Journal of Computer Science and Electrical Engineering
Print ISSN: 2663-1938
Online ISSN: 2663-1946
DOI: https://doi.org/10.61784/jcsee3113

UNDERWATER VISIBLE LIGHT COMMUNICATION AND PATH SELECTION ALGORITHM DESIGN

ZhenHan Xu, Lei Guo, XiangYu Liu*
School of Information Science and Engineering, Shenyang Ligong University, Shenyang 110159, Liaoning, China.
**Corresponding Author: XiangYu Liu*

Abstract: With the increasing demand for marine development and intelligent monitoring, underwater information transmission technologies characterized by high bandwidth, low latency, and strong anti-interference capabilities are becoming increasingly important. Underwater visible light communication (UVLC), with its advantages of high bandwidth, strong directionality, low power consumption, and absence of electromagnetic interference, is considered a highly promising underwater communication method. However, it still faces many challenges in real marine environments, such as signal absorption and scattering, fluctuations caused by turbulence and particle disturbances, and link mismatch due to environmental changes. Therefore, achieving intelligent communication and monitoring early warning in complex and dynamic waters has become a key issue. This paper, targeting dynamic underwater monitoring environments prone to link degradation, designs and implements an integrated intelligent underwater visible light communication monitoring system and path selection scheme. The core innovation lies in introducing chaotic systems and multi-physics coupling into channel modeling and path optimization, significantly improving the system's robustness and adaptability under multi-disturbance monitoring conditions, and enhancing path reliability in harsh environments. Experimental results demonstrate that the proposed monitoring channel model exhibits significantly superior performance to traditional models in predicting power attenuation and pulse broadening. Under the condition of a specific bit error rate (BER), the system can stably maintain a high link switching success rate with the aid of the chaotic optimization mechanism, while keeping the response time below the set threshold. This fully verifies that the system possesses excellent reliability and stability in complex underwater monitoring environments.
Keywords: Chaotic systems; Multiphysics coupling; Channel modeling; Path selection

1 INTRODUCTION

With the deepening of marine resource development and marine scientific research, marine informatization and intelligentization have become important development directions supporting deep-sea exploration and environmental monitoring [1,2]. Underwater communication systems, as key infrastructure connecting underwater sensing nodes and shore-based control centers, play a crucial role in marine environmental monitoring and deep-sea exploration [3]. Traditional underwater acoustic and radio communications are limited by low bandwidth, high latency, and short propagation distance in underwater environments, making it difficult to meet the demands for high-speed and stable data transmission [4,5]. In contrast, underwater visible light communication, with its high bandwidth, low latency, and high energy efficiency, shows promising application prospects. However, underwater optical channels are affected by absorption, scattering, turbulence, and suspended particles, exhibiting significant nonlinear and random fluctuation characteristics, leading to limited communication distance, increased bit error rate, and decreased link stability [6-8]. To address these issues, this paper proposes an integrated intelligent system for underwater visible light communication and environmental monitoring that combines chaos theory and dynamic path selection [9]. By constructing an underwater monitoring channel model under harsh conditions, a basis is provided for the design and parameter optimization of the path selection algorithm, thereby improving robustness under adverse channel conditions [10]. By combining real-time channel status information with dynamic path selection strategies based on node load, the system's reliability and adaptability in complex underwater environments are improved, providing effective technical support for underwater environment monitoring.
Our main contributions are as follows:
(1) Construct a chaotic underwater optical channel model with multi-physics coupling, and use Logistic and Lorenz chaotic systems to characterize the nonlinear and random fluctuation characteristics of the underwater optical channel, providing a theoretical basis for channel state prediction and adaptive parameter adjustment.
(2) Design a dynamic path selection and bit error rate early warning mechanism based on real-time channel state information (CSI) and node load to achieve stable data transmission and highly reliable environmental parameter monitoring in a multi-node underwater monitoring environment.
(3) The proposed monitoring channel model outperforms traditional models in predicting power attenuation and pulse broadening. The chaotic optimization mechanism enables the system to maintain a link switching success rate of 40% and a response time of less than $500ms$ under the condition of bit error rate 5.3×10^{-3}.

2 BUILDING A COUPLED CHANNEL MODEL IN HARSH ENVIRONMENTS

To improve the communication stability and data reliability of underwater environmental monitoring systems in complex and dynamic water bodies, we conduct research on key technologies to address the problem of misjudgment caused by insufficient channel modeling accuracy during the monitoring process.

2.1 Channel Model Composition

Based on the optical link channel model coupled by multiple physics fields, we map optical transmission characteristics to environmental parameters to achieve accurate prediction of signal attenuation and fluctuation, thereby ensuring stable data acquisition and real-time transmission of the monitoring system in complex underwater environments.

2.2 Modulation Method Selection

In constructing a multiphysics coupled underwater visible light communication system model, we find that nonlinear distortion and multipath delay spread in the dynamic attenuation channel limit system performance. Therefore, we compare the bandwidth of three commonly used modulation schemes in underwater visible light communication systems.

2.2.1 Quantitative relationship of modulation methods

The relationship between the three modulation methods is shown in Equation 1.

$$D_{OOK=} 2R_b, D_{PPM} = \frac{LR_b}{\log_2^L}, D_{DPPM} = \frac{2R_b}{\log_2^L} \tag{1}$$

Where R_b represents the signal transmission rate and L represents the length of the transmitted symbol, we control the bandwidth utilization of the signal by changing the symbol length of the transmitted signal in the system. The BER obtained for the three modulation methods are shown in Equation 2.

$$\begin{aligned} BER_{OOK} &= Q(\sqrt{\frac{P_{avg}}{N_0 B_{OOK}}}), \\ BER_{PPM} &= \frac{L-1}{2} Q(\sqrt{\frac{P_{high} L}{2N_0 B_{PPM}}}), \\ BER_{DPPM} &= Q(\sqrt{\frac{P_{high}(L+1)}{4N_0 B_{DPPM}}}) \end{aligned} \tag{2}$$

Where P_{avg} represents the average received optical power, N_0 represents the noise power spectral density, and P_{high} represents the peak optical power.

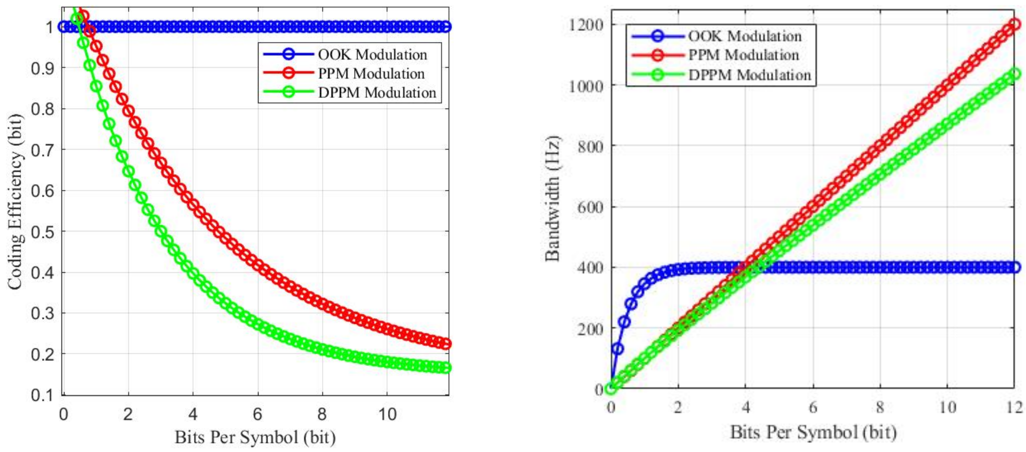
2.2.2 Comparison of modulation methods

Under the same transmission distance and bit rate conditions, we conduct a comparative analysis of the coding efficiency and bandwidth performance of the three modulation methods. The parameters are shown in Table 1, and the comparison results are shown in Figure 1.

The results show that on–off keying (OOK) consistently maintains the theoretically highest coding efficiency and stable signal transmission performance, while the efficiency of pulse position modulation (PPM) and digital pulse position modulation (DPPM) decreases significantly with an increase in the number of transmitted bits. In turbid water environments, OOK exhibits strong resistance to attenuation and interference, maintaining relatively stable bandwidth. In contrast, although PPM and DPPM can extend bandwidth by increasing power, this leads to increased energy consumption and system complexity. Considering the underwater monitoring system's requirements for low latency and high real-time path selection, this system prioritizes the simple, fast-response, and stable OOK modulation scheme in the experiment to achieve more reliable performance of the underwater optical communication monitoring system.

Table 1 Modulation Method Comparison Parameters

Control variables	Parameter
Transmission distance	3m
Sampling rate	10MHz
Turbidity	308psu



(a) (b)

Figure 1 Modulation Method Comparison Chart

2.3 Parameter Mapping Relationship in Chaotic Systems

To ensure that the chaotic system accurately reflects the dynamic changes in the underwater environment, we establish a mapping relationship between environmental parameters and the control parameters of the chaotic channel model. The system adjusts the control parameters of the chaotic model, enabling the multiphysics coupling model to adaptively adjust to changes in the environment.

2.3.1 Logistic mapping system

For a Logistic mapping system, the core control parameter k determines whether the system enters a chaotic state and the complexity of the chaotic sequence. To ensure that the model reflects real underwater physical processes, we establish a correspondence between the control parameter k and several measurable environmental variables. The correspondence is shown in Equation 3.

$$k = k_0 + \alpha C_n^2 + \beta \Delta T + \gamma \Delta S \tag{3}$$

Where k_0 is the baseline control parameter, C_n^2、ΔT、ΔS represents the turbulence intensity, temperature, and salinity gradient, respectively, and α、β、γ is the empirical coefficient obtained through experimental calibration.

In the Logistic mapping model, the control parameter k is designed as a function of the aforementioned physical quantities, allowing environmental disturbances to be directly reflected in the chaotic dynamic system. When the water body is in a relatively stable state, temperature and salinity are uniformly distributed, and turbulence intensity is low. At this time, the value of k is small, the system is in a weakly chaotic or quasi-periodic state, and the output sequence fluctuates little, corresponding to a stable channel environment. However, when the water body is subjected to increased external disturbances, significant temperature and salinity stratification, or increased turbulence energy, the refractive index of the system fluctuates significantly, the value of C_n^2、ΔT、ΔS increases, and the control parameter k increases accordingly, causing the system to enter a strongly chaotic state, and the output sequence exhibits highly random characteristics. In this case, the model can be used to simulate complex situations such as enhanced signal flicker and link instability in underwater channels.

2.3.2 Lorenz mapping system

The Lorenz system, belonging to the continuous-time chaotic model, can generate chaotic signals with a wide frequency distribution and strong energy expansion. The three core control parameters σ、ρ、β of the Lorenz system determine the system's convection intensity, chaotic energy transfer rate, and energy dissipation characteristics, respectively. To establish a correspondence between this system and the underwater physical environment, we correlate these control parameters with measurable parameters such as temperature-salinity gradient, turbulence intensity, particle concentration, and absorption-scattering coefficient. The correspondence is shown in Equation 4.

$$\sigma = f_1(\Delta T, \Delta S), \rho = f_2(C_n^2, C_p), \beta = f_3(\mu_a, \mu_s) \tag{4}$$

Where, parameter σ corresponds to the convection intensity driven by temperature and salinity. As ΔT or ΔS increases, the convection intensity strengthens, and the value of σ also rises, causing the system to exhibit more pronounced nonlinear characteristics. Parameter ρ is related to the turbulence level and suspended particle concentration. When the particle concentration C_p in the water increases or the turbulence energy increases, the non-uniformity of the medium increases, the light propagation path becomes more complex, and the system enters a higher level of chaos. Finally, parameter β corresponds to the system's energy dissipation capacity and is related to the seawater's absorption coefficient μ_a and scattering coefficient μ_s .

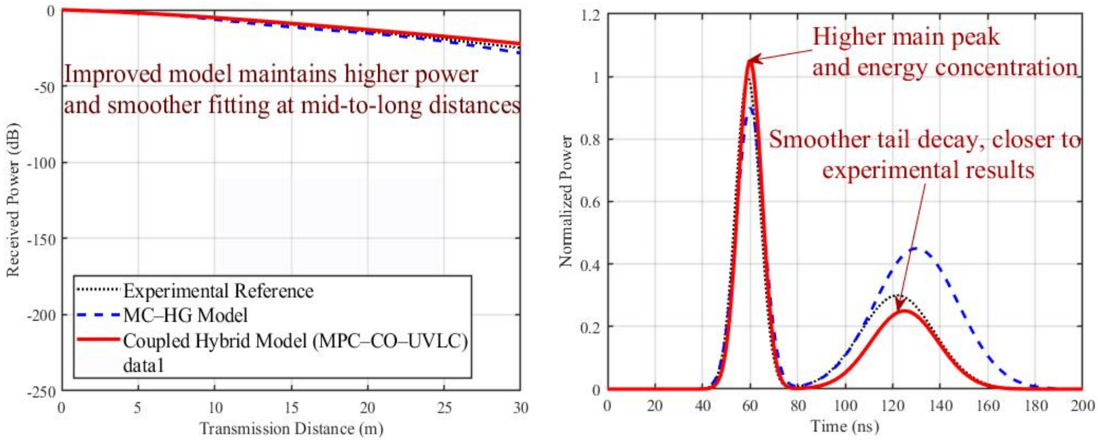
2.3.3 Comparison of multiphysics coupling models with traditional models

To verify the reliability and accuracy of the proposed multi-physics coupled hybrid model, we compare and analyze the experimental results with the classic Monte Carlo phase function benchmark model in this section. The parameters are shown in Table 2, and the specific results are shown in Figure 2.

Table 2 Experimental Parameters for Model Comparison

Experimental factors	Experimental parameters
Transmit power	20W
Transmit frequency	20MHz
Attenuation coefficient	$0.05e^{-14}m^{-2/3}$
Scattering coefficient	$0.3m^{-1}$
Turbulence intensity	$e^{-14}m^{-2/3}$
Information update cycle	200ms

As shown in Figure 2, the model based on the multiphysics coupling mechanism significantly outperforms the MC HG model in both power attenuation and time broadening dimensions. Its predicted power in the mid-to-long-range region is closer to the experimental results, with a smoother and more stable curve. Furthermore, it exhibits a higher peak amplitude and gentler wake attenuation in the channel impulse response, demonstrating more accurate energy transfer and multipath matching characteristics. These results demonstrate that the model can maintain high reliability and high accuracy in channel characterization within complex underwater monitoring environments.



(a) (b)

Figure 2 Model Comparison Chart

3 UNDERWATER PATH SELECTION ALGORITHM DESIGN

Building upon the research on multi-physics coupled channel models completed in the previous chapter, this chapter proposes a multi-path selection algorithm based on chaos theory. It utilizes chaos sensitivity to perceive signal fluctuations in real time and realizes channel evaluation and switching based on the path cost function. The design and verification of the path selection algorithm were all completed in a high-fidelity simulation environment based on Python.

3.1 Link Reliability Analysis under Harsh Monitoring Environment

In harsh underwater environments, single-path optical communication links struggle to maintain reliability over extended periods. Even minor changes in environmental parameters can cause rapid deterioration, leading to synchronization failures, spiked bit error rates, and even communication interruptions. In such cases, if the system relies solely on a single optical communication path to transmit environmental monitoring data, a deterioration in that path's performance will directly result in interrupted or lost data transmission, severely impacting the system's continuous perception of environmental changes. Furthermore, the underwater environment itself exhibits significant time-varying and unpredictable characteristics, making it difficult for a single path to simultaneously achieve long-term stability and real-time response, resulting in a clear weakness in robustness under complex conditions. Therefore, it is necessary to design a path selection algorithm based on real-time link status information for harsh underwater environments to improve the overall robustness of the system in complex conditions.

3.2 Path Selection Algorithm Design

The underwater path selection algorithm mainly consists of two key steps: chaotic feature extraction and cost function design.

3.2.1 Chaotic feature extraction

Chaotic feature extraction mainly consists of two parts: the construction of the phase space and the calculation of the correlation dimension. The construction of the phase space involves reconstructing the time series data with a delay, mapping the system's dynamic behavior from a one-dimensional signal to a multi-dimensional space to reveal its potential nonlinear characteristics. The calculation of the correlation dimension is used to quantitatively describe the degree of chaos and complexity of the system, providing key feature parameters for subsequent path selection.

First, we perform delay embedding on the light intensity sequence $S_{mn}(t)$ acquired by the receiver's APD to reconstruct the dynamic characteristic trajectory of the system. Second, we determine the delay embedding dimension to be d_e using the false nearest neighbor method, and set the delay time α to one-third of the channel coherence time to ensure that the dynamic changes of the optical signal are fully reflected in the phase space. Finally, given τ and d_e, the original light intensity sequence $\{I_t\}_{t=1}^{N}$ is reconstructed into a d_e dimensional phase space trajectory. The k vector of the phase space matrix D is defined as shown in Equation 5.

$$D_k = [I_k, I_{k+\tau}, ...I_{k+(M-1)\tau}]^T, k = 1, 2, 3, ..., N_e \tag{5}$$

Where $N-(M-1)\tau$ represents the total number of valid state vectors in the reconstructed phase space. Each row of matrix D represents a state point of the system at a certain moment.

Correlation dimension calculation is used to quantitatively describe the complexity between trajectory points in phase space, thus reflecting the structural complexity of the system at a specific time scale. Specifically, we use the Correlation Dimension to analyze the phase space trajectory, and the specific expression is shown in Equation 6.

$$C(r) = \lim_{N_e \to \infty} \frac{2}{N_e(N_e - 1)} \sum_{i=1}^{N_e} \sum_{j=i+1}^{N_e} \theta(r - \| x_i - x_j \|) \tag{6}$$

Where $\theta(\cdot)$ represents the Heaviside step function, used to determine the threshold switching condition of the system state; N_e represents the total number of phase points sampled by the system, used to calculate the dynamic phase distribution of the optical signal during propagation; $\frac{2}{N_e(N_e-1)}$ is the normalization factor to ensure that C(r) is a probability estimate with a range of [0,1], and the number of points satisfying $\| x_i - x_j \| < r$ is calculated using a double loop.

3.2.2 Cost function design

We integrate multiple factors such as stability cost, energy cost, and congestion cost into a single evaluation criterion. The constructed cost function can effectively distinguish between high-quality and suboptimal paths, providing a quantitative basis for dynamic path selection, thereby improving transmission reliability and resource utilization efficiency in multi-receiver visible light communication systems. Its expression is shown in Equation 7.

$$D_{i,j} = w_1 \cdot e^{a_{max}^{i,j}} + w_2 \Delta a_{i,j} + w_3 \left(\frac{E_{res}^{j}}{E_{init}}\right)^{-1} \tag{7}$$

Where e^{a} represent the maximum instability quantification index of path $i \to j$ at the current moment. $\Delta a_{i,j}$ represent the change or congestion increment of this path. E_{res}^{j} represent the remaining energy of node j, and E_{init} represent the initial energy.

Because the relative importance of the three criteria changes over a specific time period to meet the current task requirements, we choose to use dynamic weights instead of fixed weights. We allocate system attention based on the different weights of each candidate path, as shown in Equation 8.

$$w_k = \frac{\exp(\beta \cdot S_{chaos}^{k})}{\sum_{m=1}^{3} \exp(\beta \cdot S_{chaos}^{m})} \tag{8}$$

Parameter β controls the sensitivity of path selection. When β is large, the weights are concentrated on the item with the highest score. When β is small and close to 0, the weights tend to be uniform, achieving a balance between conservative and aggressive approaches in the system. Path chaos degree S_{chaos}^{k} can be measured by chaos degree, time series complexity, energy cost, but the values must be normalized when substituted.

3.3.3 Algorithm process analysis

To verify the convergence and synchronization performance of the improved algorithm in path planning, this section compares it with the commonly used underwater RRT* algorithm. The experiment uses time as the horizontal axis and synchronization error as the vertical axis, setting an error threshold to evaluate algorithm performance. By sampling and simulating the synchronization errors of the two algorithms under the same environment, the stability and convergence performance of the improved algorithm in different time intervals can be intuitively analyzed. The specific comparison results are shown in Figure 3.

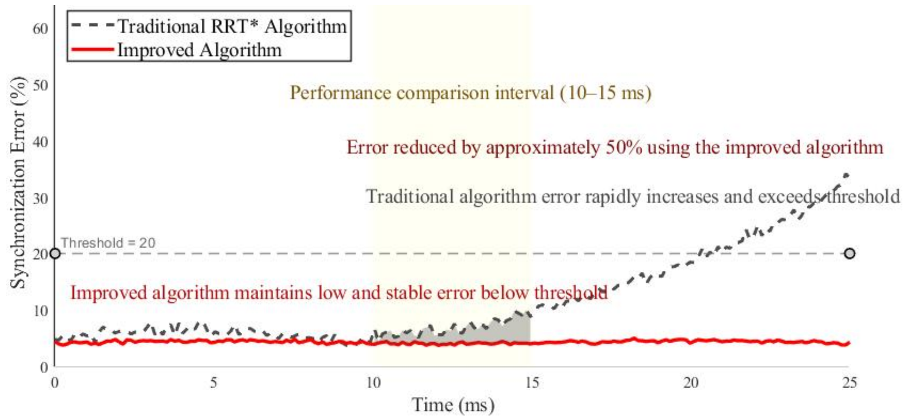


Figure 3 Algorithm Comparison Chart

As shown in Figure 3, the RRT* algorithm's error rises rapidly after step 10ms, enters an exponential growth phase after step 15ms, and quickly exceeds the set threshold. In contrast, the improved algorithm's synchronization error remains below 10% throughout the experiment, with fluctuations within $\pm 1.5\%$, demonstrating good smoothness and stability. Within the [10ms.20ms] interval, the improved algorithm's average error is approximately 7.8%, about 50% lower than the traditional algorithm, and its error growth rate is reduced by about 60%. Experimental results show that the proposed algorithm significantly improves the convergence speed and synchronization accuracy of path planning while maintaining a low error level, fully verifying the reliability and anti-interference ability of the improved method in dynamic and complex environments.

4 CONCLUSIONS

This paper addresses the technical challenges faced by underwater visible light communication systems in complex marine environments, and presents a series of innovative research findings. The main research results are as follows. (1) A dynamic modeling method for underwater optical channels based on multi-physics coupling and chaotic mapping is proposed. By establishing a mapping relationship between environmental parameters and channel disturbances, an accurate description of underwater channel characteristics is achieved. Experimental results show that the proposed model exhibits a higher peak amplitude and smoother wake attenuation in the channel impulse response, demonstrating more accurate energy transmission and multipath matching characteristics. (2) A path selection algorithm based on chaotic systems is proposed. This algorithm quantifies the chaotic characteristics of the channel through chaotic feature value extraction, phase space reconstruction, and correlation dimension calculation, and achieves dynamic path optimization by combining a multi-index cost function. Test results show that the improved algorithm reduces the average error by 50% and the error growth rate by 60% compared to the RRT* algorithm in terms of path length, while maintaining a 40% link switching success rate at a bit error rate of 5.3×10^{-3}. This research provides important theoretical support and practical reference for the practical application of underwater visible light communication technology in underwater environmental monitoring. Future research can further explore areas such as multi-sensor information fusion and energy consumption optimization, and continuously promote the development and improvement of underwater visible light communication technology.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

[1] Zhang Y, Tan S, Li X, et al. Marine ecological environment monitoring and management system based on sensor technology. 2024 International Conference on Integrated Circuits and Communication Systems (ICICACS), Raichur, India. 2024, 1-6. DOI: 10.1109/ICICACS60521.2024.10498570.

[2] Jayaweera V L, Peiris C, Darshani D, et al. Visible Light Communication for Underwater Applications: Principles, Challenges, and Future Prospects. Photonics, 2025, 12(6): 593.

[3] Singh D P, Batham D. A review of underwater communication systems. International Journal of Engineering Development and Research, 2022, 10(2): 100-104.

[4] Al-Tameemi H M, Idris A, Sarnin S S, et al. Underwater acoustic communication systems: An overview. AIP Conference Proceedings. AIP Publishing LLC, 2023, 2977(1): 020008.

[5] Zhilin I V, Bushnaq O M, De Masi G, et al. A universal multimode (acoustic, magnetic induction, optical, RF) software defined radio architecture for underwater communication. IEEE Transactions on Wireless Communications, 2021, 22(12): 9105-9116. DOI: 10.1109/TWC.2023.3268418.

[6] Zhang L, Liu X, Wu S. Intelligent Architecture for Multi-Domain Aerial-Surface-Underwater Networks with Hybrid Radio-Acoustic-Optical Communications. 2024 IEEE Smart World Congress (SWC)Nadi, Fiji. 2024, 503-510. DOI: 10.1109/SWC62898.2024.00100.

[7] Rehman A U, Galluccio L, Morabito G. AI-Driven Adaptive Communications for Energy-Efficient Underwater Acoustic Sensor Networks. Sensors, 2025, 25(12): 3729.

[8] Luo X, Yang L, Alexandropoulos G C, et al. Performance Analysis of Underwater RSMA-Assisted Covert Wireless Communications. IEEE Transactions on Communications, 2025, 73(12): 13863-13875. DOI: 10.1109/TCOMM.2025.3618170.

[9] Gonchenko S, Kazakov A, Turaev D, et al. Leonid Shilnikov and mathematical theory of dynamical chaos. Chaos: An Interdisciplinary Journal of Nonlinear Science, 2022, 32(1).

[10] Zheng C, Sun K, Gu Y, et al. Multimodal transport path selection of cold chain logistics based on improved particle swarm optimization algorithm. Journal of advanced transportation, 2022, 2022(1): 5458760.