Received: 30 October 2024 | Revised: 19 March 2025 | Accepted: 24 June 2025 | Published online: 15 July 2025

Journal of Optics and Photonics Research
2025, Vol. 00(00) 1–11
DOI: 10.47852/bonviewJOPR52024682

RESEARCH ARTICLE

BON VIEW PUBLISHING

Performance Evaluation of Underwater Optical Communication System Using Numerical and Physical Modeling

Dhanush Devappa B C[1], Kalyani Pawar[1], Shreyas Jain[1] and Appala Venkata Ramana Murthy[1,*]

[1]Department of Applied Physics, Defence Institute of Advanced Technology, India

Abstract: Underwater optical wireless communication (UOWC) is gaining significance beyond security and defense, extending to applications such as underwater exploration, surveillance, and vehicle networking. Optical communication offers advantages like higher data rates, compact system size, and easier deployment on small underwater remotely operated vehicles than acoustic methods. However, UOWC faces challenges due to the dynamic underwater environment, including turbidity and salinity variations, which impact performance. This paper investigates the feasibility of UOWC using commercially available components such as Avalanche photodiodes, LEDs, and laser diodes. The effectiveness of the communication link is evaluated through numerical modeling and validated using an experimental setup. Key performance metrics, including bit error rate, are analyzed to assess different modulation schemes and their impact on communication efficiency. Baseband modulation and forward error correction techniques are explored to enhance reliability. By combining theoretical analysis with practical implementation using a UOWC testbed, this work provides valuable insights into system performance under varying environmental conditions, contributing to the advancement of UOWC technology for real-world applications.

Keywords: underwater optical wireless communication, underwater testbed, modulation techniques, numerical modeling, link performance

1. Introduction

Underwater optical wireless communication (UOWC) stands as an emerging technology within the realm of short-range wireless communication, owing to its capability of offering high bandwidth and data rates. This burgeoning interest in UOWC is primarily fueled by its potential applications across various domains, including the Internet of Underwater Things, underwater wireless sensor networks, oil and gas exploration, mineral exploration, navigation systems, and defense applications. Despite its promising prospects, a direct realization of UOWC is a challenging task due to the unforeseen and unpredictable nature of the UOWC channel. These properties, including water turbidity, salinity, and absorption characteristics, profoundly influence the propagation of optical signals in the underwater channel, posing hurdles to the reliable transmission of data. Addressing these challenges requires a thorough understanding of the underwater environment's intricacies and the development of robust communication techniques tailored to operate effectively within such conditions. Thus, while UOWC holds immense potential, its successful implementation necessitates innovative solutions that can mitigate the inherent obstacles posed by the underwater medium [1, 2]. In addressing these issues within optical wireless communication (OWC), the utilization of adaptive solutions is a common strategy. Hence, robust modeling by both numerical and physical methods is essential and provides feasibility, pre-emptive performance evaluation of the system, and the link under a predetermined channel.

A few possible solutions for overcoming the challenges posed by the underwater channel could be first, rigorous computational modeling to understand the channel characteristics better with real-time parameters such as turbidity, salinity, and water currents from the channel side, secondly, to improve and optimize the UOWC system for its better performance with given channel conditions. This includes choosing the appropriate modulation schemes other than On-Off Keying (OOK) like pulse modulations such as pulse position modulation (PPM), pulse interval modulation (PIM), and their differential schemes. This offers both energy efficiency and bandwidth efficiency and transmission reliability in adverse conditions. Another option that we have is to send the data encoded with various encoding techniques such as Forward Error Correction codes which can minimize the error and increase the link performance. In recent years, various studies have shown the possibility of implementation of these techniques in UOWC. We have presented a few noteworthy studies in the next section.

This work presents the real-time implementation of various modulation formats, such as OOK-NRZ, RZ, and PPM, along with encoding techniques, and all are accessible through a single user-friendly interface with desirable data rates. The experimental demonstration can be further scalable up to larger distances by increasing the transmitter laser power and adjusting the receiver optics. As the underwater channel is unpredictable, the user can have good control over the system parameters to optimize the

*Corresponding author: Appala Venkata Ramana Murthy, Department of Applied Physics, Defence Institute of Advanced Technology, India. Email: avrmurthy@diat.ac.in

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communication, minimize the error, and ensure transmission reliability.

2. Literature Review

In recent years, there have been literature findings that indicate various approaches like the choice of modulation formats, and encoding techniques significantly impact the performance of communication links. In the realm of OWC, researchers have demonstrated the effectiveness of error correction codes such as Repeat codes, BCH, Reed-Solomon (RS), and Hamming codes in reducing errors and enhancing overall communication quality [3]. However, in underwater optical communication (OC), the challenges extend beyond turbulence to include turbidity and salinity [4, 5]. These environmental factors not only introduce scattering and absorption of light but also diminish the system's transmittance. Consequently, UOWC systems must contend with a more complex set of obstacles compared to their terrestrial counterparts, necessitating tailored solutions to ensure reliable communication in underwater environments. In recent years, there has been a remarkable surge in the development of UOWC systems, with a particular focus on utilizing light-emitting diodes (LEDs) [6]. Although laser diodes (LDs) remain the optimal choice for various types of OC due to their high coherence and narrow beam divergence, LEDs are gaining traction due to their cost-effectiveness and ease of implementation in underwater environments [6–8]. However, the utilization of LEDs in UOWC systems introduces several challenges that need to be addressed. One of the primary challenges is the occurrence of pointing errors, where the transmitted light beam may deviate from its intended direction due to factors such as refraction and scattering in the underwater medium. Accurate acquisition, tracking, and positioning mechanisms are crucial for mitigating these errors and ensuring reliable communication links [9]. Moreover, the design and implementation of multi-nodal devices using LDs [9–11] have garnered significant attention in academic literature. These theoretical concepts propose the use of LDs in establishing interconnected communication nodes underwater, enabling efficient data transmission over long distances and across diverse environments. In parallel, the field of OWC (OWC) is witnessing advancements in processing units using FPGA deployed at both the transmitter and receiver ends. These units play a crucial role in signal modulation, encoding, and decoding, thereby enhancing the overall performance and reliability of OWC systems. Furthermore, research efforts are actively exploring advanced techniques such as orthogonal frequency division multiplexing (OFDM) [12] and multiple-input multiple-output (MIMO) [13–15] systems in the context of OWC. OFDM facilitates efficient spectrum utilization by dividing the available bandwidth into orthogonal subcarriers, while MIMO systems exploit spatial diversity to improve channel capacity and reliability [16].

Overall, the ongoing research and development activities in the field of UOWC, as shown in Table 1 above, signify a concerted effort to overcome the inherent challenges and unlock the immense potential of OC in underwater environments [26]. The present work

Table 1
Comparing previous research done on the same domain

Reference	Year	Key points	Type of work
[17]	2024	Key parameters such as the Transmitted full divergence angle, received aperture, and Field of View (FOV) are meticulously evaluated for their impact on power loss and time delay spread for different harbor waters.	Simulation
[18]	2024	Study to show that the integration of OFDM with SAC-OCDMA in UOWC aims to enhance various quantitative parameters, including the number of simultaneous users, effective power, spectral occupancy, and quality of service.	Simulation
[19]	2025	The study proposes a UOWC-SMF-FSO hybrid link for an 8 × 1-Gb/s UWOSN using a PRF relay on an ROV for wavelength translation (WT) from visible to IR. Performance is analyzed under varying UOWC and FSO conditions using BER and Q-factor, modeled with the Gamma-Gamma channel model.	Simulation
[20]	2023	An experimental demonstration of a polarization multiplexing (PolMux) system considering bubble-induced turbulence. A theoretical transmission model is built, and experiments are carried out to investigate the impact of bubble turbulence on PolMux transmission.	Experimental & theoretical
[21]	2023	A unipolar scheme called X-transform optical orthogonal frequency division multiplexing with index modulation (XO-OFDM-IM) for underwater optical wireless communication (UOWC).	Simulation of Experimental Data
[22]	2023	Propose and demonstrate a deep learning-based fast-orthogonal frequency division multiplexing (FOFDM-DL) system for underwater optical wireless communications.	Simulation
[23]	2024	The study presents E-PA-DCO-OFDM, an efficient PA technique that reduces SE deterioration and high CC by transmitting only the index of the best PAPR-reducing pilot instead of full pilot data. It also decomposes IFFT into two low-complexity matrices, minimizing the need for multiple IFFT operations.	Simulation
[24]	2024	The study shows the model for optical carrier propagation in different types of seawater and also shows the feasibility analysis of different modulation formats.	Simulation & theoretical
[16]	2018	Proposed a dual-hop UOWC system in which the transmitter-receiver link is assisted by several amplify-and-forward relay nodes and characterized the performance gains of this relay system using the bit error rate assuming On-Off Keying modulation and investigated the impact of key system and particle distribution parameters such as the transmit power, the number of relays, and the spatial position of the attenuation spread on the performance.	Simulation
[25]	2024	Studies have been made on the effect of absorption, scattering, and the misalignment caused by spatial spreading in the sea and the effect of the UOWC systems.	Simulation
[26]	2022	Experimental study on the effect of salinity and turbidity on UOWC.	Experimental

provides an overview of the aspects of numerical modeling and physical modeling, which includes a UOWC setup on the test bed and the performance evaluation with various mitigation techniques.

1) **Numerical Modeling of the Channel:** Here, we conduct numerical modeling of the communication channel in underwater environments. Through this modeling effort, the study investigates various factors that influence UOWC performance. The results obtained are presented in Section 2.
2) **Physical Modeling-UOWC system:** Here, we describe the end-to-end development of the UOWC system including the hardware part and the end user graphical user interface (GUI) with various possible options of modulation and mitigation techniques. This will enable the user to send any kind of data with various choices. A description of this is presented in Section 3.
3) **Performance Evaluation in Different Conditions:** By employing different encoding and modulation techniques suited for different data rates, the study assesses the system's performance across a spectrum of operating conditions. This comprehensive analysis provides valuable insights into the efficacy of different communication strategies in mitigating the challenges posed by underwater environments. Additionally, the findings offer guidance for optimizing UOWC system design to achieve reliable communication under adverse conditions, thereby advancing the practical implementation of underwater OC technology which is presented in Section 4.

3. Research Methodology

A model is like a simplified version of something real, made to help us understand it better. When we simulate, we use that model to play out scenarios quickly, letting us see how things interact even if they're far apart in time or space. It's like running experiments on a pretend version of the real thing. These models are just math expressions with specific values plugged in, called parameters, to predict outcomes similar to real experiments. Modeling helps us get a sense of how things might work before we build them for real.

3.1. Numerical modeling

The underwater channel attenuates the optical carriers, the attenuation is due to the inherent optical properties of the channel these properties are scattering and absorption, and these properties change due to the majority of three environmental conditions.

3.1.1. Wavy nature of water

The movement of light through flowing bodies of water, such as rivers, streams, and canals, is influenced by the undulating nature of the water flow, causing variations in the water's refractive index. Consequently, the transmission of optical signals becomes a stochastic, or random, process. To understand and quantify this phenomenon, we need to develop models that capture the stochastic nature of these fluctuations. By modeling this process, we aim to determine the probability density function of laser intensity fluctuations in terms of the angle for the transmitted beam. This allows us to assess the impact of beam wander within the channel and its effect on communication link performance. In essence, by understanding how light behaves as it traverses through flowing water, we can better predict and optimize the performance of underwater OC systems from Majumdar et al. [27]. We know that for wavy water surface, the emerging refracted angle through waves is dependent on the velocity of wind and waves, probability density function $\phi(\epsilon)$ of this emerging angle can be given as follows.

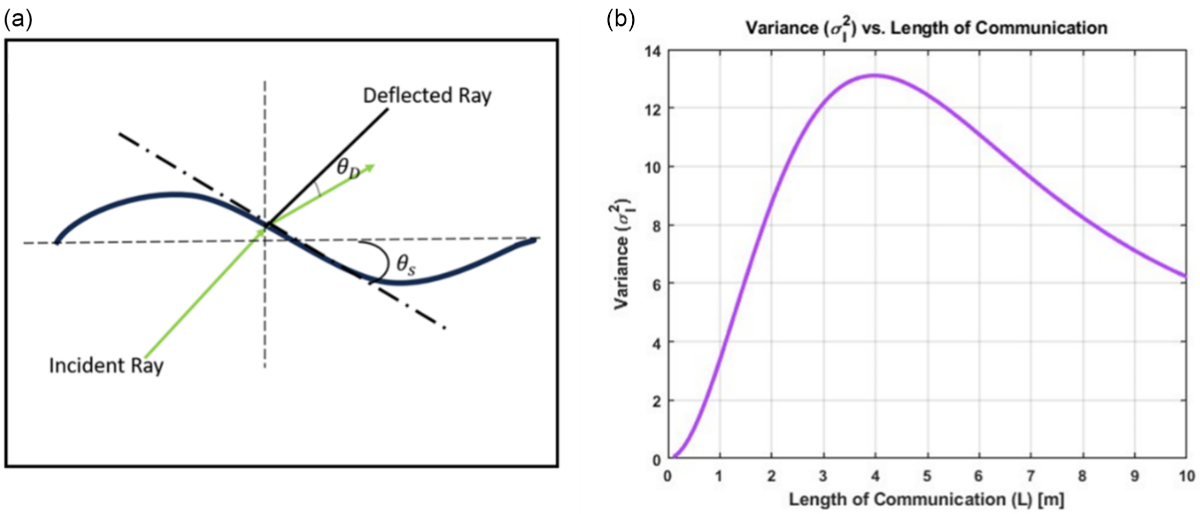
$$\phi(\epsilon) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(\epsilon-\mu)^2}{2\sigma^2}\right] \tag{1}$$

Since this density function does not strictly follow a Gaussian distribution, we use the Gram-Charlier method to model it while accounting for the non-Gaussian components. The probability density function using the Gram-Charlier series is given by:

$$P(\epsilon) = \phi(\epsilon) - \frac{A}{6}(\phi(\epsilon))^3 + \frac{B}{24}(\phi(\epsilon))^4 \tag{2}$$

In the provided equation, $P(\epsilon)$ represents the model for the probability density of refraction angles. The variables A and B denote constants. μ stands for the mean angle of emergent rays, while ϵ represents the angle of emergence. Additionally, σ symbolizes the variance or standard deviation of the wave velocity in the distribution. We used data from Majumdar et al. [27] to roughly estimate the required parameters. Additionally, we employed Beer's Law to relate the variance fluctuation of intensity to the path length and plotted a graph between them as shown in Figure 1 [27].

Figure 1
(a) Light deflecting due to varying refractive index of waves and (b) variance of intensity fluctuations using the Gram-Charlier model



3.1.2. Turbidity

Turbidity plays a crucial role in assessing the optical clarity or opacity of water bodies by measuring how light travels through them. As turbidity increases, light refraction levels rise, indicating reduced clarity. This directly affects the transmission of optical signals in underwater OC systems as higher turbidity hampers light passage through the water [28]. The international standard ISO 7027 provides guidelines for measuring turbidity using the scattered light technique. It recommends the use of a Formazine solution as the standard turbidity solution for calibration purposes. Turbidity is typically measured in nephelometric turbidity units (NTU), with NTU meters employed for measurement [29, 30]. By introducing dust and particles into the water, we can measure the attenuation coefficient for each turbidity level. These parameters are then incorporated into MATLAB for Monte Carlo simulations [31, 32].

Through these simulations, we evaluated the effectiveness of three modulation techniques: PPM [33], OOK, and Quadrature Phase Shift Keying (QPSK) [12, 34, 35]. Our findings as seen from Figure 2 suggest that OOK and QPSK perform similarly, with PPM showing slightly better performance. However, given that OOK is easier to implement physically, it is often preferred for practical applications.

4. Physical Modeling-UOWC System

4.1. Basic link design

To conduct the experimental studies and to cross-verify the numerical modeling results a laboratory-scale physical model is required. For that, we have created a 0.6 m UOWC setup. The working of the basic link design has been shown through the flowchart below in Figure 3.

4.2. Basic experimental setup

The basic experimental setup is shown in Figure 4 with a laser, detector, and both transmitting and receiver PCs. A GUI was developed in-house to create a user-friendly environment and for real-time file transfer applications using Python coding. The front view of the same is shown in Figure 5. This can be used for any type of file, including data, images, and videos, for transmission and receiving purposes. Data transmission via the UOWC channel at up to 1 Mbps is accomplished using the OOK modulation technology. An LD with a wavelength of 532 nm is used to modulate the signal. An LD with a wavelength of 532 nm is used

Figure 2
BER vs range for (a) clear water, (b) 1NTU, (c) 2NTU, and (d) 3NTU

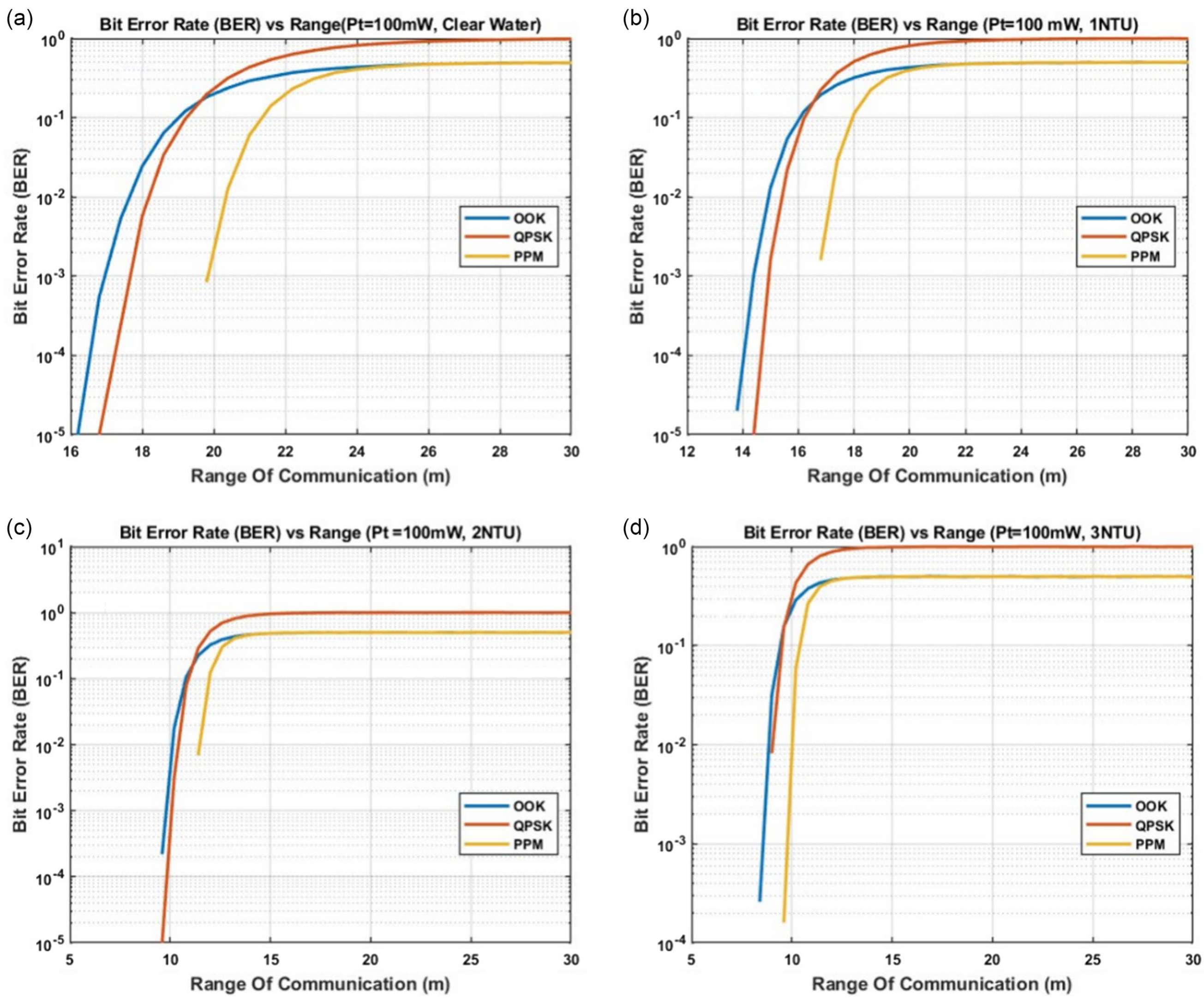
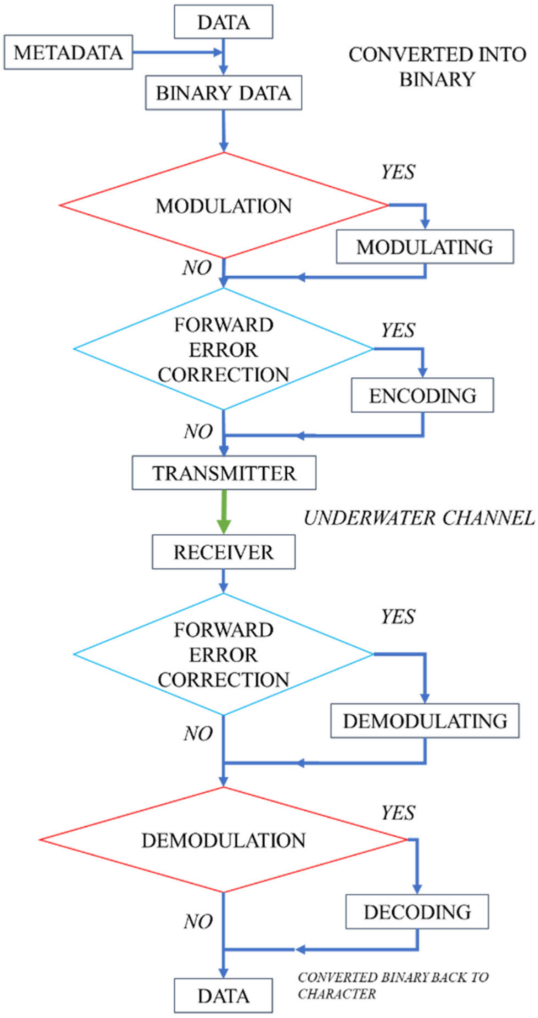


Figure 3
Flow chart of data transfer in UOWC



to modulate the signal. The apparatus used is very simple as this is an initial investigation of the modulation techniques and FEC. The LD's modulation frequency is ~100 KHz, and its optical power is ~50 mW. For bigger scale and high-speed communication, the basic LD can be replaced with a high-power laser (Tens of Watts) whose modulation frequency is in the MHz regime, these changes can be implemented with the same GUI as it is a plug-and-play setup where we just have to select the port through which the data has to be transmitted which is later fed into the optical source.

We determined likely bit error rates while transferring files in real-time at various data rates. We investigated the impact of bit error rate versus data rate by adjusting salinity concentration and turbidity.

5. Results and Discussions

5.1. Performance evaluation in different conditions with different modulation techniques

Modulation techniques offer many advantages like bandwidth efficiency, power efficiency, transmission reliability, etc., which will be necessary in real-time implementation to overcome the eye-safety restriction due to which we are required to optimize the setup to obtain the best possible output. Several modulation techniques have been designed for OWC, such as OOK-NRZ, OOK-RZ, and PPM. Modulation involves encoding data onto a carrier signal for transmission over various communication channels. This process involves modifying the carrier signal's amplitude, frequency, or phase according to the information signal, enabling efficient data transfer through media like radio waves, optical fibers, and electrical lines. The above modulation schemes are chosen over other modulation techniques as these are easy to implement and do not require an external modulator. The OOK-NRZ has the least bandwidth, whereas PPM has the highest bandwidth, while OOK-RZ and PIM lie between them, but PPM is more power efficient than OOK-NRZ. In real-time usage, the choice of modulation depends on certain scenarios, if the user requires faster transmission and can spare power efficiency, they can transmit using OOK-NRZ, but if they have a restriction in power usage, they can opt-in for PPM as it has very good power efficiency followed by PIM and OOK-RZ as compared to OOK-NRZ.

1) On-Off Keying (OOK-NRZ):

OOK is the most basic type of modulation in any form of communication. As the name suggests whenever there is a "1" bit the laser will be ON and when there is a "0" bit the laser will be off. These do not require any complex algorithms or circuitry. It can be done easily wherever digital signals can be converted into electrical signals [11, 36].

2) OOK-Return-to-Zero (OOK-RZ):

The pulse of OOK return-to-zero is also quite similar to OOK-NRZ, and the only difference is that the pulse has been halved, i.e., only half of the bit period is used (high or low) while the other half is always low. Binary modulation methods like non-return-to-zero are easy to implement and bandwidth-efficient but suffer from synchronization issues and DC component presence, as the signal

Figure 4
Working setup of underwater optical wireless communication testbed for physical modeling studies

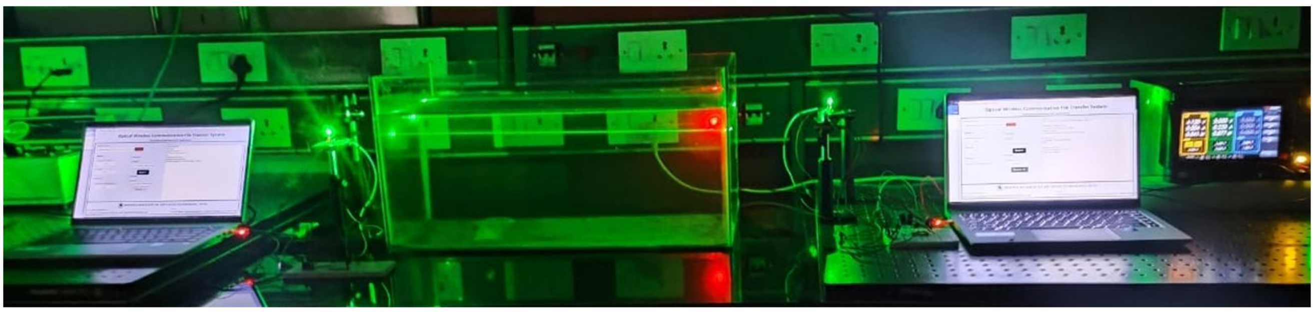
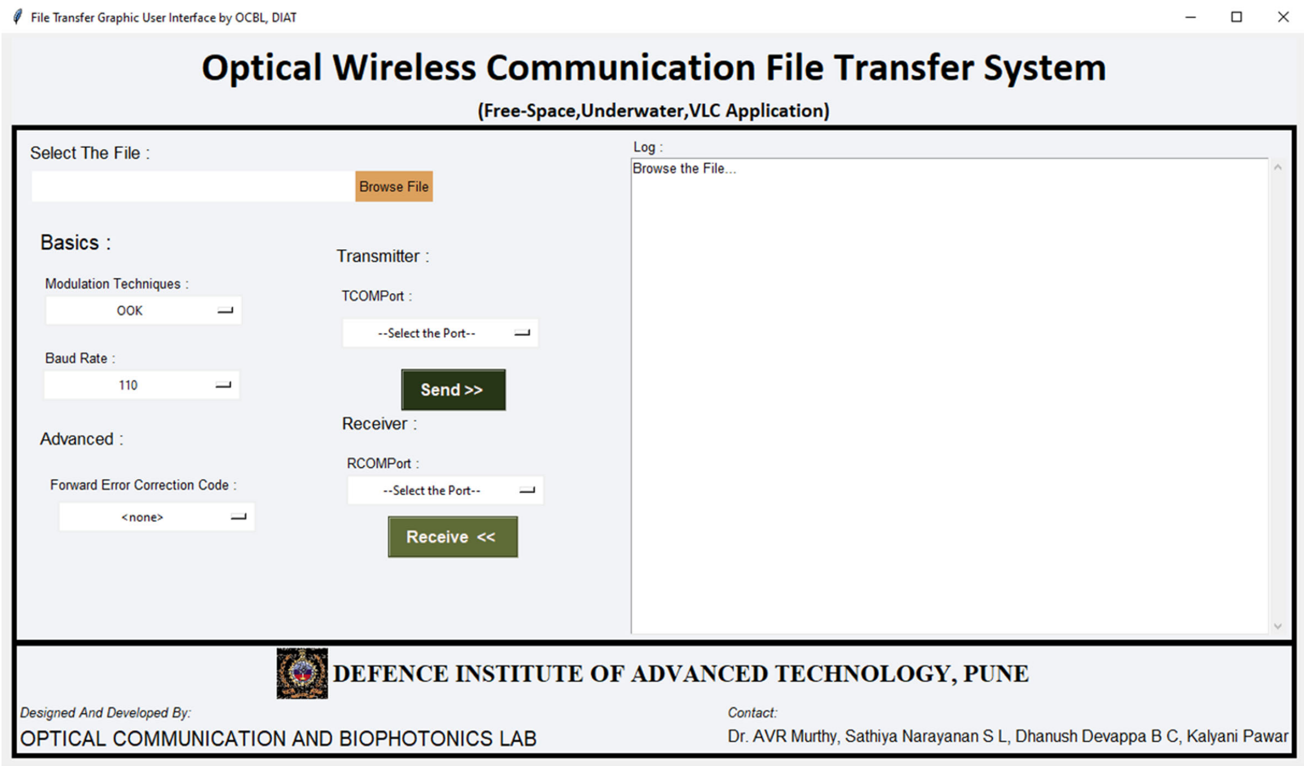


Figure 5
The graphical user interface (GUI) developed for the optical wireless communication file transfer system



maintains a constantly high or low state for each bit's duration. Return-to-zero modulation demands more bandwidth and improves synchronization by resetting to zero during each bit interval [37].

3) PPM:

Unlike OOK, it represents the information or symbol by making an ON pulse at a specific position of the data train. If t_b is the bit period, then on time t_s can be obtained by "$n \times t_b/2^n$", where n is the number of bits used to describe the symbol [38]. PPM encodes data based on the position of a pulse within a specific time frame, providing excellent noise immunity and efficient power usage, although it requires more bandwidth and precise timing.

4) PIM:

As the name suggests, the data are stored in the interval between the pulses, initially a reference pulse is sent and then the number of slots between the reference pulse and the data pulse is used to obtain the symbol. If a symbol encodes M bits of data can then be represented by a constant power pulse in one slot, followed by k slots of zero power, where $1 \leq k \leq L$ and $L = 2M$ [39]. PIM enhances power efficiency and simplifies synchronization by varying intervals between pulses to encode data, though it requires accurate timing and complex decoding.

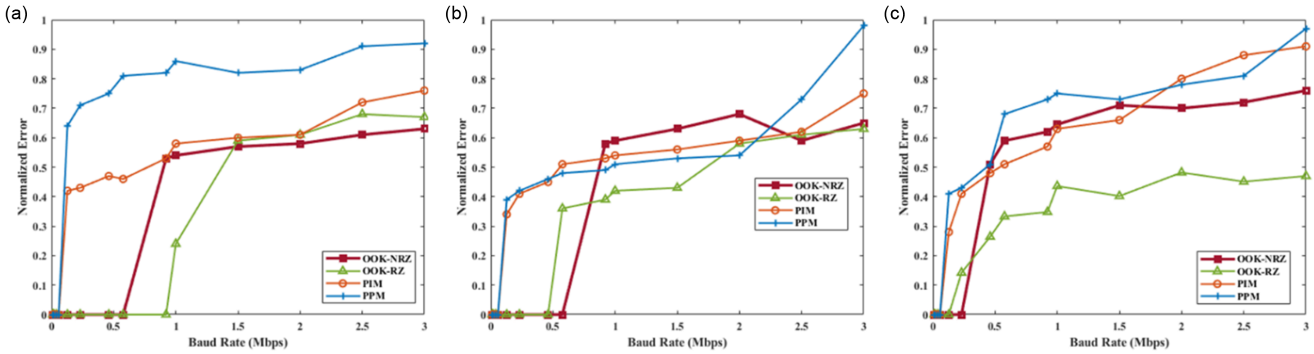
In OWC, these modulation techniques are vital for improving data transmission efficiency and reliability. OOK non-return-to-zero is favored for its simplicity and low bandwidth usage, making it suitable for low-complexity systems. OOK return-to-zero offers better signal integrity and timing accuracy, albeit with higher bandwidth requirements. PPM excels due to its robustness against noise and its efficacy in environments with significant interference, making it ideal for power-critical applications despite higher bandwidth needs. PIM further optimizes power efficiency and simplifies synchronization by encoding information in pulse intervals, reducing receiver complexity but necessitating precise timing control.

The various modulation methods, including OOK-NRZ, OOK-RZ, PPM, and PIM, have been explored, as shown in Figure 6. We can observe in Figure 6 that error starts to appear at 128 kbps for both PIM and PPM at all 3 conditions of water, whereas it is not the same with OOK-NRZ and OOK-RZ. In 0NTU OOK-NRZ starts showing errors at 921 kbps whereas OOK-RZ shows from 1 Mbps, the normalized error value at 1 Mbps of OOK-RZ is nearly half of the value shown by OOK-NRZ at 921 kbps. As the NTU value increases to 1 and 2, the normalized error starts appearing at slower speeds, 576 kbps and 230 kbps respectively. Even though OOK-RZ starts showing errors before OOK-NRZ the values of Normalized errors of OOK-RZ are lower than all other modulation schemes. PPM shows the highest errors of all, reaching almost to 1 at higher baud rates, it is followed by PIM, OOK-NRZ, and OOK-RZ. Among these, OOK-RZ has shown superior performance for 0, 1, and 2NTU, indicating its effectiveness in managing different noise and interference levels. This makes OOK-RZ a preferred choice for applications requiring high reliability and power efficiency.

5.2. Mitigation techniques

A key approach in digital communications is called forward error correction, which involves adding redundant data to transmitted data to identify and fix problems at the receiver's end. Enhancing performance and interoperability across different communication systems is the main goal of recent FEC developments [3]. FEC plays a crucial role in preserving low bit error rates in high-speed optical transmission, particularly in coherent optical systems. There is constant development in FEC techniques to increase coding gains and decrease latency. Adaptive FEC techniques enhance the dependability of real-time

Figure 6
Normalized error vs baud rate for (a) 0NTU turbid water, (b) 1NTU turbid water, and (c) 2NTU turbid water for different modulation schemes



video applications by dynamically adjusting redundancy in response to network constraints like bandwidth and packet loss. To sustain high data rates and signal integrity, fiber optics uses FEC technologies like RS-FEC and FC-FEC to assure reliable data transfer by correcting errors without requiring retransmissions. The increasing significance of FEC in preserving reliable and effective communication across many platforms and applications is reflected in these developments. We have developed Repeat code 03, Repeat code 05, Bose-Chaudhuri-Hocquenghem (BCH), Hamming code, and RS code and experimentally tested their working.

1) Repeat codes (03 and 05):

Every bit in Repeat code FEC is repeated the number of times specified; if Repeat code 03 is chosen, then each bit will be repeated three times, and if Repeat code 05 is chosen, then every bit will repeat five times. For example, if the bit was set to “10”. In Repeat code 03, it will become “111000”, and in Repeat code 05, it will become “1111100000”. These conversions take place at the transmitter end, and the appropriate algorithm is installed at the receiver end to decode the data and return it to its original form [40].

2) Hamming code:

A well-known forward error correction method for identifying and fixing transmission errors is the hamming code. This algorithm, which was first introduced by Hamming [41] in 1950, increases data reliability by adding redundancy to the message that gets transmitted. Specifically, by adding three precisely computed parity bits, the Hamming code converts a block of four data bits into a block of seven bits [41]. By carefully placing these parity bits, single-bit errors can be detected and corrected, enhancing data integrity in noisy communication channels. The Hamming code is a fundamental technique for error correction that is widely used in a variety of digital communication systems due to its simplicity and efficacy.

3) BCH code:

Multiple faults inside a data block can be detected and corrected using the robust forward error correction technique known as the BCH code. Bose and Ray-Chaudhuri [42] and Peterson [43] independently developed BCH codes, which improve data dependability by appending superfluous bits to the original message. Because of these extra bits, the code can systematically detect and fix several faults, which makes BCH codes especially useful in noisy environments [42–45]. In digital communications and storage systems where data integrity is crucial, BCH codes are frequently utilized because of their adaptability in fixing different quantities of faults.

4) RS code:

A potent forward error correction technique for identifying and fixing transmission faults is the use of RS codes. RS codes, which were first introduced by Reed and Solomon [46] in 1960, are extensively used in a variety of communication systems, including digital television, satellite communication, and data storage devices. Before transmission, the primary approach entails appending redundant symbols to the original data. The system can fix several mistakes inside a codeword thanks to the mathematical methods based on finite fields that are used to construct these symbols [46]. The error-correcting capabilities of RS codes are determined by the number of redundant symbols and the design of the code, which makes them very adaptive and efficient in preserving data integrity in noisy situations.

Section 5 highlights our experimental findings, revealing that while passive encoding techniques like forward error correction codes may not be particularly effective, they demonstrate significant efficacy with advanced modulation techniques, especially when dealing with data in a sparse vector format. Figure 7 displays the values of normalized error thrown by different forward error correction codes for various modulation techniques like OOK-NRZ, OOK-RZ, PIM, and PPM. Overall Hamming code works the best for all modulation schemes as compared to other FEC codes, followed by Repeat code 05, Repeat code 03, BCH, and RS. This trend is due to the increase in the number of bits transmitted, as the different FEC codes use different algorithms and add parity bits or jargon in the data to correct them at the receiver. The higher the data transmitted higher the risk of the data being corrupted. Even though the FEC provides more error as compared to No FEC, this comparison is done in ideal conditions where no FEC has the upper hand, in non-ideal conditions consisting of turbulence and other attenuation factors, FEC codes help significantly in reducing the errors. This demonstrates the potential of FEC to greatly enhance data integrity in more sophisticated modulation scenarios, showcasing its value in improving communication reliability.

A comprehensive study was also done for FEC codes in different turbidity conditions for OOK-NRZ modulation to study their effective correction, and the following results are plotted in Figure 8. At higher turbidity values, i.e., at 1NTU and 2NTU FEC codes reduce errors effectively as compared to 0NTU.

Figure 7
Normalized error vs baud rate for (a) OOK-NRZ, (b) OOK-RZ, (c) PIM, and (d) PPM modulation scheme using different forward error correction codes

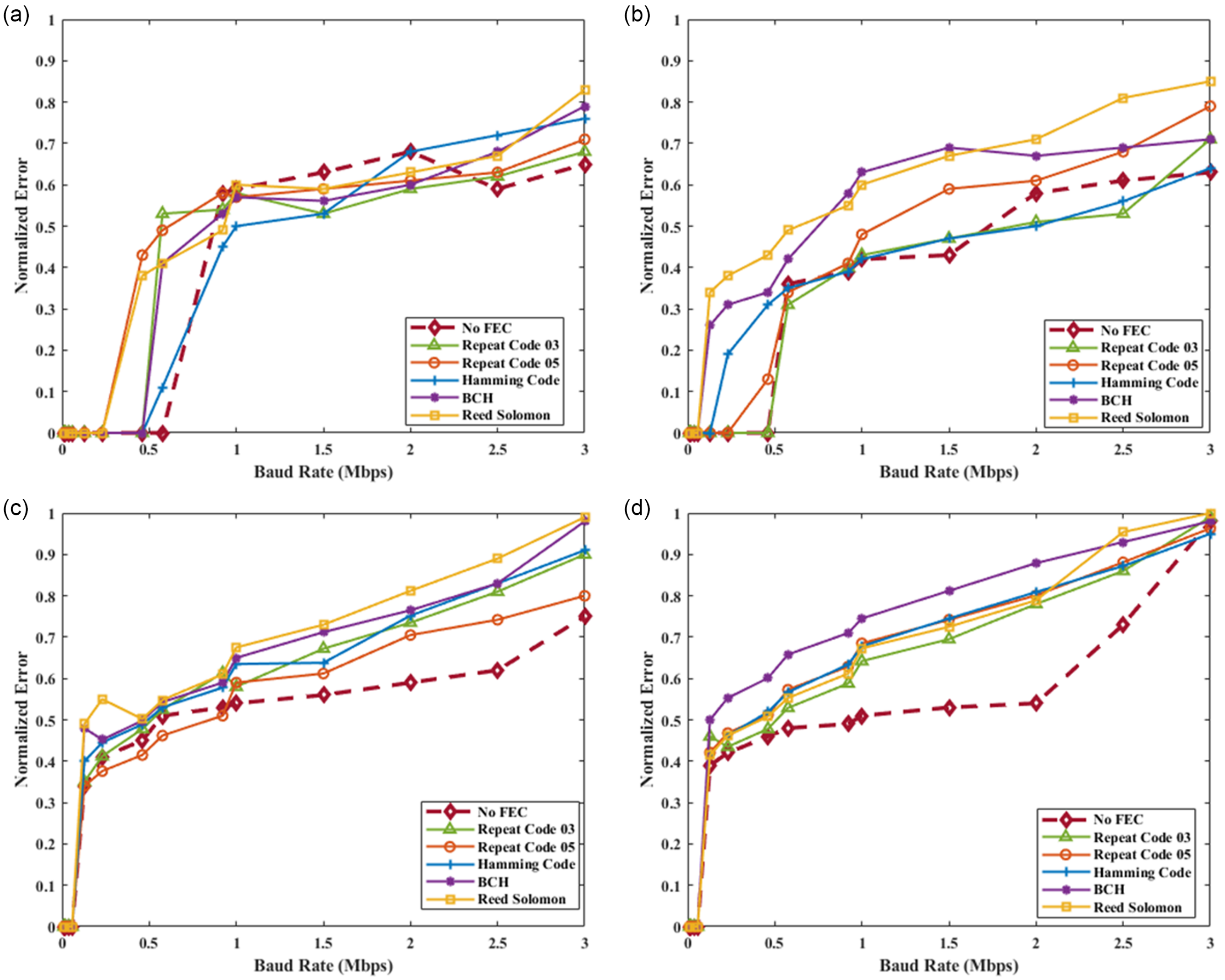
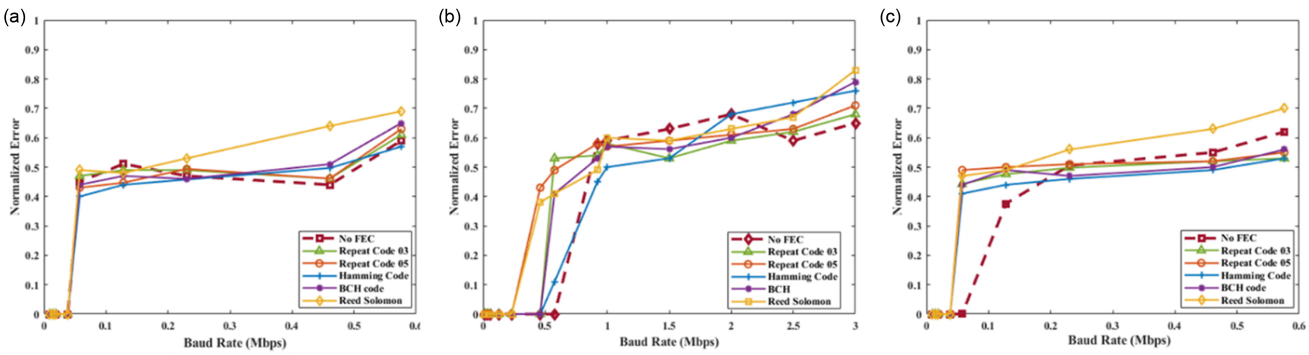


Figure 8
Normalized error vs baud rate for OOK-NRZ at (a) 0NTU, (b) 1NTU, and (c) 2NTU using different forward error correction codes



Hamming code works well in all scenarios, followed by the rest, Reed and Solomon [46] barely rectify errors at some points but fail at major baud rates. This proves the claim made in the previous paragraph stating that FEC works better in non-ideal conditions.

6. Conclusion and Future Directions

Numerical modeling played a crucial role in designing the optimal experimental setup for investigating various environmental conditions. It enabled us to select the appropriate parameters, such as modulation techniques and laser power, by estimating the probability of error or bit error rate. From our numerical modeling, we discovered that if QPSK performs similarly to OOK, then OOK becomes the preferred choice due to its simplicity and cost-effectiveness, as it can be directly incorporated with lasers without the need for expensive external modulators. Additionally, results from physical modeling and experimental setups indicated that forward error correction is highly effective in mitigating errors by nearly 40% when used in higher NTU values like 1NTU and 2NTU as compared to No FEC values. While PPM and RZ may not be the most bandwidth-efficient options, their high-power efficiency contributes to maintaining laser cavity health, further underscoring their advantages in specific applications.

The findings from this experimental study pave the way for several promising advancements in the field of underwater OC. Future research can build on this foundation to further enhance UOWC systems in multiple ways. Firstly, there is significant potential to improve data transfer speeds by implementing Ethernet protocols, which could achieve rates in the order of Gbps. This advancement would address and overcome the current limitations of the File Transfer Protocol, leading to a more robust and efficient UOWC device. Additionally, future studies could explore the deployment of this laboratory-scale prototype in real-world scenarios. By transitioning from a controlled environment to field applications, researchers can test and refine the system under actual underwater conditions, thereby validating its effectiveness and reliability in diverse marine environments. Moreover, continuing to investigate the interplay between different modulation schemes, data rates, and channel bandwidths in various seawater conditions will further optimize system performance. Special attention to the impact of environmental factors such as turbidity will be crucial, as this study has shown that strategic use of Forward Error Correction can significantly enhance communication reliability.

Ultimately, these advancements will contribute to the development of a more sophisticated, high-performance UOWC system capable of supporting reliable and high-speed underwater communications over long distances.

Acknowledgement

All authors acknowledge IIT Guwahati Technology Innovation and Development Foundation (IITG-TIDF) and Defence Institute of Advanced Technology for financial and infrastructural support.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Dhanush Devappa B C: Methodology, Software, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Kalyani Pawar:** Validation, Investigation. **Shreyas Jain:** Formal analysis, Writing-review & editing. **Appala Venkata Ramana Murthy:** Conceptualization, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

References

[1] Li, S., Yang, L., da Costa, D. B., & Yu, S. (2021). Performance analysis of UAV-based mixed RF-UWOC transmission systems. *IEEE Transactions on Communications*, *69*(8), 5559–5572. https://doi.org/10.1109/TCOMM.2021.3076790

[2] Li, S., Yang, L., da Costa, D. B., Zhang, J., & Alouini, M. S. (2020). Performance analysis of mixed RF-UWOC dual-hop transmission systems. *IEEE Transactions on Vehicular Technology*, *69*(11), 14043–14048. https://doi.org/10.1109/TVT.2020.3029529

[3] Cai, Y., Ramanujam, N., Morris, J. M., Adali, T., Lenner, G., Puc, A. B., & Pilipetskii, A. (2001). Performance limit of forward error correction codes in optical fiber communications. In *Optical Fiber Communication Conference and International Conference on Quantum Information*, TuF2. https://doi.org/10.1364/OFC.2001.TuF2

[4] Sun, X., Kong, M., Alkhazragi, O., Shen, C., Ooi, E. N., Zhang, X., . . . , & Ooi, B. S. (2020). Non-line-of-sight methodology for high-speed wireless optical communication in highly turbid water. *Optics Communications*, *461*, 125264. https://doi.org/10.1016/j.optcom.2020.125264

[5] Zhang, K., Sun, C., Shi, W., Lin, J., Li, B., Liu, W., . . . , & Zhang, A. (2024). Turbidity-tolerant underwater wireless optical communications using dense blue–green wavelength division multiplexing. *Optics Express*, *32*(12), 20762. https://doi.org/10.1364/OE.521575

[6] Alatawi, A. S. (2022). A testbed for investigating the effect of salinity and turbidity in the red sea on white-LED-based underwater wireless communication. *Applied Sciences*, *12*(18), 9266. https://doi.org/10.3390/app12189266

[7] Arvanitakis, G. N., Bian, R., McKendry, J. J. D., Cheng, C., Xie, E., He, X., . . . , & Dawson, M. D. (2020). Gb/s underwater wireless optical communications using series-connected GaN micro-LED arrays. *IEEE Photonics Journal*, *12*(2), 1–10. https://doi.org/10.1109/JPHOT.2019.2959656

[8] Lin, R., Liu, X., Zhou, G., Qian, Z., Cui, X., & Tian, P. (2021). InGaN micro-LED array enabled advanced underwater wireless optical communication and underwater charging. *Advanced Optical Materials*, *9*(12), 2002211. https://doi.org/10.1002/adom.202002211

[9] Yang, X., Tong, Z., Dai, Y., Chen, X., Zhang, H., Zou, H., & Xu, J. (2021). 100 m full-duplex underwater wireless optical communication based on blue and green lasers and high sensitivity detectors. *Optics Communications*, *498*, 127261. https://doi.org/10.1016/j.optcom.2021.127261

[10] Kong, M., Lv, W., Ali, T., Sarwar, R., Yu, C., Qiu, Y., . . . , & Xu, J. (2017). 10-m 951-Gb/s RGB laser diodes-based WDM underwater wireless optical communication. *Optics Express*, *25*(17), 20829. https://doi.org/10.1364/OE.25.020829

[11] Wang, J., Lu, C., Li, S., & Xu, Z. (2019). 100 m/500 Mbps underwater optical wireless communication using an NRZ-OOK modulated 520 nm laser diode. *Optics Express*, *27*(9), 12171. https://doi.org/10.1364/OE.27.012171

[12] Kaur, S. (2022). Performance analysis of DP-QPSK with CO-OFDM using OSSB generation. *Wireless Networks*, *28*(4), 1719–1730. https://doi.org/10.1007/s11276-022-02933-x

[13] Song, Y., Lu, W., Sun, B., Hong, Y., Qu, F., Han, J., . . . , & Xu, J. (2017). Experimental demonstration of MIMO-OFDM

underwater wireless optical communication. *Optics Communications*, *403*, 205–210. https://doi.org/10.1016/j.optcom.2017.07.051

[14] Naila, C. B., Nakamura, T., Okada, H., & Katayama, M. (2022). Evaluation of conventional and imaging MIMO OWC systems using linear array design. *IEEE Photonics Journal*, *14*(5), 1–9. https://doi.org/10.1109/JPHOT.2022.3203424

[15] Wang, Z., Zhang, J., Du, H., Niyato, D., Cui, S., Ai, B., . . . , & Poor, H. V. (2024). A tutorial on extremely large-scale MIMO for 6G: Fundamentals, signal processing, and applications. *IEEE Communications Surveys & Tutorials*, *26*(3), 1560–1605. https://doi.org/10.1109/COMST.2023.3349276

[16] Palitharathna, K. W. S., Godaliyadda, R. I., Herath, V. R., & Suraweera, H. A. (2018). Relay-assisted optical wireless communications in turbid water. In *Proceedings of the 13th International Conference on Underwater Networks & Systems*, 40. https://doi.org/10.1145/3291940.3291984

[17] Chang, C., Han, X., Li, G., Li, P., Nie, W., Liao, P., . . . , & Xie, X. (2024). Extending UWOC system applications through photon transmission dynamics study in harbor waters. *Applied Sciences*, *14*(6), 2493. https://doi.org/10.3390/app14062493

[18] Aissaoui, A., & Hacini, L. (2024). Enhancing UWOC link performance using a hybrid OFDM/SAC-OCDMA system. *Optical and Quantum Electronics*, *56*(1), 28. https://doi.org/10.1007/s11082-023-05599-7

[19] Mirza, J., Atieh, A., Kanwal, B., Ghafoor, S., Almogren, A., Kanwal, F., & Aziz, I. (2025). Relay aided UWOC-SMF-FSO based hybrid link for underwater wireless optical sensor network. *Optical Fiber Technology*, *89*, 104045. https://doi.org/10.1016/j.yofte.2024.104045

[20] Deng, B., Wang, J., Wang, Z., Qasem, Z. A. H., Li, Q., Tang, X., . . . , & Fu, H. Y. (2023). Polarization multiplexing based UOWC systems under bubble turbulence. *Journal of Lightwave Technology*, *41*(17), 5588–5598. https://doi.org/10.1109/JLT.2023.3265990

[21] Qasem, Z. A. H., Ali, A., Deng, B., Li, Q., & Fu, H. Y. (2023). Unipolar X-transform OFDM with index modulation for underwater optical wireless communications. *IEEE Photonics Technology Letters*, *35*(11), 581–584. https://doi.org/10.1109/LPT.2023.3264561

[22] Qasem, Z. A. H., Ali, A., Deng, B., Li, Q., & Fu, H. Y. (2023). Reliable deep-learning based underwater optical OFDM wireless communications. In *Opto-Electronics and Communications Conference*, 1–4. https://doi.org/10.1109/OECC56963.2023.10209946

[23] Qasem, Z. A. H., Ali, A., Deng, B., Li, Q., & Fu, H. Y. (2024). Spectral and energy efficient pilot-assisted PAPR reduction technique for underwater wireless optical communication systems. *Journal of Lightwave Technology*, *42*(2), 841–852. https://doi.org/10.1109/JLT.2023.3319080

[24] Jain, S., Devappa, B. C. D., Pawar, K., & Venkata Ramana Murthy, A. (2024). Feasibility analysis of modulation formats in different seawater types and practical implementation on underwater optical communication testbed. *Journal of Optics*, *53*(4), 3071–3081. https://doi.org/10.1007/s12596-023-01494-2

[25] Li, S., Zhang, Z., Zhang, Q., Yao, H., Li, X., Mi, J., & Wang, H. (2024). Breakthrough underwater physical environment limitations on optical information representations: An overview and suggestions. *Journal of Marine Science and Engineering*, *12*(7), 1055. https://doi.org/10.3390/jmse12071055

[26] Kumar, U., Banerjee, S., & Venkata Ramana Murthy, A. (2022). Bit error rate performance of underwater optical wireless communication test bed simulating the seawater conditions. *Optik*, *251*, 168434. https://doi.org/10.1016/j.ijleo.2021.168434

[27] Majumdar, A. K., Siegenthaler, J., & Land, P. (2012). Analysis of optical communications through the random air-water interface: Feasibility for under-water communications. In *Laser Communication and Propagation through the Atmosphere and Oceans: Proceedings of SPIE*, *8517*, 85170T. https://doi.org/10.1117/12.928999

[28] Ma, Z., Gao, G., Zhang, J., Guo, Y., Zhang, F., & Huang, S. (2025). Sea-trial of a real-time underwater wireless optical communication system in shallow turbid water with wave fluctuation. *Journal of Lightwave Technology*, *43*(3), 1140–1149. https://doi.org/10.1109/JLT.2024.3474009

[29] Komiyama, R., Kageyama, T., Miura, M., Miyashita, H., & Lee, S. S. (2015). Turbidity monitoring of lake water by transmittance measurement with a simple optical setup. In *IEEE Sensors*, 1–4. https://doi.org/10.1109/ICSENS.2015.7370456

[30] 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*. Advance online publication. https://doi.org/10.1007/s12596-024-02220-2

[31] Gabriel, C., Khalighi, M. A., Bourennane, S., Léon, P., & Rigaud, V. (2013). Monte-Carlo-based channel characterization for underwater optical communication systems. *Journal of Optical Communications and Networking*, *5*(1), 1–12. https://doi.org/10.1364/JOCN.5.000001

[32] Ren, Y., Zhu, M., Cui, K., Li, L., & Wang, S. (2023). Simulation analysis of underwater wireless optical communication based on Monte Carlo method and experimental research in complex hydrological environment. *AIP Advances*, *13*(5), 055226. https://doi.org/10.1063/5.0151481

[33] Devappa, B. C. D., Banerjee, S., Pawar, K., & Venkata Ramana Murthy, A. (2025). Practical realization and performance analysis of Rivest-Shamir-Adleman encryption for secure underwater optical communication. *Next Research*, *2*(2), 100225. https://doi.org/10.1016/j.nexres.2025.100225

[34] Bismi, B. S., & Azeem, S. (2023). Design and analysis of DPSK, QPSK modulations in underwater optical communication using free space optics. *Wireless Personal Communications*, *132*(2), 1487–1502. https://doi.org/10.1007/s11277-023-10671-2

[35] Gill, H. K., Grewal, N. S., & Walia, G. K. (2019). Comparative investigation of CSRZ-DQPSK, DRZ-DQPSK, AND MDRZ-DQPSK modulation techniques in MDM IS-OWC system. *Microwave and Optical Technology Letters*, *61*(7), 1802–1809. https://doi.org/10.1002/mop.31807

[36] Elsayed, E. E. (2024). Investigations on modified OOK and adaptive threshold for wavelength division multiplexing free-space optical systems impaired by interchannel crosstalk, atmospheric turbulence, and ASE noise. *Journal of Optics*, *1*, 1–14. https://doi.org/10.1007/S12596-024-01929-4

[37] Dwivedy, P., Dixit, V., & Kumar, A. (2023). Cooperative VLC system using OOK modulation with imperfect CSI. *Physica Scripta*, *98*(2), 025509. https://doi.org/10.1088/1402-4896/acb095

[38] Kiasaleh, K. (2005). Performance of APD-based, PPM free-space optical communication systems in atmospheric turbulence. *IEEE Transactions on Communications*, *53*(9), 1455–1461. https://doi.org/10.1109/TCOMM.2005.855009

[39] Aldibbiat, N. M., Ghassemlooy, Z. F., & McLaughlin, R. (2001). Performance of dual header-pulse interval modulation (DH-PIM) for optical wireless communication systems. In *Optical Wireless*

Communications III: Proceedings of SPIE, *4214*, 144–152. https://doi.org/10.1117/12.417505

[40] Tzimpragos, G., Kachris, C., Djordjevic, I. B., Cvijetic, M., Soudris, D., & Tomkos, I. (2016). A survey on FEC codes for 100 G and beyond optical networks. *IEEE Communications Surveys & Tutorials*, *18*(1), 209–221. https://doi.org/10.1109/COMST.2014.2361754

[41] Hamming, R. W. (1950). Error detecting and error correcting codes. *The Bell System Technical Journal*, *29*(2), 147–160. https://doi.org/10.1002/j.1538-7305.1950.tb00463.x

[42] Bose, R. C., & Ray-Chaudhuri, D. K. (1960). On a class of error correcting binary group codes. *Information and Control*, *3*(1), 68–79. https://doi.org/10.1016/S0019-9958(60)90287-4

[43] Peterson, W. W. (1960). Encoding and error-correction procedures for the Bose-Chaudhuri codes. *IRE Transactions on Information Theory*, *6*(4), 459–470. https://doi.org/10.1109/TIT.1960.1057586

[44] Salman, M., Bolboli, J., & Chung, W. Y. (2022). Experimental demonstration and evaluation of BCH-coded UWOC link for power-efficient underwater sensor nodes. *IEEE Access*, *10*, 72211–72226. https://doi.org/10.1109/ACCESS.2022.3188247

[45] Ramavath, P. N., Udupi, S. A., & Krishnan, P. (2020). Experimental demonstration and analysis of underwater wireless optical communication link: Design, BCH coded receiver diversity over the turbid and turbulent seawater channels. *Microwave and Optical Technology Letters*, *62*(6), 2207–2216. https://doi.org/10.1002/mop.32311

[46] Reed, I. S., & Solomon, G. (1960). Polynomial codes over certain finite fields. *Journal of the Society for Industrial and Applied Mathematics*, *8*(2), 300–304. https://doi.org/10.1137/0108018

How to Cite: B C, D. D., Pawar, K., Jain, S., & Murthy, A. V. R. (2025). Performance Evaluation of Underwater Optical Communication System Using Numerical and Physical Modeling. *Journal of Optics and Photonics Research*. https://doi.org/10.47852/bonviewJOPR52024682