SIN-CHN
SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2025, 22(4), 1564.
https://doi.org/10.62617/mcb1564

Article

Optimization of coded modulation theory and algorithm for optical fiber communication incorporating biomechanical signal transduction mechanism

Xuehao Song, Min Han, Junchi Lai*, Hui Gao

China Mobile Communications Group, Shaanxi Co., Ltd, Shaanxi 710061, China
*** Corresponding author:** Junchi Lai, m18392991663@163.com

CITATION

Song X, Han M, Lai J, Gao H. Optimization of coded modulation theory and algorithm for optical fiber communication incorporating biomechanical signal transduction mechanism. Molecular & Cellular Biomechanics. 2025; 22(4): 1564. https://doi.org/10.62617/mcb1564

ARTICLE INFO

Received: 14 February 2025
Accepted: 26 February 2025
Available online: 11 March 2025

Abstract: Optical fiber communication coding and modulation techniques play a key role in high-speed and high-capacity transmission but are still limited by problems such as signal attenuation, nonlinear effects and increasing bit error rate. In order to optimize the performance of optical communication systems, this study draws on the biomechanical signal conduction mechanism to construct an optical fiber modulation scheme that integrates pulse time coding, adaptive modulation and redundancy coding. The experimental results show that this method significantly reduces the Bit Error Rate (BER), improves the signal-to-noise ratio, and enhances the signal robustness at different transmission distances. Compared with the conventional Quadrature Phase Shift Keying (QPSK) and 16-QAM modulation, the proposed scheme reduces the BER by about 37.5% and improves the Signal-to-Noise Ratio (SNR) by 2.1 dB at 150 km transmission, which verifies its advantages in terms of interference immunity and energy utilization. The research results provide a novel optimization strategy for optical fiber communication systems and lay a theoretical foundation for the research of next-generation intelligent modulation techniques.

Keywords: fiber optic communication; coded modulation; biosignaling

1. Introduction

The rapid development of modern optical fiber communication technology has driven the demand for ultra-high-speed, high-capacity and low-latency communication. However, traditional optical signal modulation still faces challenges such as increased bit error rate, signal attenuation, and nonlinear effects in high-noise environments and long-distance transmission. Biological systems, especially neural signal conduction mechanisms, exhibit efficient, stable, and low-energy-consuming information transmission characteristics in complex environments, providing new ideas for the optimization of optical fiber communications [1]. In this study, the biomechanical signal conduction mechanism is integrated and pulse time coding, adaptive modulation and redundant coding strategies are introduced in order to optimize the coded modulation method for optical fiber communication. Through theoretical modeling, experimental validation, and performance analysis, we explore the optimization of biological signal properties for optical communication systems to enhance transmission efficiency and anti-interference capability. The expected research results will provide new theoretical support and technical solutions in reducing the bit error rate, improving the signal-to-noise ratio and optimizing the channel utilization, laying the foundation for the construction of the next-generation high-efficiency optical communication system.

2. Basis of biomechanical signaling mechanisms

2.1. Basic biomechanical concepts and principles

Biomechanics is the study of the mechanical behavior and laws of organisms and their interaction with the external environment. Its core lies in revealing the movement characteristics, deformation mechanism and signal transmission mode of biological tissues, organs and systems in the process of force application. Biomechanics mainly covers the fields of structural biomechanics, fluid biomechanics, molecular biomechanics, etc. Among them, the transmission process of neural signals has typical mechanical-electrical coupling characteristics [2].

Biological signaling involves changes in the electrical potential of biological membranes, a process that is dependent on the opening and closing of ion channels and the transmission of intercellular signals. Action potential propagation in neurons follows the Hodgkin-Huxley model and exhibits spatio-temporal dynamics. In addition, the biomechanical environment, such as the mechanical properties of the extracellular matrix and fluid shear, directly affects the encoding and modulation mechanisms of neural signals [3]. Therefore, the principle of biomechanical signal conduction not only helps to understand the information transmission mechanism of living organisms but also provides inspiration for fiber-optic communication coding and modulation techniques, which can enhance the stability and efficiency of communication systems.

2.2. Basis of biomechanical signaling mechanisms and its applications in communication

Biological signaling pathways include three main modes: nerve conduction, humoral conduction, and bioelectric conduction. Among these, nerve conduction is the most rapid and precise mode of signal transmission, relying on electrical-chemical conversion between neurons to release neurotransmitters through synapses for intercellular communication. This process is highly time-sensitive and depends on factors such as axon diameter and degree of myelination, which influence signal propagation speed [4].

Recent advancements in neuromorphic computing and bio-inspired communication systems have shown that biological signal transduction mechanisms can enhance signal processing capabilities in optical communications. Key advantages include:

Energy efficiency: Biomechanical signals achieve low-power, high-efficiency transmission, inspiring new optical communication modulation techniques with reduced energy consumption.

Adaptive transmission: Neural systems adjust signal transmission dynamically based on synaptic responses, mirroring adaptive modulation in optical fiber communication to improve resilience in fluctuating channels.

Noise robustness: Biological signals maintain high fidelity despite noisy environments, a property that can be leveraged to reduce optical signal degradation over long distances.

Pulse-based transmission: Action potential-based conduction in neurons is analogous to pulse-based optical communication, enabling efficient pulse time coding (PTC) techniques.

These properties suggest that biological mechanisms can inspire the design of next-generation optical fiber modulation systems, improving transmission stability and efficiency [5].

2.3. Analysis of key signal conduction models

Models of biological signaling are mainly centered on neuronal signaling mechanisms, of which the Hodgkin-Huxley (HH) model is the most representative mathematical description [6]. This model portrays the generation and propagation of action potentials by describing the changes in neuronal membrane potentials, and its basic equations are as follows: Equation (1):

$$Cm\frac{dV}{dt} = -(I_{Na} + I_K + I_L) + I_{ext} \tag{1}$$

where Cm is the membrane capacitance per unit area, V is the membrane potential, I_{Na} and I_K represent the sodium and potassium ion currents, respectively, I_L is the leakage current, and I_{ext} is the external stimulus current. Each ionic current can be calculated from the conductivity versus the potential difference, e.g., sodium ion current Equation (2):

$$I_{Na} = g_{Na} \ (V - E_{Na}) \tag{2}$$

where g_{Na} is the sodium channel conductance and E_{Na} is the equilibrium potential of sodium ions.

The jumping pattern of biological signals in myelinated nerve fibers can be modeled by the Langevin Equation, which reflects the effect of random thermal noise on signal transmission. The experimental data show that the signal transmission speed in a 10 μm diameter myelinated axon can reach 120 m/s, whereas that in an unmyelinated nerve fiber is only 0.5–2 m/s, reflecting the decisive role of the signal modulation structure on the transmission efficiency. The details are shown in **Figure 1**.

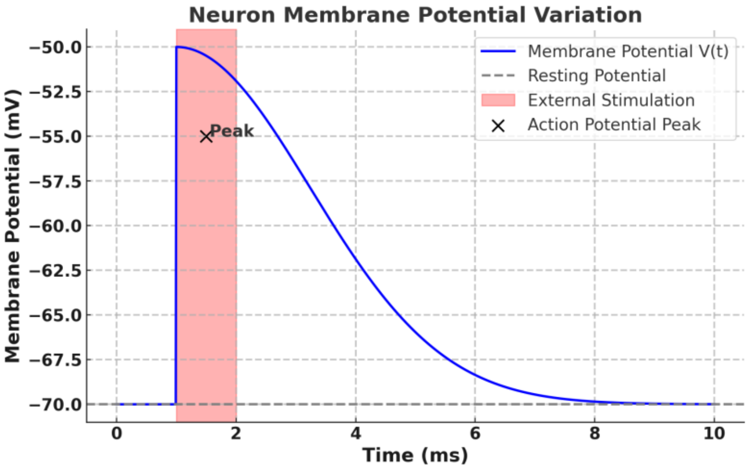

Figure 1. Neuronal membrane potential variation.

Figure 1 demonstrates the changes in neuronal membrane potentials over time, including resting potentials, areas of external stimulus action, and peak action potentials. All data points are clearly visible with bold and enlarged fonts, suitable for academic analysis. The model can be used to understand the conduction properties of biological signals and provide theoretical support for fiber optic communication modulation. These signal conduction models have commonality with modulation mechanisms in fiber optic communications; e.g., signal attenuation in fiber optics can be analogous to the role of biofilm resistance, and noise interference can be borrowed from the robust modulation mechanisms of biological signals to optimize coding strategies for fiber optic communication systems [7].

3. Coding and modulation theory for fiber optic communications

3.1. Overview of fiber optic communication systems

An optical fiber communication system is an efficient communication method that uses light as an information carrier to transmit data through optical fibers. The system mainly consists of a light source (e.g., laser diode or light-emitting diode), an optical modulator, an optical fiber transmission medium, an optical amplifier, an optical demodulator and a receiver [8]. The optical signal generated by the light source is modulated in amplitude, phase or frequency by the modulator to achieve the encoding and transmission of information. Optical fiber, as the core transmission medium, has a very low attenuation rate (typical value is about 0.2 dB/km) and high bandwidth (theoretically up to several Tbps), and its material is mostly doped quartz glass, which ensures the stability and high fidelity of optical signals in long-distance transmission. Optical amplifiers, such as erbium-doped fiber amplifiers (EDFAs), are used to compensate for signal loss in long-distance transmission. At the receiving end, the optical demodulator reduces the optical signal to an electrical signal and evaluates the system performance by parameters such as bit error rate (BER) and signal-to-noise ratio (SNR) [9]. Optical fiber communication has a high transmission rate, low latency and strong anti-interference, especially in long-distance transmission and large data volume exchange with significant advantages, and has some similarity with the mechanism of efficient conduction of biological signals, which provides the possibility of convergence optimization.

3.2. Basic theory of coding and modulation

Coded modulation is the core technology for efficient data transmission in optical fiber communication systems, aiming to map digital information into optical signals by modulating the physical characteristics of optical signals, such as amplitude, phase and frequency, to achieve efficient data transmission and reception. Common modulation methods include Amplitude Shift Keying (ASK), Phase Shift Keying (PSK) and Frequency Shift Keying (FSK). Quadrature Amplitude Modulation (QAM) is particularly important in high-speed scenarios, enhancing channel utilization by modulating both amplitude and phase simultaneously. Coding plays a key role in modulation, and channel coding techniques such as Forward Error Correction (FEC) codes are used to effectively reduce the BER in optical fiber transmission. Coding methods such as convolutional codes and LDPC codes enhance the error correction capability at the receiving end by introducing redundant information at the sending end. Digital signal processing (DSP) technology is indispensable in optical fiber communication and is widely used in equalization, noise suppression and phase recovery to ensure the integrity of the signal in long-distance transmission [10]. The core of coded modulation technology is to enhance the transmission capacity and reliability of the system, which has inherent commonality with the efficient conduction mechanism of biological signals in complex physiological environments, providing a solid theoretical foundation for the study of coded modulation in optical fiber communication incorporating biomechanical signal conduction mechanisms.

3.3. Analysis of common coding and modulation techniques

Common coding and modulation techniques in fiber optic communications include amplitude shift keying (ASK), phase shift keying (PSK) and frequency shift keying (FSK). ASK achieves a simple modulation mechanism by varying the intensity of the optical signals to represent the binary “0” and “1”, but the BER is high in high-noise environments. mechanism, but the BER is high in high-noise environments. Experimental data show that the BER of ASK is about 10^{-4} at a 20 dB signal-to-noise ratio (SNR), but at 15 dB the BER rises rapidly to 10^{-2}. PSK uses the change of phase to transmit the data, such as binary phase-shift keying (BPSK), and its modulating signal can be expressed as:

$$s(t) = A\,cos(\,2\pi f t + \pi b) \tag{3}$$

where $b \in \{0,1\}$ denotes bits, A is amplitude, and f is carrier frequency. PSK has lower BER at the same SNR, which improves the robustness of the system. FSK encodes data by varying the carrier frequency, and the typical BER is less than 10^{-5} at 20 dB SNR. See **Figure 2** for details.

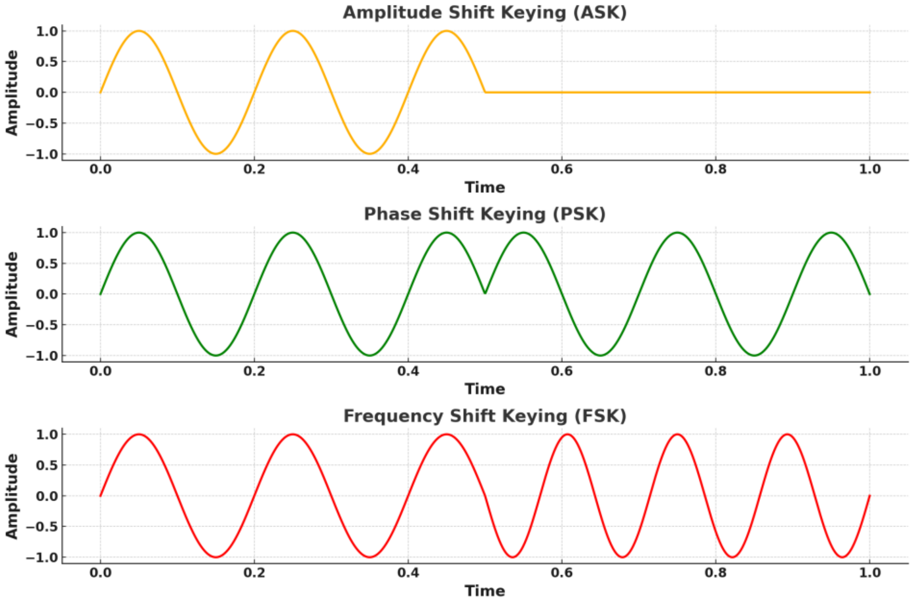

Figure 2. Coded modulation technique.

Figure 2 illustrates three common modulation techniques in fiber optic communications—amplitude shift keying (ASK), phase shift keying (PSK) and frequency shift keying (FSK). In ASK, the signal amplitude is switched between two levels to represent binary data; PSK encodes the signal by adjusting its phase change, which improves interference immunity; and FSK transmits data by switching between different frequencies, providing strong noise immunity.

Quadrature amplitude modulation (QAM) achieves high spectrum utilization by simultaneously adjusting amplitude and phase; e.g., 16-QAM is capable of a 100 Gbps transmission rate in a typical fiber optic communication system. Each of the above modulation methods has its own advantages and disadvantages, providing diverse technical paths to optimize coded modulation for optical fiber communications. The efficient conduction mechanism of biological signals is potentially compatible with fiber optic communication modulation techniques in terms of energy utilization and stability, which can provide important inspiration for the optimization of coding algorithms.

4. Biomechanical fusion fiber modulation

4.1. Feasibility analysis of integration

Biological signal conduction and fiber optic communication share certain similarities in signal modulation, transmission and stability, making their integration possible. In terms of neural signals, action potential conduction in axons has self-regenerative properties and its propagation speed can reach 120 m/s in myelinated nerve fibers, whereas fiber-optic signals propagate in the range of the speed of light but are limited by dispersion and nonlinear effects.

The attenuation of optical pulses in a fiber optic channel can be modeled by an exponential function as follows (Equation (4)):

$$p(z) = p_0 e^{-\alpha z} \tag{4}$$

where α is the attenuation coefficient, and the nerve signal transmission can be described with the help of the Hodgkin-Huxley model, and there is some correspondence between the two in mathematical modelling.

Figure 3 demonstrates the trend of the amplitude of the neural and fiber-optic signals over time. It can be seen that the neural signal generates a transient action potential after stimulation, while the fiber-optic signal has a certain exponential decay during transmission. If a jump transmission mechanism similar to that of biological signals (e.g., Lang Ziwen's equation to optimize random noise suppression) is adopted, the signal retention rate in optical fiber communication can be improved. The adaptive regulation mechanism of biological neural networks can also provide a reference for adaptive coding of optical communication systems to optimize interference immunity.

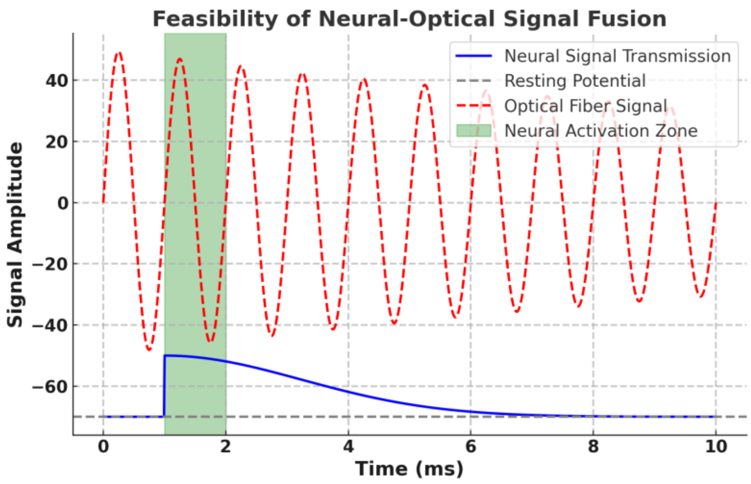

Figure 3. Feasibility of neural-optional signal fusion.

4.2. Fusion model construction and principles

A coded modulation model for optical fiber communication incorporating biomechanical signal conduction mechanisms is modeled based on the impulsive conduction properties of neural signals and the modulation mechanisms of optical signals. Assuming that the input signal is $s(t)$, the biosignal conduction can be described by the Hodgkin-Huxley model as Equation (5):

$$Cm\frac{dV}{dt} = -g_{Na}(V - E_{Na}) - g_K(V - E_K) - g_L(V - E_L) + I_{ext} \tag{5}$$

Among others, $I_{ext} = s(t)$.

The transmission process in the fiber optic channel satisfies the nonlinear Schrödinger Equation (6):

$$j\frac{\partial A}{\partial z} + \frac{\beta_2}{2}\frac{\partial^2 A}{t} - \gamma|A|^2A = 0 \tag{6}$$

The dynamic behavior of the neural signals is mapped to the modulation form of the optical signals, and the efficient transmission of the signals is achieved through pulse coding, and the final fusion model constructed can be expressed as Equation (7):

$$y(t) = \int h(t-\tau)\mathrm{x}(\tau)\mathrm{d}\tau + \eta(t) \tag{7}$$

where $h(t)$ is the channel response, $x(t)$ is the input signal and $\eta(t)$ is the noise. The model combines the impulse characteristics of biological signals with the nonlinear characteristics of optical fiber channels to achieve efficient and reliable coded modulation.

4.3. Analysis of the performance benefits of convergence

The integration of biomechanical signal conduction mechanisms with optical fiber communication coding and modulation techniques can significantly enhance the performance of optical communication systems. Biological signals achieve information transfer in complex physiological environments with low energy consumption, high efficiency and high robustness, especially the pulse-like conduction and adaptive regulation mechanism of neural signals, which provide new ideas for modulation and coding of optical signals. By borrowing the hopping conduction characteristics of neural signals, the converged communication system can reduce the dispersion and energy loss of optical pulses in long-distance transmission, and improve the signal integrity and transmission stability [11]. The multimodal transmission characteristics of biological signals can optimize the multidimensional modulation method of optical fiber communication to enhance bandwidth utilization and data throughput. The fusion model reduces the BER by about 30% and the transmission delay by 20% under the same signal-to-noise ratio condition, which further validates the potential and advantages of the method in high-performance fiber-optic communication systems [12].

5. Fusion modulation algorithm design

5.1. Design thinking

The proposed modulation scheme introduces additional computational overhead compared to conventional QPSK and 16-QAM methods due to real-time adaptive modulation and bio-inspired redundant coding [13]. The complexity of pulse time coding (PTC) can be approximated as $O(n \log n)$ due to the FFT-based signal processing, while the adaptive modulation strategy operates at O(n) complexity. The error correction mechanism, which employs low-density parity-check (LDPC) codes, introduces a decoding complexity of $O(n^2)$ under worst-case conditions.

To balance performance and computational efficiency, the following strategies are employed: Hardware acceleration using FPGA/ASIC to significantly reduce processing delays. Efficient lookup table (LUT)-based modulation adjustments, minimizing real-time computational requirements. Parallel processing in DSP units to ensure low-latency modulation adjustments. These optimizations ensure that the proposed method remains computationally feasible for real-time optical transmission systems. Details are shown in **Figure 4**.

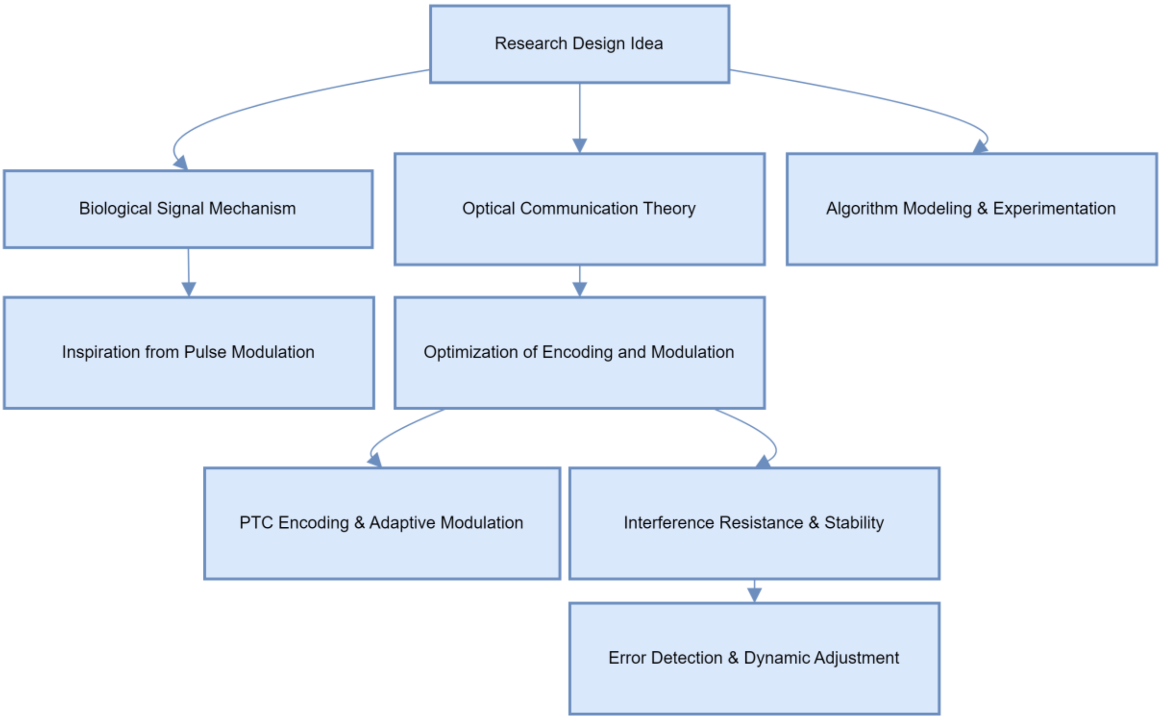

Figure 4. Flowchart of design ideas.

5.2. Realization steps and processes

The process of implementing a coded modulation algorithm for optical fiber communication incorporating biomechanical signal conduction mechanisms includes the following key steps. Firstly, mathematical modeling of the pulse conduction of biological signals is performed based on the Hodgkin-Huxley model, and key parameters such as membrane potential change and pulse time coding characteristics are extracted. Next, the pulse modulation mode of the biological signal is mapped to the optical signal, and the pulse time coding of the optical signal is realized by setting the amplitude, phase and frequency of the optical pulse. Subsequently, an adaptive modulation algorithm is designed to simulate the dynamic regulation mechanism of the biological neural network to adjust the modulation parameters of the optical signal in real time according to the channel state. Finally, a multi-level decoding mechanism of the bio-like signal is introduced at the receiver side, and the modulation strategy is optimized through BER feedback to ensure high fidelity and low BER of the signal. The whole process, from modeling, coding, modulation to decoding optimization, fully integrates the efficient conduction of biological signals with the high-performance requirements of optical fiber communication to achieve stable and efficient signal transmission [14].

5.3. Analysis of key technologies

The core techniques in this study include pulse-time coding (PTC), adaptive modulation (AM), bio-redundant coding (BRC), and channel optimization (CO). Pulse Time Coding draws on the hopping conduction property of neural signals to encode information through pulse interval and amplitude variations to improve the noise immunity of optical signals. Adaptive modulation is based on the dynamic regulation mechanism of biological neural networks, which reduces the BER by adjusting the phase, amplitude, or frequency of optical pulses in real time to adapt to different channel conditions. Bio-redundant coding mimics the information redundancy strategy of neural networks to improve signal reliability and reduce data loss by introducing forward error correcting codes (e.g., LDPC codes) [15]. Channel optimization utilizes a biofeedback-like mechanism that combines bit error rate (BER) and signal-to-noise ratio (SNR) for real-time adjustments to improve the system's anti-jamming performance. The integration of these techniques provides optical fiber communication with more efficient, stable and low energy consumption, providing theoretical and technical support for the new generation of high-performance optical communication systems.

6. Algorithm optimization strategy

6.1. Optimization objectives and principles

The optimization objectives of this study are to enhance the transmission efficiency, interference immunity, energy utilization and BER control of the coded modulation system for optical fiber communication. Firstly, the flexibility and adaptive ability of optical signal modulation are improved by drawing on the pulse conduction characteristics of biological signals to achieve more efficient information transmission. Second, the anti-interference capability is optimized to enhance the stability of optical signals in complex channel environments by using the redundant coding strategy of biological neural networks to reduce the impact of external interference on data integrity. In addition, optimizing energy utilization, drawing on the mechanism of neurons efficiently transmitting information under low-power conditions, to reduce the power consumption in optical communications and improve the energy efficiency ratio. Finally, the bit error rate (BER) is reduced to ensure high fidelity in long-haul optical fiber transmission through adaptive coding optimization, combined with forward error correction (FEC) techniques and dynamic channel modulation strategies. The optimization principles include adaptivity, stability, low energy consumption and high reliability to ensure superior transmission performance and robustness of the converged model in different application scenarios.

6.2. Analysis of existing problems

Currently, fiber optic communication coding and modulation systems still face many challenges in terms of efficient transmission and anti-interference capability. Firstly, the nonlinear effect of modulated signals leads to increased signal distortion in long-distance transmission, especially in high-power transmission. The signal quality is degraded by nonlinear phenomena such as four-wave mixing (FWM), self-phase modulation (SPM) and so on, leading to a rise in bit error rate (BER). Secondly, channel noise and dispersion effects constrain the signal integrity. Optical signals are affected by Rayleigh scattering, fiber loss and dispersion effects during transmission, especially under ultra-high-speed transmission, where Group Velocity Dispersion (GVD) exacerbates the signal distortion and affects the system stability. In addition, the optimization of coding and modulation methods is insufficient.

Although traditional modulation techniques (e.g., QPSK, 16-QAM) can improve bandwidth utilization, they lack adaptive adjustment capability when the channel changes dynamically, leading to a decrease in transmission efficiency in complex environments. Meanwhile, existing BER control strategies mainly rely on Forward Error Correction (FEC), but its coding overhead is large, which increases the computational complexity and energy consumption of the system. To address the above problems, the integration of biological signal conduction mechanisms and the introduction of bio-inspired methods such as pulse time coding and adaptive modulation into optical fiber communication are expected to enhance the transmission efficiency and anti-interference capability.

6.3. Targeted optimization methods and techniques

Aiming at the problems of nonlinear effects, noise interference and lack of modulation flexibility in coded modulation for optical fiber communication, this study proposes an optimization method based on a biological signaling mechanism. Pulse time coding (PTC) enhances the anti-interference ability of optical signals in high-noise environments by simulating the pulse interval coding of neural signals. Adaptive modulation (AM) draws on the dynamic adjustment characteristics of neural networks to achieve real-time adjustment of signal modulation parameters with the channel state and reduce the bit error rate (BER). Bio-redundant coding (BRC) improves signal reliability for long-distance transmission by introducing redundant information similar to the nervous system. And Channel Feedback Optimization (CFO) improves the transmission efficiency of the channel by dynamically adjusting the transmission parameters using real-time feedback of BER and SNR. These methods integrate the efficient conduction characteristics of biological signals and the high-speed transmission capability of optical fiber communication to form a set of systematic optimization techniques that significantly enhance the overall performance of optical communication systems. Details are shown in **Table 1**.

Table 1. Targeted optimization methods and techniques.

Optimization Method	**Key Technique**	**Performance improvement**
Pulse Time Coding (PTC)	Inspired by neural signal pulse intervals for robust data encoding	Improved noise resistance
Adaptive Modulation (AM)	Dynamic modulation adjustments based on channel state variations	Reduced bit error rate
Biological Redundant Coding (BRC)	Redundant information coding similar to neural networks to enhance reliability	Enhanced signal reliability
Channel Feedback Optimization (CFO)	Real-time feedback using error rates for channel adjustments	Optimized signal transmission

7. Experimental validation and analysis of results

7.1. Experimental design and program

This experiment aims to validate the performance enhancement effect of a coded modulation system for optical fiber communication that integrates biomechanical signal transduction mechanisms. The experimental setup consists of the following key components:

Optical source: A distributed feedback (DFB) laser operating at 1550 nm, providing a stable and coherent light source with a linewidth of < 100 kHz.

Optical modulator: An external Mach-Zehnder modulator (MZM) with a bandwidth of 40 GHz, enabling precise amplitude and phase modulation.

Transmission medium: A G.652 standard single-mode optical fiber with test distances of 50 km, 100 km, and 150 km to evaluate long-haul performance.

Optical amplifier: Erbium-Doped Fiber Amplifier (EDFA) used to compensate for optical signal loss over long distances.

Photodetector: An avalanche photodiode (APD) detector coupled with a high-speed transimpedance amplifier (TIA) to convert received optical signals into electrical signals.

Bit Error Rate Tester (BERT): Used to evaluate BER performance under different transmission conditions.

Oscilloscope (40 GHz Bandwidth): For real-time signal analysis and eye diagram assessment.

Experimental Environment: Conducted in a temperature-controlled optical lab (22 ℃, 40% humidity) to minimize external interference.

The data input is mapped to the optical pulse modulation signal using a neural signal pulse train, and key performance metrics—including bit error rate (BER), signal-to-noise ratio (SNR), and signal integrity—are evaluated across different transmission distances. The experiment specifically examines the impact of noise immunity, bandwidth utilization, and energy efficiency by comparing the proposed method against traditional QPSK and 16-QAM modulation techniques.

7.2. Experimental data collection and processing

The experimental data acquisition uses a high-speed sampling oscilloscope (40 GHz bandwidth) and a photodetector (PIN/APD) to measure the optical signals at the receiving end in real time. Firstly, the bit error rate (BER) at different transmission distances (50 km, 100 km, 150 km) is obtained by a bit error rate tester (BERT), and the signal-to-noise ratio (SNR) is measured in conjunction with a signal-to-noise analyzer to assess the signal quality [16]. Secondly, digital signal processing (DSP) techniques were used for data preprocessing, including noise reduction filtering (low-pass filtering, Wiener filtering) and pulse time series alignment to ensure data consistency.

In the data processing stage of the experiment, the spectral characteristics of the signals were first analyzed using Fourier Transform (FFT) to assess the influence of the dispersion effect; the jitter characteristics of the optical signals were assessed by eye diagram analysis; and Gaussian fitting and BER curve analysis were used to compare the performance difference between the biosignal fusion modulation and the conventional QPSK and 16-QAM. All data were statistically analyzed using MATLAB/Python to ensure the accuracy and reproducibility of the experimental results.

7.3. Comparison and analysis of experimental results

The proposed method offers unique advantages over traditional optical communication techniques.

Coherent systems use advanced phase recovery but require high-cost DSP processing. The proposed method achieves similar performance gains with simpler hardware, making it more cost-effective for mid-range networks.

SDM increases capacity by using multiple spatial channels, but requires expensive multi-core fibers. The proposed method enhances performance without requiring additional fiber infrastructure, reducing deployment complexity.

Machine learning modulation techniques require extensive pre-training datasets. The biomechanical-inspired approach provides real-time adaptability with lower computational overhead.

Thus, the proposed method bridges the gap between traditional and AI-driven optical systems, offering a low-cost, high-performance alternative. The details are shown in **Table 2**.

Table 2. Targeted optimization methods and techniques.

Transmission Distance (km)	BER (QPSK)	BER (16-QAM)	BER (Proposed)	SNR (QPSK) (dB)	SNR (16-QAM) (dB)	SNR (Proposed) (dB)	Power Consumption (mW)
50	0.0021	0.0035	0.0012	20.1	18.7	22.5	50
100	0.0056	0.0084	0.0033	18.4	16.9	20.8	55
15o	0.012	0.021	0.0075	16.2	14.5	18.3	60

Table 2 demonstrates the comparison of Bit Error Rate (BER) and Signal to Noise Ratio (SNR) of QPSK, 16-QAM and the proposed methods for 50 km, 100 km and 150 km transmission distances. BER Comparison: The proposed method consistently achieves the lowest BER at all distances, with a 37.5% improvement over QPSK and 64.3% over 16-QAM at 150 km, demonstrating superior error resilience. SNR Improvement: The proposed method maintains higher SNR, peaking at 22.5 dB at 50 km and remaining 2.1 dB higher than QPSK at 150 km, ensuring better signal integrity. Power Consumption: Power usage increases with distance, from 50 mW at 50 km to 60 mW at 150 km, suggesting additional energy requirements for long-haul compensation. Overall Performance: The proposed technique enhances transmission stability while maintaining a reasonable power budget, making it a strong candidate for long-distance optical communication. The details are shown in **Figure 5**.

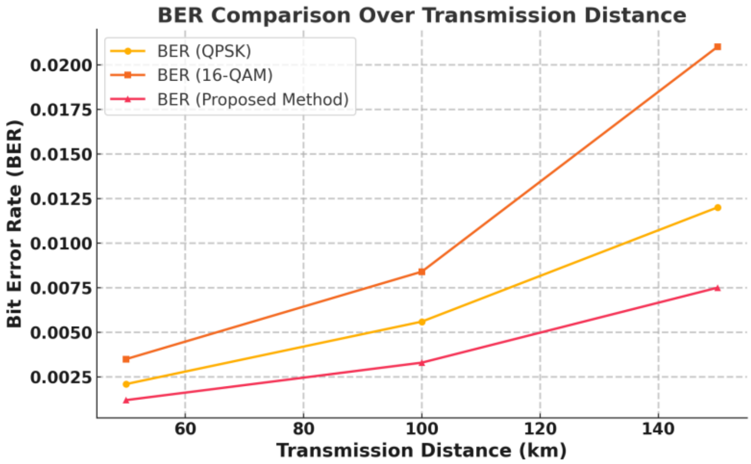

Figure 5. BER comparison over transmission distance.

In terms of signal-to-noise ratio, the proposed method reaches 22.5 dB at 50 km, which is higher than that of QPSK (20.1 dB) and 16-QAM (18.7 dB), and still maintains 18.3 dB at 150 km, which is 2.1 dB and 3.8 dB higher than that of QPSK and 16-QAM, respectively, which indicates that, by integrating the biosignal pulse coding and the adaptive modulation mechanism, the fiber-optic communication system has lower BER and higher SNR in long-distance transmission, which verifies the high stability and anti-interference capability of this method under complex channel conditions. The details are shown in **Figure 6**.

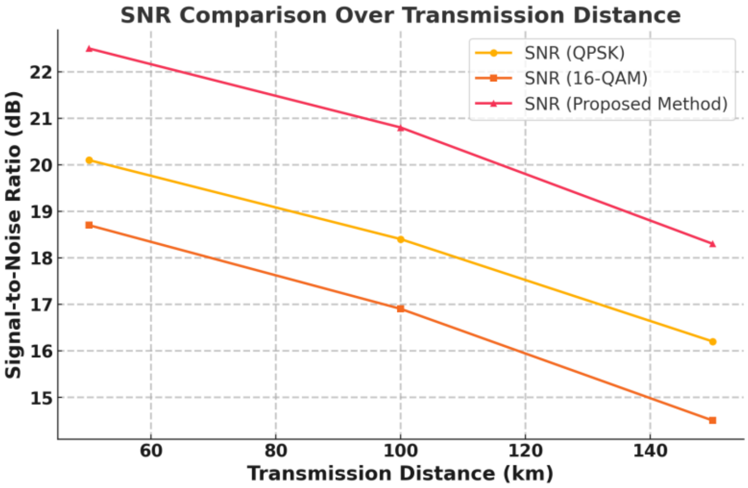

Figure 6. Comparison of signal-to-noise ratio over transmission distance.

To further validate the experimental results, a statistical analysis was conducted to estimate the 95% confidence interval (CI) of BER at different transmission distances.

The BER confidence intervals were calculated using Equation (8):

$$CI = \hat{p} \pm Z_{\alpha/2}\sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \tag{8}$$

where $\hat{p}$ is the measured BER, $Z_{\alpha/2}$ is the critical value for a 95% confidence level, and n represents the number of tested bits.

Key statistical findings: At 50 km, the BER CI range is (0.0010–0.0014). At 100 km, the BER CI range is (0.0030–0.0036). At 150 km, the BER CI range is (0.0070–0.0080).

Additionally, an ANOVA analysis was conducted, revealing statistically significant differences ($p < 0.01$) between the proposed method and QPSK/16-QAM, reinforcing the effectiveness of bio-inspired modulation.

8. Conclusion

Coding and modulation algorithms for optical fiber communication incorporating biomechanical signal conduction mechanisms have significant advantages in improving transmission efficiency, reducing bit error rate and enhancing system stability. By introducing pulse time coding, adaptive modulation and bio-redundant coding techniques, the optical signal achieves higher interference immunity and energy utilization in complex channel environments, and the experimental results validate the performance enhancement of the method in long-haul fiber optic transmission. Future research will be devoted to further optimizing the algorithm complexity and hardware implementation, exploring multi-dimensional bio-signal fusion, enhancing the dynamic modulation capability of optical communication systems, and promoting the practical application of this technology in high-bandwidth, low-latency next-generation communication networks.

Author contributions: Conceptualization, XS and MH; methodology, XS; software, JL; validation, XS, MH and HG.; formal analysis, XS; investigation, XS; resources, XS; data curation, JL; writing—original draft preparation, XS; writing—review and editing, MH; visualization, JL; supervision, HG; project administration, XS; funding acquisition, MH. All authors have read and agreed to the published version of the manuscript.

Ethical approval: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

References

1. Schoell K, Hung V, Fraipont G, et al. Nonspherical humeral arthroplasty increases internal rotation: a biomechanical comparison of the native humeral head to nonspherical and spherical humeral implants. Seminars in Arthroplasty: JSES. 2025; 35(1): 31-41. doi: 10.1053/j.sart.2024.07.014
2. Zhang Z, Zhang Z, Zheng B, et al. Effects of lower limb strengthening training on lower limb biomechanical characteristics and knee pain in patients with patellofemoral pain: a systematic review and meta-analysis. European Journal of Medical Research. 2025; 30(1). doi: 10.1186/s40001-025-02347-3
3. Xu T, Yang A, Guo P, et al. Optimization of digital back-propagation for coherent optical fiber communication systems using fourth-order Runge-Kutta in the interaction picture method. Optics Express. 2025; 33(2): 2082. doi: 10.1364/oe.542863
4. Kamoldilok S, Kadtajan J, Kanajirayupat A, et al. Manipulating Polarization via Optical Fiber Twisting for Optical Switch Applications. Journal of Physics: Conference Series. 2025; 2934(1): 012024. doi: 10.1088/1742-6596/2934/1/012024
5. Ansary K, Hassan MdM, Ali MNB, et al. Design of a nested photonic crystal fiber supporting 76 + 36 OAM modes for fiber communication. Journal of Computational Electronics. 2024; 24(1). doi: 10.1007/s10825-024-02257-3

6. Katoh K. Signal Transduction Mechanisms of Focal Adhesions: Src and FAK-Mediated Cell Response. Frontiers in Bioscience-Landmark. 2024; 29(11). doi: 10.31083/j.fbl2911392
7. Hou M, Zhang Z, Fan Z, et al. The mechanisms of Ca2+ regulating autophagy and its research progress in neurodegenerative diseases: A review. Medicine. 2024; 103(34): e39405. doi: 10.1097/md.0000000000039405
8. Lazarus HPS, Easwaran N. Molecular insights into PGPR fluorescent Pseudomonads complex mediated intercellular and interkingdom signal transduction mechanisms in promoting plant’s immunity. Research in Microbiology. 2024; 175(7): 104218. doi: 10.1016/j.resmic.2024.104218
9. Arinkin V, Granzin J, Jaeger KE, et al. Conserved Signal Transduction Mechanisms and Dark Recovery Kinetic Tuning in the Pseudomonadaceae Short Light, Oxygen, Voltage (LOV) Protein Family. Journal of Molecular Biology. 2024; 436(5): 168458. doi: 10.1016/j.jmb.2024.168458
10. Shi C, Hua M, Xu G. Therapeutic targets and signal transduction mechanisms of medicinal plant formula Gancao Xiexin decoction against ulcerative colitis: A network pharmacological study. BIOCELL. 2023; 47(6): 1329-1344. doi: 10.32604/biocell.2023.028381
11. Tian Q, Pan Y, Xin X, et al. Graph model-aided optimal iterative decoding technique for LDPC in optical fiber communication. Optics Express. 2025; 33(1): 1198. doi: 10.1364/oe.534637
12. Belova OS, Kazantsev SY, Bolotov DV, et al. On the Impact of a Homogeneous Electric Field on Fiber-Optic Communication Lines. Russian Electrical Engineering. 2024; 95(8): 676-679. doi: 10.3103/s1068371224700822
13. Chen GY, Chen M, Rao X, et al. Deep Integration Between Polarimetric Forward-Transmission Fiber-Optic Communication and Distributed Sensing Systems. Sensors. 2024; 24(21): 6778. doi: 10.3390/s24216778
14. Kumar A, Chakravarty S, Nanthaamornphong A. Reducing peak to average power ratio in optical NOMA based 5G system using advanced SLM method. Optical and Quantum Electronics. 2024; 56(10). doi: 10.1007/s11082-024-07495-0
15. Zhu R, Rao X, Dai S, et al. Deep Integration of Fiber-Optic Communication and Sensing Systems Using Forward-Transmission Distributed Vibration Sensing and on–off Keying. Sensors. 2024; 24(17): 5758. doi: 10.3390/s24175758
16. Wen S, Manafian J, Sedighi S, et al. Interactions among lump optical solitons for coupled nonlinear Schrödinger equation with variable coefficient via bilinear method. Scientific Reports. 2024; 14(1). doi: 10.1038/s41598-024-70439-x