q2 (including Q2) or at top conferences, focusing on high-impact and high-quality research within the field.
- Publications were highly relevant to the topic. They focused on the algorithmic improvements, performance analysis, or system design of one or more DSP technologies, i.e., OFDM, precoding, index modulation, or chaotic encryption.
- The research background involves complex channel environments, anti-interference, reliability, physical layer security, etc.

Firstly, using the database screening tool and manual verification, we excluded the papers that did not meet the quality standards. Subsequently, we conducted multiple rounds of review on the titles, abstracts, and full texts of the remaining papers to assess whether they met the aforementioned criteria.

2.4. Data Extraction and Comprehensive Analysis

From the ultimately included literature, we extracted the following key information for analysis:

- Technical attributes: technological principles, advantages, and performance metrics (such as interference resistance, bit error rate performance, spectral efficiency, and security enhancement).
- Application scenario: the specific communication system, such as optical fiber communication, wireless communication, etc.
- Relevance to railway applications: how the mentioned DSP technologies map to railway communication.
- Development trend: technological evolution path, existing limitations and future research directions.

Through these approaches, this paper aims to present a comprehensive review of the relevant technologies, thereby laying a solid foundation for subsequent discussions on their integrated applications in intelligent railway systems.

3. Advanced Digital Signal Processing Methods

A range of advanced digital signal processing techniques have been proposed and extensively studied to address complex channel environments, enhance transmission performance, and ensure information security. This section systematically reviews the current research status of multi-carrier technology, precoding technology, index modulation technology, and chaotic encryption technology. The existing literature provides differentiated solutions to meet diverse channel conditions, performance requirements, and security challenges in modern communication systems. By analyzing the application scenarios of these technologies, this section aims to offer theoretical foundations and insights for integrated innovation in the development direction, system architecture design, and cross-layer optimization for next-generation railway mobile communication systems.

3.1. Multi-Carrier Technology

Single-carrier and multi-carrier technologies are primary signal transmission methods in modern communication systems. Table 2 provides the performance comparison between multi-carrier and single-carrier systems. However, with the advancement of communication technologies, single-carrier technology has exposed some obvious limitations, particularly in complex multipath propagation environments. To overcome these issues, especially the effects of multipath environments and frequency-selective fading, multi-carrier technology emerged. Orthogonal frequency division multiplexing (OFDM) is a typical multi-carrier technology. Direct current-biased optical OFDM (DCO-OFDM) [7] and asymmetrically clipped optical OFDM (ACO-OFDM) [8,9] are widely used modified OFDM schemes. DCO-OFDM suffers from relatively low power efficiency, while ACO-OFDM has low spectral efficiency. Based on this, researchers have developed a series of layered O-OFDM schemes to balance power efficiency and spectral efficiency. For example, Hybrid ACO-OFDM transmits ACO-OFDM on odd-indexed sub-carriers combined with pulse amplitude-modulated discrete multitone on even sub-carriers. However, only the imaginary parts of even sub-carriers are modulated, and the real parts of even sub-carriers have not yet been used [10]. In 2022, R. Bai et al. proposed layered ACO-OFDM (LACO-OFDM), which improves spectral efficiency by combining ACO-OFDM signals from different layers.

However, it suffers from high computational complexity and significant processing delay [11]. Ref. [12] proposed asymmetrically clipped DC-biased optical OFDM. This scheme allocates odd sub-carriers to ACO-OFDM and even sub-carriers to DCO-OFDM, utilizing all sub-carriers for data transmission and balancing their advantages and disadvantages.

However, conventional ADO-OFDM receivers are affected by clipping noise when the DC bias is low, leading to degraded BER performance [13]. A research group from Nanjing University of Information Science and Technology proposed the adaptively biased layered optical OFDM scheme, which uses an adaptive bias to achieve positive real-value transmission [14]. Furthermore, compared with ACO-OFDM, this scheme employs multiple layers of sub-carriers for data transmission, achieving high spectral efficiency. Compared with LACO-OFDM, it requires only one inverse fast Fourier transform (IFFT) operation and is easy to demodulate with low complexity. In 2024, a research group from Northeast Normal University proposed a flexible dual-layer optical OFDM scheme. This scheme uses an adaptive DC bias to make the time-domain superimposed bipolar signal positive, facilitating transmission in visible light communication (VLC) systems [15]. In 2025, a research group from Tsinghua University proposed a DCO-OFDM scheme for free-space optical-integrated sensing and communication (FSO-ISAC) [16]. This scheme models the clipping noise of DCO-OFDM as additive colored Gaussian noise and establishes an equivalent frequency-selective channel for FSO-ISAC. It formulates joint communication-centric and sensing-centric power allocation problems, revealing the trade-off relationship between communication and sensing. These research studies represent improved multi-carrier technologies based on the OFDM scheme.

Table 2. Comparison of single-carrier and multi-carrier characteristics.

Characteristic	Single Carrier	Multi-Carrier (OFDM)
Resistance to Multipath Fading	Poor	Strong
Spectral Efficiency	Low	High
PAPR	Low	High
Sensitivity to Frequency Offset	Relatively insensitive	Very sensitive, requires precise synchronization

In addition, orthogonal chirp division multiplexing (OCDM) is a novel multi-carrier transmission technique proposed in 2016. OCDM essentially orthogonally multiplexes multiple chirp waveforms of the same bandwidth to achieve the maximum communication rate. The foundation of OCDM is the Fresnel transform, similar to the Fourier transform in OFDM. But it can provide stronger resistance to fading and better anti-noise capability compared with OFDM [17]. In 2023, J. Zhao et al. proposed an orthogonal circulant multiplexing (OCM) technique for bandwidth-limited direct-detection optical systems. This technique uses orthogonal cyclic matrices for multiplexing and demultiplexing, enabling uniform noise distribution across sub-carriers. It can achieve a flatter inter-symbol interference/inter-carrier interference (ISI/ICI) distribution, enabling superior performance compared with conventional OCDM [18].

It can be seen that multi-carrier technology is a necessary method to enhance the performance of communication systems. Different multi-carrier schemes can be adapted to various transmission systems, thereby improving the overall transmission performance. The multi-carrier technologies summarized in this paper can mitigate the interference issues caused by traditional OFDM multi-carrier schemes, further enhancing the performance of transmission systems.

3.2. Precoding Technology

In multi-carrier transmission systems, a high PAPR is a significant issue that can lead to nonlinear distortion, reduced power amplifier efficiency, and degraded system

performance [19]. Common methods for reducing the PAPR include signal clipping and filtering [20], selective mapping [21], partial transmission sequences [22], and tone reservation [23]. Table 3 provides a performance comparison of these schemes.

Table 3. Comparison of PAPR reduction schemes.

Schemes	PAPR Suppression Performance	Computational Complexity	Core Cost/Drawbacks
Clipping and Filtering	Excellent (direct effect, controlled by threshold)	Very low	Achieved at the cost of signal distortion and BER degradation
Companding Transform	Good	Low	Sensitive to noise, dynamic range affected
Selective Mapping	Good–excellent (improves with number of candidate sequences U)	Medium–high (requires U IFFT operations)	Trade-off between complexity and spectral efficiency
Partial Transmit Sequence	Excellent (best performance among probabilistic methods)	High–very high (requires searching for optimal phase combination)	High computational complexity, difficulty in optimal search
Tone Reservation	Good–excellent (improves with number of reserved sub-carriers)	High (requires iterative calculation of peak-canceling signal)	Direct cost in spectral efficiency
Tone Injection	Good	High (requires search in expanded constellation)	Complex implementation, receiver requires special design

Compared with these methods, the precoding method is a simpler and more easily implementable approach to PAPR reduction. This technique does not require channel state information and can achieve PAPR reduction through the design of the precoding matrix. Additionally, precoding can equalize the uneven signal-to-noise ratio caused by frequency-selective fading in the channel, thereby enhancing the anti-noise ability. Precoding matrices include the discrete Fourier transform (DFT) [24], constant-amplitude zero auto-correlation sequence-based matrix transformation (CAZAC) [25], Zadoff–Chu matrix transformation (ZCT) [26], orthogonal circulant matrix transformation (OCT) [27], Walsh–Hadamard transform (WHT) [28], discrete cosine transform (DCT) [29], and discrete Hartley transform (DHT) [30]. In 2021, Chen Ming et al. applied channel-independent precoding technology to a filter bank multi-carrier with offset quadrature amplitude modulation (FBMC/OQAM) system for short-reach intensity-modulation and direct-detection (IM/DD) systems [31]. The results demonstrated that at a bit error rate of 3.8×10^{-3}, the use of precoding technology improved the system's receiver sensitivity by approximately 2 dB. In 2023, researchers proposed a low-complexity fast Walsh–Hadamard transform (FWHT)-based interleaved block precoding for a digital low-pass delta-sigma modulation-enabled DAC-free FBMC signal generation scheme. It was experimentally investigated in a red light-emitting diode-based visible light communication system [32]. Experimental results showed that the FBMC signal generated by this scheme could achieve a net data rate of 2.38 Gbit/s over a 2.3 m free-space transmission distance while maintaining a bit error rate below 3.8×10^{-3}.

In 2024, J. Zhang et al. proposed a chromatic dispersion-aware OCT precoding scheme. It was experimentally demonstrated in a C-band 100 Gb/s IM/DD-OFDM transmission system over 50 km of standard single-mode fiber [33]. The proposed scheme not only outperformed conventional OFDM, DFT precoding, and standard OCT precoding schemes

in performance but also achieved higher capacity. In addition, J. Qiu et al. proposed applying DFT precoding with different redundancy sampling factors to ACO-OFDM in power-constrained optical wireless communication systems [34]. This scheme utilized the weighted Bussgang theorem to analyze the impact of DFT precoding on ACO-OFDM systems under transmit power constraints. Numerical results validated the effectiveness of this method in balancing signal-to-noise ratio and bit error rate performance. In 2025, Y. Liu et al. proposed a real-valued precoding-based asymmetrically clipped assisted hybrid optical FBMC modulation scheme to reduce PAPR and equalize sub-carrier signal-to-noise ratio, thereby improving transmission performance [35]. The precoding technique achieved a PAPR reduction of up to 4.7 dB and reduced the bit error rate by approximately one order of magnitude.

In summary, precoding technology can achieve PAPR reduction and SNR equalization, thereby enhancing signal quality and reliability. Consequently, precoding technology can effectively mitigate nonlinear interference in multi-carrier transmission systems, providing robust support for high-capacity, high-quality communication systems.

3.3. Index Modulation Technology

Conventional OFDM technology utilizes multiple sub-carriers for signal transmission, but its spectral efficiency is limited due to the Hermitian symmetry. Index modulation (IM) is a novel modulation technique that has been proposed. In index modulation, information is not only conveyed through M-ary signal constellations as in traditional OFDM but also implicitly transmitted via the index bits of the activated sub-carriers, significantly enhancing the system's spectral efficiency [36,37]. Furthermore, since the additional index bits do not consume energy, the energy efficiency is improved [38]. IM can enhance the system's energy efficiency by adjusting the number of active sub-carriers, achieving a trade-off between spectral efficiency and energy efficiency [39]. IM schemes can be classified into single-mode index modulation, dual-mode index modulation (DM-IM) [40], and multi-mode index modulation (MM-IM).

D. Zheng et al. proposed a differential index modulation OFDM scheme that enhances spectral efficiency by eliminating inactive sub-carriers at the ends of sub-blocks [41]. Another study integrated LACO-OFDM with index modulation, improving both spectral efficiency and bit error rate performance by filtering the out-of-band clipping harmonics [42]. However, single-mode index modulation only activates a portion of sub-carriers for data transmission, resulting in limited spectral efficiency. T. Mao et al. developed dual-mode index modulation OFDM (DM-OFDM), which achieves higher spectral efficiency by activating all sub-carriers [43]. Researchers further proposed a Generalized DM-OFDM scheme which enhances spectral efficiency by dynamically adjusting the number of sub-carriers in each mode and improves bit error rate performance through interleaving techniques [44]. The research team developed two optical DM-OFDM schemes, DM-IM DC-biased optical OFDM and DM-IM-aided unipolar OFDM, with both demonstrating significant performance improvements over conventional schemes at the same spectral efficiency [45]. In 2022, a partitioned DFT-spread OFDM dual-mode index modulation scheme was proposed, incorporating both block-based and interleaved constellation partitioning implementations [46]. In 2025, S. Choi et al. introduced a Reed–Muller code-based DM-OFDM index codebook that effectively reduces bit error rate by maximizing the distance between index codewords [47].

Compared with DM-OFDM, MM-OFDM demonstrates stronger environmental adaptability and system flexibility by superimposing multiple constellation modes, enabling adaptation to diverse transmission environments [48]. The increase in index modulation modes also enhances the number of index bits and the achievable system data rate. In 2018,

M. Wen et al. proposed generalized MM-OFDM, which achieves optimal BER performance in high-SNR regions [49]. In 2020, L. Cho et al. introduced a block-based MM-OFDM using PSK, which incorporates a novel constellation design to implement two-level power allocation, improving BER performance without increasing computational complexity [50]. To address the high-PAPR issue, H. Wen et al. proposed a CAZAC precoding-based MM-OFDM scheme, which outperforms conventional MM-OFDM and OFDM in both PAPR and BER performance [51]. In 2023, a research team enhanced the spectral efficiency of IM-OFDM by extending index modulation to both energy and constellation domains, though the use of BPSK modulation limited further SE improvement [52]. Most existing IM techniques are based on two-dimensional constellations. A research group expanded index modulation to high-dimensional spaces, leveraging the larger minimum Euclidean distance to improve spectral efficiency, energy efficiency, and BER performance [53–55]. In 2023, they further proposed a coordinate-interleaved high-dimensional OFDM with index modulation scheme, which achieves additional diversity gain and enhanced BER performance [56]. Moreover, index modulation can adaptable to various channel conditions. Table 4 summarizes different index modulation schemes.

Table 4. Comparison of index modulation schemes.

References	Transmission Signal	Index Modulation Schemes	Channel Conditions
[57]	AFDM	Dual-mode IM	Linear time-varying (LTV) channels
[58]	AFDM	Generalized Code Index Modulation	Doubly selective fading channels
[59]	AFDM	Pre-chirp index modulation	Doubly dispersive channel
[60]	OFDM	Hybrid Index Modulation	Rayleigh fading channel
[61]	QPSK/BPSK	Composition Index Modulation	NOMA
[62]	OFBMC	Sub-carrier index modulation	Free-space link
[63]	OFDM	Generalized Joint Index Modulation	Frequency-selective Rayleigh fading channel
[64]	OFDM	Multiple-Mode IM	Frequency-selective Rayleigh fading
[65]	OTFS	Sub-Band Index Modulation	LTE-EVA channel
[66]	OTFS	Index modulation	TF selective channel
[67]	OTFS	Dual-mode index modulation	Time-varying channel
[68]	Active RIS	Amplification factor-indexed modulation	Wireless channels exhibit Rayleigh flat fading
[69]	ETN-mCAP	Gapped index modulation	VLC
[70]	Multi-Band CAP	Multi-mode index modulation	Band-limited VLC

These research studies use various index modulation schemes to flexibly accommodate transmission signal requirements, thereby enhancing spectral efficiency and BER performance.

3.4. Chaotic Encryption Technology

In recent years, the rapid increase in data transmission volume has posed severe challenges to communication security. With the continuous development of chaos theory, scholars have attempted to combine chaotic systems with traditional encryption algorithms [71,72]. Chaotic encryption technology, due to its simple implementation, unpredictable sequence, strong security, and high sensitivity to initial conditions, has become a competitive technical solution in the field of physical layer encryption [73].

In short-range communication scenarios, this technology is widely adopted due to its ability to effectively resist interference and eavesdropping [74]. In 2022, F. Wang et al. implemented a physical layer encryption scheme based on a three-dimensional digital multi-vortex chaotic system in a 340 GHz terahertz optical wireless transmission system. They successfully demonstrated the transmission of probabilistically shaped encrypted OFDM signals over 20 km of standard single-mode fiber and 25/54 m of wireless distance [75]. In 2023, X. Liang et al. proposed a chaotic Hilbert transform-based encryption technique for passive optical network OFDM (OFDM-PON). By constructing chaotic Hilbert transforms to scramble the key space, the scheme enhanced overall system security [76]. Experimental results verified that this approach could support stable transmission of 35.29 Gb/s signals over 20 km of fiber and in back-to-back systems. In the same year, M. Wu et al. proposed a three-dimensional probabilistic shaping optical transmission system based on the prefix-free code distribution matching and polar code joint coding [77]. Using Logistic and Lorenz chaotic models for the multi-layer masking of constellation diagrams, the encrypted PCDM-encoded signals achieved approximately 3 dB improvement in BER performance compared with conventional unencrypted 3D-32QAM systems, with a key space reaching 10^{119}.

In 2024, G. Chen et al. proposed a three-dimensional non-orthogonal multiple-access secure transmission scheme based on constellation chaotic selective mapping [78]. This scheme enhances system resistance to attacks through dual encryption. In 2025, Y. Lei et al. developed a dynamic chaotic encryption scheme for fiber–wireless communication systems [79], which intercepts and encrypts static chaotic sequences using dynamic keys, effectively strengthening physical layer security. Furthermore, chaotic encryption has been implemented in OCDM systems. In 2022, S. Zhu et al. [80] achieved joint time–frequency encryption using Lorenz and Logistic chaotic models, attaining a key space of 10^{144} and a 1.48 dB improvement in receiver sensitivity compared with OFDM. In 2024, Z. Guo et al. proposed a gated recurrent unit-based chaotic encryption method using small-scale datasets, achieving a key space of 10^{322} and an effective transmission rate of 6.82 Gb/s [81]. Research demonstrates that chaotic encryption technology, with its high sensitivity and anti-interference characteristics, has significant advantages and application potential in the field of communication security. To systematically demonstrate its application, Table 5 summarizes the specific applications of this technology in different communication systems.

These four technologies enhance the performance of traditional communication systems across multiple dimensions including transmission reliability, spectral efficiency, and communication security. Their application in railway systems can achieve more economical, secure, and reliable signal transmission. Subsequent sections will analyze the fundamental principles of these signal processing technologies while discussing their performance across various communication systems and exploring innovative applications in intelligent railway transportation.

Table 5. Chaotic encryption schemes in different communication systems.

References	Scheme	Transmission Medium	Key Space
[82]	3D-CAP-PON	SSMF	2.1×10^{85}
[83]	OFDM	underwater WOC	9.7×10^{179}
[84]	PAM-8	underwater VLC	1.75×10^{154}
[85]	OFDM	7-core fiber	10^{135}
[86]	DM-OFDM-IM	short-distance magnetic communication	10^{146}
[87]	HDMM-IM OFDM	VLC	10^{198}
[88]	OFDM-IM	SSMF	10^{210}
[89]	PAM4	7-core fiber	10^{40}
[90]	DSM	RoF	10^{490}
[91]	OFDM	RoF	10^{160}
[92]	OFDM	MMW-RoF	10^{103}
[93]	MSBS-64QAM	SSMF	10^{90}
[94]	OTFS	SSMF	10^{90}
[95]	OFDM	7-core fiber	10^{240}
[96]	CO-OFDM	SSMF	10^{324}
[97]	OFDM	wireless channel	10^{223}

4. Technical Principles

Based on the review of existing research in Section 3, this section will elaborate on the fundamental mathematical models, signal processing procedures, and key performance parameters of the discussed technologies. This aims to provide an in-depth understanding of their principles, advantages, and adaptability in communication scenarios. By establishing a clear technical framework at the theoretical level, it lays a solid foundation for practical applications.

4.1. The Principle of Multi-Carrier Technology

Multi-carrier technology enables more efficient utilization of the spectrum, enhances channel resource utilization, and offers excellent flexibility and scalability. It is widely applied in wireless communications, broadcasting, and broadband access. OCDM is a multi-carrier technology that has been proposed recently as an improvement on OFDM [17,18]. Just like the Fourier transform in OFDM systems, OCDM takes the Fresnel transform as the basis of the system. The (m, n)-th element of the $N \times N$ order discrete Fresnel transform (DFnT) matrix can be expressed as

$$\Phi(m,n) = \frac{1}{\sqrt{N}} e^{-j\frac{\pi}{4}} \times \begin{cases} e^{j\frac{\pi}{N}(m-n)^2}, & N \equiv 0 \pmod 2 \\ e^{j\frac{\pi}{N}\left(m+\frac{1}{2}-n\right)^2}, & N \equiv 1 \pmod 2 \end{cases} \quad (1)$$

where $m, n = 0, 1, \ldots, N-1$. It should be noted that the DFnTs for N being an even number and an odd number are slightly different.

It can be obtained that the terms of the DFnT matrix are composed of the DFT matrices of the additional quadratic terms

$$\Theta_1(m) = e^{-j\frac{\pi}{4}} \times \begin{cases} e^{j\frac{\pi}{N}m^2}, N \equiv 0(\mathrm{mod}2) \\ e^{j\frac{\pi}{4N}} e^{j\frac{\pi}{N}(m^2+m)}, N \equiv 1(\mathrm{mod}2) \end{cases} \tag{2}$$

$$\Theta_2(n) = \begin{cases} e^{j\frac{\pi}{N}n^2}, N \equiv 0(\mathrm{mod}2) \\ e^{j\frac{\pi}{N}(n^2-n)}, N \equiv 1(\mathrm{mod}2) \end{cases} \tag{3}$$

Thus, the DFnT can be implemented in three steps, and the OCDM principle is shown in Figure 2. At the transmitter, after performing serial-to-parallel (S/P) conversion and QAM mapping on the binary bit stream, the IDFnT is achieved through three steps: first multiply by a chirp phase Θ_2^*, then perform IDFT via IFFT, and finally multiply by another chirp phase Θ_1^*. Among them, $*$ represents the conjugate operation. After processing, CP and TS are inserted, and the signal is transmitted after parallel-to-serial (P/S) conversion. At the receiver, after timing synchronization and channel estimation, the TS and CP are removed, and the inverse DFnT is executed: multiply by a chirp phase Θ_1, FFT transformation, and multiply by a chirp phase Θ_2. Finally, frequency-domain equalization, QAM demapping, and P/S conversion are performed.

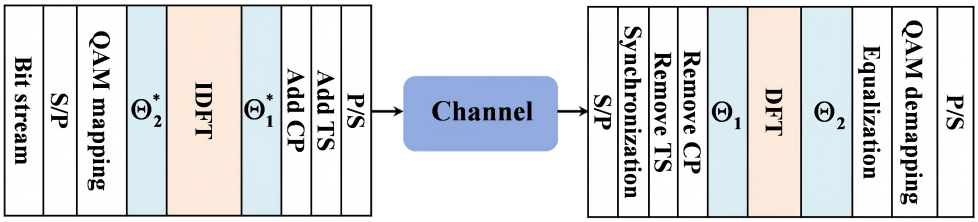


Figure 2. Schematic diagram of OCDM systems.

4.2. The Principle of Precoding Technology

The principle of precoding technology is to multiply the precoding matrix by sub-carrier signals after QAM mapping, thereby achieving the redistribution of signal energy. This method does not rely on channel state information and significantly reduces system complexity and implementation costs compared with traditional pre-equalization techniques. At the transmitter, signals are multiplied with the precoding matrix after QAM mapping, followed by IFFT transformation. At the receiver, after FFT and frequency-domain equalization, the signal is restored using the inverse precoding matrix. Without introducing redundant information, this technique maintains spectral efficiency while effectively improving system robustness and implementation simplicity.

Firstly, the precoding matrix **C** can be expressed as

$$C = \frac{1}{\sqrt{N_1}} \begin{bmatrix} c_{11} & \cdots & c_{1N_1} \\ \vdots & \ddots & \vdots \\ c_{N_1 1} & \cdots & c_{N_1 N_1} \end{bmatrix} \tag{4}$$

Among them, N_1 represents the number of effective data sub-carriers.

The elements c_{mn} $(m, n = 1, 2, \ldots, N_1)$ in the DFT precoding matrix can be expressed as

$$c_{mn} = \exp\left(-j2\pi \frac{(m-1)(n-1)}{N_1}\right) \tag{5}$$

CAZAC precoding, ZCT precoding and OCT precoding are all precoding matrices generated by Zadoff–Chu sequences. The elements of the Zadoff–Chu sequence can be expressed as

$$c_k = \begin{cases} \exp\left(j\frac{2\pi r}{M}\left(\frac{(k-1)^2}{2} + q(k-1)\right)\right), M \text{ is even} \\ \exp\left(j\frac{2\pi r}{M}\left(\frac{k(k-1)}{2} + q(k-1)\right)\right), M \text{ is odd} \end{cases} \tag{6}$$

where k is an integer ranging from 1 to N_1, q is an integer, and r is a relative prime number with respect to N_1. In CAZAC and ZCT precoding, $M = N_1^2$, while in OCT precoding, $M = N_1$. The elements of CAZAC, ZCT, and OCT precoding are respectively expressed as

$$p_{m,n}^{CAZACT} = c_{m+(n-1)N_1} \tag{7}$$

$$p_{m,n}^{ZCT} = c_{n+(m-1)N_1} \tag{8}$$

$$p_{m,n}^{OCT} = \begin{cases} c_{n-m+1}, & n-m+1 > 0 \\ c_{n-m+1+N_1}, & n-m+1 \leq 0 \end{cases} \tag{9}$$

These precoding matrices are all constructed with complex-valued elements. Compared with complex-valued precoding, real-valued precoding offers simpler implementation and lower complexity. The WHT real-valued precoding is constructed from Hadamard matrices. If N_1 is a power of 2, we generate an N_1-order Hadamard matrix using H_2:

$$H_{N_1} = \begin{bmatrix} H_{N_1/2} & H_{N_1/2} \\ H_{N_1/2} & -H_{N_1/2} \end{bmatrix} \tag{10}$$

DCT and DHT are also real-valued precodings. The elements of their matrices are not limited by powers of 2 and can be expressed as

$$p_{m,n}^{DCT} = \begin{cases} 1, \ m = 1 \\ \sqrt{2}\cos(\pi(2n-1)(m-1)/2N_1), \ m \neq 1 \end{cases} \tag{11}$$

$$p_{m,n}^{DHT} = \cos(\frac{2\pi mn}{N_1}) + \sin(\frac{2\pi mn}{N_1}) \tag{12}$$

Among them, $m, n = 1, 2, \ldots, N_1$. Taking DCT real-valued precoding as an example, the symbols Q after QAM mapping are multiplied by the precoding matrix $\mathbf{C}$ to obtain Y:

$$Y = CQ \tag{13}$$

The signal after transmission through the channel can be expressed as

$$Y' = HY + n \tag{14}$$

n represents noise, and H is the channel matrix. Therefore, after frequency domain equalization, the estimated signal can be obtained:

$$\hat{Q} = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_{N_1} \end{bmatrix} + \frac{1}{\sqrt{N_1}} \begin{bmatrix} c_{11}^H n_1 + c_{21}^H n_2 + \cdots + c_{N_1 1}^H n_{N_1} \\ c_{12}^H n_1 + c_{22}^H n_2 + \cdots + c_{N_1 2}^H n_{N_1} \\ \vdots \\ c_{1N_1}^H n_1 + c_{2N_1}^H n_2 + \cdots + c_{N_1 N_1}^H n_{N_1} \end{bmatrix} \tag{15}$$

It can be seen that noise is distributed across each sub-carrier. Precoding technology effectively equalizes the SNR by uniformly distributing noise among sub-carriers,

thereby mitigating the performance degradation caused by frequency-selective fading. This technique significantly improves the BER performance of multi-carrier systems, enhances anti-interference capability, and has substantial application value in 5G/6G communication systems.

4.3. The Principle of Index Modulation Technology

Index modulation technology enhances both energy efficiency and spectral efficiency through index bits. The DM-OFDM employs two distinguishable constellation sets to modulate all sub-carriers, achieving full utilization of spectral resources while retaining the advantages of index modulation.

Figure 3 illustrates the structure of a DM-OFDM transmitter. At the transmitting end, the input bit stream of h bits is divided into G sub-blocks, with each sub-block containing $b = h/G$ bits. These bits are further split into two parts: b_1 index bits select the number and positions of activated sub-carriers (implicitly transmitted without energy consumption), while b_2 symbol bits are transmitted through M-order constellation modulation. The system utilizes a total of N sub-carriers, with each sub-block containing $l = N/G$ sub-carriers. Among these, k sub-carriers employ constellation set M_A, and $(l-k)$ sub-carriers use constellation set M_B. The values of b_1 and b_2 in each sub-block can be determined as follows:

$$b_1 = \left\lfloor \log_2\left(\frac{l!}{(l-k)!k!}\right)\right\rfloor \tag{16}$$

$$b_2 = k\log_2(M_A) + (l-k)\log_2(M_B) \tag{17}$$

where $\lfloor \cdot \rfloor$ represents the floor operator. Consequently, the theoretical spectral efficiency of DM-OFDM can be derived as

$$\eta_{DM-OFDM} = \frac{b_1 + b_2}{l} = \frac{\left\lfloor \log_2\left(\frac{l!}{(l-k)!k!}\right)\right\rfloor + k\log_2(M_A) + (l-k)\log_2(M_B)}{l} \tag{18}$$

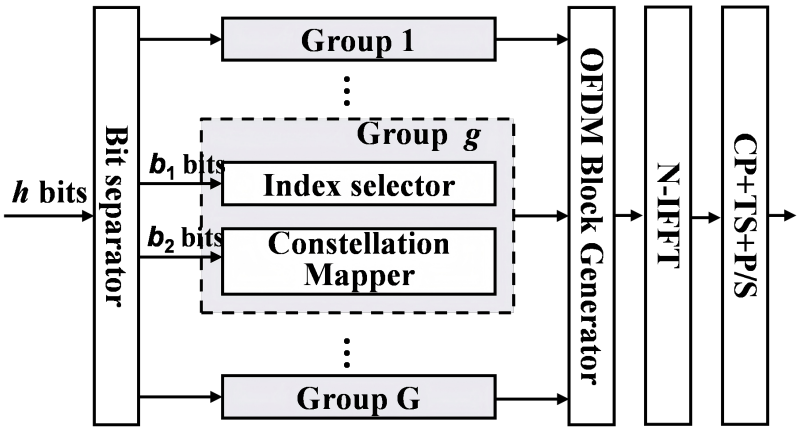


Figure 3. Schematic diagram of index modulation transmitter.

We take the g-th sub-block as an example. The symbols after index modulation are expressed as

$$S^g = \left[S_1^g \cdots S_l^g\right] \tag{19}$$

The index selector divides the index into two subsets, with n_I=2^{b1} index patterns. The set of the index is represented as

$$\mathcal{I}_A \in \{I_A^{(1)}, I_A^{(2)}, \cdots, I_A^{(n_I)}\} \tag{20}$$

The sets of constellations A and B are respectively represented as

$$\mathcal{M}_A = \left\{ S_A(j) : 1 \le j \le M_A \right\} \tag{21}$$

$$\mathcal{M}_B = \left\{ S_B(j) : 1 \le j \le M_B \right\} \tag{22}$$

At the transmitter, the signal is modulated using the look-up table (LUT) [40,43]. After the constellation mapping, the sub-blocks are connected using the OFDM block generator. Then, an N-point IFFT operation is performed. Next, a CP is inserted to prevent ISI/ICI. Finally, after the P/S transformation, it is transmitted through the channel.

Figure 4 shows the structure of the DM-OFDM receiver. The received signal is converted from serial to parallel, the CP is removed, and then an FFT operation is performed. After separating the sub-blocks, a maximum likelihood (ML) detector is used to demodulate the index and symbol bits. The ML detection formula is

$$\left\{ I_A^{(i^*)}, S_{I_A^{(i^*)}}^{(j^*)} \right\} = \arg \min_{I_A^{(i)} \in \mathcal{I}_A, S_{I_A^{(i)}}^{(i)} \in \mathcal{S}_{I_A^{(i)}}} \sum_{k=1}^{n} \left| Y_k^{(g)} - H_k^{(g)} S_{I_A^{(i)}}^{(j)}(k) \right|^2 \tag{23}$$

where Y_k represents the received signal and H_k denotes the channel response. The complexity of ML detection for each sub-block is given by $\mathcal{O}\left(2^{b_1} M_A^k M_B^{(l-k)}\right)$. The complexity of the ML detector increases sharply with rising parameter values.

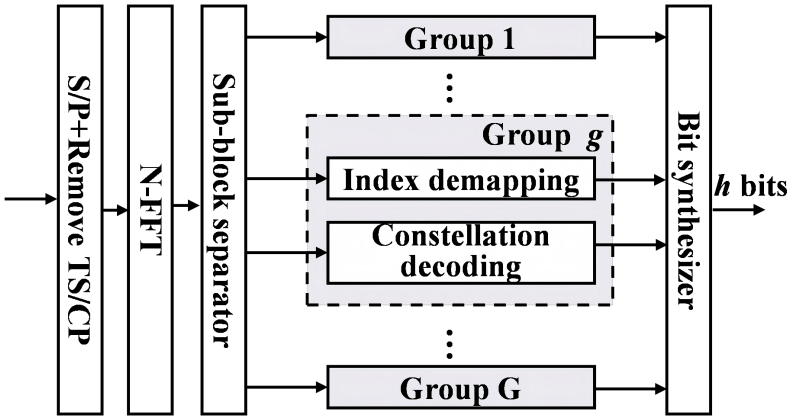


Figure 4. Schematic diagram of index modulation receiver.

To reduce detection complexity, a log-likelihood ratio (LLR) detector is proposed for DM-OFDM demodulation, with its formula expressed as

$$\gamma_n = \ln \left(\frac{\sum_{j=1}^{M_A} \Pr(X_n = S_A(j) | Y_n)}{\sum_{q=1}^{M_B} \Pr(X_n = S_B(q) | Y_n)} \right) \tag{24}$$

where $1 \le n \le N$. Using Bayes' theorem, the expression can be rewritten as

$$\begin{aligned} \gamma_n = \ln\left(\frac{M_B k}{M_A (l-k)} \right) + \ln\left(\sum_{j=1}^{M_A} \exp\left(-\frac{1}{N_0} |Y_n - H_n S_A(j)|^2 \right) \right) \\ - \ln\left(\sum_{q=1}^{M_B} \exp\left(-\frac{1}{N_0} |Y_n - H_n S_B(q)|^2 \right) \right) \end{aligned} \tag{25}$$

Compared with ML detection, the LLR detection algorithm can significantly reduce computational complexity.

4.4. The Principle of Chaotic Encryption Technology

A digital chaotic system is a type of complex dynamic system highly sensitive to initial conditions, where tiny differences in initial values can lead to significant deviations. These systems are typically described by nonlinear equations, in which the output is not proportional to the input, resulting in complex and seemingly unpredictable patterns.

The Logistic chaotic model is a classical one-dimensional mapping widely used in the study of population dynamics and ecological systems. Its mathematical expression is

$$f(i+1) = ef(i)(1 - f(i)) \tag{26}$$

where i represents the step size and the control parameter e is within the range of [2.8, 4], while $f(i)$ is within the range of [0, 1]. As the parameter e changes, the dynamics of the Logistic system undergo significant alterations. As shown in Figure 5, this bifurcation diagram clearly reveals the system's transition from order to chaos, fully demonstrating the complexity of nonlinear systems.

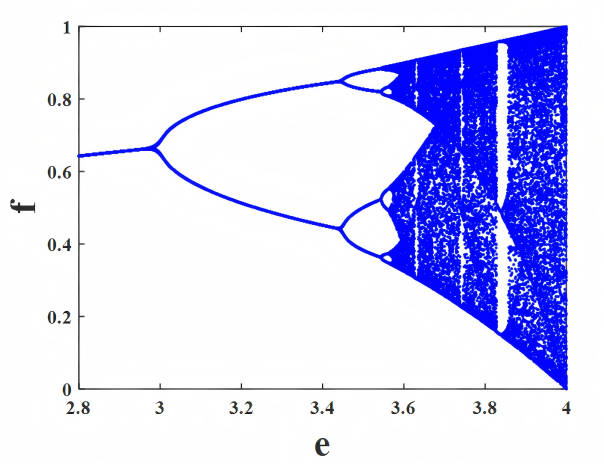


Figure 5. Bifurcation diagram of Logistic chaos model.

The Chua chaotic model is a well-known nonlinear circuit model which is a three-dimensional chaotic system. Its basic form is

$$\begin{cases} \partial x/\partial t = a(y - x - f(x)) \\ \partial y/\partial t = x - y + z \\ \partial z/\partial t = -by \end{cases}$$
$$f(x) = dx + 0.5(c + d)(|x + 1| - |x - 1|) \tag{27}$$

where x, y, and z are variables, while a, b, c, and d are control parameters, and t represents the step size. The phase diagram in Figure 6 shows that the system's trajectory is a disordered curve within a bounded region, characterized by a complex structure and no repetitive patterns, indicating a state of chaos.

The three-dimensional Lorenz chaotic model was proposed by meteorologist Edward Lorenz in 1963 and was initially used to describe atmospheric convection. Its equations are

$$\begin{cases} dx/dt = \rho(y - x) \\ dy/dt = rx - y - xz \\ dz/dt = xy - \beta z \end{cases} \tag{28}$$

x, y, and z are variables; ρ, r, and β are control parameters; and t represents the step size. The phase diagram in Figure 7 displays the dynamic trajectory of the system, with its classic three-dimensional "butterfly pattern" reflecting the complex evolutionary process. Starting from a single point, the trajectory continuously evolves and moves in the three-dimensional space.

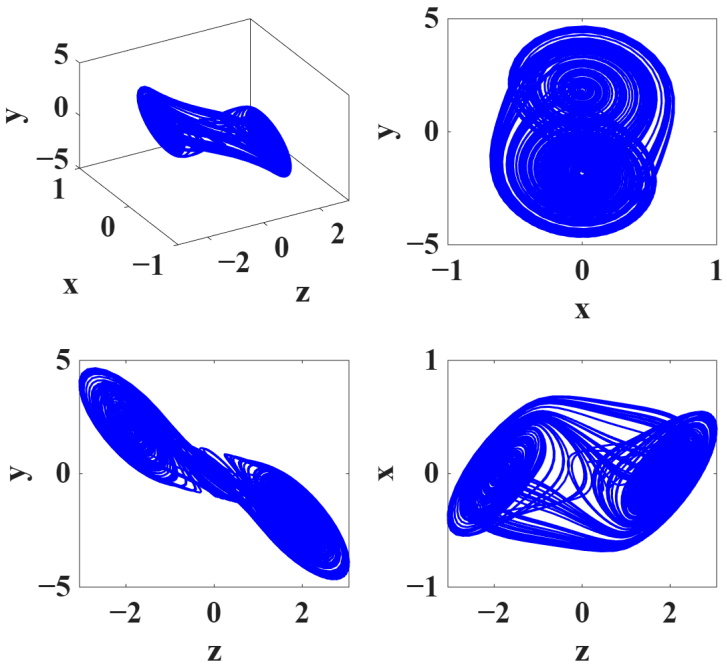


Figure 6. Phase diagram of Chua chaos model.

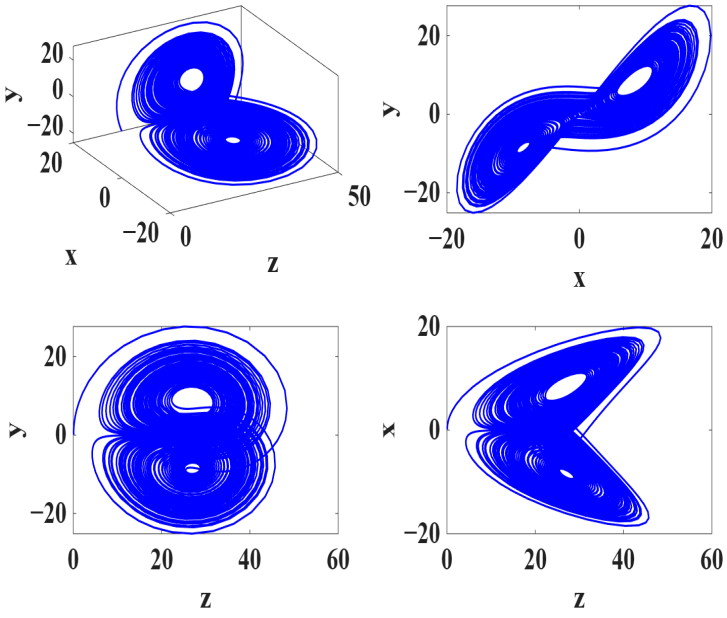


Figure 7. Phase diagram of Lorenz chaos model.

The Rössler three-dimensional chaotic model, proposed by mathematician Otto Rössler in 1976, is another classic example in chaos theory. Its equations are

$$\begin{cases} dx/dt = -wy - z \\ dy/dt = wx + \alpha y \\ dz/dt = \beta + z(x - \gamma) \end{cases} \tag{29}$$

where x, y, and z are variables; α, β, γ, and w are control parameters; and t represents the step size. Figure 8 shows the phase diagram of the Rössler chaotic model. The trajectory of the Rössler system often exhibits a "spiral" pattern, which demonstrates characteristics of chaos.

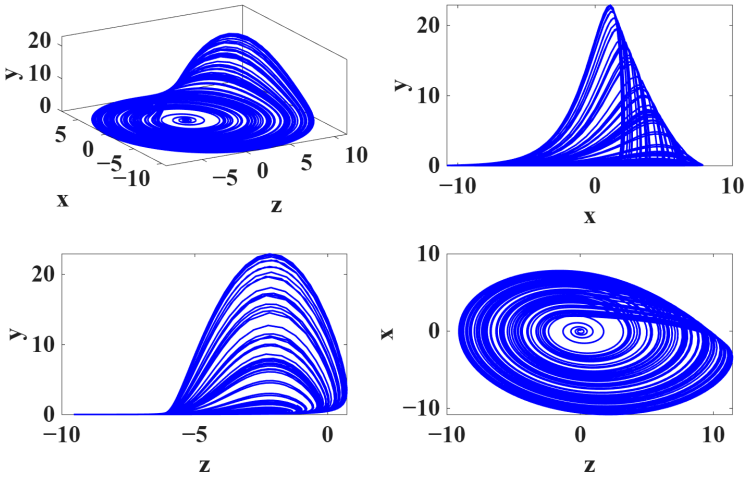


Figure 8. Phase diagram of Rossler chaos model.

Digital chaotic systems, as pivotal models in nonlinear dynamics, exhibit remarkable application value in the field of information security owing to their high sensitivity, complexity, and unpredictability. With continuous technological advancement, these systems are playing an increasingly vital role in data encryption, information protection, and secure communications, providing robust theoretical foundations and methodological guidance for the innovation of secure transmission systems.

5. Application of Several Technologies in Communication Systems

To further evaluate their effectiveness and applicability in engineering practice, this section will systematically examine the application performance of several key technologies in typical communication systems. By focusing on representative systems such as wireless communication, optical fiber communication, and radio-over-fiber (RoF) communication, it provides practical evidence and references for building next-generation railway communication systems with high performance, high reliability, and high security.

5.1. Introduction to Several Communication Systems

The preceding chapters have conducted an in-depth analysis of the fundamental principles of several DSP technologies. These technologies, as key techniques for enhancing the spectral efficiency, transmission reliability, and physical layer security of communication systems, are valuable for their excellent environmental adaptability and potential for cross-scenario deployment. For the complex railway communication system, deeply integrating these general-purpose technologies with railway-specific channel models, and service requirements is the essential path to achieving the upgrade of intelligent railway communication. This chapter will focus on three transmission media in the railway system—optical fiber communication, wireless communication, and RoF communication. It will systematically elaborate on practical application cases of the DSP technologies within these transmission media.

Optical fiber communication, with its large bandwidth and anti-electromagnetic interference properties, constitutes the "main artery" of the railway communication network. It mainly undertakes the large-capacity backhaul tasks among railway lines, base stations, and dispatching centers. Its transmission principle is shown in Figure 9.

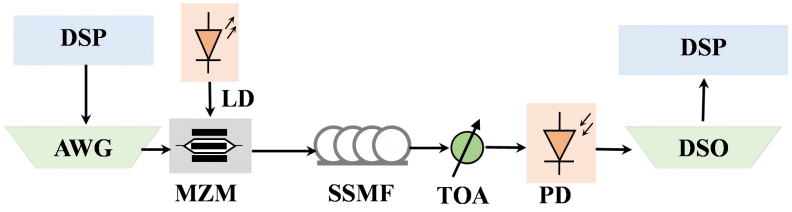


Figure 9. Principle of optical fiber communication system. (AWG: arbitrary waveform generator; MZM: Mach–Zehnder modulator; LD: Laser Diode; SSMF: standard single-mode fiber; TOA: Tunable Optical Attenuator; PD: Photodetector; DSO: Digital Storage Oscilloscope).

Wireless communication is a core technology supporting the railway system in achieving dynamic train-to-ground interaction, flexible station access, and ubiquitous sensing along the lines. When trains operate at speeds of up to 350 km/h or higher, continuous and seamless "train-to-ground communication" must be maintained through wireless base stations along the route. It mainly carries train operation control information, real-time status monitoring data, and passenger service information. VLC systems, a typical wireless communication technology, have demonstrated significant application potential in various fields in recent years due to their advantages, such as high bandwidth, absence of electromagnetic interference, and strong security. The transmission process is illustrated in Figure 10.

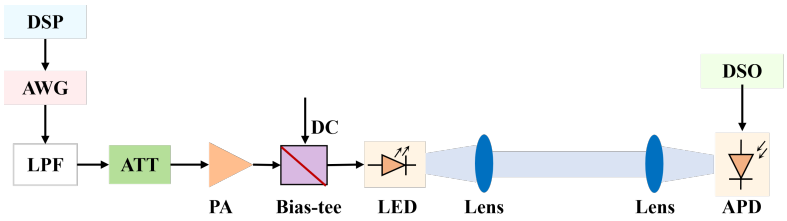


Figure 10. Principle of VLC system. (LPF: low-pass filter; ATT: Attenuator; PA: Power Amplifier; DC: direct current bias; LED: light-emitting diode; APD: Avalanche Photodetector).

RoF systems serve as a "bridge" integrating optical fiber and wireless technologies, playing a crucial role in large station yards and distributed coverage scenarios. They fully leverage the low-loss, high-bandwidth characteristics of optical fiber and the flexibility of wireless access, making them a core technology in fields such as 5G/6G mobile fronthaul, millimeter-wave communication, and intelligent transportation, as illustrated in Figure 11.

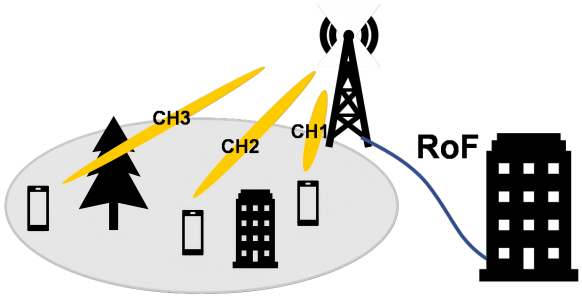


Figure 11. RoF system.

These DSP technologies demonstrate cross-scenario applicability and can be flexibly adapted to meet the transmission requirements of different systems. Analyzing the application of these technologies in typical communication scenarios will demonstrate how these technologies can break through the limitations of scenarios and provide continuous support for the various communication systems.

5.2. The Application of Precoding Technology in Communication Systems

In communication systems, precoding technology can be widely applied in optical fiber communication, wireless communication (taking visible light communication as an example), and RoF communication.

As shown in Figure 12a, the schematic diagram of signal transmission in an optical fiber system is illustrated. At the transmitter, the mapped signal undergoes precoding processing, followed by IFFT and CP addition. It is then modulated onto an optical carrier via an Mach–Zehnder modulator (MZM), transmitted through standard single-mode optical fiber (SSMF), and finally received by a photodiode (PD). Precoding effectively compensates for dispersion and nonlinearity. In the visible light communication system shown in Figure 12b, similar baseband processing is adopted. The signal is driven by a bias tee to an LED for transmission and is received by an APD. In the RoF system shown in Figure 12c, the signal is transmitted through the wireless link and the optical channel. Precoding technology can effectively improve transmission performance in different systems.

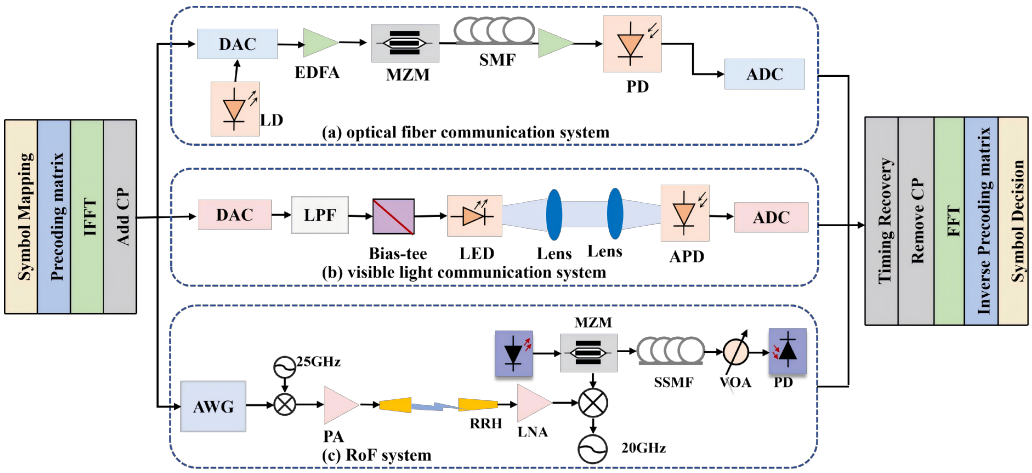


Figure 12. Transmission process of precoding in various communication systems. (**a**) Optical fiber communication system; (**b**) Visible light communication system; (**c**) RoF system.

Figure 13 shows the relationship between the PAPR and the complementary cumulative distribution function (CCDF) under different precoding techniques. The signals with precoding demonstrate a reduction in the PAPR compared with the original signals. This result verifies that precoding technology can effectively decrease the PAPR, mitigate frequency-selective fading, and thereby enhance the performance of communication systems.

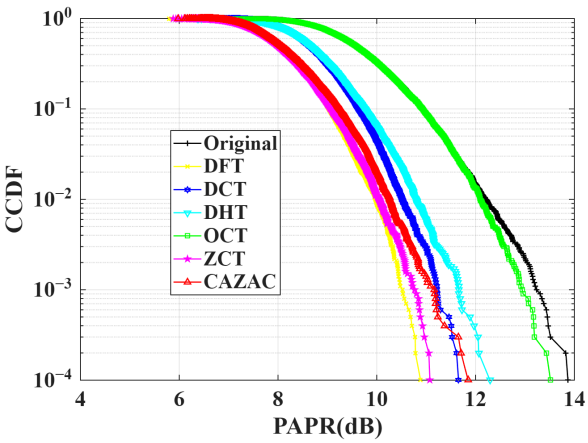


Figure 13. Relationship between PAPR and CCDF.

Figure 14 illustrates the relationship between sub-carriers and the SNR under different precoding techniques. The SNR of the original signal decreases with the increase in the sub-carrier index, while the application of precoding methods such as DFT and DCT results in a flattened SNR distribution. This demonstrates that precoding technology can effectively equalize the SNR, thereby enhancing system transmission reliability.

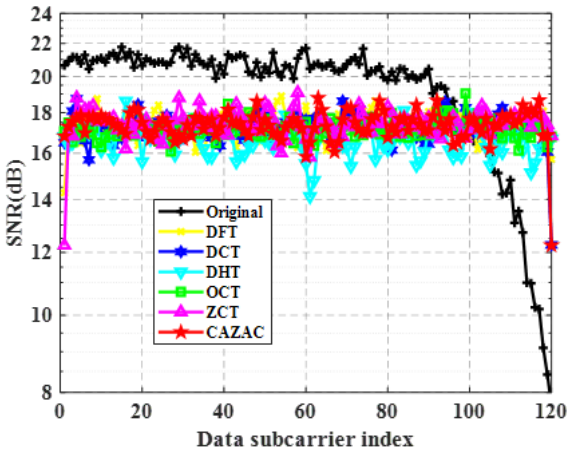


Figure 14. Relationship between sub-carrier index and SNR.

5.3. The Application of Index Modulation Technology in Communication Systems

Taking the application of index modulation technology in the RoF system as an example, Figure 15 shows the RoF principle block diagram. The system includes wireless and optical fiber channels: The signal is generated by an arbitrary waveform generator, and then, two intermediate frequency signals are upconverted into millimeter waves. After power amplification, they are transmitted through the antenna. At the receiver, after low-noise amplification and downconversion, the signal is converted into an optical signal by a Mach–Zehnder modulator. It is transmitted through SSMF and then converted back into an electrical signal by the PD for signal demodulation.

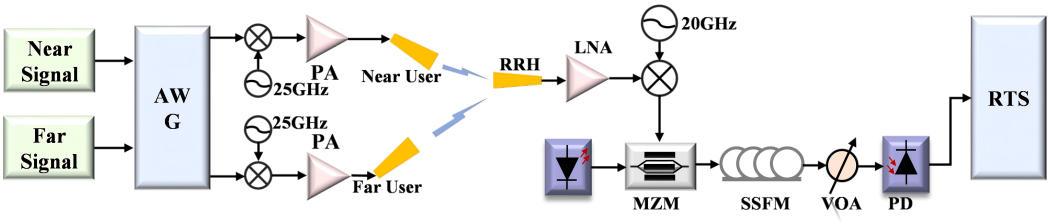


Figure 15. RoF communication system.

Herein, signals can be transmitted using IM-OFDM. To effectively distinguish signals from different users, it is necessary to maintain a fixed power ratio between any users to achieve optimal NOMA demodulation performance. However, maintaining this optimal power ratio is particularly challenging, especially in the uplink of wireless access networks: nearby users can receive higher power, whereas limited power is received by far-end users.

In this scheme, nearby users employ conventional OFDM for transmission, while distant users use IM-OFDM. Index modulation enables flexible power control through parameter adjustment. Table 6 provides a lookup table for different parameters, where N represents the number of sub-carriers per group and K denotes the number of activated sub-carriers per group. When $K = 3$, three sub-carriers of each group are activated, resulting in higher system power. Conversely, when $K = 1$, only one sub-carrier of each group is activated, leading to lower power. This demonstrates that adjusting IM parameters can

achieve a certain power ratio, which can be adapted based on the nearby users and the distant users to meet different requirements.

Table 6. Lookup table.

$N = 4, K = 3$			$N = 4, K = 2$			$N = 4, K = 1$		
Bits	**Index**	**Sub-Blocks**	**Bits**	**Index**	**Sub-Blocks**	**Bits**	**Index**	**Sub-Blocks**
$[0,0]$	1	$[0,s,s,s]$	$[0,0]$	1	$[s,0,0,s]$	$[0,0]$	1	$[s,0,0,0]$
$[0,1]$	2	$[s,0,s,s]$	$[0,1]$	2	$[s,s,0,0]$	$[0,1]$	2	$[0,s,0,0]$
$[1,0]$	3	$[s,s,0,s]$	$[1,0]$	3	$[0,0,s,s]$	$[1,0]$	3	$[0,0,s,0]$
$[1,1]$	4	$[s,s,s,0]$	$[1,1]$	4	$[0,s,s,0]$	$[1,1]$	4	$[0,0,0,s]$

5.4. The Application of Chaotic Encryption Technology in Communication Systems

Chaotic encryption technology utilizes the extreme sensitivity, ergodicity and quasi-random characteristics of chaotic systems to generate sequences suitable for data encryption, providing physical layer security for communication signals. This technology has been applied to various physical layer communication systems such as optical fiber communication, wireless communication, and radio-over-fiber communication and has been extensively studied and implemented.

Chaotic encryption technology demonstrates remarkable versatility, with its transmission principle being illustrated in Figure 16. Particularly in multi-carrier systems such as OFDM, the application of chaotic encryption is more diverse due to its parallel transmission structure and flexible resource allocation. The primary encryption locations include bit streams, constellation points, sub-carriers, and symbols. Each location has its unique encryption process and mathematical representation.

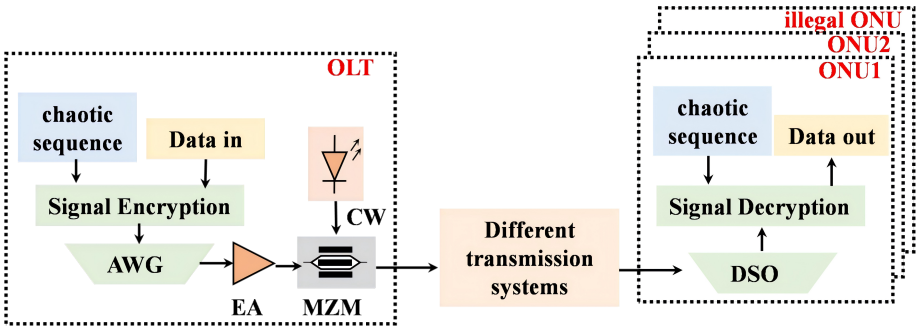


Figure 16. Transmission principle of a chaotic encryption system.

Bit stream encryption achieves security protection by performing mathematical operations between a chaotic sequence and the original bit stream. The process involves the following steps: Firstly, preprocess the chaotic sequence by steps such as quantization and binarization to convert it into a binary sequence. Then, perform a bitwise XOR operation between this sequence and the original bit stream. By using the reversible nature of the XOR operation, the receiver can decrypt the bit stream. Figure 17 illustrates the schematic diagram of this encryption principle.

The constellation points before encryption are shown in Figure 18a. Constellation point encryption is achieved by using chaotic sequences to control the rotation angles of constellation points. The chaotic sequence is preprocessed and mapped to the $(0, 2\pi)$ angle range. Each constellation point is then rotated by its corresponding angle to complete encryption, as shown in Figure 18b. Decryption is achieved at the receiver through inverse rotation.

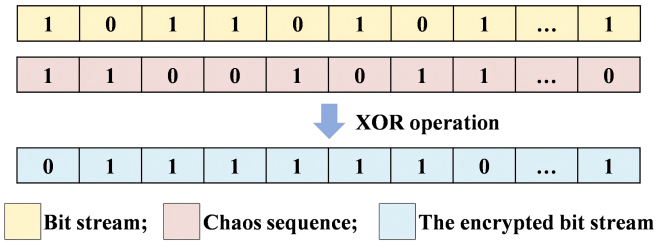


Figure 17. Bit stream encryption principle.

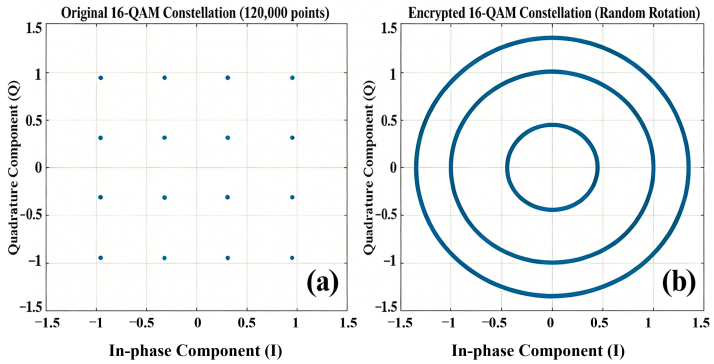


Figure 18. Principle of constellation point encryption. (**a**) Before encryption; (**b**) After encryption.

Similarly, sub-carrier encryption begins with the generation and processing of chaotic sequences, which is then used to alter the positions of sub-carriers or symbols, as illustrated in Figure 19a,b, respectively. One frame contains Q symbols, and each symbol has P subcarriers. Compared with traditional cryptographic encryption, this chaos-based physical layer encryption enables low-complexity real-time encryption and realizes unique security characteristics of the physical layer.

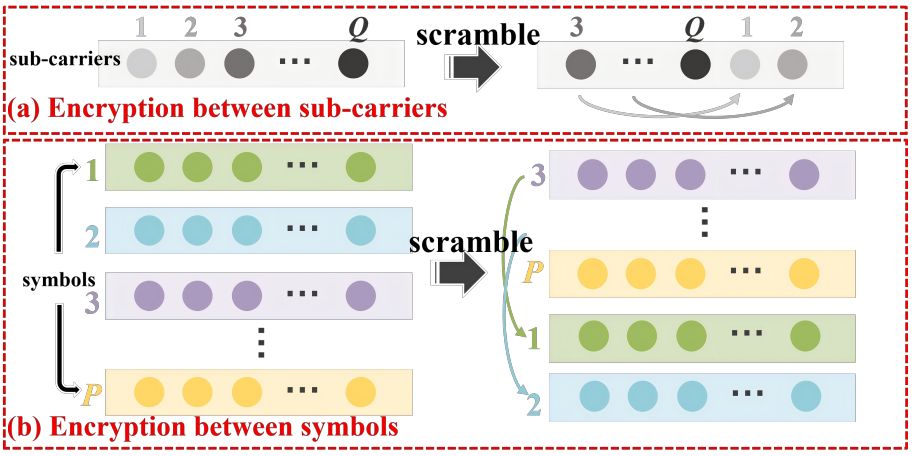


Figure 19. Sub-carrier and symbol encryption.

6. The Application Prospects of Several Technologies in Railway Transportation Systems

The development of intelligent and high-speed railways has placed higher demands on the speed, stability, and security of communication systems. Advanced digital signal processing technologies can achieve efficient, reliable, and intelligent information transmission in complex, dynamic, and interference-prone environments. The specific application prospects of several technologies in intelligent railway systems are as follows:

- Multi-carrier technology: Due to its high spectral efficiency and anti-multipath capability, it is suitable for high-capacity data transmission in high-speed railways.

By dividing sub-channels, it effectively mitigates the impacts of Doppler shift and time delay spread in complex railway environments. Its flexible resource allocation capability can meet differentiated requirements such as train control, passenger services, and video surveillance

- Precoding technology: To address the nonlinear distortion in railway communication, the precoding technology can compensate for frequency-selective fading, thereby improving signal quality. It can ensure the reliable transmission of train communication signals.
- Index modulation technology: As an emerging spectrum-efficient transmission scheme, IM transmits information by selecting different index numbers, thereby enhancing spectral efficiency. The index resources can be antennas, sub-carriers, time slots, etc. This technology is particularly suitable for massive data uploads in railway networks and efficient information exchange between trains and ground equipment.
- Chaotic encryption technology: It provides a novel solution for railway communication security by using the extreme sensitivity to initial conditions and unpredictability of chaotic systems, achieving security protection at the physical layer. It offers advantages such as a large key space, real-time performance, and high resistance to decryption, making it especially suitable for protecting critical data like train control information.

The application of these advanced digital signal processing technologies in intelligent railway systems will collaboratively drive the development of railway communication systems toward greater efficiency, reliability, intelligence, and security, demonstrating broad application prospects.

More importantly, the value of these technologies is not merely additive; their deep integration will foster a system-level capability leap that achieves a "1 + 1 > 2" effect. With the deployment of 5G-R and future 6G-R in railway systems, the synergistic innovation of these technologies will play an even greater role. The incorporation of new technologies such as artificial intelligence and edge computing will further drive the intelligent development of railway communications. From a long-term technological evolution perspective, the integration of emerging technologies with these key technologies will bring breakthroughs to railway communication systems, supporting cutting-edge applications.

Overall, digital signal processing technologies such as multi-carrier, precoding, index modulation, and chaotic encryption hold broad application prospects in railway systems. Their continuous innovation will propel railway communications toward higher speeds, reliability, and security, providing solid support for the construction of intelligent railways.

7. Conclusions

This review systematically demonstrates the synergistic application potential of technologies such as OFDM, precoding, index modulation, and chaotic encryption in high-speed railway communication systems. The review transcends the boundaries between traditional communication theory and railway engineering applications, proposing a collaborative design framework tailored to complex scenarios. By deeply integrating digital signal processing techniques from optical communications with the highly dynamic channel characteristics unique to railways, this paper reveals the relationships among index modulation for enhancing spectral efficiency, precoding for suppressing multipath interference, and chaotic encryption for establishing physical layer security. It further validates the feasibility of achieving system performance improvements under high-speed mobility conditions.

However, several challenges remain to be addressed, such as balancing algorithmic real-time performance with system complexity and verifying robustness in extreme scenarios. Looking ahead, the field could advance in the following directions:

- Intelligent Dynamic Resource Management: Achieve real-time channel state prediction and adaptive resource allocation by leveraging machine learning and deep learning techniques, thereby reducing system overhead and enhancing adaptability in extreme scenarios.
- Integrated Communication-Sensing-Computing Network Architecture: Develop a railway-specific 6G network architecture that deeply integrates communication, sensing, and edge intelligence.
- Standardization and Cross-System Interoperability: Focus on mechanisms for cross-system handover, spectrum sharing, and collaborative management, promoting the evolution of railway communication systems toward greater openness and standardization.

This review lies not only in its analysis and integration of multiple technologies but also in its proposal of a development path for next-generation railway communication systems. This research study provides insights for scholars in the field to advance from theoretical validation to engineering implementation. And it indicates that integrated innovation and system optimization will be the main breakthrough for enhancing railway communication performance in the future.

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