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Design and Simulation of Cross-Medium Two-Hop Relaying Free-Space Optical Communication System Based on Multiple Diversity and Multiplexing Technologies

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Abstract

To address the issues of link mismatch and channel impairment in wireless optical communication across atmospheric-oceanic media, this paper proposes a two-hop relay transmission architecture based on the multiple-input multiple-output (MIMO)-enhanced multi-level hybrid multiplexing. The system implements decode-and-forward operations via maritime buoy/ship relays, achieving physical layer isolation between atmospheric and oceanic channels. The transmitter employs coherent orthogonal frequency division multiplexing technology with quadrature amplitude modulation to achieve frequency division multiplexing of baseband signals, combines with orthogonal polarization modulation to generate polarization-multiplexed signal beams, and finally realizes multi-dimensional signal transmission through MIMO spatial diversity. To cope with cross-medium environmental interference, a composite channel model is established, which includes atmospheric turbulence (Gamma–Gamma model), rain attenuation, and oceanic chlorophyll absorption and scattering effects. Simulation results show that the multi-level hybrid multiplexing method can significantly improve the data transmission rate of the system. Since the system adopts three channels of polarization-state data, the data transmission rate is increased by 200%; the two-hop relay method can effectively improve the communication performance of cross-medium optical communication and fundamentally solve the problem of light transmission in cross-medium planes; the use of MIMO technology has a compensating effect on the impacts of both atmospheric and marine environments, and as the number of light beams increases, the system performance can be further improved. This research provides technical implementation schemes and reference data for the design of high-capacity optical communication systems across air-sea media.

Keywords: free-space optical communication; cross-medium communication; multi-level hybrid multiplexing; two-hop relay system; communication performance



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1. Introduction

Free-space optical communication (FSO) possesses a series of remarkable advantages, including high bandwidth, rapid deployment, and strong anti-jamming capability. Due to the high frequency of light waves, theoretically, it has a large transmission capacity, making it highly suitable for high-speed data transmission [1]. Additionally, this technology does not require the laying of optical fibers in the atmosphere, which effectively reduces the

construction difficulty and shortens the construction period. Especially in harsh topographical conditions, it can play an important role in emergency communication. Furthermore, laser has good directivity, and the signal is not easy to intercept, so it has high security. Of course, in practical applications, the influence of atmospheric turbulence and various weather factors on the transmission of optical signals needs to be fully considered.

Traditional underwater communication mainly relies on acoustic and radio frequency technologies, but it is limited by problems such as narrow bandwidth (the bandwidth of sound waves is only at the kHz level) or large transmission attenuation (the propagation distance of RF underwater is less than 1 m), making it difficult to meet the needs of modern marine engineering for high-speed data transmission [2]. Underwater wireless optical communication (UWOC) takes advantage of the penetration characteristics of the blue-green light band (450–550 nm) to achieve a transmission rate of the Gb/s level and an effective transmission distance at the hundred-meter level, opening up a new development dimension for the field of underwater communication. Moreover, optical signals are not affected by underwater electromagnetic noise (such as ship radars, biological electric fields, etc.), and there are no restrictions on spectrum regulation; its narrow beam characteristic (divergence angle $< 0.1^\circ$) can effectively avoid enemy detection, showing extremely prominent advantages in military communication. Due to the characteristics of low propagation delay and high real-time performance of the UWOC system, it is very suitable for remotely controlling devices that require real-time control, such as remotely operated vehicles and underwater drones. However, underwater wireless optical communication also has certain limitations, such as the absorption and scattering of light waves by the underwater channel, and the influence of turbulence on the transmission of light waves, among which the absorption and scattering of light waves by chlorophyll are particularly obvious [3]. In the face of these challenges, some technologies that can effectively improve system performance have been verified and successfully applied. Taking the multiple-input multiple-output technology (MIMO) as an example; this technology can significantly improve the data transmission rate and system throughput by increasing the number of transmitters and receivers [4].

Quadrature amplitude modulation (QAM), also known as amplitude-phase keying, carries information of multilevel symbols through joint modulation of carrier amplitude and phase, demonstrating superior anti-jamming performance compared with pure amplitude or phase modulation schemes. The in-phase and quadrature carriers of QAM share the same optical frequency, enabling independent amplitude modulation with a 90° phase difference. Orthogonal Frequency Division Multiplexing (OFDM), a multi-carrier modulation scheme, divides the total transmission bandwidth into multiple narrow subcarriers, which are modulated by QAM. OFDM systems employ Inverse Fast Fourier Transform and Fast Fourier Transform (FFT) algorithms to optimize transmission and reception, while inserting guard intervals to mitigate the impacts of Inter-Symbol Interference, Inter-Carrier Interference, Polarization Mode Dispersion, and chromatic dispersion [5]. Its main limitations lie in sensitivity to phase noise (including Self-Phase Modulation and Cross-Phase Modulation), frequency offset, and High Peak-to-Average Power Ratio.

Coherent orthogonal frequency division multiplexing (CO-OFDM) integrates the advantages of coherent detection and OFDM [6]. CO-OFDM exhibits strong robustness against polarization dispersion and features high power efficiency and spectral efficiency. Notably, coherent reception requires the polarization state of the local oscillator to strictly match that of the received signal; otherwise, system performance will significantly degrade. Recent studies show that Reference [7] designs a 750 m communication link in foggy environments based on QAM and CO-OFDM; Reference [8] constructs a UWOC system using DPSK and DDO-OFDM technologies, focusing on performance within a 200 m

communication range; Reference [9] investigates the architectures of single-channel and four-channel direct-detection/coherent-detection optical OFDM systems, demonstrating that a 10 Gbps data rate can be achieved in single-channel systems and 40 Gbps in four-channel systems.

Given that each data channel in Polarization Division Multiplexing (PDM) corresponds to a unique polarization angle, modulated signals transmitted independently can achieve bandwidth multiplication in orthogonal communication states, which is typically used to enhance the spectral efficiency of optical communication systems [10]. Chaudhary et al. [11] proposed an UWOC system based on on-off keying (OOK) and PDM and simulated and analyzed the performance of the systems under different salinity levels. Singh et al. [12] proposed an FSO communication system based on the hybrid of wavelength division multiplexing (WDM), PDM, and OFDM and simulated and analyzed the system performance under different atmospheric conditions.

With the deepening understanding of the mechanism of free-space optical communication, an increasing number of studies have focused on schemes to improve the performance of wireless optical communication systems. The most common approaches are to adopt schemes that combine multiple diversity and multiplexing technologies, as well as multi-hop system schemes, to enhance the overall performance of the system. Adopting schemes that combine multiple diversity and multiplexing technologies can not only increase channel capacity but also leverage the advantages of various diversity and multiplexing techniques to improve system performance [13–16]. The multi-hop strategy in wireless optical communication is typically employed to cope with harsh channel environments and extend transmission distances [17–20].

Although extensive research has been conducted in the field of optical communication, significant research gaps still exist in many directions, especially for optical communication across atmosphere–ocean hybrid media, where systematic achievements are lacking. Key scientific issues such as the coupling effect of atmospheric and oceanic turbulence and the synergistic mechanism of seawater chlorophyll absorption remain underexplored, making it difficult to directly apply existing technologies to typical scenarios such as cross-sea platform interconnection and submarine unmanned aerial vehicle (UAV) communication [21]. Moreover, although existing UWOC systems can achieve theoretical transmission rates at the Gb/s level, in cross atmosphere–ocean media transmission scenarios, the actual effective data rate is often lower than the theoretical value due to the dual-medium channel attenuation and composite turbulence effect. When the transmission distance exceeds 500 m, high-speed transmission causes an exponential increase in bit error rate, which makes it difficult to meet the real-time requirements of TB-level data transmission for the marine internet of things (IoT) [22].

Table 1 shows the notable contribution of our work and prior works related to the cross-medium wireless optical communication (WOC) system. Lian et al. [23] investigated the application potential of orthogonal time and frequency space (OTFS) modulation technology in wireless optical communication across air-seawater media. In complex multipath channel environments, OTFS technology can significantly improve the reliability and throughput of data transmission. Lian et al. [24] derived the mathematical expression for the outage probability of the Direct Air-to-Underwater Optical Wireless Communication system but did not consider the water quality conditions. Yang et al. [25] proposed a hybrid FSO-UWOC two-hop system and analyzed the communication performance of the system under the consideration of turbulence and pointing errors. Ali et al. [26] proposed a two-hop cross-medium wireless communication model based on PAM (Pulse Amplitude Modulation) hybrid FSO and VLC (Visible Light Communication) and derived the mathematical expressions for the BER and outage probability of this model. Yadav et al. [27]

proposed a two-hop parallel relay hybrid FSO-UWOC system model and derived the mathematical expression for the outage probability of this system. Levidala et al. [28] proposed a two-hop MIMO hybrid FSO-UWOC system and analyzed the BER performance of this system. Based on the above analysis, it is widely recognized that two-hop systems serve as an effective solution for cross-medium wireless optical communication. However, current research is limited to simple modulation schemes and simplified channel models. To achieve long-distance and high-speed data transmission in cross-medium wireless optical communication, this paper proposes a hybrid transmission architecture of polarization multiplexing based on MIMO-enhanced CO-OFDM and analyzes its performance.

Table 1. Comparison of research contents between the relevant literature and this paper on the cross-medium WOC system.

Ref.	Relay	Atmospheric Link			Oceanic Link			Metrics
		Modulation	Channel	Length	Modulation	Channel	Length	
[23]	×	OTFS	Wind speed	>100 m	OTFS	Clean water	>50 m	BER, Throughput
[24]	×	IM/DD	Turbulence, Fog, Pointing Errors	20 m	-	Turbulence, Air-to-Water interface	20–80 m	Outage Probability
[25]	✓	IM/DD	Turbulence, Pointing Errors	-	IM/DD	Turbulence, Pointing Errors	-	BER, Capacity, Outage Probability
[26]	✓	PAM	Turbulence, Weather, Pointing Errors	500 m	PAM	Turbulence, Water Quality	<100 m	BER, Outage Probability
[27]	✓	IM/DD	Turbulence, Angle of Arrival	1000 m	IM/DD	Turbulence, Water quality	-	Outage Probability
[28]	✓	IM/DD, MIMO	Turbulence, Weather, Pointing Errors	2000 m	IM/DD, MIMO	Turbulence, Water Quality	<30 m	Outage Probability
This	✓	QAM, CO-OFDM, PDM, MIMO	Turbulence, Weather	1000 m	QAM, CO-OFDM, PDM, MIMO	Turbulence, Water Quality	<1100 m	BER, Capacity, Q Factor

The core research work of this paper is as follows:

(1) For the requirements of wireless optical communication across atmosphere–ocean media, a novel communication architecture integrating polarization multiplexing, MIMO technology, and CO-OFDM is proposed—a MIMO-enhanced hybrid CO-OFDM and polarization multiplexing transmission architecture, which optimizes system performance through the synergistic effect of multi-multiplexing technologies. As three channels of polarization-state data are transmitted simultaneously, the proposed system not only improves spectral efficiency but also helps mitigate the adverse effects of polarization-induced fading.

(2) In the proposed communication architecture, the influences of various hybrid channel models, such as weather factors, seawater chlorophyll concentration, and ocean–atmosphere turbulence, are comprehensively considered to construct a simulation model closer to the actual transmission environment.

(3) For different hybrid channel environments and system parameter configurations, key performance indicators such as Q factor, bit error rate (BER), and communication distance of the proposed system are simulated and quantitatively evaluated, providing useful references for engineering applications.

2. Design and Parameters of the Proposed System

The cross-medium two-hop relay wireless optical communication architecture based on decode-and-forward designed in this paper is shown in Figure 1. For both atmospheric and underwater links, multi-level hybrid multiplexing technology is adopted (Figure 2). In the atmospheric sub-link, 20 Gbps random binary signals in each independent sub-channel first undergo 4-QAM mapping, then are imported into subcarriers of different frequencies through an OFDM modulator and a low-pass filter. Subsequently, a Mach–Zehnder Modulator (MZM) is used to convert these OFDM-modulated signals

into optical signals with a wavelength of 1550 nm. The three modulated optical signals ($20 \text{ Gbps} \times 3 = 60 \text{ Gbps}$) are converted into polarized light at different angles (0° , 45° , and 90°) through different polarizers, and then these three polarized lights are combined using a polarization combiner before being transmitted into the atmospheric channel via MIMO diversity technology. After atmospheric transmission, the receivers on the water surface relay platform detect multiple optical signals transmitted through the atmospheric channel. The received optical signals are separated into polarized light at different angles (0° , 45° , and 90°), then further converted into electrical signals by PIN photodetectors with a responsivity of 1 A/W . The electrical signals are decoded and de-mapped by an OFDM demodulator, and finally, signal restoration, error detection, and error correction are performed. The restored binary signals serve as the signal source for underwater transmission. Through the decode-and-forward scheme, a transmission scheme nearly identical to that used for atmospheric transmission is adopted (with an optical wavelength of 450 nm) for underwater optical signal transmission.

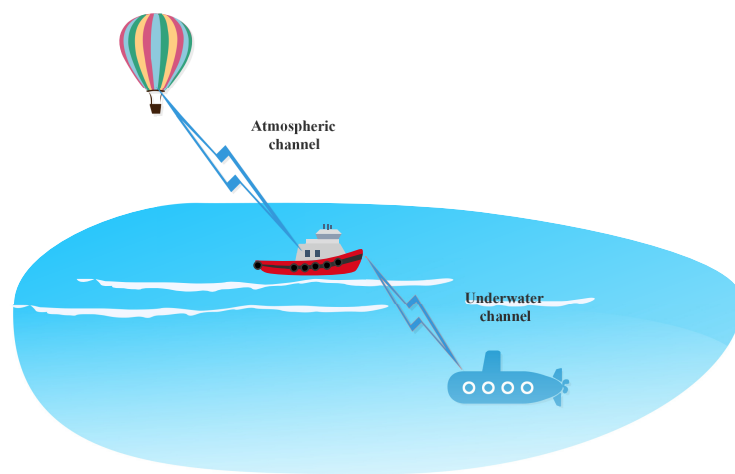


Figure 1. Cross-medium hybrid two-hop wireless optical communication model.

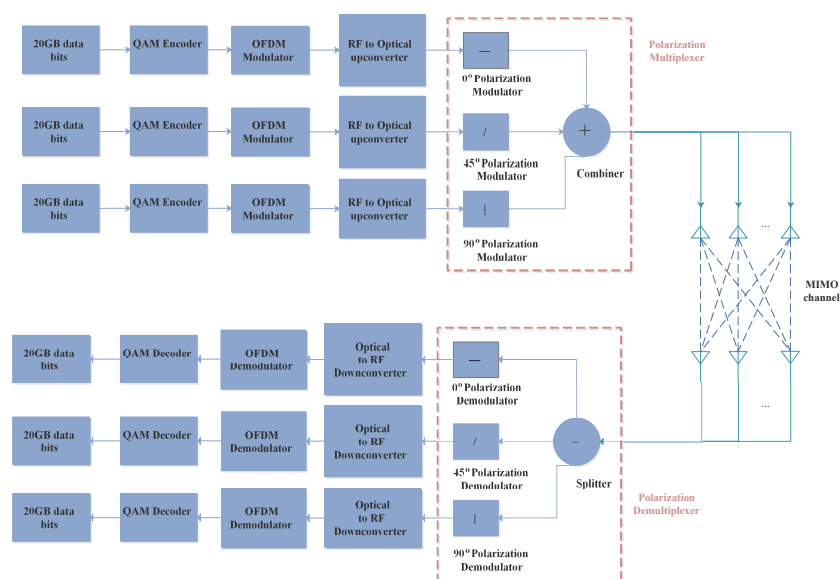


Figure 2. Multi-level hybrid multiplexing technology.

The specific system parameters are shown in Table 2. The divergence angles of the transmitters in both the atmospheric link and the marine link are 2 mrad. In the two links, the apertures of the transmitters and receivers are 5 cm and 7 cm, respectively. In the OFDM modulator, 4-QAM data is mapped onto 104 subcarriers through a serial-to-parallel converter and a 128-point FFT, forming a high-speed OFDM analog data signal. In the atmospheric channel, the impacts of atmospheric turbulence and weather conditions (clear sky, foggy, and rainy) are primarily considered. In the seawater channel, however, the focus is on oceanic turbulence and chlorophyll concentration (water quality).

Table 2. Parameters of the hybrid two-hop relay system.

Atmospheric Subsystem Parameters	Value	Underwater Subsystem Parameters	Value
Wavelength	1550 nm	Wavelength	450 nm
Data source number	3	Data source number	3
Transmission rate of data source	20 Gps	Transmission rate of data source	20 Gps
Transmitter optical power	15.945 dBm	Transmitter optical power	15.945 dBm
Transmitter divergence angle	2 mrad	Transmitter divergence angle	2 mrad
Transmitter/receiver aperture	5 cm/7.5 cm	Transmitter/receiver aperture	5 cm/7.5 cm
Photo detector	PIN	Photo detector	PIN
Dark current	10 nA	Dark current	10 nA
Responsivity	1 A/W	Responsivity	1 A/W
Modulation	QAM	Modulation	QAM
OFDM N_{FFT} length	128	OFDM N_{FFT} length	128
OFDM sub-carriers number	104	OFDM sub-carriers number	104
Channel medium	Atmosphere	Channel medium	Seawater
MIMO antenna configurations	4×4	MIMO antenna configurations	$1 \times 1, 2 \times 2, 4 \times 4$
Atmospheric channel	Value	Underwater channel	Value
Turbulence intensity (C_n^2)	Moderate $5 \times 10^{-15} \text{ m}^{-2/3}$, Weak $1 \times 10^{-17} \text{ m}^{-2/3}$	Turbulence intensity (C_n^2)	Moderate $5 \times 10^{-15} \text{ m}^{-2/3}$, Weak $1 \times 10^{-17} \text{ m}^{-2/3}$
Weather	Clear sky, Foggy, Rainy	Chlorophyll concentration (water quality)	General, Poor

3. Channel Model

3.1. Oceanic and Atmospheric Turbulence Model

In atmospheric and oceanic environments, the most representative ones are the log-normal distribution model and the Gamma–Gamma distribution model [29]. The log-normal distribution model has good applicability when simulating weak turbulence. As the turbulence intensity increases, the multiple scattering effect enhances significantly, and at this time, the Gamma–Gamma distribution model shows good applicability. The turbulence model used in this paper is the Gamma–Gamma distribution model, whose probability density function can be expressed as follows:

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta} \left(2\sqrt{\alpha\beta}I \right) \quad (1)$$

where $K_m(\cdot)$ is the Bessel function of the second kind of order m ; α represents the effective number of large-scale turbulences; β represents the effective number of small-scale turbulences.

$$\alpha = \exp \left[\frac{0.49\sigma_R^2}{\left(1 + 1.11\sigma_R^{12/5} \right)^{5/6}} \right] - 1 \quad (2)$$

$$\beta = \exp \left[\frac{0.51\sigma_R^2}{\left(1 + 0.69\sigma_R^{12/5}\right)^{5/6}} \right] - 1 \quad (3)$$

where the Rytov variance σ_R^2 is expressed as follows:

$$\sigma_R^2 = 1.23C_n^2 k^{7/6} z^{11/6} \quad (4)$$

where C_n^2 is the refractive index structure constant; k is the optical wave number; z is the optical propagation distance.

3.2. Weather Model

In the atmospheric channel, it is necessary to consider not only the influence of turbulence but also the impact of different weather conditions on signal transmission. According to the description of Beer–Lambert Law [30], the atmospheric loss affected by weather can be expressed as follows:

$$\alpha_a = e^{-\sigma z} \quad (5)$$

where σ is the weather attenuation coefficient and z is the transmission distance. In this paper, for clear sky, haze, and rainy conditions, σ is selected as 0.1 dB/km, 4.28 dB/km, and 6.27 dB/km, respectively [31].

3.3. Chlorophyll Model

In the ocean, chlorophyll has a significant impact on the absorption and scattering of light waves. The absorption of light waves by chlorophyll can be expressed as follows [32]:

$$a(\lambda) = \left[a_w(\lambda) + 0.06a_c(\lambda) \cdot C_{Chlor}^{0.65} \right] \{1 + 0.2 \exp[-0.014(\lambda - 440)]\} \quad (6)$$

where λ represents the wavelength of light; $a_w(\lambda)$ represents the absorption of light waves with wavelength λ by pure water; $a_c(\lambda)$ represents the absorption of light waves with wavelength λ by chlorophyll; and C_{Chlor} represents the chlorophyll concentration. The scattering of light waves by chlorophyll can be expressed as follows:

$$b(\lambda) = 0.3 \frac{550}{\lambda} C_{Chlor}^{0.65} \quad (7)$$

Then the extinction coefficient of chlorophyll can be expressed as follows:

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (8)$$

The chlorophyll concentration in general water quality is typically 19 mg/m³, while that in poor water quality is 30 mg/m³.

4. Results and Discussion

Since research on laser transmission in the atmosphere is relatively mature, the distance of the atmospheric transmission link is set to 1 km in this paper. Additionally, due to the complex transmission environment of the system and the significant impact of the atmospheric link environment on the overall performance of the system, a 4 × 4 MIMO diversity scheme is adopted for the atmospheric link to improve the overall performance of the communication system. In this paper, both the atmospheric link and the underwater link consider the influence of Gamma–Gamma turbulence. For the atmospheric link, the focus is on examining the impact of clear sky, foggy, and rainy environments on the performance

of the communication system. For the underwater link, the main considerations are the effects of different MIMO diversity technologies and different chlorophyll concentrations on the communication system.

4.1. Simulation and Analysis of the Atmospheric Subsystem

Considering the influence of weather on the atmospheric subchannel, Figures 3 and 4 respectively show the relationship between the communication system performance of the atmospheric subsystem and the transmission distance under weak turbulence and moderate turbulence conditions. It can be seen from Figures 3 and 4 that weather has an obvious impact on the communication performance of the atmospheric subsystem: the subsystem achieves the best communication performance under clear sky conditions, while the worst performance occurs on rainy days. For example, under weak turbulence with a BER of 5.41×10^{-7} , the maximum transmission distances of the atmospheric subsystem are 1600 m, 1100 m, and 1000 m for clear sky, foggy, and rainy days, respectively. Similarly, at a communication distance of 1400 m, the Q-factors of the atmospheric subsystem for clear sky, foggy, and rainy days are much greater than 1000, 23.38, and 9.96, respectively. By comparing Figures 3 and 4, it can be observed that turbulence also has a significant impact on the communication performance of the atmospheric subsystem and narrows the performance gap caused by weather conditions—the stronger the turbulence intensity, the worse the performance. For instance, under moderate turbulence with a BER of 5.41×10^{-7} , the maximum transmission distances of the atmospheric subsystem are 1100 m, 850 m, and 800 m for clear sky, foggy, and rainy days, respectively. Likewise, at a communication distance of 1400 m, the Q-factors of the atmospheric subsystem for clear sky, foggy, and rainy days are much greater than 119.01, 11.882, and approaching 0, respectively. It can thus be concluded that both weather factors and turbulence intensity have a significant impact on the communication performance of the atmospheric subsystem.

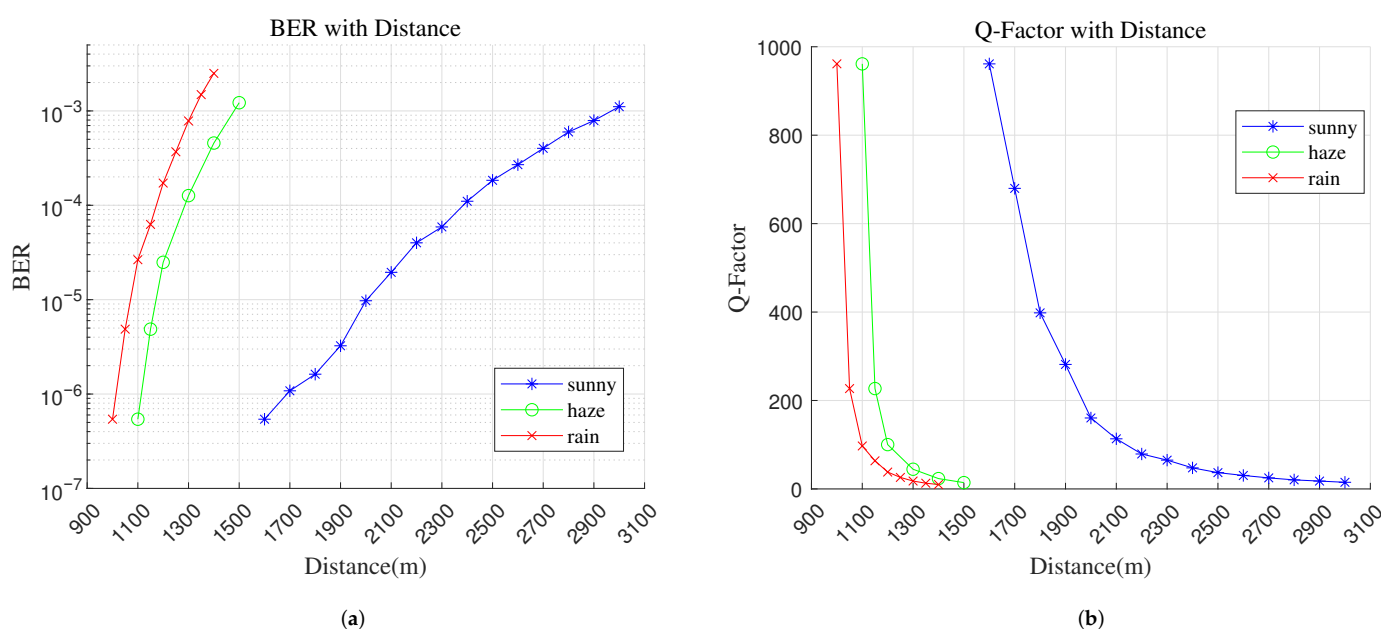


Figure 3. Relationship between the performance of the atmospheric subsystem and transmission distance under weak turbulence conditions. (a) BER. (b) Q factor.

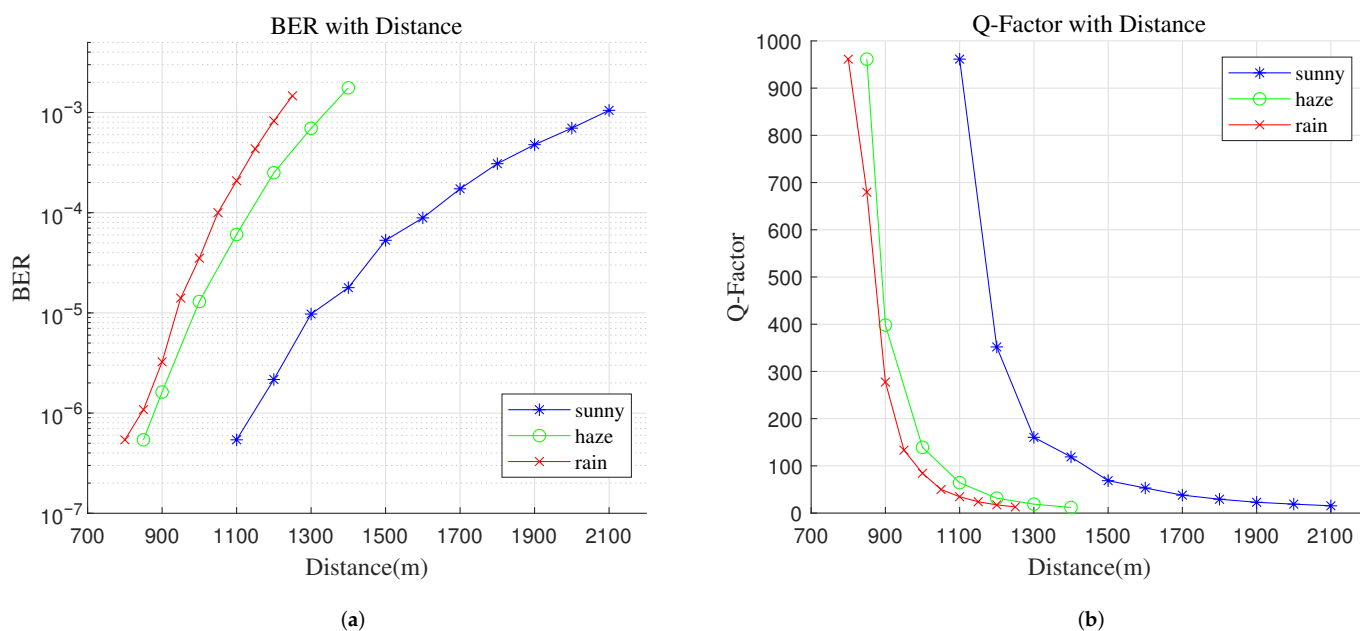


Figure 4. Relationship between the performance of the atmospheric subsystem and transmission distance under Moderate turbulence conditions. (a) BER. (b) Q factor.

4.2. Simulation and Analysis of the Hybrid Two-Hop Relay System

Since there is extensive literature on the impact of atmospheric turbulence on wireless optical communication systems, this section focuses on weak atmospheric turbulence and 4×4 atmospheric MIMO channels, primarily examining the effects of different weather conditions, underwater turbulence, chlorophyll concentrations, and various underwater MIMO structures on the performance of the hybrid two-hop system.

Under conditions of weak underwater turbulence and general water quality, Figures 5, 6 and 7, respectively, illustrate the relationship between the communication performance of the hybrid two-hop system and transmission distance under clear sky, foggy, and rainy weather. By comparing Figures 4 and 6, it is easy to observe that the communication performance of the hybrid two-hop system is inferior to that of the atmospheric subsystem, which is attributed to the BER accumulation in the two-hop system. For example, in Figure 5, when the BER reaches 5.41×10^{-7} , the underwater transmission distances of the hybrid two-hop system with 1×1 , 2×2 , and 4×4 underwater MIMO structures are 650 m, 850 m, and 1100 m, respectively. Under the same conditions, at an underwater communication distance of 1400 m, the Q-factors of the hybrid two-hop system with 2×2 and 4×4 underwater MIMO structures are 11.85 and 70.87, respectively. It can also be seen that although increasing the number of light beams can effectively improve the performance of the communication system, the communication performance of the hybrid two-hop system remains inferior to that of the atmospheric subsystem due to the existence of BER accumulation. A further comparison of Figures 5–7 reveals that the difference in the impact of different weather factors on the communication performance of the hybrid two-hop system is relatively small. Moreover, regardless of the weather conditions, the more beams in the underwater MIMO, the better the communication performance of the hybrid two-hop system. For instance, under weak underwater turbulence with a 2×2 underwater MIMO structure and a BER of 5.41×10^{-7} , the underwater transmission distances of the hybrid two-hop system are 850 m, 850 m, and 800 m for clear sky, foggy, and rainy days, respectively. Similarly, with a 2×2 underwater MIMO structure and an underwater transmission distance of 1300 m, the Q-factors of the hybrid two-hop system are 18.73, 18.27, and 18.11 for clear sky, foggy, and rainy days, respectively.

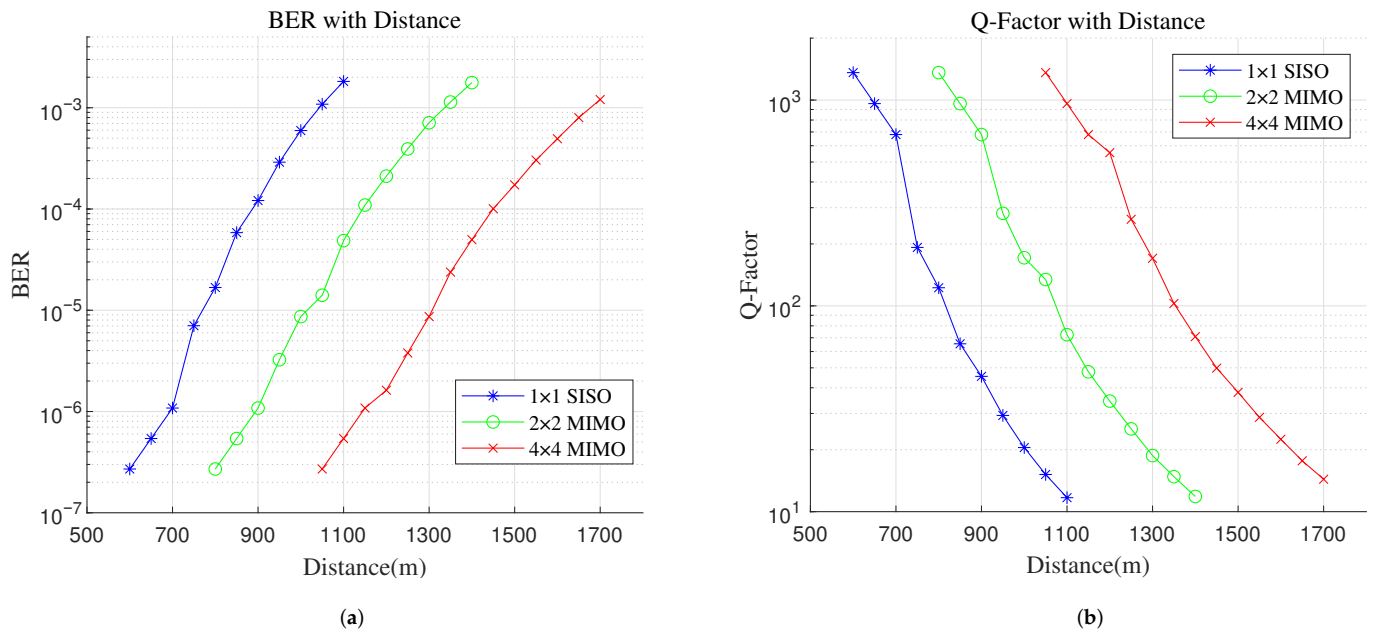


Figure 5. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of clear sky, weak underwater turbulence, and general water quality. (a) BER. (b) Q factor.

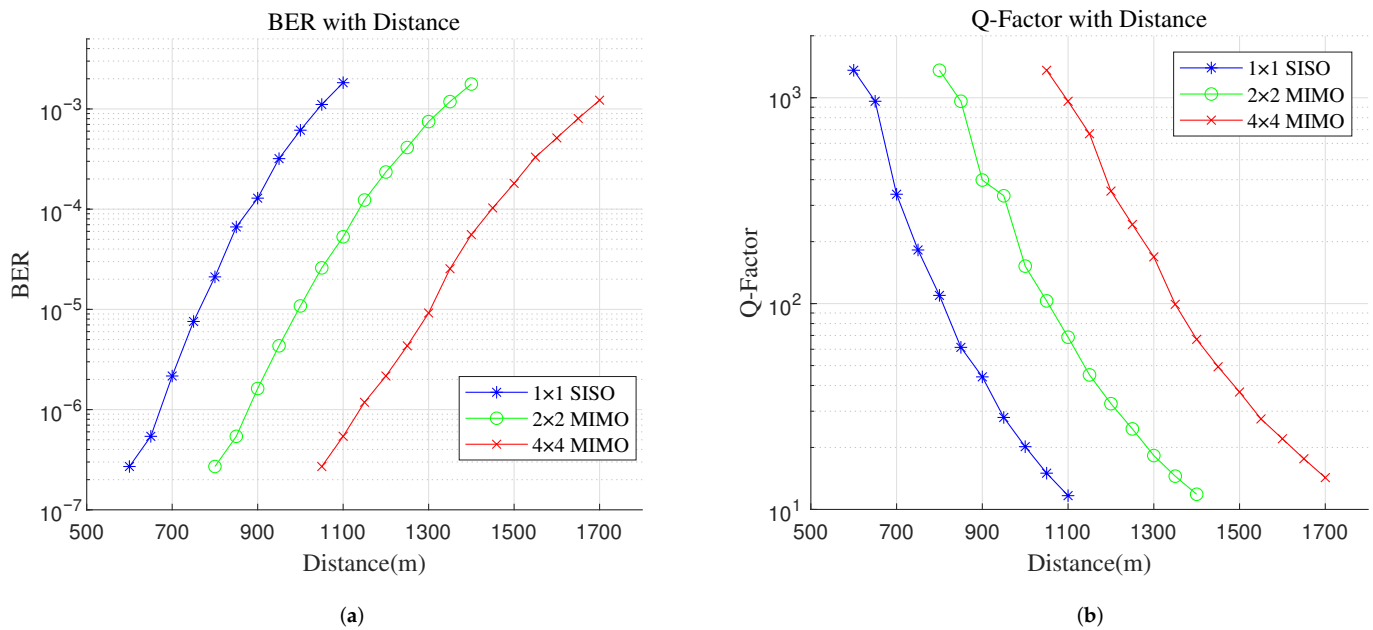


Figure 6. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of foggy, weak underwater turbulence, and general water quality. (a) BER. (b) Q factor.

Under conditions of moderate underwater turbulence and general water quality, Figures 8, 9 and 10, respectively, present the relationship between the communication performance of the hybrid two-hop system and transmission distance under clear sky, foggy, and rainy weather. By comparing Figures 5–10, it is easy to find that under the same atmospheric environment, the stronger the underwater turbulence, the worse the communication performance of the hybrid two-hop system. For example, under moderate underwater turbulence with a 2×2 underwater MIMO structure and a BER of 5.41×10^{-7} , the underwater transmission distances of the hybrid two-hop system are 350 m, 300 m,

and 300 m for clear sky, foggy, and rainy days, respectively. Similarly, under moderate underwater turbulence with a 2×2 underwater MIMO structure and an underwater transmission distance of 700 m, the Q-factors of the hybrid two-hop system are 16.29, 15.82, and 15.81 for clear sky, foggy, and rainy days, respectively. A comparison of Figures 8–10 leads to a conclusion similar to the above: the differences in the impact of different weather factors on the communication performance of the hybrid two-hop system are relatively small, and in any weather environment, the more beams the underwater MIMO has, the better the communication performance of the hybrid two-hop system.

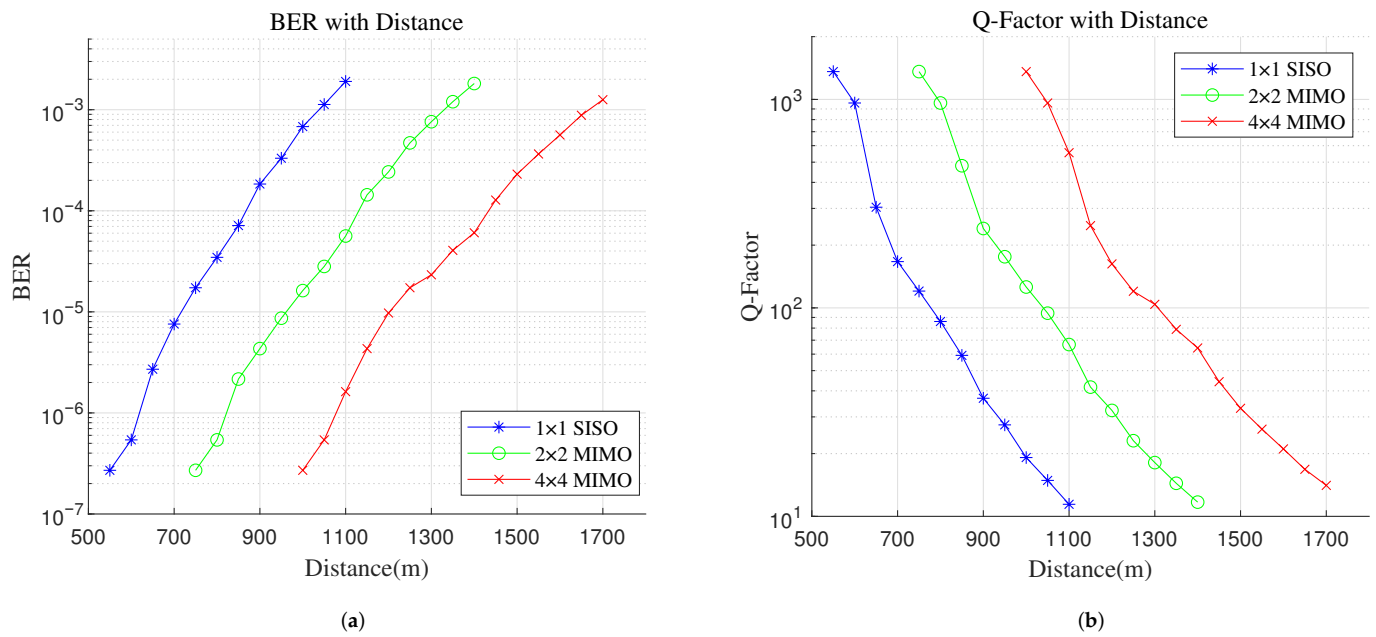


Figure 7. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of rainy, weak underwater turbulence, and general water quality. (a) BER. (b) Q factor.

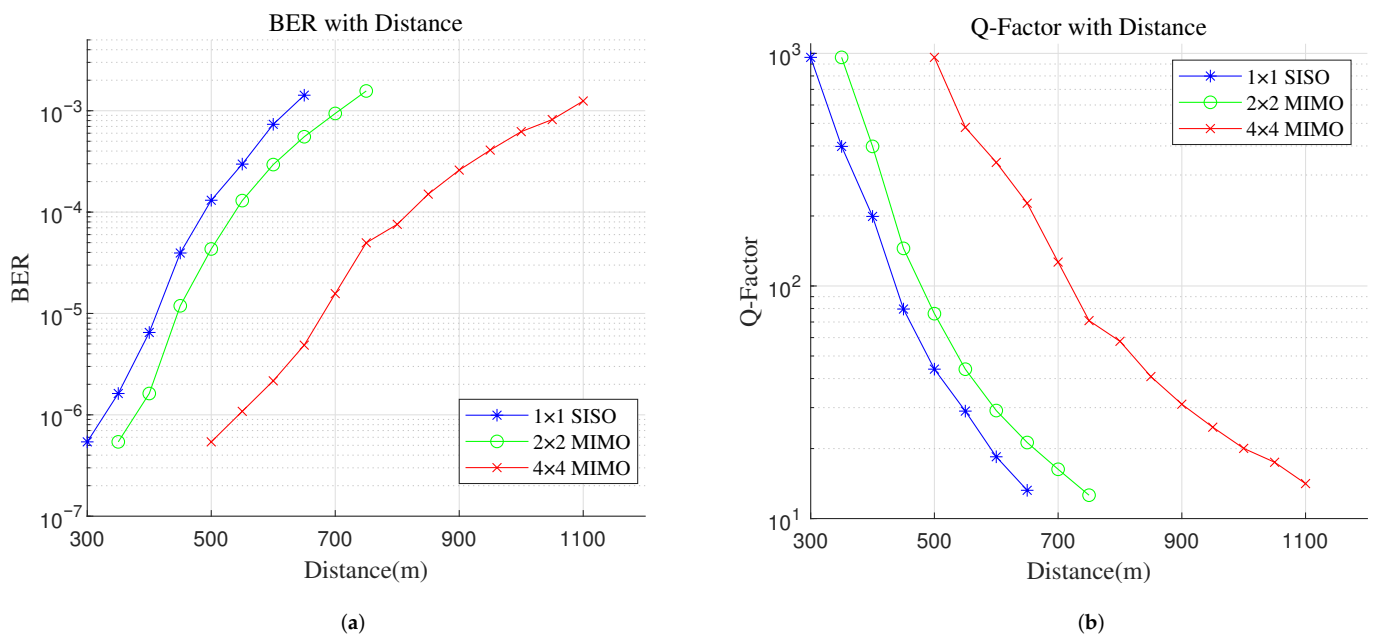


Figure 8. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of clear sky, moderate underwater turbulence, and general water quality. (a) BER. (b) Q factor.

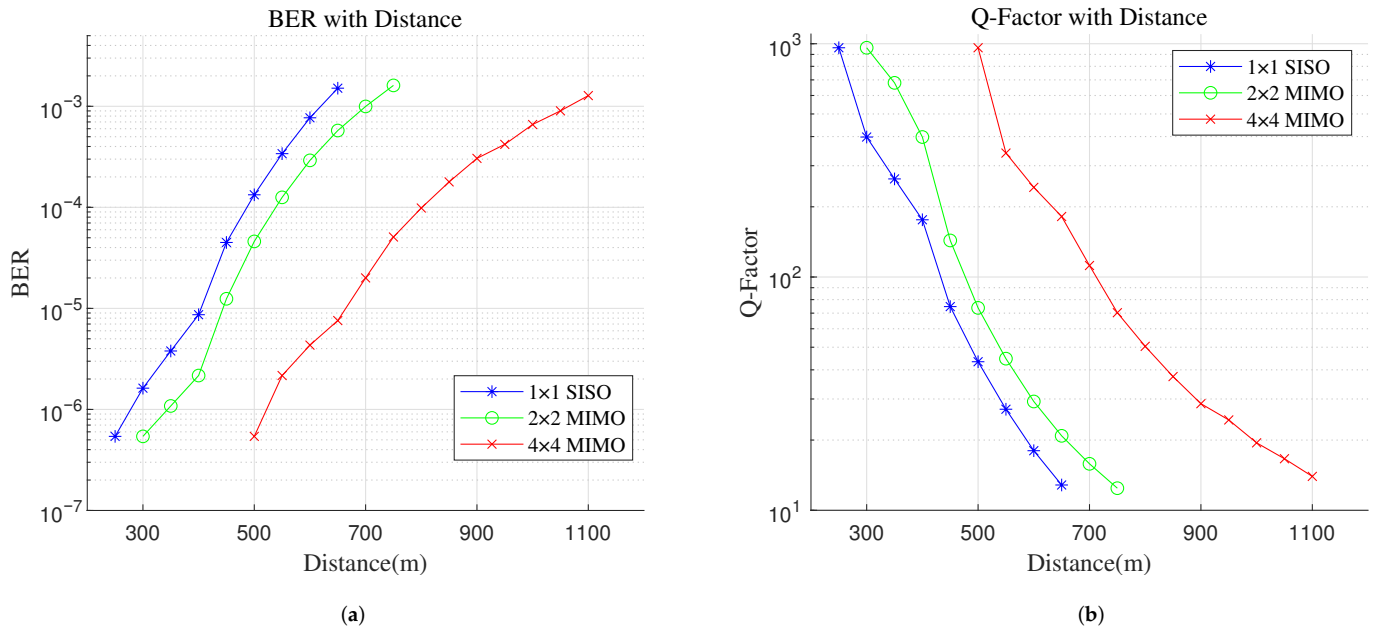


Figure 9. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of foggy, moderate underwater turbulence, and general water quality. (a) BER. (b) Q factor.

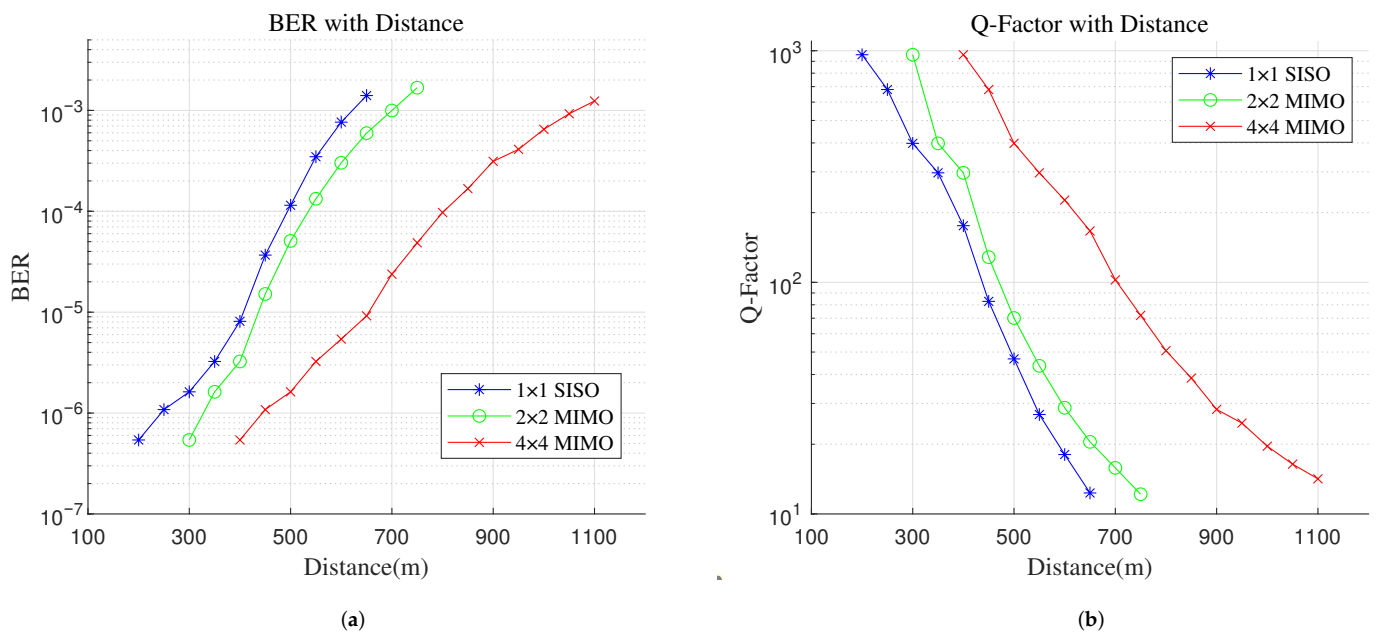


Figure 10. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of rainy, moderate underwater turbulence, and general water quality. (a) BER. (b) Q factor.

Under conditions of weak underwater turbulence and poor water quality, Figures 11, 12 and 13, respectively, show the relationship between the communication performance of the hybrid two-hop system and transmission distance under clear sky, foggy, and rainy weather. By comparing Figures 5–7 and 11–13, it can be found that under the same weather conditions, different water qualities have little impact on the BER of the hybrid two-hop system, but the Q-factor decreases significantly. This is because the increase in chlorophyll concentration enhances the absorption and scattering of light by water. For example, in Figure 11, when the BER reaches 5.41×10^{-7} , the underwater transmission

distances of the hybrid two-hop system with 1×1 , 2×2 , and 4×4 underwater MIMO structures are 600 m, 800 m, and 1050 m, respectively. Under the same conditions, at an underwater communication distance of 1400 m, the Q-factor of the hybrid two-hop system with a 4×4 underwater MIMO structure is 28.07. By comparing Figures 5–13, it is easy to find that underwater turbulence has a more significant impact on the communication performance of the hybrid two-hop system than water quality.

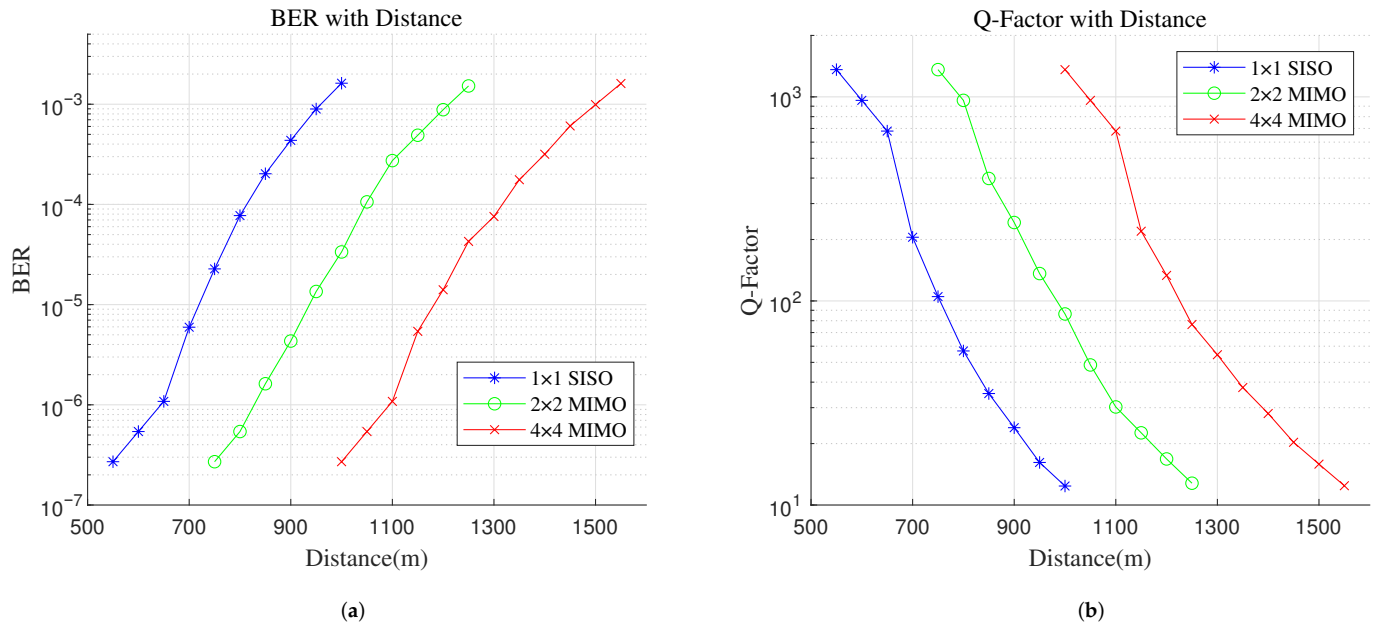


Figure 11. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of clear sky, weak underwater turbulence, and poor water quality. (a) BER. (b) Q factor.

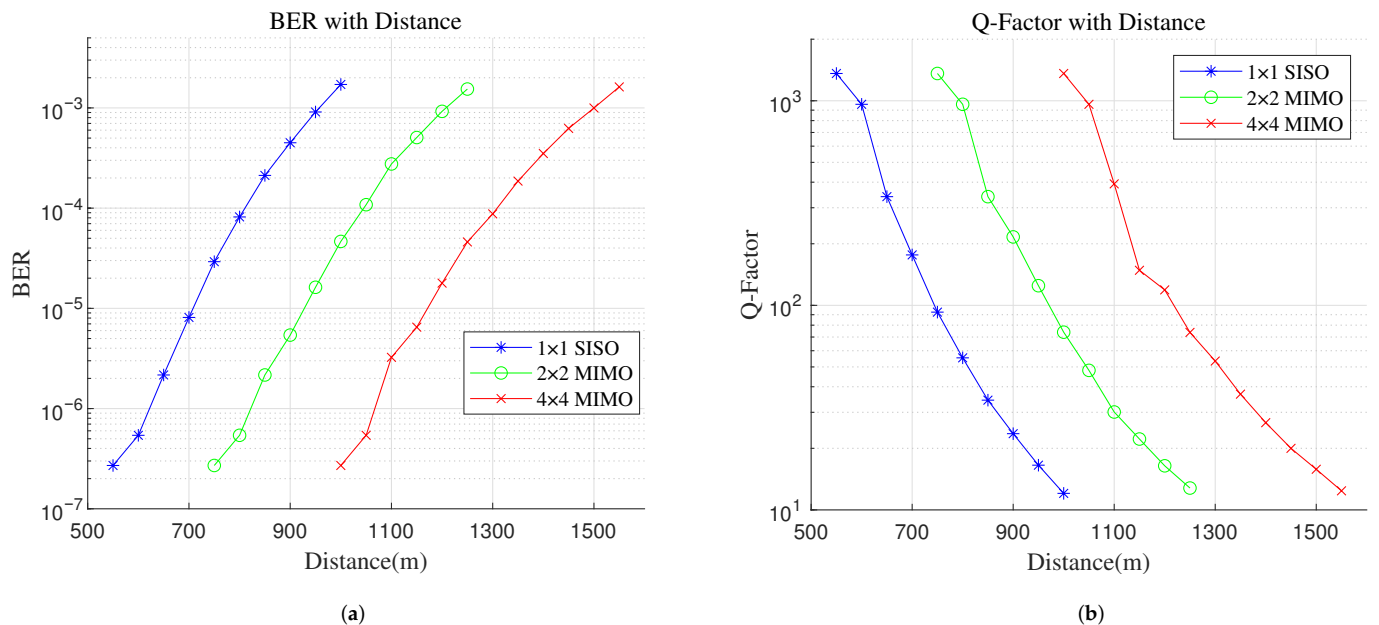


Figure 12. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of foggy, weak underwater turbulence, and poor water quality. (a) BER. (b) Q factor.

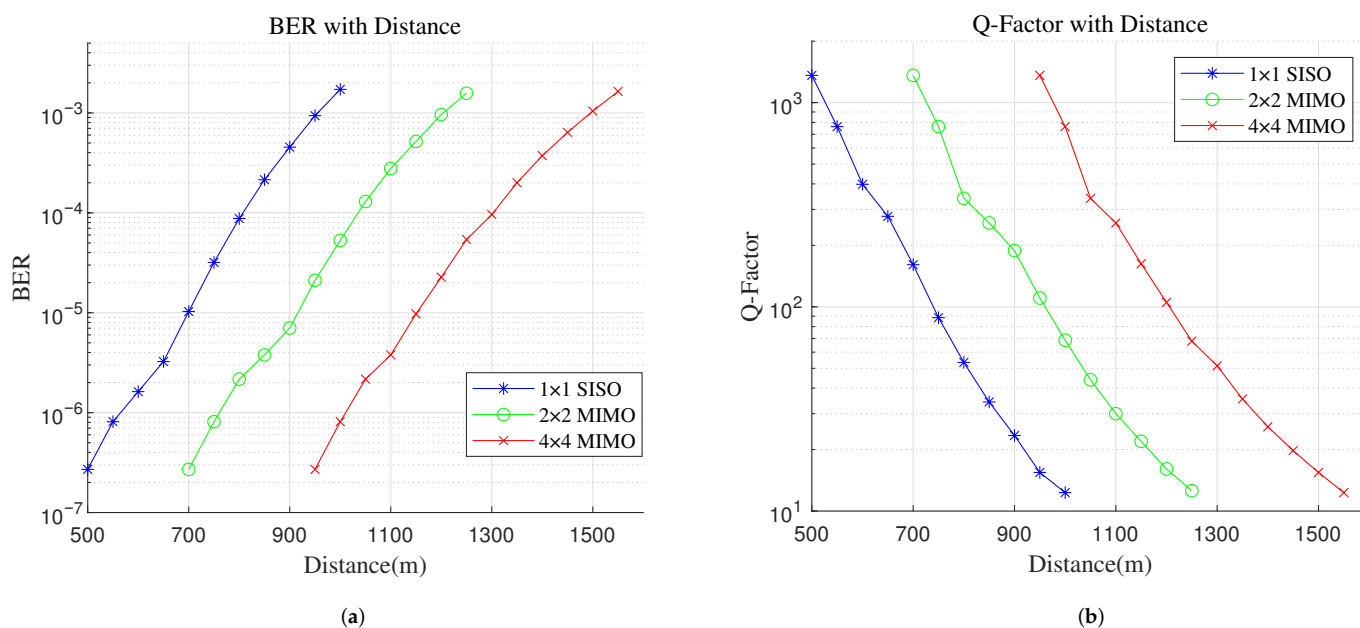


Figure 13. Relationship between communication performance and transmission distance of the hybrid two-hop system under conditions of rainy, weak underwater turbulence, and poor water quality. (a) BER. (b) Q factor.

5. Conclusions

This paper proposes a two-hop relay wireless optical communication system based on MIMO-enhanced hybrid CO-OFDM and PDM. By integrating technologies such as CO-OFDM multiplexing, PDM multiplexing, and MIMO spatial diversity, this system achieves a cross-medium (atmosphere-seawater) and large-capacity (60 GB) wireless optical communication system. The following conclusions can be drawn from the system simulation results: Although the two-hop system will cause BER accumulation, it is still an effective solution for long-distance and cross-medium wireless optical communication. Increasing the number of beams in MIMO diversity can significantly improve the communication performance of the hybrid two-hop system; Multi-level multiplexing can increase the transmission rate of the wireless optical communication system; Although different weather conditions have a large difference in their impact on the performance of subsystems, their impact on the communication performance of the hybrid two-hop system shows a small difference; Not only does atmospheric turbulence have a significant impact on the performance of the atmospheric subsystem, but underwater turbulence also has a great influence on the performance of the hybrid two-hop system. Different water qualities and different weather conditions have the same level of impact on the BER performance of the hybrid two-hop system, and the differences caused by these impacts are small. However, due to the increased chlorophyll concentration, which enhances light absorption and scattering, different water qualities have a significant impact on the Q-factor of the hybrid two-hop system.

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