

Performance analysis of polarization shift keying using linear, circular, and elliptical polarizations in underwater wireless optical communication under hybrid fading channels

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Underwater wireless optical communication (UWOC) networks with high data rate demands are affected by absorption, scattering, and turbulence in aquatic environments. This work investigates polarization shift keying with linear, circular, and elliptical polarization under hybrid log-normal and Gamma–Gamma fading channels. At 10 m optical link at 520nm is simulated for clear, coastal, and turbid waters. Linear polarization achieves a Q-factor of 7.75 and bit error rate (BER) of 3.42×10^{-15} at 45° , but degrades at 90° (Q-factor = 0, BER ≈ 1), indicating high sensitivity to alignment. Elliptical polarization shows comparable performance under channel impairments, circular is moderate; BER is lowest in clear water and highest in turbid water.

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1. Introduction

Underwater wireless communication systems play a crucial role in a wide range of applications, including autonomous underwater vehicles (AUVs), environmental monitoring, and defense operations [1,2]. However, radio-frequency (RF) signals experience severe attenuation in seawater, resulting in highly limited communication ranges. Acoustic communication, although widely used, suffers from inherent limitations such as low bandwidth, high latency, and poor energy efficiency [3]. To overcome these challenges, underwater wireless optical communication has emerged as a promising alternative. UWOC offers gigabit-level data rates, low latency, and enhanced security over moderate transmission distances, particularly under favorable water conditions [4,5]. Nevertheless, its performance is significantly affected by environmental factors such as absorption, scattering, and turbulence, especially in coastal and turbid waters. These impairments introduce random intensity fluctuations and degrade the signal-to-noise ratio (SNR) [6,7]. Such channel effects create significant challenges for conventional intensity-modulation/direct-detection (IM/DD) techniques [8]. In this context, polarization-based modulation schemes, particularly polarization shift keying (PolSK), have gained attention as effective alternatives. By encoding information in orthogonal states of polarization, PolSK reduces sensitivity to amplitude fading, enhances transmission security, and enables efficient multiplexing [9,10]. Recently, the differential quadrature polarization shift keying (DQPolSK) scheme proposed by Chen et al. (2025) eliminates the need for polarization tracking by encoding

information in relative polarization variations. This approach improves robustness against polarization instability, resulting in reduced bit error rate and enhanced spectral efficiency compared with conventional PolSK systems [11]. In this work, linear, circular, and elliptical polarization modulation schemes are investigated under hybrid fading conditions that incorporate both scattering and turbulence effects. A 10 m UWOC link operating at a wavelength of 520 nm is modeled using OptiSystem. System performance is evaluated in terms of eye diagrams, BER, SNR and Q-factor. Additionally, sensitivity to polarization alignment is analyzed by considering linear polarization orientations of 0° , 45° and 90° .

2. Overview of underwater wireless optical communication

Compared with traditional radio-frequency and acoustic communication systems, underwater wireless optical communication offers several advantages, including reduced latency, high bandwidth, and inherent immunity to certain environmental disturbances. Seawater severely attenuates RF transmissions, significantly limiting communication range, while acoustic communication suffers from high propagation delays and limited data rates. In contrast, UWOC can achieve gigabit-per-second data rates over distances ranging from several meters to a few tens of meters in clear water, making it suitable for high speed, short to moderate range applications [12,13]. However, UWOC performance is strongly influenced by environmental factors such as absorption, scattering,

turbulence, and bioluminescence interference [14,15]. Absorption leads to signal attenuation, while scattering causes multipath effects and depolarization. Turbulence introduces random intensity fluctuations that degrade signal

quality. In addition, ambient light and bioluminescence increase noise levels, further affecting the reliability of data transmission. The main underwater channel impairments are summarized in Table 1.

Table 1. Key characteristics of underwater wireless optical communication channel impairments

Impairment	Cause	Effect on Signal	References
Absorption	Water molecules, dissolved salts	Power loss	[14]
Scattering	Suspended particles, plankton	Multipath fading, depolarization	[15],[16]
Turbulence	Temperature/ salinity gradients	Random intensity fluctuations	[17],[18]
Bioluminescence	Marine organisms	Background noise	[19],[20]

Table 1 illustrates the most significant physical impairments affecting underwater wireless optical communication links. Absorption and scattering primarily cause power attenuation, multipath effects, and polarization degradation, whereas turbulence contributes to random intensity fluctuations. Furthermore, bioluminescence introduces background noise, which limits link reliability and the achievable communication range.

2.1. Role of polarization in optical communication

One essential property of light that is highly relevant to underwater wireless optical communication is polarization. It can be effectively utilized for information encoding, multiplexing, and improving noise resilience. Polarization Shift Keying has emerged as a promising modulation technique that enhances flexibility and robustness in UWOC systems [21]. In clear and coastal waters, polarization states are generally preserved over short to moderate distances, enabling reliable communication despite partial depolarization caused by scattering [22].

Depolarization results from the interaction of light with suspended particles and aquatic microorganisms, which alters the polarization state of the transmitted signal. Furthermore, polarization diversity techniques employing multiple polarization components can mitigate multipath effects and improve signal integrity. Polarization-based modulation has therefore emerged as an effective approach for enhancing the reliability of UWOC links [23]. Compared with conventional schemes such as on-off keying (OOK), Pulse position Modulation (PPM), and Quadrature Amplitude Modulation (QAM), PolSK offers advantages by exploiting polarization as an additional degree of freedom for information transmission. This approach provides improved resilience against scattering and turbulence while maintaining a balance between spectral efficiency and implementation complexity. Table 2 illustrates that PolSK enables polarization-based transmission with moderate complexity and improved power efficiency compared to traditional intensity modulation techniques, making it a suitable approach for UWOC system design.

Table 2. Comparison of underwater wireless optical communication modulation schemes in terms of implementation complexity, power efficiency, and polarization capability

Modulation	Complexity	Power Efficiency	Polarization Support	References
OOK	Low	Low	No	[13],[14]
PPM	Medium	Low	No	[15]
QAM	High	High	No	[17],[18]
POLSK	Medium	Medium to High	Yes	[21],[22] [23]

2.2. Polarization in underwater systems

Underwater wireless optical communication can benefit significantly from the use of light polarization. Gökçe et al. [24] investigated binary phase shift keying

(BPSK) with subcarrier intensity modulation under mild ocean turbulence, providing a foundation for polarization-aware modulation analysis. Sharma et al. [25] demonstrated that polarization division multiplexing, combined with advanced modulation schemes, improves bit

error rate performance and link reliability in visible light communication based UWOC, even under challenging water conditions. Singh et al. [26] showed that dual-polarization approaches can enable high-capacity links exceeding 80 Gbps using a 16-QAM OFDM scheme, highlighting the potential of polarization multiplexing for next-generation underwater optical communication systems.

2.3. Research gap

Although significant progress has been made in high-capacity modulation techniques [12–13] and channel modeling [14–20] for underwater wireless optical communication, most polarization based studies have focused primarily on binary PolSK or polarization multiplexing under controlled laboratory conditions [21–25]. Comprehensive simulation-based evaluations of linear, circular and elliptical polarization states under hybrid fading scenarios remain limited. In particular, a detailed comparison of linear polarization performance at different orientation angles is lacking in the existing literature. To address these gaps, this study investigates linear, circular, and elliptical polarization schemes over a 10 m UWOC link operating at 520 nm under hybrid fading channels represented by combined log normal and Gamma Gamma distributions for clear, coastal, and turbid water conditions using MATLAB. In addition, OptiSystem simulations are performed for linear polarization to further validate system performance in terms of Q-factor and bit error rate.

3. System modeling

A comprehensive system model is developed to evaluate the performance of polarization shift keying in underwater wireless optical communication. This section presents the mathematical representation of the transmitted signal, underwater channel characteristics, receiver noise modeling, polarization state identification using Stokes parameters, and the computation of decision variables and error probability. Fading and turbulence models are employed to characterize the impact of varying water conditions on system reliability. PolSK mitigates the effects of fading by encoding information in the state of polarization rather than relying solely on signal amplitude. In underwater channels, absorption and scattering primarily affect signal intensity, while the polarization state is comparatively less affected [5]. As a result, the polarization state can still be reliably detected even in the presence of amplitude fluctuations. Therefore, polarization-based modulation schemes such as PolSK can provide enhanced robustness against turbulence-induced fading, as demonstrated in recent analytical and experimental studies [10], [22].

3.1. Transmitted signal representation

Let the binary data sequence $b_k \in \{0,1\}$ be transmitted with bit duration T_b . The optical field at the transmitter output can be expressed using the Jones vector formalism as

$$E_{tx}(t) = \sqrt{P_{tx}} J_k \rho(t - kT_b) \quad (1)$$

in which P_{tx} is the power that is transmitted, $\rho(t)$ is the normalized pulse shape, and J_k denotes the polarization state mapped to the k^{th} bit.

For different modulation formats:

For linear polarization, the polarization state $J(\theta)$ is represented by Jones vector

$$J(\theta) = \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} \quad (2)$$

where the polarization angle of orientation is denoted by " θ ".

Circular right-hand

$$J_{RCP} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -j \end{bmatrix} \quad (3)$$

Circular left handed

$$J_{LCP} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ +j \end{bmatrix} \quad (4)$$

Elliptical

An elliptically polarized wave's electric field is expressed as

$$J_{(\psi, \chi)} = \begin{bmatrix} \cos \chi \cos \psi + i \sin \chi \sin \psi \\ \cos \chi \sin \psi - i \sin \chi \cos \psi \end{bmatrix} \quad (5)$$

where ψ is the azimuth angle and χ is the ellipticity angle. Elliptical polarization is characterized by unequal amplitudes and a phase difference between two orthogonal electric-field components, providing an additional degree of freedom compared with purely linear polarization. This property enhances tolerance to polarization-state variations caused by scattering and turbulence in underwater channels [31]. Furthermore, previous studies have reported that underwater interfaces, bubbles, and multiple scattering processes can transform incident linear polarization into elliptical or circular states, demonstrating the practical relevance of such polarization modes in marine environments [32, 33].

3.2. Channel modeling in underwater

The underwater channel provides stochastic turbulence as well as deterministic attenuation. The received irradiance can be expressed as

$$I_r = h_\ell(\lambda, r) h_\tau \quad (6)$$

where $h_\ell(\lambda, r) = \exp[-c(\lambda)r]$ illustrates the exponential attenuation caused by scattering and absorption, with $c(\lambda) = a(\lambda) + b(\lambda)$ being the attenuation coefficient at

wavelength λ and r is the link distance [14],[15]. The term h_τ is modeled using log-normal or Gamma-Gamma statistics, representing turbulence-induced fading [18], [27].

The equivalent link loss in dB is

$$L_{dB}=4.343 C(\lambda) r \quad (7)$$

3.3. Stokes parameters and polarization detection

For a Jones vector $J=[E_x E_y]^T$, the four Stokes parameters are defined as [28]

$$\begin{aligned} S_0 &= |E_x|^2 + |E_y|^2, \\ S_1 &= |E_x|^2 - |E_y|^2, \\ S_2 &= 2 \operatorname{Re} \{E_x E_y^*\}, \\ S_3 &= 2 \operatorname{Im} \{E_x E_y^*\}. \end{aligned} \quad (8)$$

Practical analyzers provide photocurrents proportional

$$\begin{aligned} I_{0^\circ} &= \frac{1}{2}(S_0 + S_1), \quad I_{90^\circ} = \frac{1}{2}(S_0 - S_1), \\ \text{to } I_{+45^\circ} &= \frac{1}{2}(S_0 + S_2), \quad I_{-45^\circ} = \frac{1}{2}(S_0 - S_2), \\ I_R &= \frac{1}{2}(S_0 + S_3), \quad I_L = \frac{1}{2}(S_0 - S_3). \end{aligned} \quad (9)$$

Thus, Stokes estimates are obtained by subtraction, e.g.,

$$\hat{S}_1 = I_{0^\circ} - I_{90^\circ}, \hat{S}_2 = I_{+45^\circ} - I_{-45^\circ}, \hat{S}_3 = I_R - I_L \quad (10)$$

3.4. Decision variable and error probability

The decision statistic for PolSK using linear polarization states (using S_1) or PolSK using circular polarization (using S_3) is compared against zero. The quality factor is given by [27].

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad (11)$$

and the corresponding bit error rate is

$$\text{Ber} = \frac{1}{2} \operatorname{erfc} \left(\frac{Q}{\sqrt{2}} \right) \quad (12)$$

For EP-PolSK, the decision is performed in a two-dimensional subspace of the Poincare sphere, with

BER following the same form but computed along the optimum linear discriminate.

3.5. Hybrid log-normal–Gamma–Gamma fading model

The hybrid Log-Normal and Gamma-Gamma (LN–GG) model effectively characterizes composite turbulence in underwater wireless optical communication by capturing both weak and strong turbulence effects. This model provides a comprehensive representation of channel impairments for system performance evaluation by incorporating small-scale turbulence effects (scattering) and large-scale effects (beam wandering) across diverse aquatic environments, including clear, coastal, and turbid waters.

The general expression for irradiance fading is given as follows:

$$h = H_{LN} * H_{GG} \quad (13)$$

4. System design and methodology

Fig. 1(a) illustrates the proposed underwater wireless optical communication system based on polarization shift keying. Since green wavelengths experience relatively low attenuation in water, a continuous-wave (CW) laser operating at 520 nm is employed as the optical source. The emitted beam passes through a linear polarizer to establish a reference polarization state and is then divided into orthogonal vertical and horizontal components using a polarization beam splitter (PBS). Binary data are encoded into discrete polarization states by modulating each component with complementary electrical bit streams through amplitude modulators. As the optical beam propagates through the underwater Optical Wireless Channel (OWC), the combined effects of turbulence, scattering, and absorption lead to degradation of the received signal quality. At the receiver, a PBS separates the orthogonal polarization components, which are detected by PIN photodiodes. The resulting electrical outputs are processed using a differential subtractor circuit to enhance the signal-to-noise ratio (SNR) and suppress common-mode noise. The decision unit then analyzes the recovered signal, and system performance is evaluated in terms of bit error rate. By employing orthogonal polarization states, the proposed configuration enables polarization-based modulation, improves resilience to channel-induced impairments, and enhances detection reliability.

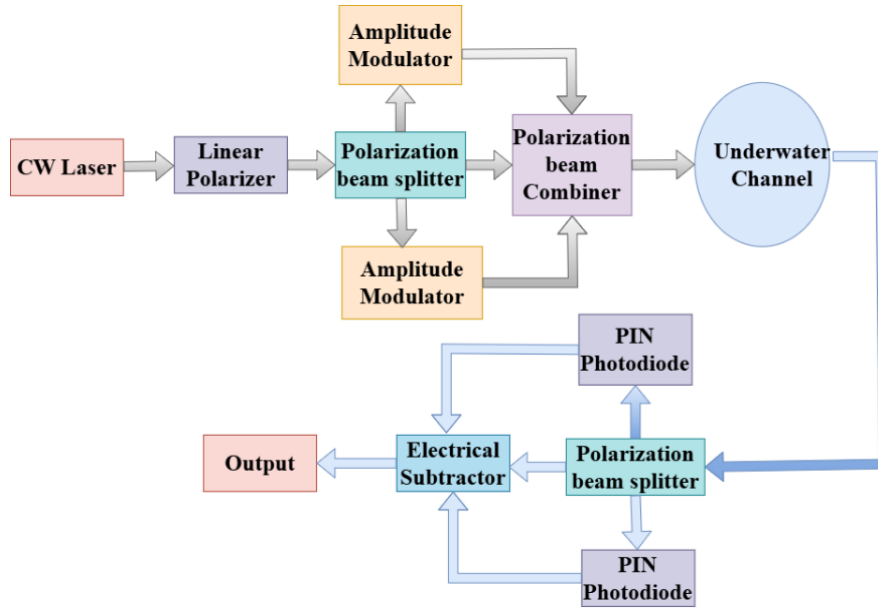


Fig. 1(a). Schematic diagram of the Linear Polarization Shift Keying based underwater wireless optical communication system, illustrating the transmitter, underwater channel, and receiver components (colour online)

4.1. OptiSystem simulation setup

Fig. 1(b) illustrates the OptiSystem simulation setup of the proposed UWOC system with linear polarization. The setup consists of a user-defined bit sequence generator,

laser source, linear polarizer, underwater optical channel, photodetector, filter and BER analyzer. The polarized optical signal is transmitted through a linear polarizer at orientation angles of 0° , 45° and 90° . System performance is evaluated in terms of BER and Q-factor.

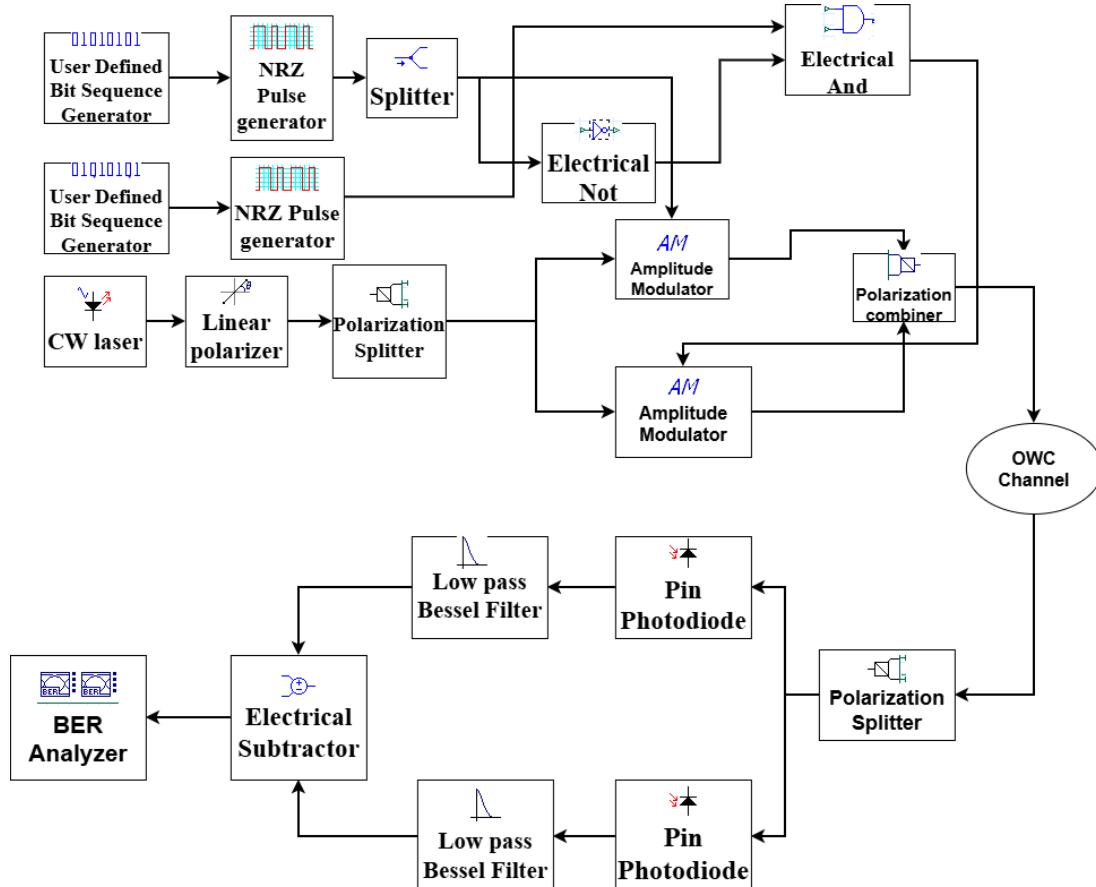


Fig. 1(b). OptiSystem simulation setup of the proposed linear polarization-based UWOC system under different underwater channel conditions (colour online)

4.2. Simulation parameters

The primary OptiSystem simulation parameters used to evaluate the proposed UWOC system are presented in Table 3. The system is evaluated under clear, coastal and turbid channel conditions at a data rate of 5Gbps over a 10 m underwater link using various polarization modes. The selected data rate is consistent with recent high-speed UWOC demonstrations reporting 5Gbit/s transmission using OFDM techniques and advanced beam engineering

[29]. The wavelength of 520 nm was selected as it lies within the blue-green transmission window of seawater, where optical attenuation due to absorption and scattering is relatively low. Within this spectral region, 520 nm provides a favorable balance between scattering and absorption effects, resulting in improved propagation performance. Consequently, it is widely used in UWOC systems for performance evaluation and enhanced link-reliability [5], [10], [30], [34, 35]. System performance is evaluated using Q-factor, BER and eye diagram metrics.

Table 3. Simulation parameters and data used for the performance analysis of the underwater wireless optical communication system

Parameter	Value	Notes
Wavelength (λ)	520 nm	Green optical window for UWOC
Laser line width	10 MHz	Source stability
Transmitter power	5 dBm	Optical launch power
Bit rate	5 Gbps	High-speed UWOC
Distance (m)	10 m	Fixed link Distance
Polarization Modes	Linear, circular Elliptical	Polsk modulation
Polarizer Orientations	0°, 45°, 90°	Linear polarization cases
Channel type	Optical wireless channel(OWC)	UWOC link model
Photo diode responsivity	0.8 A/W	Receiver sensitivity
Dark current	10 nA	Noise source
Simulation tool	OptiSystem 13	System-level simulation
Performance Metrics	Q-factor, BER, Eye diagram	Evaluated using BER analyzer in Opti System

Table 3 presents the simulation parameters used for the PolSK based UWOC system, including the operating wavelength, polarization configurations and performance evaluation metrics.

5. Results and discussion

The performance of polarization shift keying in underwater wireless optical communication systems is evaluated under clear, coastal and turbid water conditions. The analysis is conducted under hybrid fading conditions at a wavelength of 520 nm over a 10 m communication link. Key metrics, including Q-factor, bit error rate, and eye diagrams, are used to assess system performance with emphasis on different polarization modes (linear, circular and elliptical). The impact of linear polarizer orientations (0°, 45° and 90°) is also examined to analyze how different orientations influence signal quality and overall transmission performance.

5.1. Performance of linear polarization at different angles

Figs. 2–4 present the eye diagrams obtained using linear polarization at orientation angles of 0°, 45° and 90°. Among the examined cases, the 45° orientation provides the best overall communication performance in terms of signal quality, exhibiting optimal signal integrity, with the highest Q-factor of 7.75, the lowest BER of 3.42×10^{-15} and the largest eye height of 5.63×10^6 . The 0° orientation also demonstrates strong performance, achieving a Q-factor of 7.67 and a BER of 6.10×10^{-15} , indicating minimal inter-symbol interference and a clear eye opening. In contrast, the 90° orientation results in complete eye closure, with a BER of 1 and a Q-factor of 0, indicating severe polarization mismatch and communication failure. These results confirm the strong orientation sensitivity of linear polarization, with effective transmission at 0° and 45° and signal rejection at 90°. Table 4 summarizes the corresponding performance metrics.

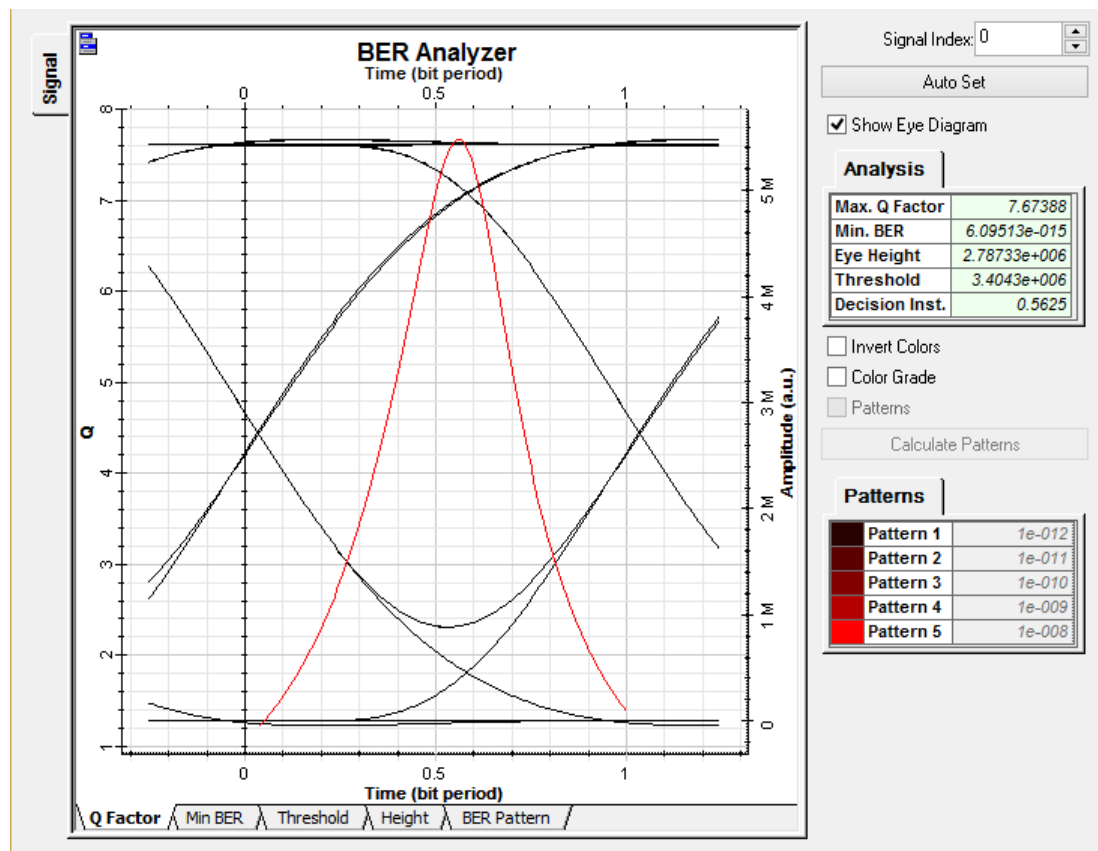


Fig. 2. Eye diagram of the underwater wireless optical communication system using a 0° linear polarizer (colour online)

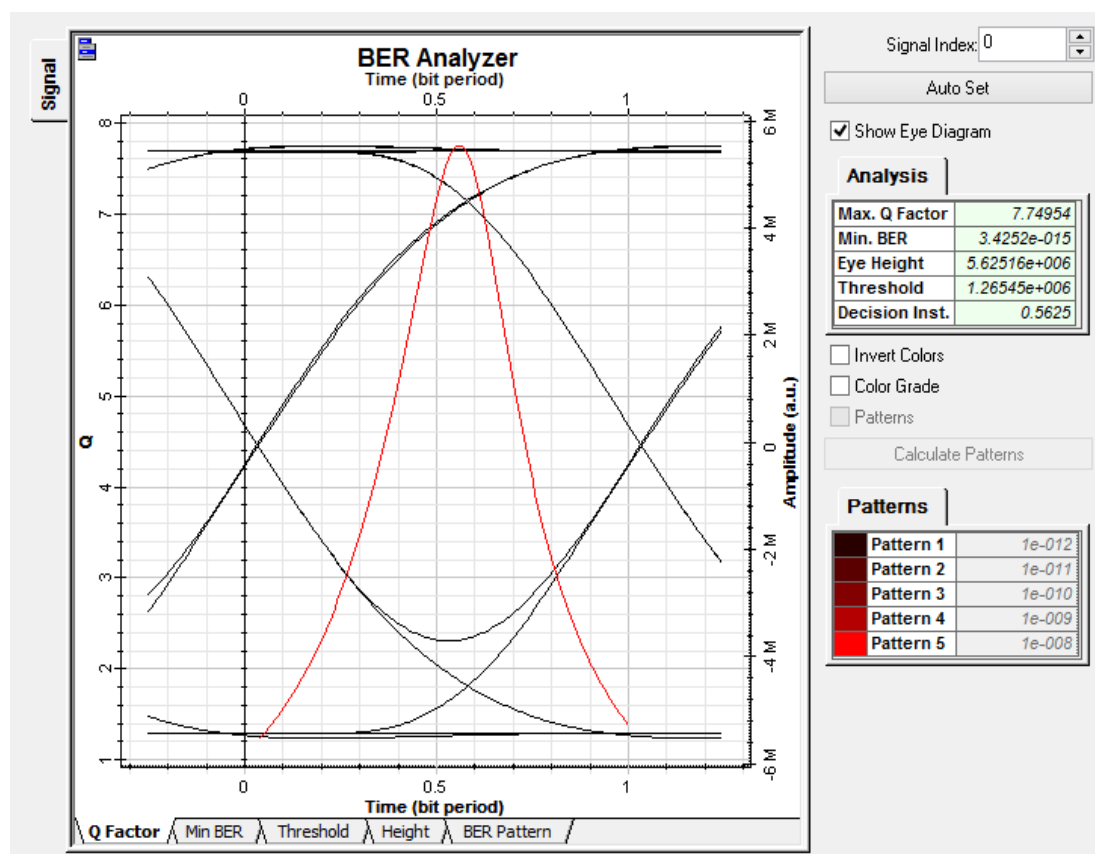


Fig. 3. Eye diagram of the underwater wireless optical communication system using a 45° linear polarizer (colour online)

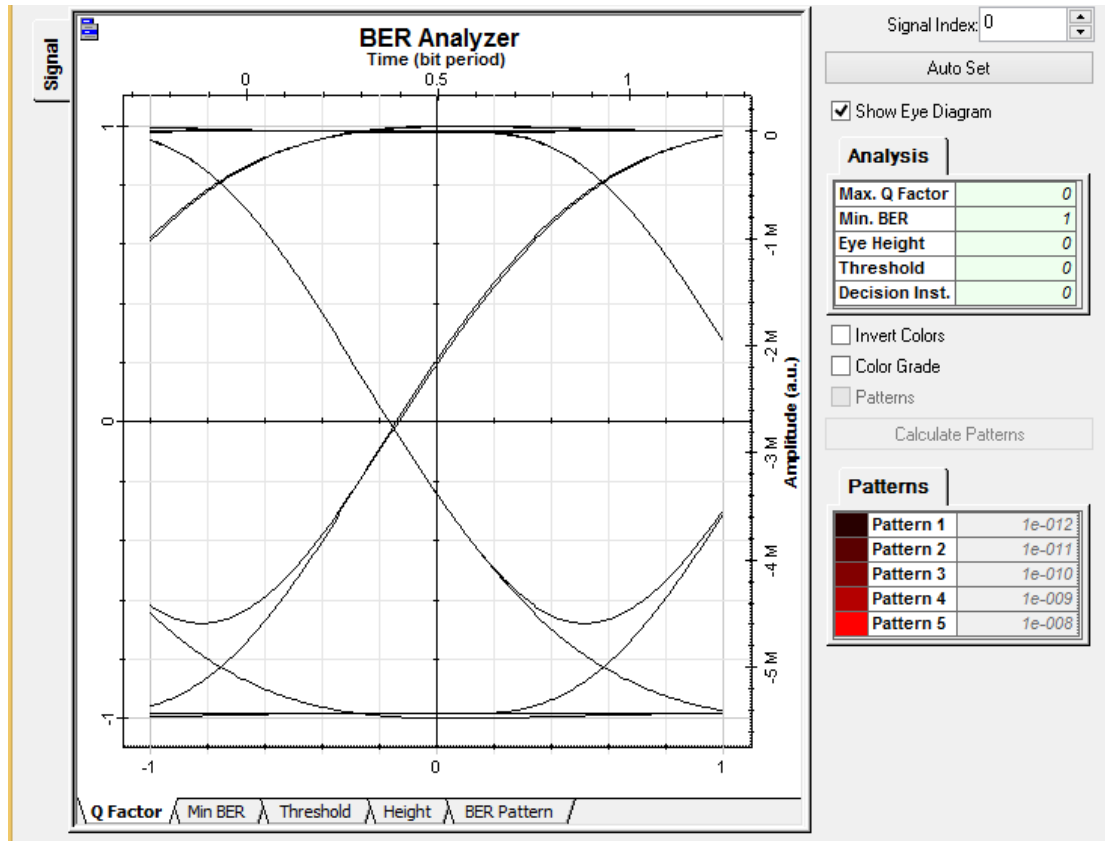


Fig. 4. Eye diagram of the underwater wireless optical communication system using a 90° linear polarizer (colour online)

Table 4. Performance metrics for different polarization states

Polarization Angle	Q- factor	BER	Eye height	Observation
linear polarization at 0°	7.67	6.10×10^{-15}	2.75×10^6	Low ISI, clear eye opening, and reliable transmission
linear polarization at 45°	7.75	3.42×10^{-15}	5.63×10^6	Optimal signal integrity with the lowest BER and highest eye opening
linear polarization at 90°	0	1.0	0	Communication breakdown due to polarization mismatch

5.2. Power efficiency calculation

The power efficiency of the proposed UWOC system was calculated using the ratio of received optical power to transmitted optical power, given by

$$\eta = \frac{P_r}{P_t} \times 100\% \quad (14)$$

where P_r is the received power P_t is the transmitted power

Power-efficiency analysis shows that the 0° linear polarization case achieves the highest received-power efficiency, whereas the 45° case shows slightly lower efficiency. However, despite the reduced received power, the 45° orientation achieves improved BER and Q-factor performance under the considered conditions. This indicates that system performance depends not only on received power but also on polarization alignment, channel effects, and noise characteristics.

5.3. SNR modeling and noise consideration

The signal-to-noise ratio of the proposed UWOC system is evaluated by considering both underwater channel attenuation and receiver noise contributions. The received optical power is estimated using the Beer–Lambert law as [36]

$$P_r = P_t e^{-cL} \quad (15)$$

where P_t is the transmitted optical power, c is the attenuation coefficient, and L is the transmission distance. The total noise variance is composed of multiple physical noise sources and is expressed as [36]

$$\sigma^2 = \sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2 + \sigma_{\text{bg}}^2 \quad (16)$$

where σ_{shot}^2 represents shot noise due to the discrete nature of photon detection, $\sigma_{\text{thermal}}^2$ corresponds to thermal noise originating from receiver electronics, and σ_{bg}^2 accounts for background noise caused by ambient light and bioluminescence in underwater environments. Based on these parameters, the SNR is defined in terms of the electrical signal after photo detection as [37].

$$\text{SNR} = \frac{(RP_r)^2}{\sigma^2} \quad (17)$$

where R is the photodetector responsivity. This formulation provides the baseline SNR under fixed channel conditions. To evaluate system performance over a wider range of operating conditions, the SNR is varied from 0 to 30 dB by

appropriately adjusting the noise variance relative to the signal power. For each SNR level, the corresponding noise variance is computed and applied to the received signal, enabling controlled performance evaluation. The resulting SNR values are then used to calculate the bit error rate and Q-factor, establishing a direct relationship between channel conditions and system performance.

5.4. Comparative Q-factor performance

Figs. 5–7 illustrate the variation of Q-factor with SNR for linear, circular, and elliptical polarization under different water conditions. In all cases, the Q-factor increases with SNR, indicating improved signal-to-noise separation. Linear polarization demonstrates a significant increase in Q-factor, particularly in clear water, where the polarization state is well preserved under low-scattering conditions. Circular polarization exhibits moderate performance with a steady increase in Q-factor, reflecting reduced sensitivity to polarization orientation fluctuations. Elliptical polarization achieves slightly higher Q-factor values in clear and coastal water, with a smooth and consistent trend under varying channel conditions. However, in turbid water, all polarization schemes experience significant degradation due to severe absorption and scattering effects. Overall, the results indicate that polarization performance is strongly influenced by channel conditions, with elliptical polarization providing marginally higher Q-factor under favorable conditions. Table 5 summarizes these trends.

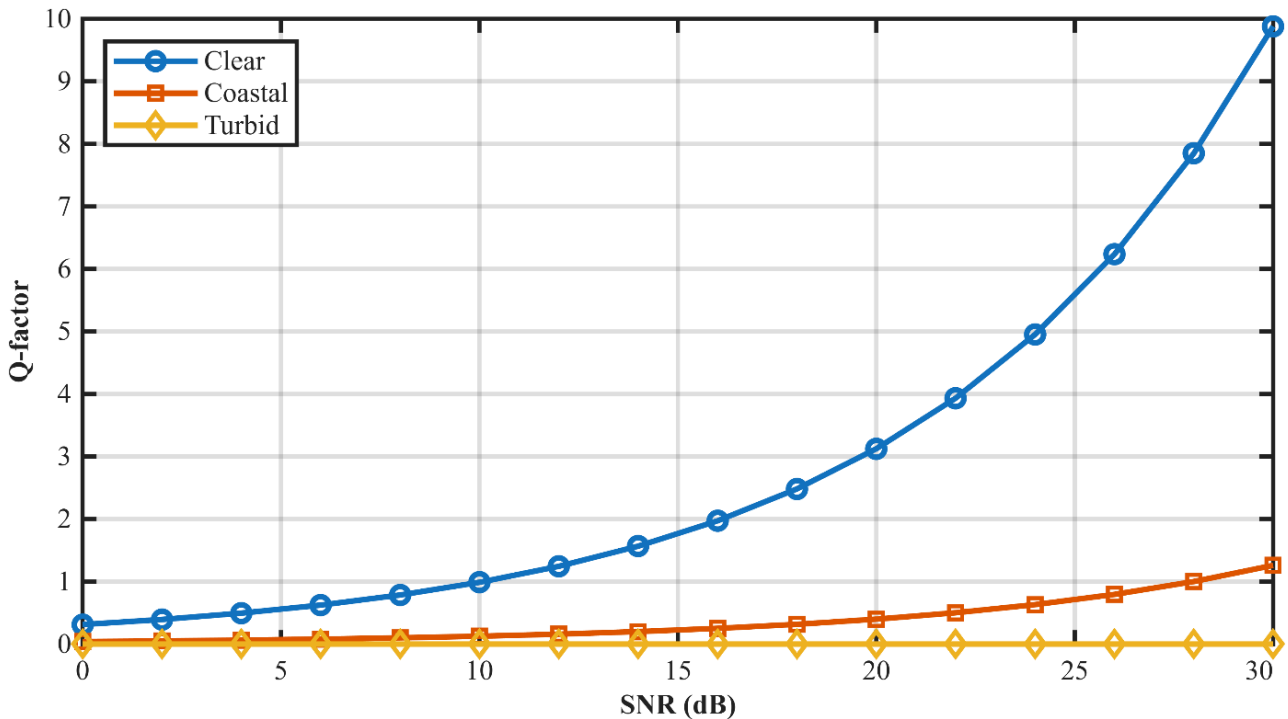


Fig. 5. Q-factor versus SNR for linear polarization in UWOC (colour online)

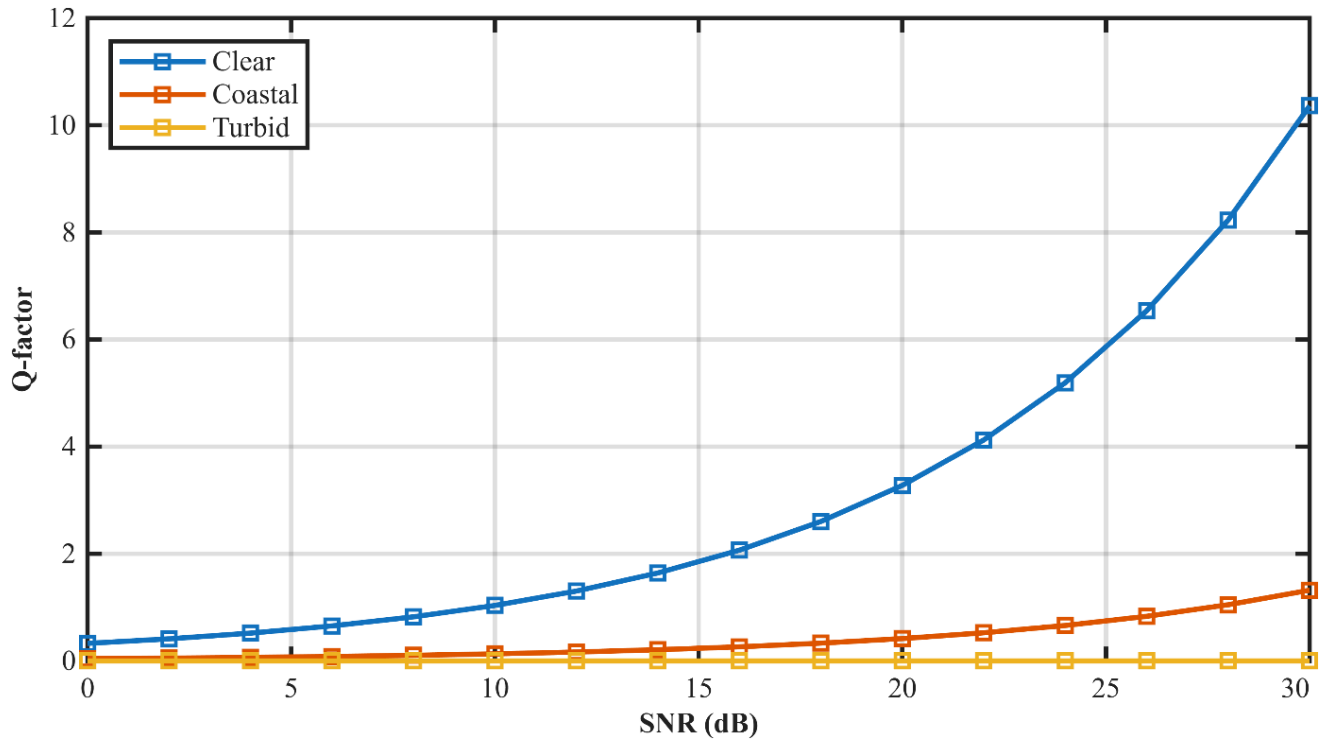


Fig. 6. Q -factor versus SNR for circular polarization in UWOC (colour online)

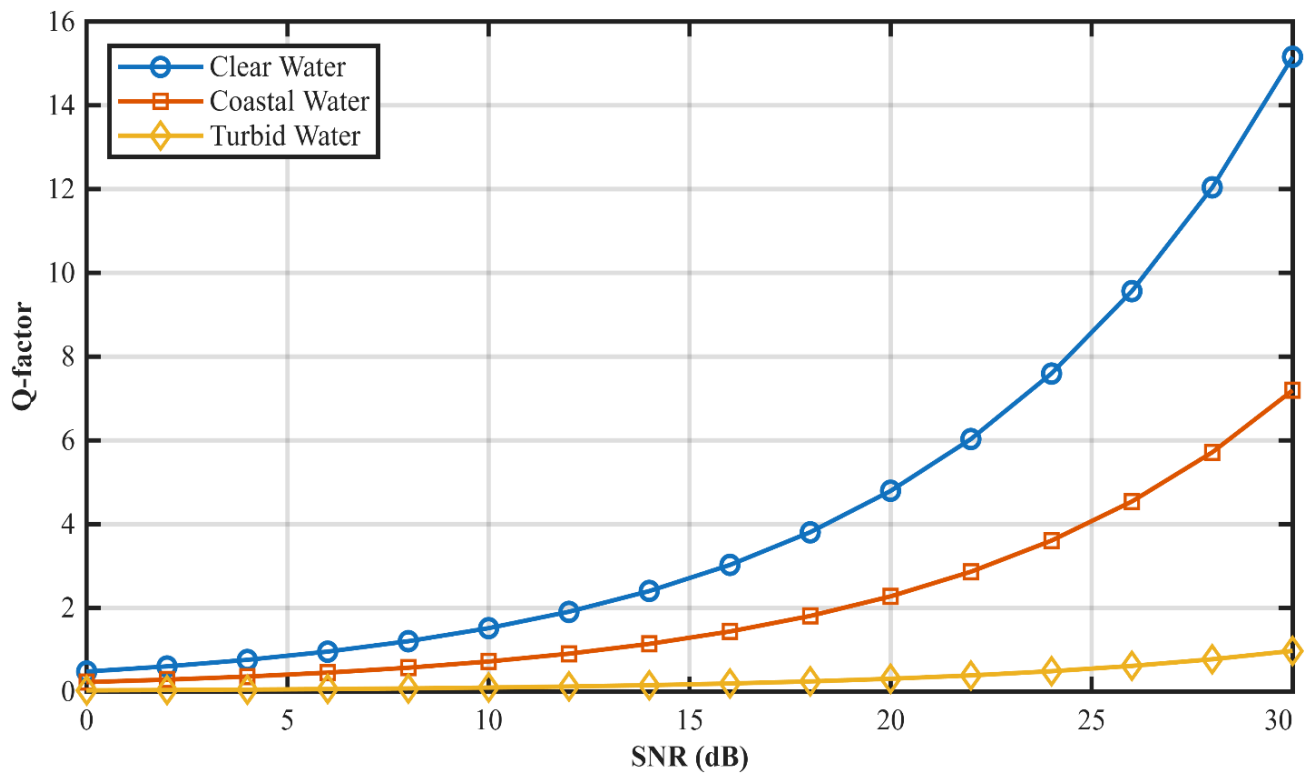


Fig. 7. Q -factor versus SNR for Elliptical polarization in UWOC (colour online)

Table 5. Trends in *Q*-factor for various polarization techniques in the underwater wireless optical communication system under hybrid fading channel conditions

Polarization mode	Clear Water (Q-Factor)	Coastal Water (Q-Factor)	Turbid Water (Q-Factor)
Linear polarization	Strong increase, reaches up to ~9	Moderate increase, up to ~1.3	Very low, (remaining close to 0)
Circular polarization	Lower than linear, steady increase	Moderate growth, slightly below linear	Very low, almost flat
Elliptical polarization	Slightly higher Q-factor under certain conditions, reaching up to ~15	Noticeable increase, up to ~6	Very low, almost flat

Table 5 summarizes the observed *Q*-factor trends for the three polarization techniques under different water conditions. Elliptical polarization generally provides slightly higher *Q*-factor values in clear and coastal water. In contrast, under turbid conditions, the *Q*-factor for all schemes remains low due to severe channel impairments.

5.5. BER analysis under hybrid fading

Figs. 8–10 illustrate the BER performance of linear, circular, and elliptical polarization as a function of SNR under different water conditions. In all cases, BER

decreases with increasing SNR, reflecting improved signal quality. Linear polarization achieves slightly better performance in clear water, particularly at higher SNR. Circular polarization exhibits a steady and moderate reduction in BER across all water types, indicating relatively uniform behavior. Elliptical polarization demonstrates a smooth and consistent decrease in BER, under varying channel conditions. Overall, the results indicate that system performance is primarily influenced by channel conditions, while the differences among polarization schemes remain relatively small.

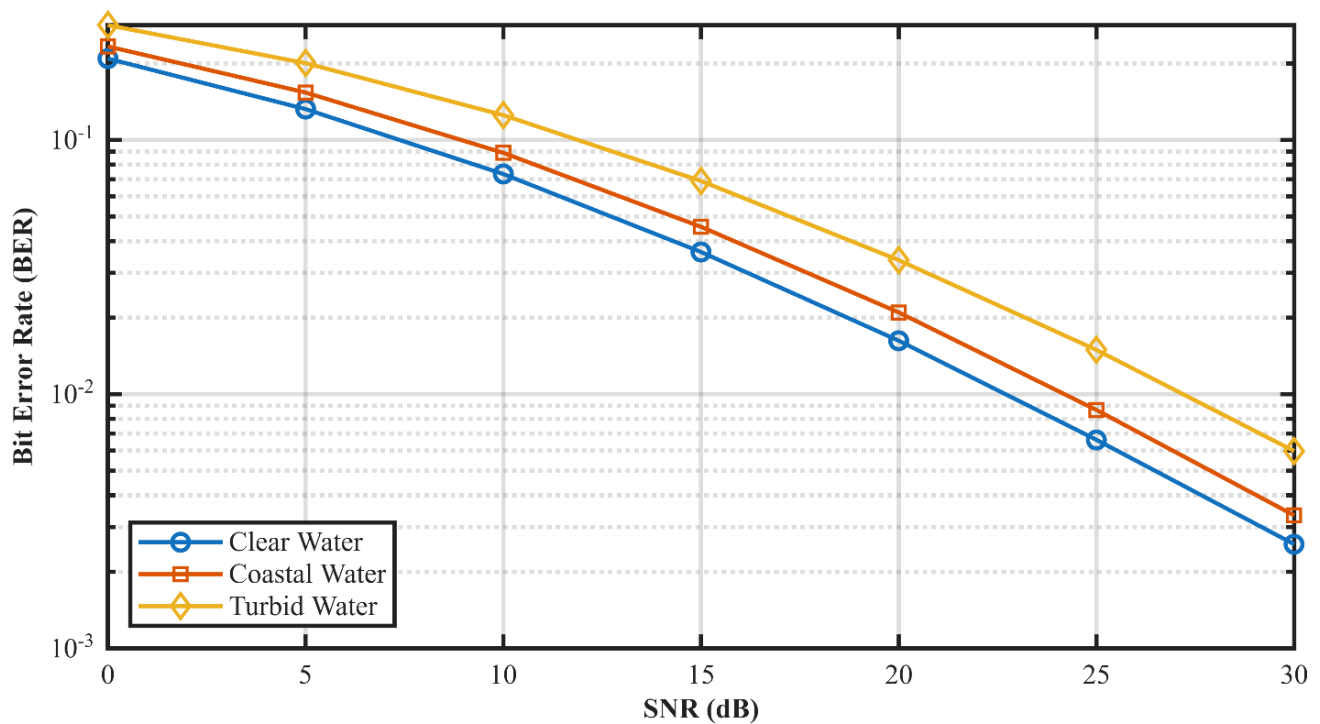


Fig. 8. BER vs. SNR for linear polarization in UWOC (colour online)

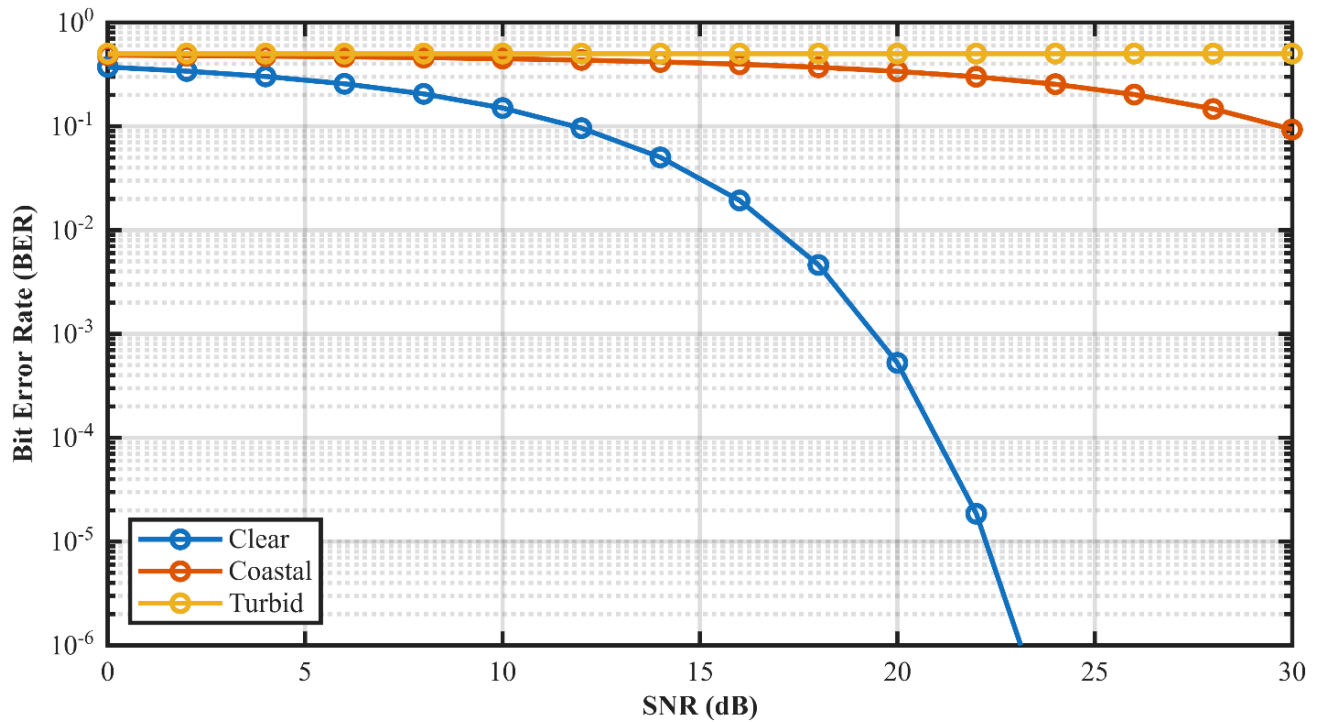


Fig. 9. BER vs. SNR for circular polarization in UWOC (colour online)

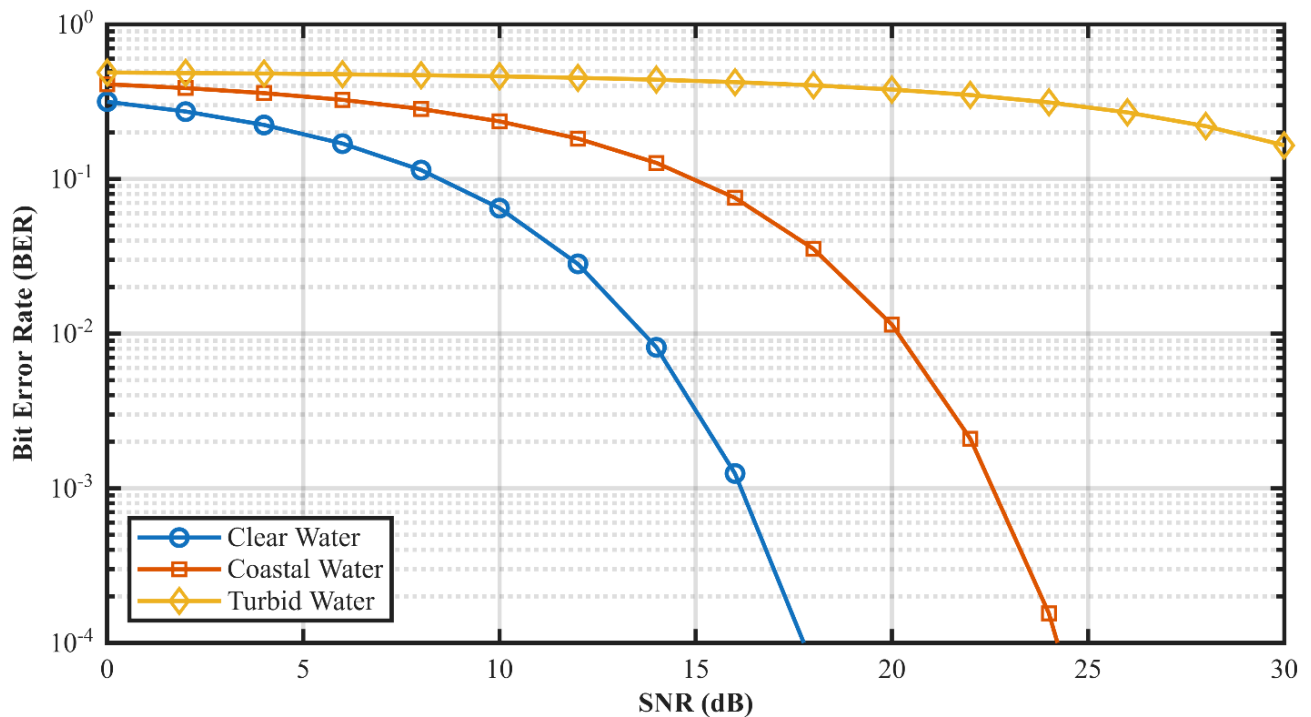


Fig. 10. BER vs. SNR for elliptical polarization in UWOC (colour online)

5.6. Comparative study of polarization schemes

Figs. 11 and 12 provide a direct comparison of BER and Q-factor for the three polarization schemes under identical environmental conditions. As expected, BER decreases and Q-factor increases with SNR across all water types. The best performance is observed in clear water,

followed by coastal and turbid conditions. Among the polarization schemes, linear polarization achieves slightly better BER performance at higher SNR, while elliptical polarization exhibits marginally higher Q-factor under favorable conditions. Circular polarization shows intermediate performance between the two.

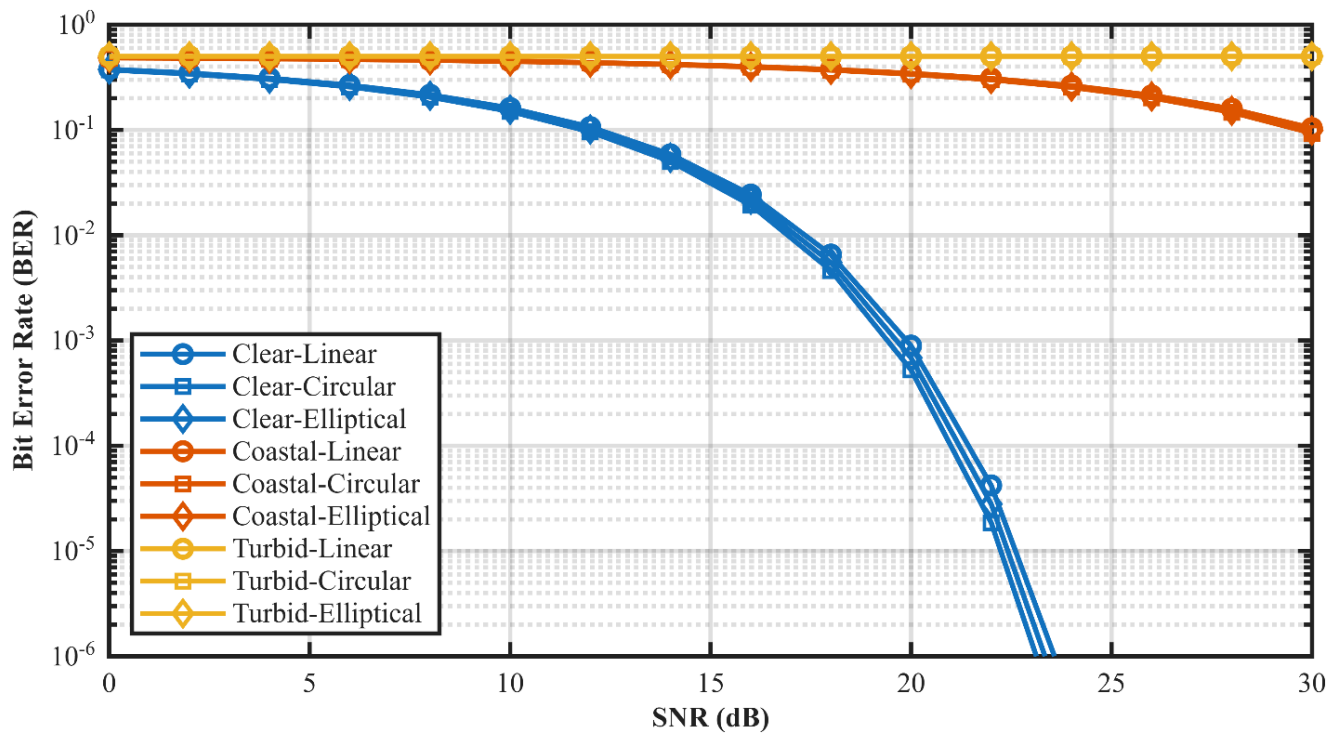


Fig. 11. BER vs. SNR for linear, circular and elliptical polarization in different water types (colour online)

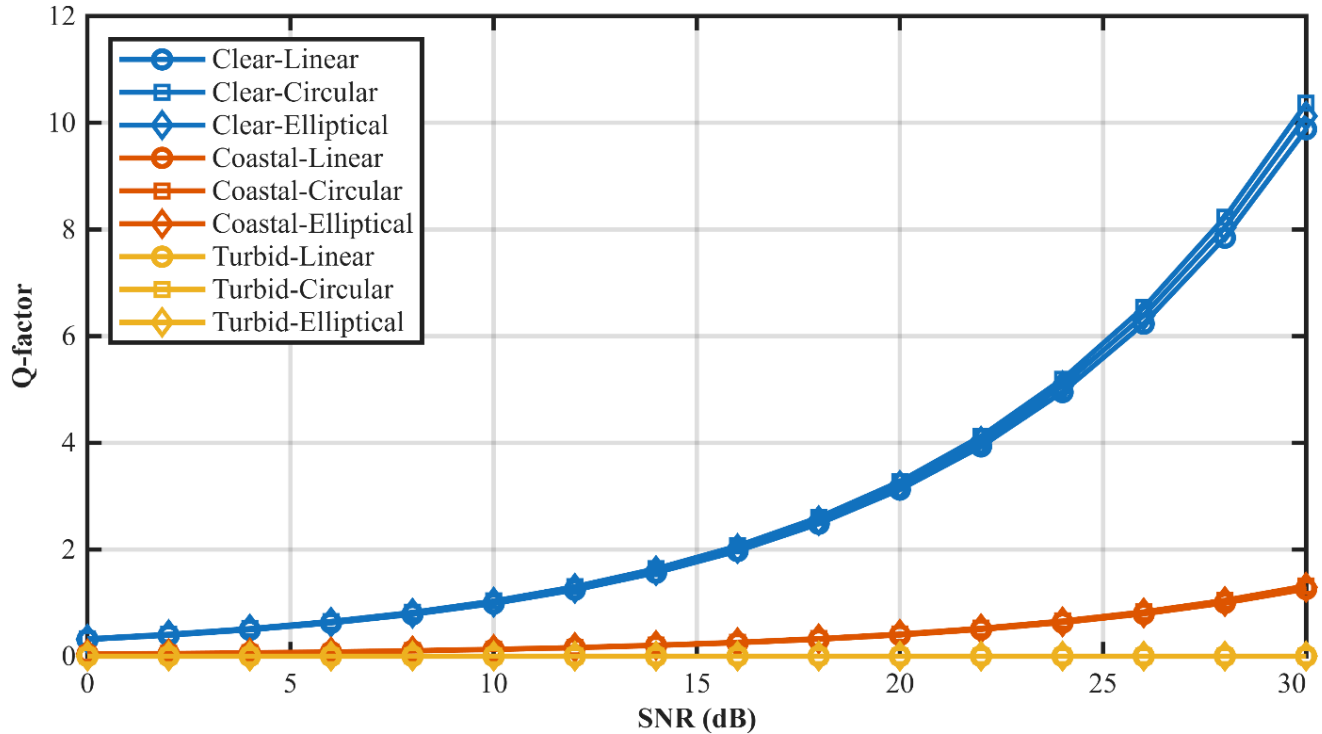


Fig. 12. Q-factor vs. SNR for linear, circular and elliptical polarization in different water types (colour online)

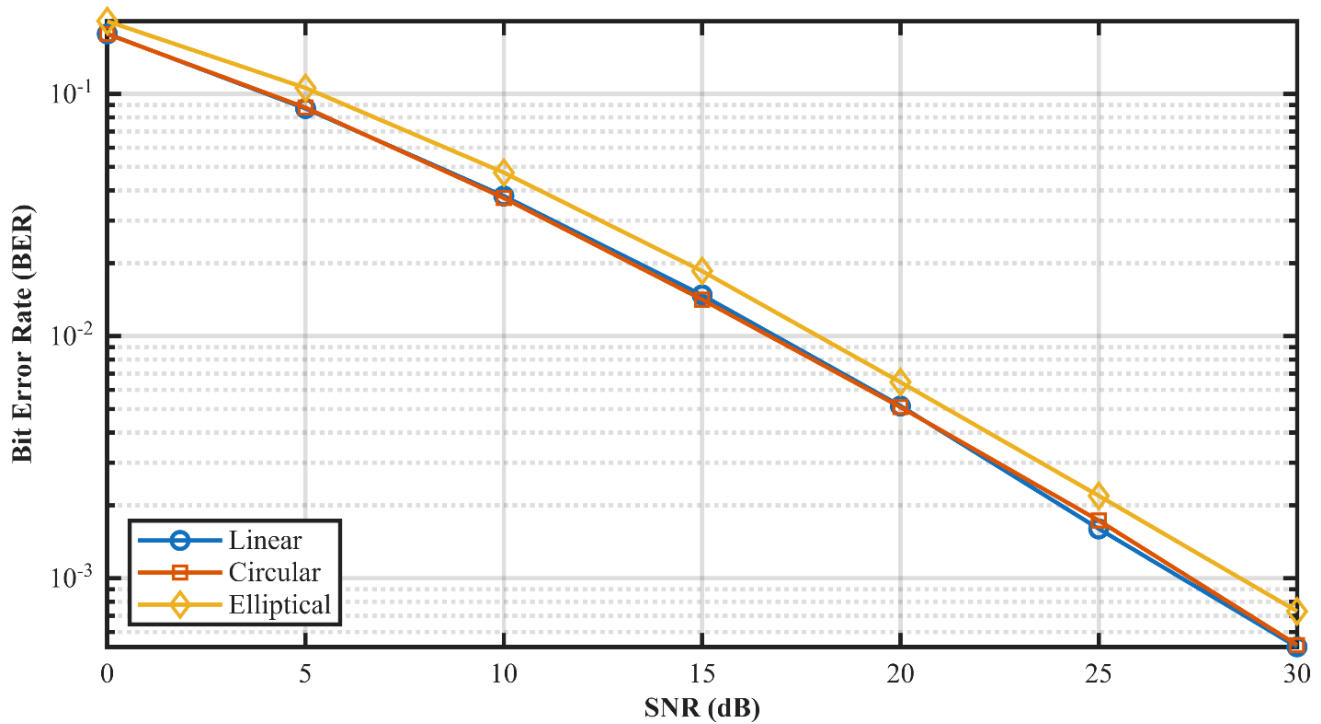


Fig. 13. BER vs. SNR for different polarization states in UWOC (colour online)

Fig. 13 illustrates the BER performance of linear, circular, and elliptical polarization as a function of SNR. As expected, the BER decreases with increasing SNR for all polarization schemes, indicating improved signal quality. Among the three schemes, linear polarization achieves slightly lower BER, particularly at higher SNR values. Circular and elliptical polarization exhibit comparable performance with marginal differences. Overall, the results indicate that all polarization schemes provide similar BER performance under the considered conditions, with linear polarization offering a slight advantage.

5.7. BER performance versus transmission distance

Fig. 14 illustrates the variation of bit error rate as a function of transmission distance for clear, coastal and turbid water environments. As the propagation distance increases, the received optical power decreases exponentially due to absorption and scattering effects, as

described by the Beer–Lambert law. This reduction in received power leads to a degradation in the signal-to-noise ratio, which in turn results in an increase in BER. Among the considered water types, clear water exhibits the best performance due to its low attenuation coefficient, maintaining very low BER over longer distances. Coastal water shows moderate degradation, while turbid water experiences a rapid increase in BER due to severe absorption and scattering losses. In highly turbid conditions, the received signal becomes significantly attenuated, causing the BER to approach unity even at relatively short distances. These results clearly demonstrate that UWOC system performance is strongly dependent on water clarity. Furthermore, the observed trends are influenced by both channel attenuation and receiver noise contributions, as modeled in Section 5.3. To maintain reliable communication in coastal and turbid environments, performance enhancement techniques such as increased transmit power, spatial diversity or forward error correction may be required.

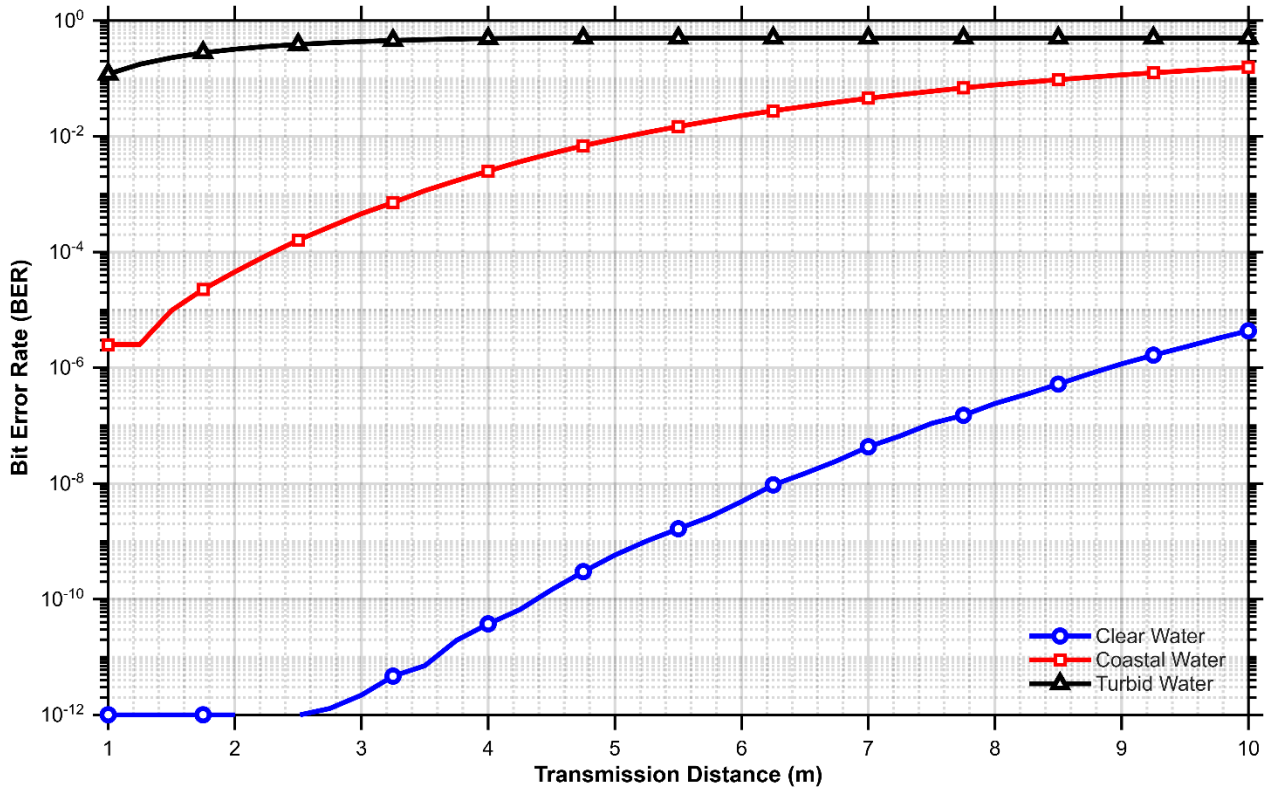


Fig. 14. BER vs. distance for clear, coastal and turbid water (colour online)

5.8. Comparative analysis with existing UWOC systems

Table 6 compares the proposed UWOC system to existing approaches.

Table 6. Comparison of existing polarization based UWOC systems with the proposed PolSK scheme under hybrid fading channel conditions

Ref.	Method	Performance	Limitation	Relevance to This Work
Cox et al. [21]	Basic PolSK, experimental UWOC	Mbps, short-range (~few m)	No fading model; limited data rate	This work incorporates hybrid fading and evaluates performance at 5 Gbps.
Ye et al. [22]	PolSK under turbulence channel	Mbps, short-range	Single channel condition considered	This work evaluates performance across multiple water types (clear, coastal, turbid).
Liu et al. [10]	Multilevel PolSK with Gamma turbulence	312.5–625 kbps /15 m	Limited polarization optimization	This work analyzes multiple polarization states with improved BER performance.
Dong et al. [12]	ANN-equalized experimental UWOC	1Gbps over 250 m	High computational complexity; BER near FEC threshold	This work provides a lower-complexity polarization-based approach.
Liu et al. [13]	OOK-based green laser UWOC	2.7Gbps over 34.5 m	No polarization diversity considered	This work investigates polarization diversity effects on BER.
Han X et al. [29]	Pin-like beam with OFDM, experimental UWOC	5Gbps, short-range	Requires SLM beam shaping hardware	This work avoids complex beam shaping by using polarization diversity (linear, circular, and elliptical states) and evaluates their impact on BER under hybrid fading conditions.
This Work	PolSK (linear, circular, elliptical), hybrid fading	5Gbps over 10 m	Simulation-based validation	Achieves BER $\approx 10^{-15}$ with comparative analysis across multiple water conditions.

Previous research has primarily focused on increasing transmission distance or simplifying channel modeling, often at the expense of higher receiver complexity or reduced data rates. In contrast, the proposed approach incorporates polarization diversity along with a hybrid log-normal and Gamma–Gamma fading model, enabling a more realistic system-level evaluation. The system employs a relatively simple receiver architecture and achieves BER values of 10^{-15} at a data rate of 5Gbps. These results demonstrate that the proposed system provides an effective trade-off between system complexity, data rate and communication reliability under varying channel conditions, particularly when compared to existing approaches that rely on more complex hardware or simplified channel assumptions.

6. Conclusion

Polarization shift keying in underwater wireless optical communication is investigated using linear, circular and elliptical polarization under hybrid log-normal and Gamma–Gamma fading conditions for clear, coastal and turbid water environments. A 10 m optical link operating at 520 nm is considered. The results demonstrate that system performance is strongly influenced by water type, polarization state and alignment conditions, with clear water providing the most favorable transmission environment. Linear polarization achieves the best performance under well-aligned conditions, reaching a Q-factor of 7.75 and a BER of 3.42×10^{-15} , but shows high sensitivity to misalignment. Circular polarization provides moderate performance, while elliptical polarization exhibits comparable performance under channel impairments. In addition, BER increases with transmission distance for all water types, with clear water maintaining lower error rates and turbid water experiencing rapid degradation. Overall, these results highlight the importance of polarization selection in improving UWOC system performance under varying channel conditions.

7. Future scope

The study highlights significant insights into polarization's role in Underwater Wireless Optical Communication while suggesting several future research directions: 1) developing adaptive polarization control mechanisms for diverse water types; 2) enhancing system performance using MIMO and polarization diversity; 3) employing adaptive modulation and machine learning for real-time channel optimization in dynamic environments; 4) conducting experimental validations in maritime test beds to bridge the simulation-practice gap; and 5) expanding polarization-based UWOC systems to broader ranges, various wavelengths, and advanced coding techniques. These initiatives aim to optimize polarization's contributions and advance dependable, fast, and energy-efficient underwater optical networks.

Disclosures

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that could have influenced the objectivity of this research or the writing of this paper

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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