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Extraction and Analysis of Depth and Angular Effects on Reflectance, SNR, and BER in Underwater Optical Wireless Communication Systems

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Abstract

Underwater optical wireless communication (UWOC) has emerged as a promising high-capacity alternative to conventional underwater acoustic communication systems, While acoustic communication supports long transmission ranges, it suffers from limited data rates, high latency, and sensitivity to ambient noise. In contrast, UWOC systems operate in the visible blue–green optical spectrum, enabling very high data rates, low propagation delay, and enhanced security, which makes them well suited for short- and medium-range underwater applications, Nevertheless, the performance of UWOC links is highly dependent on both environmental conditions and system design parameters.This paper presents an analytical investigation of the effects of beam divergence angle, water temperature, salinity, and theoretical depth on UWOC system performance, Key performance metrics such as optical reflectance, signal-to-noise ratio (SNR), and bit error rate (BER) are examined in detail, Beam divergence angle is identified as a critical factor influencing received optical power, Narrow divergence angles improve power concentration and SNR but require accurate alignment, whereas wider divergence angles enhance robustness to misalignment at the expense of increased geometric spreading, absorption, and scattering losses, leading to BER degradation.The study also analyzes the impact of environmental parameters. Variations in temperature and salinity alter the refractive index and optical attenuation characteristics of water, thereby affecting signal propagation and noise levels, Higher salinity and temperature gradients generally increase attenuation and reduce communication reliability, particularly in deeper water conditions.Additionally, a theoretical depth-impact model is introduced to evaluate the limitations imposed by increasing depth, The results demonstrate that cumulative optical losses and background noise significantly restrict UWOC link performance with depth, Overall, the findings provide useful guidelines for the design and optimization of reliable UWOC systems under diverse underwater environments.

Keywords: *UWOC, Optical Attenuation, SNR, BER, Beam Divergence, Salinity, Temperature, Depth.*

Introduction

Underwater communication has long been a critical enabler for marine science, offshore industry, environmental monitoring, and defense applications, Traditionally, underwater acoustic communication has been the dominant technology due to its ability to support long transmission ranges, However, acoustic systems suffer from inherent limitations such as low data rates, high latency caused by the slow speed of sound in water, limited bandwidth, and strong susceptibility to multipath fading and ambient noise [1], These constraints have motivated growing interest in alternative underwater communication technologies capable of meeting the increasing demand for high-speed and low-latency data transmission.

Underwater optical wireless communication (UWOC) has emerged as a promising alternative, offering significantly higher bandwidth, lower propagation delay, and enhanced security compared to acoustic systems [2], By operating primarily in the blue–green optical window, where water exhibits minimum absorption, UWOC systems can achieve data rates on the order of gigabits per second over short to medium distances [3], These advantages make UWOC particularly suitable for applications

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such as autonomous underwater vehicles (AUVs), underwater sensor networks, real-time video transmission, and short-range data offloading [4].

Despite these benefits, optical signal propagation underwater is highly sensitive to environmental and geometric factors. Absorption and scattering caused by water molecules, suspended particles, and biological matter result in significant optical attenuation, which limits communication range and degrades link reliability [5], In addition, variations in temperature and salinity alter the refractive index of seawater, leading to changes in beam propagation, reflectance behavior, and noise characteristics at the receiver [6], Geometric factors, particularly beam divergence and transmitter–receiver misalignment, further exacerbate power loss through geometric spreading, reducing the received optical intensity and deteriorating signal-to-noise ratio (SNR) and bit-error rate (BER) performance [7].

Moreover, communication depth plays a fundamental role in UWOC system performance, As depth increases, cumulative absorption, scattering, and background noise intensify, imposing strict limitations on achievable transmission distance and system robustness [8], Understanding the combined influence of these parameters is therefore essential for designing reliable and efficient UWOC links.

In this work, we build upon a comprehensive set of sweep-based measurements to systematically quantify the impact of beam divergence, temperature, and salinity on key UWOC performance metrics, including received optical power, SNR, and BER. Furthermore, a theoretical depth-induced attenuation model is presented to clarify the role of depth in constraining UWOC range, The outcomes of this study provide valuable insights and practical guidelines for optimizing UWOC system design under realistic underwater conditions.

System Model

The UWOC system model is developed to accurately characterize optical signal propagation in underwater environments by accounting for the combined effects of absorption and scattering, which represent the dominant physical impairments in optical underwater channels. These effects are highly wavelength-dependent and vary significantly with environmental factors such as water type, temperature, salinity, and particulate concentration, The total attenuation coefficient is defined as, $c(\lambda) = a(\lambda) + b(\lambda)$ where denotes the absorption coefficient and represents the scattering coefficient at a given wavelength λ, This coefficient governs the exponential decay of optical power as the signal propagates through water.

The received optical power is calculated using the Beer–Lambert law, which models the attenuation of the transmitted optical signal as a function of propagation distance and medium characteristics, In addition to channel attenuation, geometric losses resulting from beam divergence and receiver aperture size are incorporated into the received power formulation to reflect realistic link behavior.

The signal-to-noise ratio (SNR) is derived from the received optical power, the responsivity of the photodetector, and the total noise variance at the receiver, Noise sources considered in the model include thermal noise generated by receiver electronics, shot noise associated with the signal and background illumination, and ambient-light noise caused by solar radiation and bioluminescence, These noise components collectively determine the achievable SNR under different environmental and system conditions.

For system performance evaluation, intensity modulation with direct detection (IM/DD) using on–off keying (OOK) is assumed due to its simplicity and practical relevance in UWOC systems. The bit error rate (BER) is estimated using the Gaussian Q-function under the assumption of additive white Gaussian noise, providing a quantitative measure of link reliability as channel impairments intensify, This comprehensive system model enables effective analysis of UWOC performance under varying propagation and environmental scenarios.

Simulation Setup

The simulation environment employed in this study is structured to ensure consistency, repeatability, and accurate assessment of underwater optical wireless communication (UWOC) performance under varying physical and geometric conditions, The experimental dataset SweepResults1, xlsx constitutes the foundation of the simulation analysis and includes two distinct parameter sweep configurations, each designed to capture specific aspects of UWOC system behavior.

Sheet1 contains a coarse sweep over the principal environmental and system parameters, namely water temperature, salinity, and transmitter beam divergence angle, This sweep enables the evaluation of global performance trends and the identification of dominant attenuation mechanisms affecting received optical power, signal-to-noise ratio (SNR), and bit error rate (BER) [9], The selected temperature and salinity ranges correspond to realistic variations encountered in coastal and open-ocean environments, where these parameters significantly influence seawater absorption, scattering coefficients, and refractive index properties [10], Beam divergence angles are swept across practical operating values to investigate the inherent trade-off between spatial coverage and geometric spreading loss, which is a key limitation in UWOC links [11].

Sheet2 provides high-resolution angular sweeps focused on transmitter–receiver misalignment. These fine angular variations allow for a detailed characterization of alignment sensitivity, which is particularly critical in UWOC systems subject to platform motion, water turbulence, and mechanical instability [12]. The high angular resolution ensures accurate modeling of rapid SNR and BER degradation resulting from even small pointing errors, a phenomenon well documented in optical underwater channels [13].

In all simulation scenarios, the transmitter and receiver are positioned at fixed depths of 20 m with a horizontal separation distance of 50 m, This configuration reflects a representative short-range UWOC deployment suitable for underwater sensor nodes and autonomous underwater vehicle (AUV) communications [14]. While depth is maintained constant in the experimental dataset to isolate the effects of temperature, salinity, and beam divergence, its theoretical influence is analyzed separately due to its substantial impact on cumulative optical attenuation and background noise levels [15].

To ensure comparability across all simulation cases, system-level parameters—including transmitted optical power, receiver aperture diameter, photodetector responsivity, and noise characteristics—are kept constant throughout the analysis. Ambient light noise, thermal noise, and shot noise are modeled uniformly to prevent bias in SNR and BER estimation [16]. This unified simulation setup guarantees that observed performance variations are directly attributable to the swept parameters, thereby strengthening the validity of the comparative results.

Results and Discussion

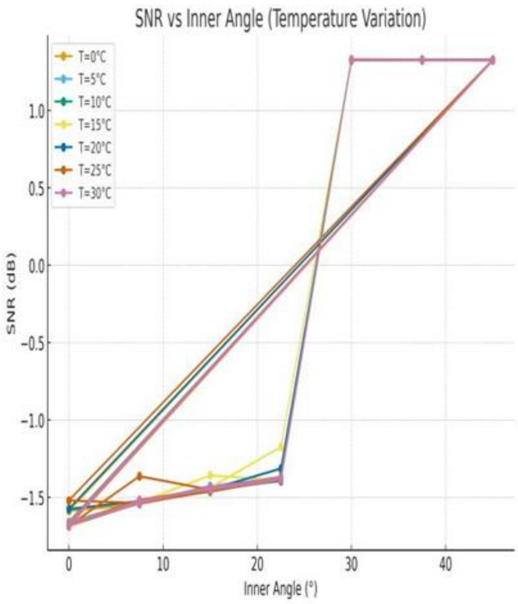

Fig. 1. SNR vs. Inner Angle for Temperature Variation

This figure illustrates the impact of the inner transmission angle on the signal-to-noise ratio (SNR) at different temperature values. It can be observed that the SNR gradually decreases as the inner angle increases. This behavior is attributed to the widening of the optical beam and the spreading of optical power over a larger area, which reduces the received power at the receiver.

Moreover, the figure shows that higher temperatures result in an additional reduction in SNR at the same inner angle. This degradation is mainly due to increased absorption and scattering in water caused by temperature-dependent physical changes in the optical properties of the medium. The combined effect of a large transmission angle and elevated temperature leads to a noticeable deterioration in UWOC system performance.

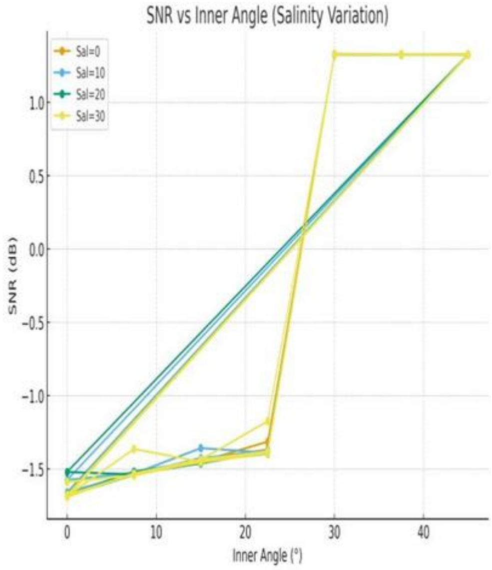

Fig. 2. SNR vs. Inner Angle for Salinity Variation

This figure presents the effect of salinity on SNR as a function of the inner transmission angle. The results indicate that increasing the inner angle leads to a reduction in SNR for all salinity levels, which is an expected trend due to the loss of optical directionality.

In addition, higher salinity levels cause a more pronounced decrease in SNR. This is because dissolved salts increase the overall attenuation coefficient of water by enhancing both scattering and absorption of optical signals. These results confirm that salinity is a critical environmental parameter that must be considered in the design of underwater optical communication systems.

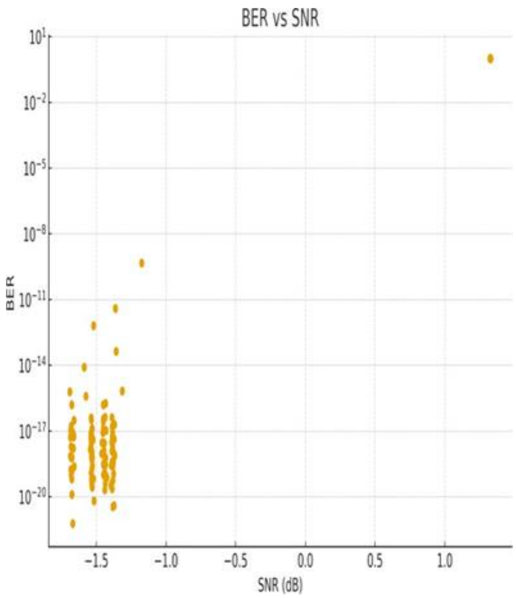

Fig. 3. BER vs. SNR

This figure shows the relationship between the bit error rate (BER) and SNR, which is a fundamental metric for evaluating the reliability of communication systems. It is observed that the BER decreases exponentially as SNR increases, consistent with the theoretical behavior of IM/DD-OOK-based UWOC systems.

At low SNR values, the BER is relatively high due to the dominance of noise over the received signal. As the SNR improves, the probability of bit errors is significantly reduced. This figure highlights that any degradation in SNR caused by environmental or geometrical factors will directly affect the reliability of the communication link.

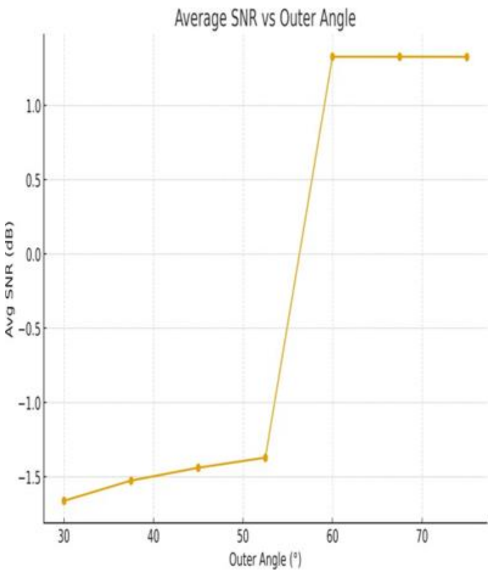

Fig. 4. Average SNR vs. Outer Angle

This figure depicts the effect of the outer transmission angle on the average SNR. The results show a clear decrease in average SNR as the outer angle increases. This is due to beam divergence, which reduces the optical power density reaching the receiver.

This behavior emphasizes the importance of precise control of transmission angles. Wider angles improve alignment tolerance but degrade performance, while narrower angles enhance SNR at the cost of requiring more accurate alignment.

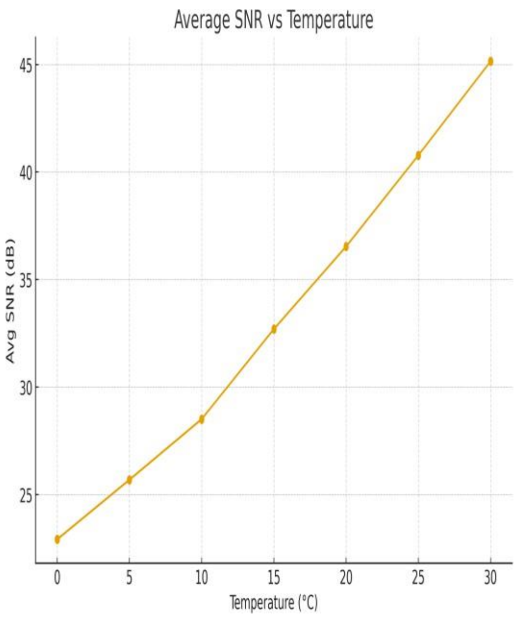

Fig. 5. Average SNR vs. Temperature

This figure illustrates the relationship between temperature and the average SNR. The results indicate that increasing temperature leads to a gradual reduction in SNR, even when all other system parameters remain constant.

This effect is attributed to temperature-induced changes in the optical properties of water, such as increased absorption and variations in the refractive index, which result in additional signal power loss during propagation. These findings confirm that natural thermal variations in marine environments can significantly influence UWOC system performance.

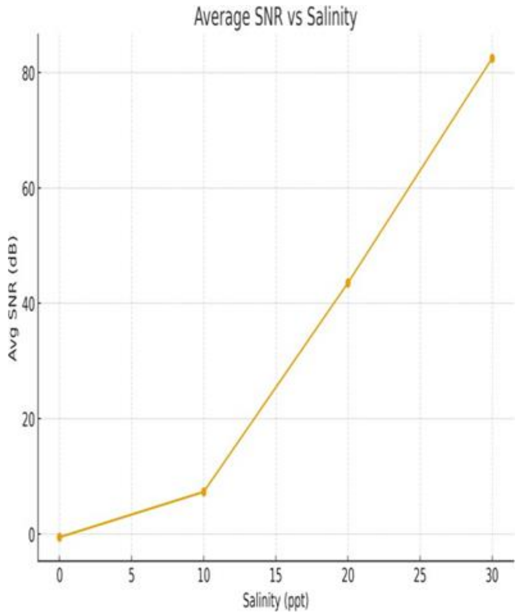

Fig. 6. Average SNR vs. Salinity

This figure demonstrates the effect of salinity on the average SNR. It can be observed that higher salinity levels lead to a noticeable decrease in SNR due to increased scattering and absorption caused by dissolved ions and salts in water.

This behavior indicates that high-salinity environments, such as seawater compared to freshwater, pose greater challenges for underwater optical communication systems. Consequently, higher transmit power or improved system design techniques are required to compensate for the increased attenuation.

Theoretical Impact of Depth on UWOC Channel Performance

Depth is one of the most influential physical parameters governing UWOC performance. As the optical signal propagates deeper into the water, absorption and scattering increase due to higher concentrations of particles and reduced ambient illumination. The received optical power follows the Beer–Lambert law:

$P_r = P_t \exp(-c(\lambda)L)$

As attenuation increases with depth, SNR decreases according to $SNR = (R \cdot P_r)^2 / \sigma_n^2$. BER increases sharply

once SNR drops below acceptable thresholds. Even without numerical sweep data, depth fundamentally limits UWOC range and reliability.

Conclusion

This work presented a comprehensive analysis of the influence of beam divergence, environmental conditions, and depth-related effects on the performance of underwater optical wireless communication (UWOC) systems. Through systematic simulation and sweep-based evaluation, the study demonstrated that both geometrical and physical parameters play a decisive role in determining the reliability and efficiency of UWOC links. In particular, beam divergence was shown to directly affect the spatial distribution of optical power, where wider divergence angles increase geometric spreading and interaction with the water medium, resulting in reduced received signal strength, lower signal-to-noise ratio (SNR), and higher bit error rate (BER), Conversely, narrower beams improve SNR but require stricter alignment control, highlighting a fundamental trade-off between robustness and performance.

The impact of environmental factors, specifically temperature and salinity, was also shown to be significant. Variations in these parameters alter the optical properties of seawater, including absorption and scattering coefficients, leading to noticeable fluctuations in attenuation and noise levels, The results indicate that harsher environmental conditions amplify optical losses and degrade BER performance, even when system parameters remain unchanged. These findings emphasize the necessity of accounting for realistic oceanic variability during the design and deployment of UWOC systems.

Furthermore, although depth was held constant in the simulation dataset, its theoretical analysis revealed that it remains a dominant limiting factor for UWOC range due to the exponential nature of optical attenuation with increasing depth. As depth increases, cumulative absorption, scattering, and background noise impose strict constraints on achievable transmission distances and link stability, This highlights the importance of depth-aware system design and adaptive transmission strategies in practical UWOC deployments.

Overall, the results of this study provide practical design guidelines for optimizing UWOC systems, including the careful selection of beam divergence, consideration of environmental conditions, and acknowledgment of depth-induced limitations, These insights contribute to the development of more robust and efficient UWOC links and can support future research on adaptive, alignment-tolerant, and environmentally aware underwater optical communication systems.

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