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Modeling and Analysis of Underwater Optical Wireless Communication Channels

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Abstract – Underwater Optical Wireless Communication (UOWC) has emerged as a highly efficient method for high-speed, low-latency data transfer in underwater environments, driven by the growing demand for applications in environmental monitoring, underwater exploration, disaster prevention, and military operations. The deployment of UOWC systems, however, faces significant challenges due to the underwater medium's inherent complexities, including light absorption, scattering, and turbulence-induced fading. This paper offers an in-depth analysis and modeling of UOWC channels, employing theoretical and simulation-based approaches to evaluate critical channel parameters. Key factors such as water type, attenuation coefficients, scattering properties, and turbulence effects—modeled through log-normal, Gamma-Gamma, Generalized Gamma, and Weibull fading distributions—are analyzed to characterize signal propagation accurately. Using a 450 nm blue laser diode-photo-source (LD-PS) and an avalanche photodetector with a receiver sensitivity of -35 dBm, the study evaluates the performance of UOWC systems employing OOK modulation techniques under various environmental conditions. Comprehensive noise modeling includes thermal noise, dark noise, shot noise, and ambient light noise, all of which significantly influence communication reliability. The paper focuses on critical output metrics such as bit error rate (BER) and received power to assess system performance. Simulation results emphasize the challenges of achieving robust communication over extended distances and varying turbidity levels. By examining the interplay between optical path loss, turbulence-induced fading, and noise contributions, this work advances the understanding of underwater optical channels and provides valuable insights for optimizing UOWC system design. These findings lay the groundwork for future underwater communication systems that leverage optical signals for enhanced performance and reliability.

Keywords: Underwater Optical Wireless Communication (UOWC), Channel Modeling, Signal Propagation, Environmental Effects, Optical Transmission.

I. Introduction

Underwater communication has become a critical component in various applications such as environmental monitoring, underwater exploration, oceanographic research, military operations, and disaster prevention [1]-[3]. These applications demand high-speed, secure, and reliable communication systems to operate effectively in underwater environments. While acoustic waves have been the traditional medium for underwater communication due to their ability to travel long distances through water, they are limited by low data transmission rates, high latency, and significant bandwidth constraints [3],[4]. The increasing need for higher-speed data transfer, coupled with the growing interest in the Internet of Underwater Things (IoUT), has led to the exploration of optical wireless communication (OWC) systems as a promising alternative [5],[6].

OWC is recognized as a viable solution in air and free space for high-throughput communication, and there is considerable potential to leverage it in underwater environments. UOWC, unlike its acoustic counterpart, can support much higher data rates, smaller form factors, and lower latency [7]-[10]. However, UOWC systems face several significant challenges that differ from those in terrestrial optical communication, making the modeling and analysis of underwater optical channels a critical research area.

Water itself presents a unique set of challenges for optical signals. Optical waves in the underwater medium undergo significant attenuation due to scattering, absorption, and other environmental factors [11],[12]. The propagation of optical signals is highly dependent on the water type (e.g., clear, turbid, or saline water), depth, temperature, and the presence of particulate matter or dissolved substances [13]. These environmental variations significantly affect the performance of UOWC systems and necessitate precise channel modeling and analysis to understand signal behavior and optimize system design. Additionally, underwater optical channels are subject to turbulence, which can distort optical wavefronts, further complicating the modeling process.

The primary motivation for this work stems from the growing importance of UOWC in applications where high-bandwidth, low-latency, and secure communication is paramount. Accurate channel modeling and analysis are essential for predicting the performance of UOWC systems under varying environmental conditions, aiding in the design of robust and efficient systems. By understanding the underlying propagation mechanisms, communication engineers can design optimal optical transceivers, signaling schemes, and modulation techniques that maximize data throughput and minimize signal degradation.

I.1. Motivation

Several factors motivate the need for improved modeling and analysis of underwater optical wireless channels:

- Limitations of Acoustic Communication: Acoustic communication is slow, has low bandwidth, and suffers from multipath interference and high signal loss over longer distances, making it unsuitable for high-speed underwater communication.
- Growing Demand for High-Speed Communication: In applications like underwater robotics, oceanic research, and autonomous underwater vehicles (AUVs), the demand for higher data rates and lower latency is growing, making optical wireless channels an attractive alternative.
- Turbulence and Dynamic Environment: Underwater environments are subject to rapid changes in conditions, such as water turbulence, current variations, temperature gradients, and salinity differences. These factors require the development of dynamic channel models that can accurately represent the changing medium.
- Potential for Advancing IoUT: As the concept of an interconnected ecosystem of underwater devices evolves, UOWC systems are essential to the infrastructure of IoUT, where real-time data transmission from submerged sensors is critical.
- Integration with Emerging Technologies: The growth of next-generation optical devices, such as high-efficiency photodetectors and LED light sources, presents an opportunity to enhance the reliability and efficiency of UOWC systems.

I.2. Key Contributions

This work makes several key contributions toward advancing the understanding of underwater optical wireless communication:

1. Development of a Comprehensive Channel Model: This paper proposes a detailed model that accounts for both the static and dynamic parameters influencing optical signal propagation in underwater environments. Key parameters, such as water turbidity, attenuation coefficients, scattering, and absorption, are incorporated into the model.
2. Inclusion of Turbulence Effects in Channel Modeling: For the first time, the paper incorporates the effects of underwater turbulence (caused by currents and environmental changes) on the propagation of optical signals, an important but often neglected factor in previous research.
3. Environmental Factor Analysis: A systematic study of how varying water types (e.g., clear, saline, and murky) impact channel performance, including their attenuation characteristics and scattering coefficients, is provided. The work offers comprehensive comparisons and predictions on the impact of different environmental conditions on optical communication.
4. Simulation Framework for UOWC Systems: The paper presents a simulation framework designed to evaluate and visualize how different environmental conditions affect underwater optical signal propagation. This includes a thorough evaluation of path loss, received power, and channel capacity over a range of underwater depths and distances.
5. Performance Analysis under Varied Conditions: Extensive simulations are performed to assess the overall performance of UOWC systems, including the analysis of optical signal strengths, data rate reliability, received power and BER under the effects of scattering, attenuation, and turbulence.
6. Recommendations for System Design and Optimization: Practical guidelines for optimizing the design of UOWC systems are derived, offering suggestions on transceiver configurations, suitable wavelength choices, and adaptive modulation schemes to improve performance in real-world underwater environments.

By exploring these fundamental aspects of underwater optical wireless channels, this work provides essential insights for improving the design and performance of future UOWC systems, advancing the field, and supporting the critical applications of underwater communication in a range of scientific, industrial, and military domains.

The structure of this paper is organized as follows: **Section II** outlines the foundational concepts that underpin the study and offers a comprehensive review of the current state-of-the-art research in UWOC. **Section III** illustrates the block diagram of the proposed system, delineating the core components and their interrelations. **Section IV** delves into the classification of water types, examining their distinctive optical properties and how they influence UWOC system performance. In **Section V**, a detailed overview of the proposed system architecture is presented, encompassing the structural and design principles tailored to enhance underwater communication. **Section VI** describes the proposed system model, elucidating the methodology and framework adopted to achieve reliable performance. **Section VII** focuses on aquatic channel modeling, providing insights into the physical phenomena, equations, and modeling techniques employed to represent underwater communication channels accurately. **Section VIII** introduces the simulation parameters, specifying the configuration and conditions used to evaluate the system’s performance under diverse scenarios. **Section IX** provides an in-depth analysis and discussion of the simulation results, emphasizing key findings and their practical implications. Finally, **Section X** concludes the study by summarizing the main contributions and offering suggestions for future research directions in the field of UWOC systems.

II. Foundational Concepts and Literature Review

The modeling and analysis of underwater optical wireless channels involve understanding the unique challenges posed by the underwater environment, including light attenuation, scattering, and turbulence. Previous research has focused on developing theoretical models to describe signal propagation in various water conditions, highlighting the impact of environmental factors such as water type and turbidity. Key studies have explored optical communication techniques, channel impairments, and performance metrics like path loss, BER, and SNR in underwater settings. This work builds upon these foundational concepts to improve the accuracy and reliability of underwater optical communication systems. The literature review of this paper is summarized as follows:

The study in [14] reviewed the evolution and key characteristics of OWCs, focusing on the impact of optical carriers, range, mobility, and power efficiency on system performance. It examined the main optical channel factors affecting link performance, such as DC gain, RMS delay spread, frequency response, path loss, and shadowing. The study covered various communication environments, including indoor, outdoor, underwater, and underground settings, and compared existing OWC channel models based on their speed, complexity, and accuracy. The survey concluded by highlighting the need for further measurement campaigns and the development of more realistic channel models for practical implementation.

According to [15], this study investigated underwater optical channel modeling, focusing on the channel impulse response and time dispersion under varying water types, link distances, and transmitter/receiver parameters. Using Monte Carlo simulations, the study simulated photon trajectories and showed that, in most practical scenarios, time dispersion is negligible and does not cause inter-symbol interference (ISI). The model demonstrated that even for distances up to 50 meters in clear water, the channel is effectively frequency non-selective, eliminating the need for complex signal processing like channel equalization at the receiver.

The authors of [16] developed a comprehensive UWOC channel model that simultaneously considers absorption, scattering, and turbulence effects in seawater. By combining Monte Carlo simulations with multiple phase screen approaches, the study explored the impacts of various system and channel conditions. The results revealed that increasing turbidity and turbulence intensities caused greater dispersion in the received light signal's probability density function. Additionally, turbulence introduced a path loss increase of about 5 dB and resulted in a 50% decrease in the channel impulse response peak, along with noticeable temporal spread.

As noted in [17], this study introduced an innovative composite channel model that incorporates multi-size bubbles, absorption, and fading caused by scattering, based on Mie theory, geometrical optics, and the absorption-scattering model within the Monte Carlo framework. The simulations analyzed how the number, size, and position of bubbles affected the optical communication system’s performance. Results showed that a higher number of bubbles led to greater attenuation, reducing received power, increasing the channel impulse response, and highlighting a prominent peak in the scattering function. The findings indicated that both bubble- and particle-induced scattering must be considered in designing reliable underwater optical wireless communication links.

Ref. [18] evaluated the performance of wireless optical communication (WOC) in terms of received optical power for both air and water as channel mediums. Experimental results showed that received optical power decreases with increasing channel length, with a greater degradation observed in water compared to air. The presence of air bubbles further degraded the performance of UWOC. Mathematical modeling of the UWOC channel was performed, and the experimental and theoretical results were found to be in good agreement, confirming the higher attenuation and performance loss in water and with bubbles.

In [19], this paper proposed a system model for UOWC that considered turbulence, scattering, absorption, and noise effects, including shot, thermal, and background noise. The model was evaluated across three types of water: clear, coastal, and harbor, over an 8-meter transmission span. Results showed that link performance degraded in less-clear waters and under turbulence with increasing transmission distance. The BER for clear and coastal waters remained near zero, while for harbor waters, it was $4.1{\times}10^{-3}$. The study also demonstrated acceptable BER levels up to 30m, 15m, and 6m for clear, coastal, and harbor waters, respectively.

The authors of [20] focused on underwater optical communication by analyzing the optical path and refractive index of different water types. The receiver signal power was calculated using the free-space optical communication formula, considering factors like link margin, data rate, and SNR as functions of distance and water refractive index. Results showed that as the refractive index and distance increased, the data rate and SNR decreased. Pure and clean water exhibited the highest received signal power, link margin, and data rate compared to other water types. The study highlighted that lower refractive indices improve SNR and system performance.

As reported in [21], this study developed a closed-form path loss expression for underwater visible light communication (UVLC) systems, considering factors like water type, beam divergence angle, and receiver aperture diameter. The expression, a modification of the Beer-Lambert formula, accounted for scattered rays' geometrical propagation. Validated through Monte Carlo simulations, the results showed that in clear conditions, transmission ranges of up to 43.95 meters were achievable. However, in more turbid waters, such as coastal and harbor waters, the achievable range decreased significantly. The study also explored the effect of water turbidity on maximum link distances for UVLC systems.

The study in [22] investigated the impact of different statistical distributions (lognormal, gamma, K, Weibull, and exponentiated Weibull) on fading in UWOC systems. A general channel model incorporating absorption and scattering was used, and turbulence effects were included as a multiplicative fading coefficient. The study derived closed-form expressions for average BER and outage probability. Results showed that as turbulence strength (scintillation index) increased, the gap between performance predictions from different distributions widened, especially in the slope of the BER and outage probability curves. These findings highlight the need for accurate channel models in UWOC system design.

As noted in [23], this study investigated the performance of UWOC links, considering turbulence, absorption, and scattering effects. Weak turbulence was modeled with a log-normal distribution, while moderate and strong turbulence used a gamma-gamma distribution. The Rytov variance for oceanic turbulence and the scintillation index were derived, and closed-form expressions for BER were obtained. Results showed that turbulence, along with absorption and scattering, significantly degraded performance, with the effects of turbulence becoming comparable to absorption and scattering at higher levels. Various system parameters and underwater medium conditions were analyzed, emphasizing the need for mitigation techniques like adaptive optics, spatial diversity, and aperture averaging to maintain acceptable BER in practical UWOC systems.

The authors of [24] modeled vertical UVLC links, considering ocean stratification due to varying temperature and salinity with depth. The link was modeled as a cascaded fading channel with independent fading coefficients for non-mixing layers. Closed-form expressions for BER were derived using lognormal and Gamma-Gamma distributions for weak and moderate/strong turbulence. The study showed that assuming constant turbulence strength for vertical links leads to inaccurate BER estimates. The diversity gain was analyzed, revealing its dependence on the minimum effective number of large-/small-scale cells in cascaded channels. Additionally, closed-form expressions for average ergodic capacity were derived, and the impact of layering on capacity was investigated.

Our current study focused on modeling and analyzing UOWC channels to address challenges like light absorption, scattering, and turbulence. It evaluated key factors such as water type, attenuation coefficients, and noise impacts on signal propagation. Using theoretical and simulation methods, the study examined channel parameters and their effects on UOWC system performance. Results highlighted significant challenges in maintaining reliable communication over long distances under various environmental conditions, providing valuable insights for optimizing UOWC system design and advancing underwater communication technologies.

III. The Proposed System Block Diagram

Figure 1 illustrates the block diagram of the essential components of an UWOC system.

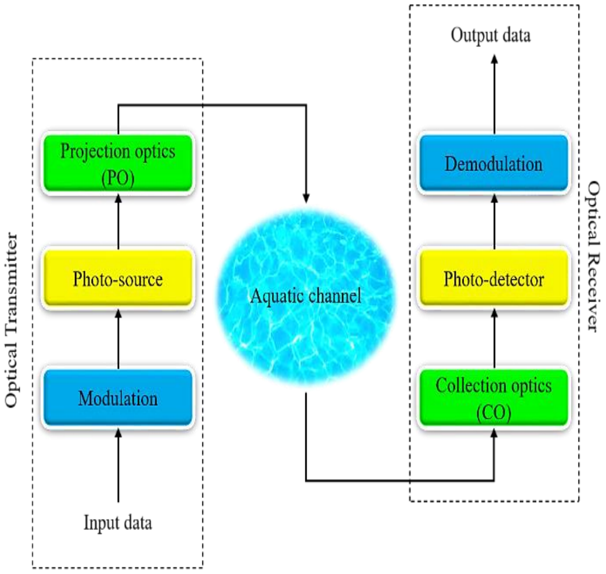

Fig.1. The block diagram of the UWOC system

The block diagram illustrates the essential components of an UOWC system, detailing the systematic flow of signal transmission and reception in underwater environments. The process begins with modulation, where raw data, such as multimedia or sensor readings, is transformed into a suitable signal format for optical transmission. Common modulation techniques like OOK, Pulse Position Modulation (PPM), or Quadrature Amplitude Modulation (QAM) prepare the data to interact efficiently with the photo-source.

The photo-source acts as the light emitter, typically a laser or LED, chosen for its wavelength (commonly in the blue-green spectrum) to minimize absorption and scattering losses in water. The optical signal produced by the photo-source is directed and focused into the underwater channel using projection optics, which ensure that the transmitted energy is collimated and aligned with the receiver.

The aquatic channel represents the underwater medium through which the light propagates, and it presents several challenges, such as absorption, scattering, and turbulence, all of which degrade the signal. These factors vary depending on water turbidity, salinity, and environmental conditions, significantly influencing the reliability of communication. At the receiving end, collection optics capture and focus the scattered optical signal, maximizing its strength for detection.

The photo-detector then converts the received optical signal into an electrical signal. Devices such as photodiodes or avalanche photodiodes are used based on their responsivity and sensitivity, critical parameters in minimizing errors during detection. Finally, the demodulation process extracts the original data from the electrical signal, reconstructing it with minimal distortion despite challenges introduced during transmission.

This block diagram emphasizes the importance of each component in overcoming underwater channel impairments and highlights the need for optimization to enhance communication efficiency, reliability, and range in UOWC systems.

IV. Types of Water

In UWOCs, different water types significantly influence signal propagation and system performance due to their unique optical properties, such as absorption and scattering coefficients. **Pure seawater** exhibits the lowest turbidity and the least attenuation, allowing optical signals to travel longer distances with minimal distortion, making it ideal for high-performance communications. **Clear ocean water**, while slightly more absorptive and scattering than pure seawater, still offers favorable conditions for UWOC systems, especially in mid-range communication scenarios. **Coastal ocean water** introduces moderate levels of turbidity due to higher concentrations of organic matter and sediments, resulting in increased scattering and absorption, which can challenge communication reliability. **Turbid harbor water** represents the most extreme case, with very high levels of turbidity caused by suspended particles, pollutants, and biological activity, leading to significant attenuation and scattering that severely limit communication range and effectiveness. Understanding these water types and their impacts is essential for designing and optimizing UWOC systems tailored to specific environments [25],[26]. Figure 2 shows an illustrative diagram of water types.

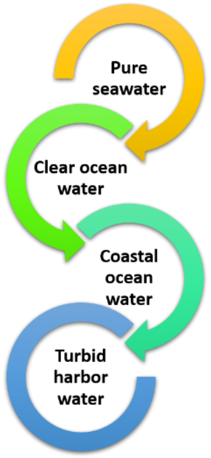

Fig.2. Diagram of water types

V. The Proposed System Architecture

Figure 3 illustrates the architecture of the proposed UWOC system.

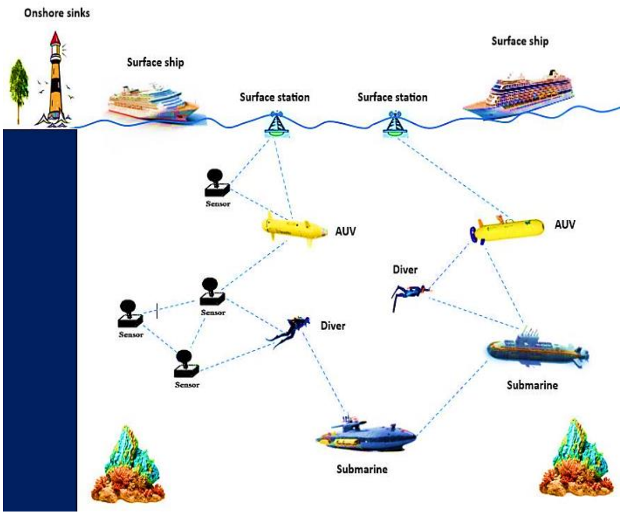

Fig.3. UWOC system architecture [10]

A UWOC system is designed with a network of strategically positioned nodes operating in the underwater environment. At the water's surface, a central sink node—often a buoy, surface vessel, or surface autonomous vehicle (SAV)—serves as the primary hub for collecting and transmitting data. Beneath the surface, nodes like sensors, Autonomous Underwater Vehicles (AUVs), and Unmanned Underwater Vehicles (UUVs) are deployed to perform targeted operations or gather environmental data. These underwater nodes encode the collected data into optical signals using advanced optical transmitters. The signals are then transmitted through the water to the surface sink node, which is equipped with sophisticated receivers and projection optics designed to maximize light capture and reduce signal losses caused by absorption and scattering. Upon receiving the optical signals, the sink node processes the data and relays it to a remote monitoring center onshore, where further analysis and management are performed. This robust architecture effectively integrates underwater and surface components, enabling seamless and real-time communication to support applications like marine exploration, environmental monitoring, and scientific research in challenging underwater environments.

VI. The Proposed System Model

This study focuses on the use of underwater VLC for uplink transmission. As depicted in Figure 4, the system comprises a transmitter, positioned at the ocean floor, acting as the source node. This transmitter emits light signals upward with a beam divergence angle θ *and* semi-angle at half power ($\theta_{1/2}$). At the water's surface, a sink node serves as the receiver, designed to capture the incoming light signal at an incident angle ϕ. The receiver features a specific field of view (FOV) angle ϕ_{FOV}, which, along with the alignment of the nodes, determines the feasible range *d* for reliable communication within the underwater channel.

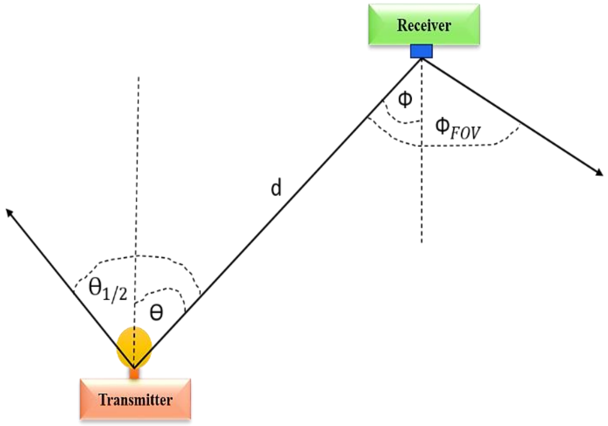

Fig.4. The proposed system model

VII. Aquatic Channel Modeling

Aquatic channel modeling involves the study of signal propagation in underwater environments, considering factors such as absorption, scattering, turbulence, noise and various water types. These models are crucial for designing effective underwater communication systems, as they simulate how light or acoustic waves interact with the medium, influencing signal quality, range, and reliability in aquatic environments.

VII.1 Attenuation in UOWC: Absorption and Scattering

The attenuation of an optical signal in water is characterized by the Beer-Lambert Law [9],[10],[26]:

$$P_r(d) = P_t . \exp(-c . d) \tag{1}$$

where: $P_r(d)$ is the received optical power at a distance d (W), P_t is the transmitted optical power (W), $c = a + b$: is the total attenuation coefficient (m^{-1}), a is the absorption coefficient (m^{-1}), b is the scattering coefficient (m^{-1}), and d is the transmission distance (m).

Scattering Anisotropy Factor: The effect of forward scattering is given by the Henyey-Greenstein phase function:

$$g = \frac{\int_0^\pi I(\theta) \cos\theta \, d\theta}{\int_0^\pi I(\theta) \, d\theta} \tag{2}$$

where g determines the fraction of forward vs backward scattering.

The blue-green wavelengths (450–520 nm) are extensively used in UWOC systems due to their minimal absorption and scattering in water, enabling efficient light propagation over longer distances compared to other wavelength ranges. These wavelengths match the optical window of water, making them ideal for achieving high data rates with reduced power losses. Their suitability across different water types, from clear ocean waters to murky environments, further establishes their prominence in UWOC applications, including underwater exploration, IoUT deployments, and environmental monitoring. Figure 5 illustrates the absorption coefficient of the light as a function of wavelength in pure seawater.

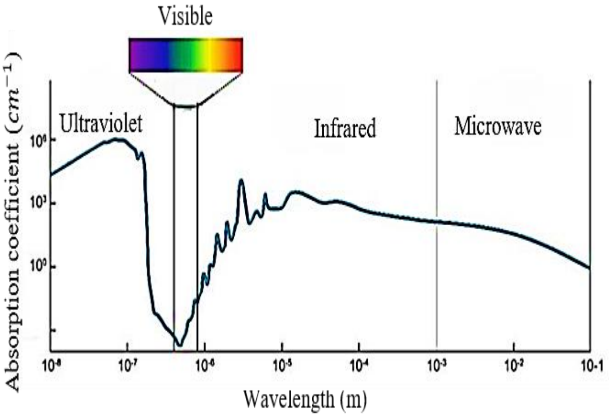

Fig.5. The absorption coefficient of the light as a function of wavelength in pure seawater [5].

The blue wavelength, particularly at 450 nm, is extensively used in UWOCS due to its minimal absorption and scattering properties in water. This wavelength falls within the "optical window" where water demonstrates its highest transparency, allowing for greater transmission distances. Its efficiency makes it ideal for achieving low power loss, high data rates, and robust performance in challenging underwater environments. Applications include data transfer for underwater exploration, IoUT devices, and high-resolution imaging systems. Table I illustrates the values of absorption, scattering, and total attenuation coefficients of the blue color wavelength (450 nm) for various types of water.

TABLE I
Absorption, Scattering, AND Extinction Coefficients For Different Types of At Wavelenght = 450 nm [5],[25].

Types of Water	Absorption Coefficient $a(\lambda)$ (m^{-1})	Scattering Coefficient b (λ) (m^{-1})	Extinction Coefficient c (λ) (m^{-1})
Pure Sea	0.03899	0.0009495	0.0399395
Clear Ocean	0.07888	0.01281	0.09169
Costal Ocean	0.2967	0.1041	0.4008
Turbid Harbor	2.276	0.5499	2.8259

VII.2 Noise in UOWC Systems

Total noise is modeled as the sum of multiple noise sources:

$$Total\ noise, \sigma^2_{total} = \sigma^2_{thermal} + \sigma^2_{dark} + \sigma^2_{shot} + \sigma^2_{ambient} \tag{3}$$

(a) Thermal Noise

$$\sigma^2_{thermal} = \frac{4K\ T\ B}{R_f} \tag{4}$$

where: k is the Boltzmann constant (1.38×10^{-23} J/K), T is the absolute temperature (K), B is the bandwidth (Hz), and R_f is the load resistance (Ω).

(b) Dark Current Noise

$$\sigma^2_{dark} = 2qI_d\ B \tag{5}$$

where: q is the electron charge (1.6×10^{-19} C) and I_d is the dark current (A).

(c) Shot Noise

$$\sigma^2_{shot} = 2q(I_s + I_b)B \tag{6}$$

where: I_s is the signal current (A) and I_b is the background current (A).

(d) Ambient Light-Induced Noise

$$\sigma^2_{ambient} = k\ B\ P_{ambient} \tag{7}$$

where: k is the efficiency factor and $P_{ambient}$ is the ambient light power.

VII.3 Turbulence in UOWC

Mathematical modeling of turbulence in UOWC systems captures the effects of turbulence-induced refractive index fluctuations on signal propagation. These models quantify intensity fluctuations, power loss, and channel fading using statistical and physical distributions.

1. Intensity Fluctuation Models

The received intensity I fluctuates due to underwater turbulence, which can be represented as a multiplicative random variable:

$$I = I_o X \tag{8}$$

where: I_o is the mean received intensity in the absence of turbulence and X is the turbulence-induced fluctuation factor (statistical distribution).

2. Common Statistical Models for X

(a) Log-Normal Distribution

Used for weak turbulence conditions, where fluctuations are mild:

$$P(X) = \frac{1}{X\sqrt{2\pi\sigma_X^2}} \exp\left(-\frac{(ln\, X - \mu_X)^2}{2\ \sigma_X^2}\right) \tag{9}$$

where: μ_X is the Logarithmic mean of X, σ_X^2 is the Logarithmic variance.

(b) Gamma-Gamma Distribution

Combines small- and large-scale turbulence effects:

$$P(X) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}} X^{\frac{\alpha+\beta}{2}-1}}{\Gamma(\alpha)\Gamma(\beta)} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta X}\right) \tag{10}$$

where: α is the small-scale turbulence parameter, β is the large-scale turbulence parameter, and $K_{\alpha-\beta}$ is the modified Bessel function of the second kind.

(c) Weibull Distribution

Useful for moderate to strong turbulence:

$$P(X) = \frac{k}{\lambda}\left(\frac{X}{\lambda}\right)^{k-1} e^{-\left(\frac{X}{\lambda}\right)^k} \tag{11}$$

where: k is the shape parameter and λ is the scale parameter.

(d) Generalized Gamma Distribution

A flexible model encompassing multiple turbulence regimes:

$$P(X) = \frac{\gamma\, \eta^{v}}{\Gamma(v)}\, X^{v-1} \exp\left(-\eta\, X^{\gamma}\right) \qquad (12)$$

where: γ, η, v are the shape and scale parameters.

VII.4 Received Power

The received optical power accounting for turbulence, absorption, and scattering is given by:

$$P_r = P_t \eta_t \eta_r \frac{A_r}{4\pi\, d^2} \exp(-c\, d)\,.X \qquad (13)$$

where: η_t, η_r are the transmitter and receiver efficiencies, A_r is the receiver aperture area(m^2), and X is the fading due to turbulence.

VII.5 Signal-to-Noise Ratio (SNR)

The SNR at the receiver is:

$$SNR = \frac{(RP_r)^2}{\sigma_{total}^2} \qquad (14)$$

where: R is the responsivity of the photodetector (A/W).

VII.6 Bit Error Rate (BER)

For On-Off Keying (OOK) in the presence of noise:

$$BER = Q\left(\sqrt{\frac{R^2 P_r^2}{\sigma_{total}^2}}\right) \qquad (15)$$

where: $Q(x)$ is the Q-function:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} \exp\left(-\frac{t^2}{2}\right) dt \qquad (16)$$

VII.7 Link Reliability

Link reliability (R_{link}) is modeled as the probability of maintaining sufficient SNR over the channel:

$$R_{link} = p(SNR > SNR_{threshold}) \qquad (17)$$

Using the PDF of turbulence and noise distributions, this can be computed numerically.

Also, Link reliability is a probabilistic metric that takes into account factors like link outages due to attenuation, noise, and interference. It can be expressed as the probability that the received signal power is above a certain threshold:

$$R_{link} = p(P_{received} \geq P_{threshold}) \qquad (18)$$

where $P_{threshold}$ is the power threshold required for successful reception, which depends on the minimum SNR required for the modulation scheme to function reliably.

VII.8 Channel Capacity

The capacity C of an optical wireless channel can be estimated using the Shannon-Hartley theorem:

$$C = B.\log_2(1 + SNR) \qquad (19)$$

where: C is the channel capacity in bits per second, B is the bandwidth of the channel (Hz), and SNR is the signal-to-noise ratio.

In underwater optical communication systems, where the bandwidth can be limited by attenuation and other environmental conditions, the capacity might be reduced, and the link design should consider various trade-offs.

VII.9 *Impact of Beam Wander and Spot Size Expansion*

Beam wander and expansion are modeled as a function of the refractive index structure parameter C_n^2 (similar to atmospheric turbulence):

$$\Delta R = \sqrt{2\pi}\, \frac{w_o^2 \sqrt{d}}{\sqrt{k C_n^2}} \qquad (20)$$

where: ΔR is the effective beam radius, w_o is the initial beam waist, d is the transmission distance, and k is the optical wavenumber.

The overall performance of an underwater optical wireless communication link is determined by a combination of channel characteristics, noise models, turbulence effects, and system design choices such as modulation schemes. Effective modeling and optimization require an understanding of the complex interactions between absorption, scattering, and noise sources, as well as ensuring that link reliability and channel capacity meet the required thresholds for specific applications.

VIII. The Simulation Parameters

The simulation parameters for modeling and analyzing UOWC channels typically include physical and environmental factors that influence signal transmission. Key parameters involve the wavelength of the optical signal, water types (pure, clear, coastal, or turbid) with their respective absorption and scattering coefficients, beam divergence angles, transmission distance, and turbulence strength. Additional factors include the type of light source (LED or LD), transmitted power, receiver sensitivity, receiver aperture area, and FOV angles. Noise contributions, such as background noise, thermal noise, and signal shot noise, are also modeled. Metrics like received optical power, SNR, BER and Channel capacity are calculated to evaluate system performance under various underwater conditions. Table II illustrates the simulation parameters which used in this current study.

TABLE II
SIMULATION PARAMETERS

Parameter	**Symbol**	**Value and Unit**
Type of photo-source		LD-PS
Wavelength	λ (blue color)	450 nm
Transmitter efficiency	η_t	0.9
Transmitted power	P_t	1 W
Transmitter light beam divergence angle	Θ	0.1°-10°
Transmitter semi-angle at half power	$\theta_{1/2}$	0.03°
Modulation Scheme		OOK
Transmission Distance	d	1-100 m
Channel bandwidth	B	100 MHz
Water Types		Pure, clear, coastal, and turbid harbor waters
Total attenuation coefficient [5],[25]	C (λ)	Pure 0.0399395 m^{-1}
		Clear 0.09169 m^{-1}
		Coastal 0.4008 m^{-1}
		Turbid 2.8259 m^{-1}
Noise sources		Thermal, shot, dark, ambient
Noise model		AWGN
Turbulence Model		Log-Normal, Gamma-Gamma, Generalized Gamma, Weibull
Receiver efficiency	η_r	0.9
Receiver light beam incident angle	Φ	0°-15°
Type of photo-detector		APD
Receiver FOV angle	Φ_{FOV}	30°
Refractive index of lens at PD	n	1.5
Receiver PD aperture area	A_r	5 mm^2
Photodetector Sensitivity	P_s	-35 dBm
Simulation Tool		Python

IX. Simulation Results Analysis and Discussions

Figures 6 to 9 provide a detailed illustration of the relationship between received optical power, measured in decibels relative to one milliwatt (dBm), and the communication link range, measured in meters (m), in UWOCs. This analysis captures the variations in optical power across a diverse range of water types, which include pure seawater, clear ocean water, coastal ocean water, and turbid harbor water. Each water type represents unique optical properties influenced by factors such as salinity, temperature, and suspended particulates, which directly impact light absorption and scattering. Additionally, the study incorporates a comprehensive comparison of various turbulence models, including log-normal, generalized gamma, gamma-gamma, and Weibull distributions. These models simulate underwater environmental fluctuations caused by temperature gradients, pressure variations, and flow irregularities, thereby offering valuable insights into system performance under realistic conditions. The presented results aim to highlight the influence of both water quality and turbulence on optical signal attenuation over varying distances.

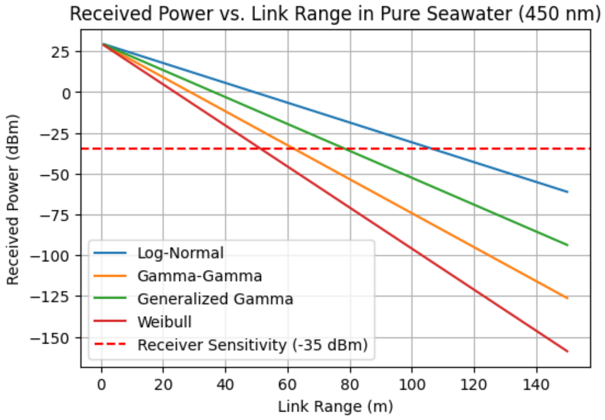

Fig.6. The received power vs. link range in pure seawater for various turbulence models.

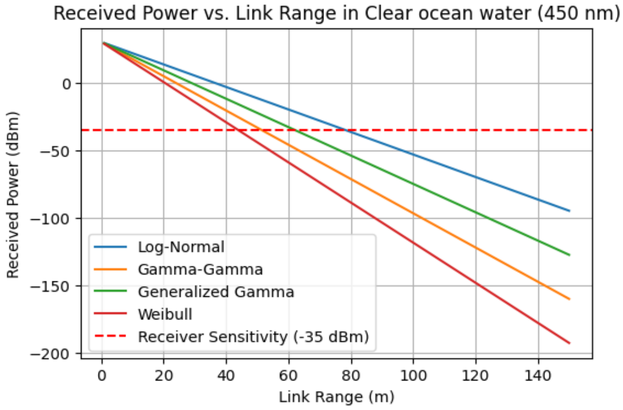

Fig.7. The received power vs. link range in clear ocean water for various turbulence models.

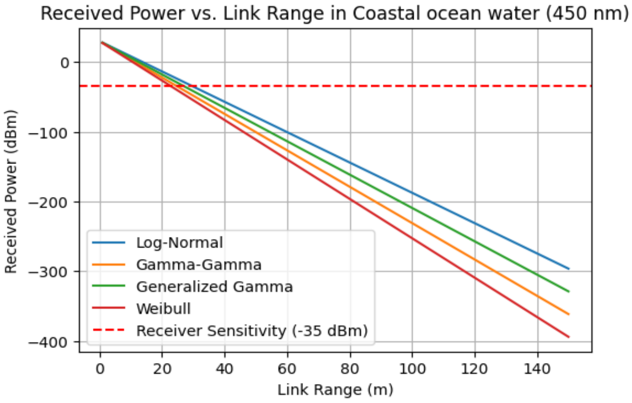

Fig.8. The received power vs. link range in coastal ocean water for various turbulence models.

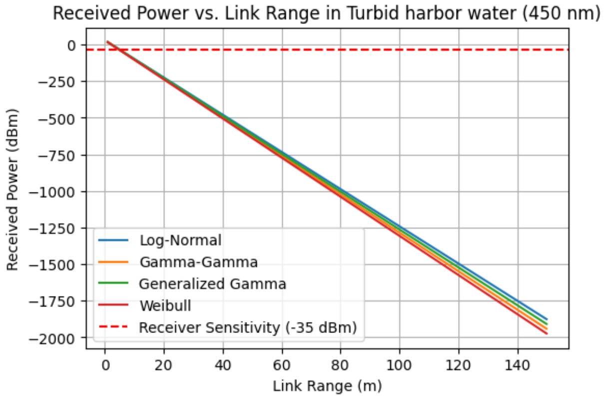

Fig.9. The received power vs. link range in turbid harbor water for various turbulence models.

The results presented in Table III illustrate the feasible communication link ranges in UWOC systems for different water types and turbulence models at a receiver sensitivity of -35 dBm. These results provide insights into the impact of optical properties and environmental conditions on communication performance in underwater environments.

TABLE III
THE VALUES OF THE FEASIBLE COMMUNICATION LINK RANGE FOR VARIOUS WATER TYPES AND TURBULENCE MODELS AT RECEIVER SENSITIVITY -35 DBM

Feasible communication link range (m)				
Water Types	**Turbulence Models**			
	Log-Normal	Generalized-Gamma	Gamma-Gamma	Weibull
Pure seawater C (λ) =0.0399395 m^{-1}	106.45	78.26	62	51.26
Clear ocean water C (λ) =0.09169 m^{-1}	77.51	61.55	51	43.5
Coastal ocean water C (λ) =0.4008 m^{-1}	29.8	27.1	24.86	23
Turbid harbor water C (λ) =2.8259 m^{-1}	7	6.03	5.03	4.88

1. Influence of Water Types

The communication link range significantly varies across water types due to differences in attenuation coefficients (C(λ)), which quantify the combined effects of absorption and scattering.

- Pure Seawater: Exhibits the lowest attenuation coefficient ($C(\lambda)=0.0399395\,m^{-1}$), resulting in the longest feasible link ranges across all turbulence models. The maximum range is observed under the log-normal turbulence model (106.45 m), highlighting pure seawater's excellent optical clarity, which minimizes signal degradation.
- Clear Ocean Water: With an attenuation coefficient of $0.09169\,m^{-1}$, clear ocean water supports shorter communication ranges compared to pure seawater. Here, the log-normal model yields the longest range of 77.51 m, showing that while clear ocean water offers better performance than more turbid waters, it is more restrictive than pure seawater due to higher scattering and absorption.
- Coastal Ocean Water: The higher attenuation coefficient ($C(\lambda)=0.4008\,m^{-1}$) in coastal waters limits feasible link ranges further. The log-normal model achieves a range of 29.8 m, while other models, such as Weibull, result in lower ranges (23 m). The increased particulate matter and suspended sediments characteristic of coastal regions significantly hinder optical signal transmission.
- Turbid Harbor Water: With the highest attenuation coefficient ($C(\lambda)=2.8259\,m^{-1}$), turbid harbor water allows the shortest communication ranges. Even under the best turbulence conditions (log-normal model), the feasible range is only 7 m. This is attributed to extreme light scattering and absorption caused by high concentrations of pollutants and organic matter in harbor environments.

2. Influence of Turbulence Models

The turbulence models have a pronounced effect on the communication link range, reflecting how environmental factors such as temperature gradients, salinity fluctuations, and underwater currents disrupt the optical signal.

- Log-Normal Model: This model consistently yields the longest communication ranges across all water types, suggesting it best represents mild turbulence conditions where signal coherence is relatively preserved.
- Generalized-Gamma and Gamma-Gamma Models: These models represent moderate to strong turbulence, leading to reduced link ranges compared to log-normal conditions. For example, in pure seawater, ranges decrease from 106.45 m (log-normal) to 78.26 m (generalized-gamma) and further to 62 m (gamma-gamma).
- Weibull Model: Yields the shortest feasible ranges, indicating it captures severe turbulence scenarios where intense refractive distortions and scattering significantly impair communication. This model demonstrates the most considerable performance decline across all water types.

3. Physical Interpretation

The interplay between attenuation coefficients and turbulence effects determines the performance limits of UWOC systems. Lower attenuation coefficients in clearer water types allow light to travel longer distances before being absorbed or scattered, while higher attenuation in turbid waters restricts the feasible link range regardless of turbulence. On the other hand, turbulence-induced intensity fluctuations further limit the range by causing signal fading and power loss.

4. Practical Implications

These findings highlight the need for adaptive UWOC system designs tailored to the optical properties of specific underwater environments.

- In **clear waters**, robust communication is achievable over tens of meters, enabling applications like environmental monitoring or underwater robotics.
- In **turbid environments**, the limited feasible range underscores the necessity for localized networks, beam divergence optimization, and advanced error-correction techniques.

The analysis of Table III emphasizes that UWOC system performance depends on both water quality and turbulence models. The log-normal model, paired with low-attenuation water types such as pure seawater or clear ocean water, offers the most extended communication link ranges. However, turbid waters and severe turbulence necessitate optimized hardware and protocols to achieve reliable performance in challenging underwater scenarios.

Figures 10 through 13 provide a comprehensive visualization of the relationship between BER and communication link range for various water types and turbulence models in UWOCs. These figures offer valuable insights into the interplay of environmental factors, such as water quality and optical turbulence, on system performance. The analysis includes different water types—ranging from pure seawater, known for its high optical clarity, to highly turbid harbor water, which exhibits significant attenuation due to suspended particles and impurities. Moreover, the turbulence models considered—log-normal, generalized-gamma, gamma-gamma, and Weibull—capture the effects of varying degrees of refractive index fluctuations caused by temperature gradients, salinity variations, and underwater currents. This detailed investigation highlights how both link range and BER are strongly influenced by the combined impacts of light attenuation and turbulence-induced signal fading, providing a foundation for understanding the design constraints and optimization strategies in UWOCs.

In pure seawater, as illustrated in Figure 10, the BER curves for all turbulence models demonstrate the highest achievable link range compared to other water types. Among these models, the Log-Normal turbulence model exhibits the largest link range, spanning approximately 100–110 m before exceeding the 10^{-5} BER threshold. This performance can be attributed to the minimal scattering and attenuation in pure seawater, which enhances the BER. In contrast, other turbulence models, such as Gamma-Gamma, Generalized Gamma, and Weibull, display reduced maximum link ranges of approximately 40–80 m, reflecting their varying sensitivities to turbulence effects. Furthermore, the exponential increase in BER beyond these specific ranges underscores a sharp degradation in link quality once the system surpasses a critical threshold.

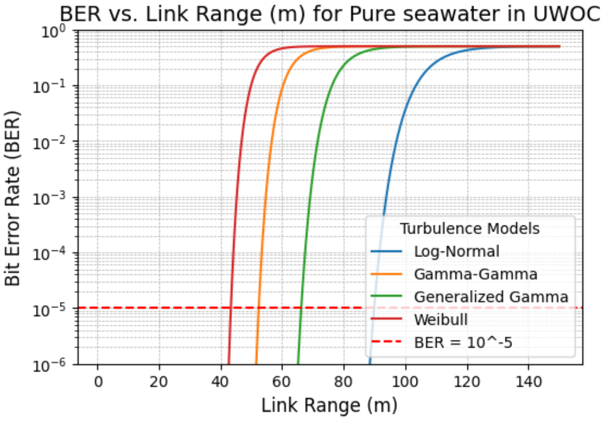

Fig.10. BER vs. link range in pure seawater for various turbulence models.

In clear ocean water, as shown in Figure 11, the maximum link ranges are notably shorter than those in pure seawater due to the higher attenuation coefficients characteristic of this water type. The Log-Normal turbulence model continues to exhibit superior performance, achieving a maximum range of approximately 60–70 m before reaching the BER threshold. In contrast, the Gamma-Gamma, Generalized Gamma, and Weibull models show reduced maximum ranges, varying between 40–55 m, and demonstrate a faster degradation in performance compared to pure seawater. These trends highlight the increased impact of attenuation and scattering caused by turbidity and particulate content, which are more pronounced in clear ocean water.

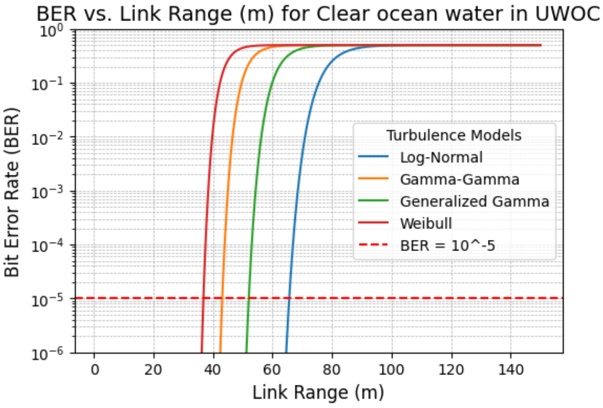

Fig.11. BER vs. link range in clear ocean water for various turbulence models.

In coastal ocean water, depicted in Figure 12, the high turbidity and scattering result in the shortest link ranges across all turbulence models. The BER threshold is exceeded for all models beyond approximately 15–25 m, as the increased optical signal attenuation in this environment significantly restricts the system’s effective range. The close proximity of the turbulence model curves highlights the dominance of absorption and scattering over turbulence effects in such high-attenuation conditions. This convergence indicates that the influence of varying turbulence distributions becomes negligible as attenuation effects predominate. The sharp increase in BER further underscores the limited feasibility of using underwater optical wireless communications in highly turbid environments without substantial design improvements.

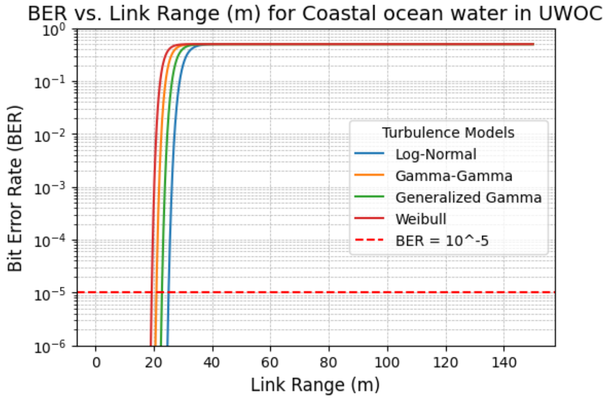

Fig.12. BER vs. link range in coastal ocean water for various turbulence models.

In turbid harbor water, depicted in Figure 13, the high turbidity and scattering result in the shortest link ranges across all turbulence models. The BER threshold is exceeded for all models beyond approximately 2–5 m, as the increased optical signal attenuation in this environment significantly restricts the system's effective range. The close proximity of the turbulence model curves highlights the dominance of absorption and scattering over turbulence effects in such high-attenuation conditions. This convergence indicates that the influence of varying turbulence distributions becomes negligible as attenuation effects predominate. The sharp increase in BER further underscores the limited feasibility of using underwater optical wireless communications in highly turbid environments without substantial design improvements.

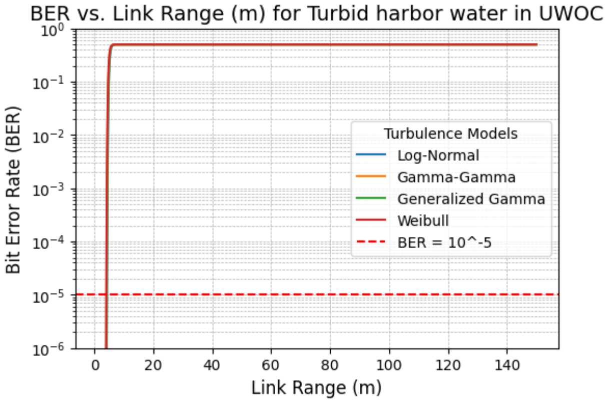

Fig.13. BER vs. link range in turbid harbor water for various turbulence models.

The Figures 10 through 13 collectively demonstrate that:

- Log-Normal turbulence outperforms other models in terms of link range, consistently showing the best BER performance across all water types. This model effectively represents weaker turbulence conditions.
- Gamma-Gamma, Generalized Gamma, and Weibull models degrade BER performance more rapidly as the link range increases, showing higher susceptibility to turbulence.
- The BER threshold of 10^{-5} is achievable over longer ranges in less turbid water types like Pure seawater and Clear Ocean water, but performance is severely constrained in Coastal water, underlining the need for additional techniques such as advanced modulation, error correction, or channel coding to extend link ranges.

These results underscore the significant role of environmental conditions in determining BER performance in UWOCs, highlighting the necessity to optimize system parameters and adapt designs based on the specific water type and expected turbulence models.

X. Conclusion and Future Work

This study presents a comprehensive modeling and analysis framework for UOWC channels by incorporating critical physical and environmental factors that affect performance. The research accounts for absorption and scattering, which are significant challenges in underwater optical propagation, varying across different water types such as pure seawater, clear ocean, coastal waters, and turbid harbors. The impact of turbulence is thoroughly examined using statistical models, including Log-Normal, Gamma-Gamma, Generalized Gamma, and Weibull distributions, which accurately represent optical wave distortions caused by underwater refractive index variations. Furthermore, diverse noise sources, such as thermal, shot, dark, and ambient noise, are modeled to reflect their cumulative effects on signal quality. Key metrics like BER and received power under OOK modulation are evaluated across different underwater conditions. The results highlight the interplay between environmental parameters, turbulence, and noise on UOWC system performance, offering insights into achieving reliable and efficient communication under various scenarios.

Future research can explore advanced modulation schemes beyond OOK, such as PPM and QAM, to improve spectral and power efficiencies under complex underwater conditions. The integration of machine learning techniques, such as deep neural networks, could further enhance system adaptability and robustness by predicting environmental changes and optimizing system parameters in real-time. Moreover, the impact of multiple light sources and multi-hop communication on channel capacity and BER can be studied to extend the communication range. Incorporating hybrid acoustic-optical systems could also provide a balanced approach to achieving long-range and high-speed data transmission. Experimental validation of the presented models in controlled and real-world underwater environments, along with the development of prototype systems, will be crucial in bridging the gap between theoretical analysis and practical implementation. This multi-faceted exploration can significantly advance the state of UOWC systems for IoUT applications.

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Author Contributions

The authors declare that the study was conducted in collaboration with each other with equal responsibility. The manuscript was read and approved by all authors.

Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request.

Competing Interests

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

References

[1] Ali, M. F., Jayakody, D. N. K., Chursin, Y. A., Affes, S., & Dmitry, S. Recent advances and future directions on underwater wireless communications. *Archives of Computational Methods in Engineering*, *27*, 1379-1412. (2020).

[2] Sun, K., Cui, W., & Chen, C. Review of underwater sensing technologies and applications. *Sensors*, *21*(23), 7849. (2021).

[3] Menaka, D., Gauni, S., Manimegalai, C. T., & Kalimuthu, K. Challenges and vision of wireless optical and acoustic communication in underwater environment. *International Journal of Communication Systems*, *35*(12), e5227. (2022).

[4] Preisig, J. Acoustic propagation considerations for underwater acoustic communications network development. *ACM SIGMOBILE Mobile Computing and Communications Review*, *11*(4), 2-10. (2007).

[5] Zayed, M. M., Mohsen, S., Alghuried, A., Hijry, H., & Shokair, M. IoUT-Oriented an Efficient CNN Model for Modulation Schemes Recognition in Optical Wireless Communication Systems. *IEEE Access*. (2024). http://doi.org/10.1109/ACCESS.2024.3515895

[6] Zayed, M. M., Shokair, M., Elagooz, S., & Elshenawy, H. Multihop optical wireless underwater communication links utilizing various routing protocols for IoUT applications. *Journal of Optics*, 1-25. (2024). https://doi.org/10.1007/s12596-024-02290-2

[7] Al-Zhrani, S., Bedaiwi, N. M., El-Ramli, I. F., Barasheed, A. Z., Abduldaiem, A., Al-Hadeethi, Y., & Umar, A. Underwater optical communications: A brief overview and recent developments. *Engineered Science*, *16*, 146-186. (2021).

[8] Schirripa Spagnolo, G., Cozzella, L., & Leccese, F. Underwater optical wireless communications: Overview. *Sensors*, *20*(8), 2261. (2020).

[9] Zayed, M. M., Shokair, M., Elagooz, S., & Elshenawy, H. Feasibility analysis of line of sight (LOS) underwater wireless optical communications (UWOCs) via link budget. *Optical and Quantum Electronics*, *56*(6), 1012. (2024). https://doi.org/10.1007/s11082-024-06879-6

[10] Zayed, M. M., Shokair, M., Elagooz, S., & Elshenawy, H. Non-line-of-sight (NLOS) link budget analysis for underwater wireless optical communications (UWOCs). *Optical and Quantum Electronics*, *56*(7), 1206. (2024). https://doi.org/10.1007/s11082-024-07104-0

[11] Zhu, S., Chen, X., Liu, X., Zhang, G., & Tian, P. Recent progress in and perspectives of underwater wireless optical communication. *Progress in Quantum Electronics*, *73*, 100274. (2020).

[12] Yang, H., Kong, J., Hu, H., Du, Y., Gao, M., & Chen, F. A review of remote sensing for water quality retrieval: progress and challenges. *Remote Sensing*, *14*(8), 1770. (2022).

[13] Mohseni, F., Saba, F., Mirmazloumi, S. M., Amani, M., Mokhtarzade, M., Jamali, S., & Mahdavi, S. Ocean water quality monitoring using remote sensing techniques: A review. *Marine environmental research*, *180*, 105701. (2022).

[14] Al-Kinani, A., Wang, C. X., Zhou, L., & Zhang, W. Optical wireless communication channel measurements and models. *IEEE Communications Surveys & Tutorials*, *20*(3), 1939-1962. (2018).

[15] Gabriel, C., Khalighi, M. A., Bourennane, S., Leon, P., & Rigaud, V. Channel modeling for underwater optical communication. In *2011 IEEE GLOBECOM Workshops (GC Wkshps)* (pp. 833-837). IEEE. (2011, December).

[16] Wen, H., Yin, H., Ji, X., & Huang, A. Modeling and performance analysis of underwater wireless optical absorption, scattering, and turbulence channels employing Monte Carlo-multiple phase screens. *Applied Optics*, *62*(26), 6883-6891. (2023).

[17] Kou, L., Zhang, J., Zhang, P., Yang, Y., & He, F. Composite channel modeling for underwater optical wireless communication and analysis of multiple scattering characteristics. *Optics express*, *31*(7), 11320-11334. (2023).

[18] Aravind, J. V., Kumar, S., & Prince, S. Mathematical modelling of underwater wireless optical channel. In *2018 International Conference on Communication and Signal Processing (ICCSP)* (pp. 0776-0780). IEEE. (2018, April).

[19] Majlesein, B., Gholami, A., & Ghassemlooy, Z. A complete model for underwater optical wireless communications system. In *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)* (pp. 1-5). IEEE. (2018, July).

[20] Ali, M. A. A. Characteristics of optical channel for underwater optical wireless communication system. *IOSR Journal of electrical and electronics engineering*, *10*(1). (2015).

[21] Elamassie, M., Miramirkhani, F., & Uysal, M. Channel modeling and performance characterization of underwater visible light communications. In *2018 IEEE International Conference on Communications Workshops (ICC Workshops)* (pp. 1-5). IEEE. (2018, May).

[22] Sharifzadeh, M., & Ahmadirad, M. Performance analysis of underwater wireless optical communication systems over a wide range of optical turbulence. *Optics Communications*, *427*, 609-616. (2018).

[23] Ata, Y., & Kiasaleh, K. Analysis of optical wireless communication links in turbulent underwater channels with wide range of water parameters. *IEEE Transactions on Vehicular Technology*, *72*(5), 6363-6374. (2023).

[24] Elamassie, M., & Uysal, M. Vertical underwater visible light communication links: Channel modeling and performance analysis. *IEEE Transactions on Wireless Communications*, *19*(10), 6948-6959. (2020).

[25] Zayed, M. M., Shokair, M., Elagooz, S., & Elshenawy, H. (2024). A more detailed mathematical model for analyzing the link budget in UWOCs for both LoS and N-LoS scenarios. *Journal of Optics*, 1-29. https://doi.org/10.1007/s12596-024-02220-2

[26] Zayed, M. M., Shokair, M., Elagooz, S., & Elshenawy, H. (2024). Link budget analysis of LED-based UWOCs utilizing the optimum Lambertian order (OLO). *Optical and Quantum Electronics*, *56*(9), 1396. https://doi.org/10.1007/s11082-024-07341-3