Light Through Turbulent Waters: BER Analysis of Image Transmission in Underwater Optical Wireless Systems

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Abstract—**Optical wireless communication plays a significant role in underwater environments due to its high-speed transmission capability and lower absorption characteristics compared to conventional radio frequency (RF) communication systems.Furthermore, optical communication offers higher data transmission rates and lower latency compared to conventional acoustic communication techniques employed in underwater applications. In this paper, the transmission of images captured underwater and communicated to an air–water surface station under different underwater turbulence conditions is investigated. The captured underwater image is transformed into binary data and transmitted through the underwater optical wireless communication channel using On-Off Keying (OOK) modulation. The system performance is evaluated by analyzing the Bit Error Rate (BER) under different underwater turbulence conditions. The analysis is further carried out for different transmitted optical powers and data rates. At the receiver side, the received binary sequence is reconstructed into an image and compared with the original transmitted image to study the impact of underwater turbulence on image quality and transmission reliability. The proposed study is useful for marine exploration, underwater surveillance, environmental monitoring, and other underwater communication applications.**

Index Terms— **Underwater Image, Optical Wireless Communication, Bit Error Rate, On-Off Keying, Data Rates**

I. INTRODUCTION

Underwater communication refers to the transfer of information through the underwater medium. Nearly 72% of the Earth's surface is covered by water, and underwater environments contain vast resources and unexplored regions. Effective communication in such environments is essential for applications such as marine exploration, environmental monitoring, underwater surveillance, disaster prevention, and autonomous underwater vehicles (AUVs). Radio Frequency (RF), acoustic, and optical wireless communication are the major technologies used for underwater communication systems [1–3].

RF communication is widely used in free-space communication systems; however, in underwater environments, RF waves experience severe attenuation and absorption, which significantly limits the communication range. Acoustic communication, on the other hand, provides longer communication distances but suffers from low data rates, high latency, and limited bandwidth [4,5]. Due to these limitations, underwater image transmission using acoustic communication requires a longer transmission time. Compared to RF and acoustic communication systems, optical wireless communication using light waves experiences lower absorption in water and provides higher data rates with low latency [6,7]. Hence, optical wireless communication is considered a promising technology for high-speed underwater image transmission applications [8].

Underwater image transmission is one of the important applications of underwater communication systems. It enables the capture and transmission of underwater images from locations that are difficult or impossible for humans to access directly [9,10]. The transmitted images can be received at the surface station for further

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processing, monitoring, and analysis. Several underwater communication studies have been reported in the literature; however, efficient underwater image transmission under varying channel conditions remains an active area of research [11]. In this study, underwater image transmission using optical wireless communication is investigated [12,13].

Despite the advantages of optical wireless communication, several challenges still exist in underwater environments. One of the major challenges is underwater turbulence, which occurs due to random fluctuations caused by temperature variation, salinity changes, air bubbles, and rapid water movement [14,15]. Underwater turbulence degrades the communication performance and affects the quality of the received image. Depending on the scintillation index, turbulence conditions can be classified as weak, moderate, and strong turbulence [16]. In the literature, the log-normal distribution is commonly used for modeling weak turbulence conditions, whereas the Gamma-Gamma distribution is widely used for modeling moderate and strong turbulence conditions [17,18]. In this work, different underwater turbulence conditions are considered for performance analysis.

The main motivation of this paper is to investigate the transmission of underwater images through optical wireless communication channels under different turbulence conditions. The captured underwater image is converted into binary data and transmitted using On-Off Keying (OOK) modulation. Bit Error Rate (BER) analysis is carried out for different turbulence conditions, transmitted optical powers, and data rates. Based on the obtained results, the impact of turbulence on image transmission performance is analyzed, which can help in optimizing the power requirements and improving reliable underwater optical wireless communication systems.

II. SYSTEM AND CHANNEL MODEL

The proposed system model considered in this work is shown in Fig. 1. In the proposed system, an underwater camera is used to capture the underwater image. The captured image is converted into binary data using MATLAB tools. The generated binary sequence is transmitted through the underwater optical wireless communication channel using a laser source with OOK modulation. Based on the incoming binary sequence, the OOK modulator controls the laser source by turning it ON or OFF. If the transmitted bit is “1”, the laser source is turned ON, whereas for the transmitted bit “0”, the laser source is turned OFF.

The transmitted optical signal propagates through the underwater optical wireless channel, which is affected by underwater turbulence conditions. The communication distance of the underwater optical wireless channel is assumed to be d. At the receiver side, a photodetector placed at the surface station is used to detect the received optical signal.The photodetector transforms the received optical signal into an electrical signal. The received signal at the photodetector is given by [11]

$$Y_R = \eta s\sqrt{P_T T_b} I_T + Z \tag{1}$$

where η represents the responsivity of the photodetector, s denotes the transmitted bit, P_T is the transmitted optical power of the laser source, and T_b is the bit duration, which is the reciprocal of the data rate R_b. The term Z represents the additive white Gaussian noise (AWGN) present at the receiver side with zero mean and variance σ^2.

In Eq. (1), I_T represents the fading coefficient caused by underwater turbulence. The underwater turbulence conditions can be classified as weak, moderate, and strong turbulence. For weak turbulence conditions, the fading coefficient follows a log-normal distribution. The probability density function (PDF) of the log-normal distribution is expressed as [14]

$$f_{I_T}(I_T) = \frac{1}{2I_T\sqrt{2\pi\sigma_X^2}} \exp\left(-\frac{(\ln(I_T)-2\mu_X)^2}{8\sigma_X^2}\right), \tag{2}$$

where σ_X^2 and μ_X represent the variance and mean of the log-normal distribution, respectively.

Likewise, under moderate-to-strong turbulence conditions, the fading coefficient is modeled using the Gamma-Gamma distribution, and the corresponding PDF is expressed as follows [14]:

$$f_{I_T}(I_T) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}(I_T)^{\frac{(\alpha+\beta)}{2}-1}K_{\alpha-\beta}(2\sqrt{\alpha\beta I_T}), \tag{3}$$

where α and β denote the Gamma-Gamma shaping parameters.

III. BER ANALYSIS

The received signal at the photodetector is further processed using Maximum Likelihood Estimation (MLE). The MLE detector takes the received signal as input and estimates the transmitted bits by minimizing the Euclidean distance between the received signal and all possible transmitted symbols. The estimated bit $\hat{s}$ can be expressed as [11]

$$\hat{s} = \underset{s\in\{0,1\}}{\operatorname{argmin}} \left\| Y - \eta\sqrt{P_T T_b}\, s I_T \right\|^2 \tag{4}$$

The Bit Error Rate (BER) is calculated by comparing the original transmitted bits with the estimated bits obtained at the receiver. The BER is expressed as

$$BER = \sum_{i=1}^{l} (s_i \oplus \hat{s}_i) \tag{5}$$

where l denotes the total number of transmitted bits obtained after converting the image into a binary sequence, s_i represents the transmitted bit, $\hat{s}_i$ denotes the estimated bit at the receiver, and $\oplus$ represents the Exclusive-OR (XOR) operation.

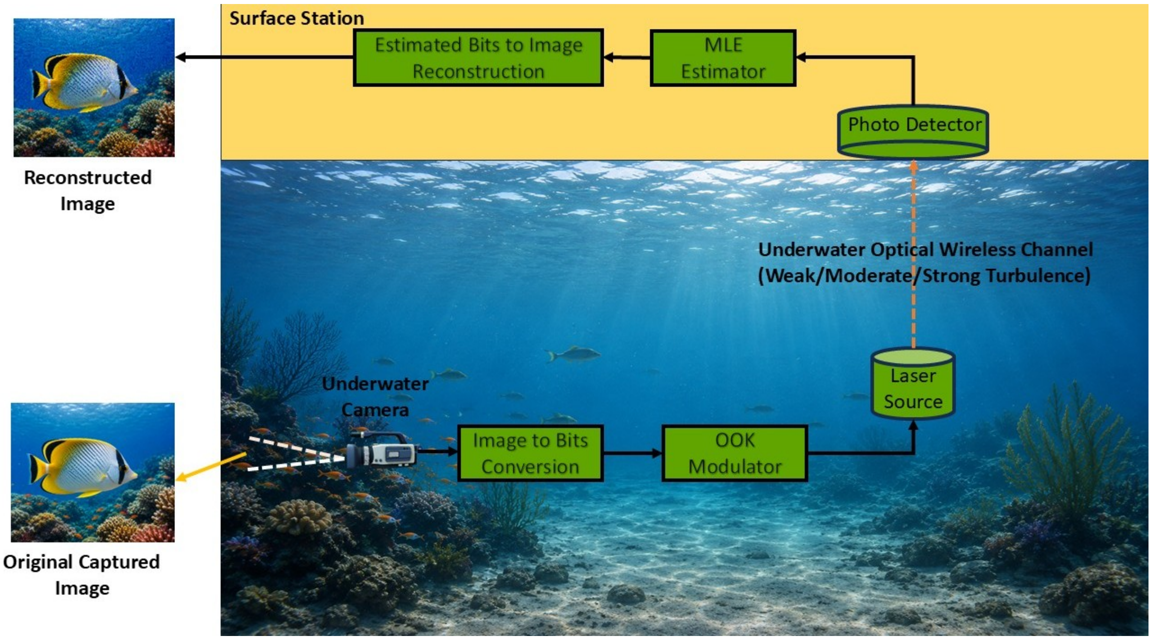


Fig. 1. Proposed System Model

IV. Results and Discussions

TABLE I
System and Simulation Parameters

Parameter	Value
η	1 A/W
d	30 m
Scintillation Index (σ_I^2)	0.44 for WT 1 for MT 5.51 for ST
σ^2	-130 dB
σ_x^2	0.092
(α, β)	(4.39, 2.56) for MT (4.70, 1.21) for ST

In this section, the Bit Error Rate (BER) performance of underwater image transmission is presented for different scenarios, including varying underwater turbulence conditions, transmitted optical power levels of the laser source, and different data rates. The system parameters considered for the performance analysis are listed in Table I [19,20].

TABLE II
BER Performance under Different Underwater Turbulence Conditions

Turbulence	BER
WT	9.43×10^{-5}
MT	3.73×10^{-3}
ST	2.06×10^{-2}

Figure 2 illustrates the original and reconstructed images at the receiver under different underwater turbulence conditions. In this analysis, three different turbulence conditions, namely Weak Turbulence (WT), Moderate Turbulence (MT), and Strong Turbulence (ST), are considered. The transmitted optical power of the laser source is fixed at $P_T = 100$ mW and the data rate is fixed at $R_b = 1$ Gbps for all three turbulence conditions.

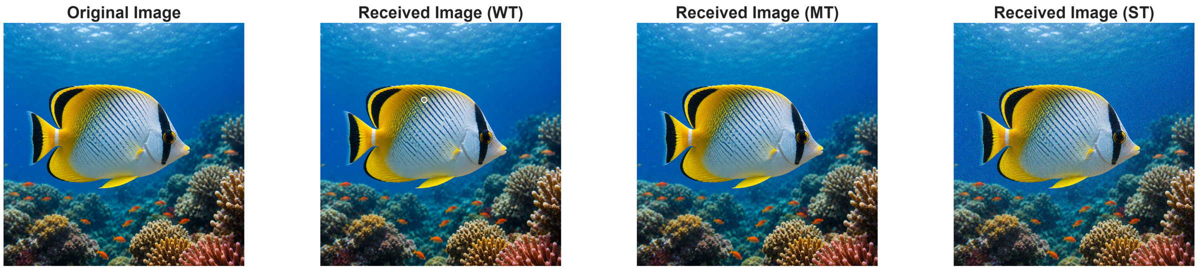
The BER performance analysis is carried out for all the considered turbulence conditions, and the corresponding BER values are presented in Table II. From Fig. 2, it can be observed that the quality and clarity of the reconstructed image at the receiver degrade as the turbulence level increases. Furthermore, from Table II, it is evident that the BER under Weak Turbulence (WT) is the lowest, whereas the BER increases for Moderate Turbulence (MT) and becomes highest for Strong Turbulence (ST). This increase in BER under strong turbulence conditions results in significant degradation of the reconstructed image quality.

TABLE III
BER Performance for Different Transmitted Power Levels under Various Underwater Turbulence Conditions

Turbulence	1 mW	10 mW	50 mW
WT	1.17×10^{-1}	1.00×10^{-2}	4.97×10^{-4}
MT	1.46×10^{-1}	3.21×10^{-2}	7.53×10^{-3}
ST	1.83×10^{-1}	6.93×10^{-2}	3.02×10^{-2}

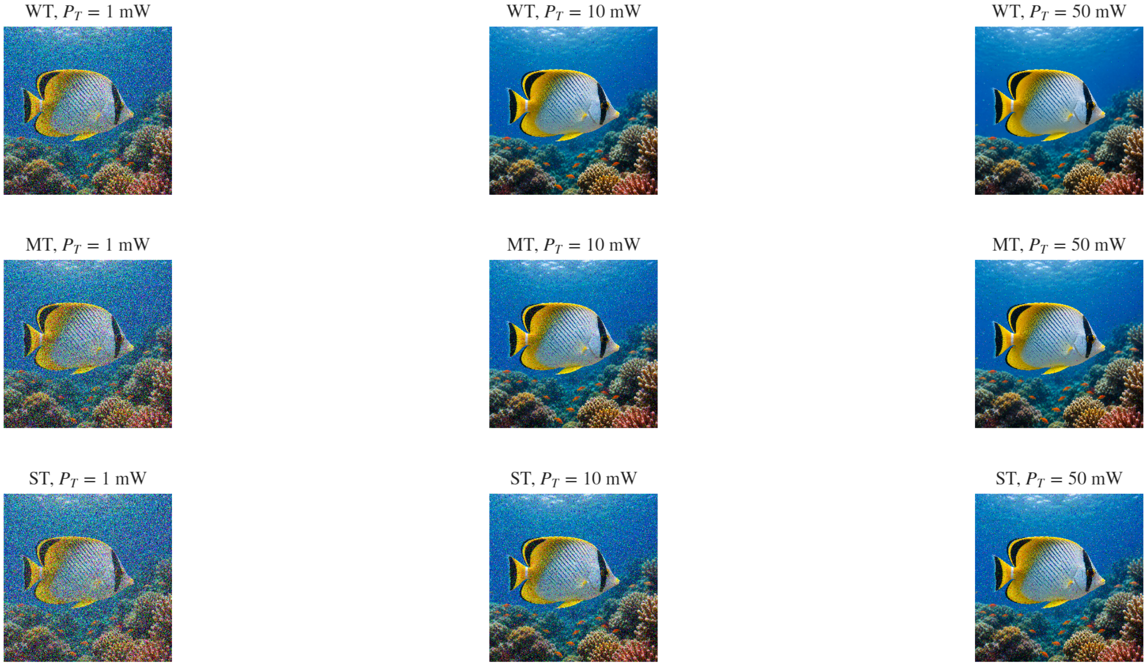
Figure 3 presents the reconstructed images at the receiver for different transmitted optical power levels. In this analysis, the transmitted optical power levels considered are $P_T = 1$ mW, 10 mW, and 50 mW. For each transmitted power level, the reconstructed images are analyzed under different underwater turbulence conditions, namely WT, MT, and ST. The corresponding BER values for all the considered conditions are presented in Table III. The data rate used for the simulation is fixed at $R_b = 1$ Gbps.

From Fig. 3, it can be observed that the quality of the reconstructed image improves as the transmitted



Original Image
Received Image (WT)
Received Image (MT)
Received Image (ST)

Fig. 2. Original and reconstructed underwater images under weak, moderate, and strong underwater turbulence conditions for fixed transmitted optical power and data rate.



WT, $P_T = 1$ mW
WT, $P_T = 10$ mW
WT, $P_T = 50$ mW
MT, $P_T = 1$ mW
MT, $P_T = 10$ mW
MT, $P_T = 50$ mW
ST, $P_T = 1$ mW
ST, $P_T = 10$ mW
ST, $P_T = 50$ mW

Fig. 3. Reconstructed underwater images for different transmitted optical power levels under weak, moderate, and strong underwater turbulence conditions.

optical power increases. This improvement is due to the reduction in BER at higher transmitted power levels. Furthermore, from Table III, it is evident that the BER decreases with an increase in transmitted optical power for all turbulence conditions. However, the BER remains higher under ST conditions compared to WT and MT.

TABLE IV
BER PERFORMANCE FOR DIFFERENT DATA RATES UNDER VARIOUS UNDERWATER TURBULENCE CONDITIONS

Turbulence	**1 Gbps**	**5 Gbps**	**10 Gbps**
WT	9.44×10^{-5}	3.17×10^{-3}	9.98×10^{-3}
MT	3.73×10^{-3}	1.78×10^{-2}	3.21×10^{-2}
ST	2.06×10^{-2}	4.90×10^{-2}	6.92×10^{-2}

Figure 4 presents the reconstructed images at the receiver for different transmitted data rates. In this analysis, the transmitted data rates considered are $R_b = 1$ Gbps, 5 Gbps, and 10 Gbps. For each transmitted data rate, the reconstructed images were evaluated under varying underwater turbulence conditions, including WT, MT ans ST. The corresponding BER values for all the considered conditions are presented in Table IV. The transmitted optical power used for the simulation is fixed at $P_T = 100$ mW.

From Fig. 4, it can be observed that the quality of the reconstructed image degrades as the transmitted data rate increases. This degradation is mainly due to the increase in BER at higher data rates. Furthermore, from Table IV, it is evident that the BER increases with an increase in data rate for all turbulence conditions. Among all the turbulence conditions, ST exhibits the highest BER, whereas WT achieves the lowest BER performance.

V. CONCLUSIONS

In this paper, an underwater optical wireless communication (UOWC) system for underwater image transmission has been presented and analyzed under different underwater turbulence conditions. The captured underwater image was converted into binary data and transmitted through the underwater optical wireless channel using On-Off Keying (OOK) modulation. At the

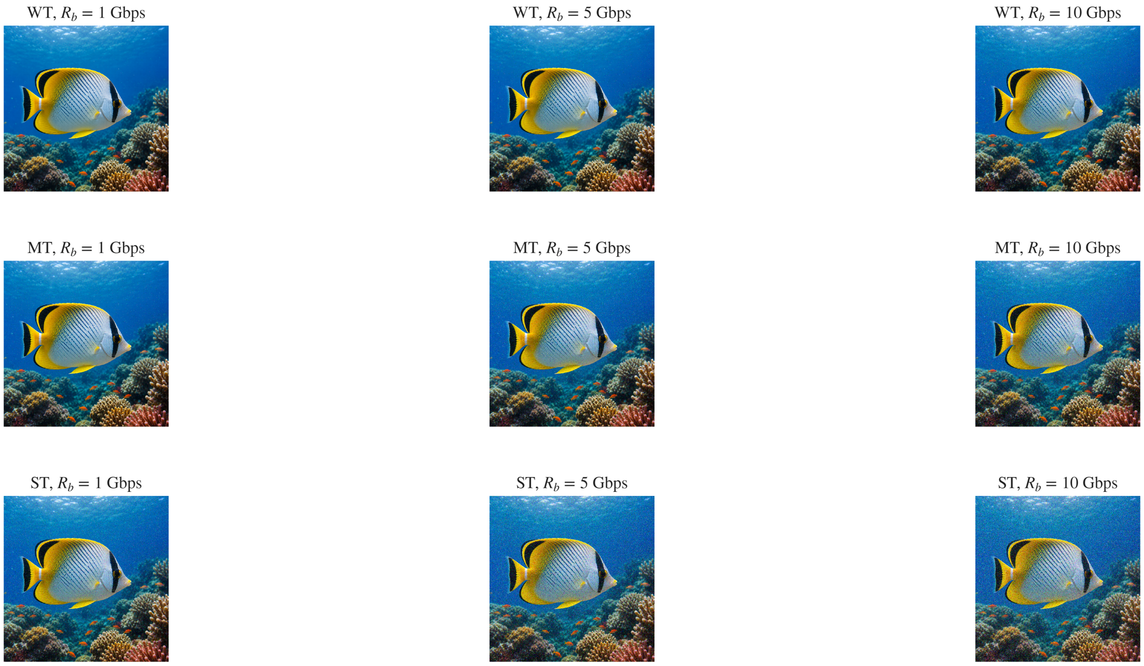


Fig. 4. Reconstructed underwater images for different data rates under weak, moderate, and strong underwater turbulence conditions.

receiver side, Maximum Likelihood Estimation (MLE) was employed to estimate the transmitted bits and reconstruct the received image.

The proposed system was analyzed based on Bit Error Rate (BER) performance and reconstructed image quality under weak, moderate, and strong turbulence conditions. Furthermore, the impact of transmitted optical power and data rate on system performance was investigated. The obtained results demonstrated that the BER increases and the quality of the reconstructed image degrades with an increase in underwater turbulence and transmitted data rate. In contrast, increasing the transmitted optical power improves the reconstructed image quality and reduces the BER performance degradation.

The presented study highlights the effectiveness of underwater optical wireless communication for high-speed underwater image transmission applications such as marine exploration, underwater monitoring, and underwater surveillance systems. Future work can focus on advanced modulation techniques, adaptive turbulence mitigation methods, and machine learning-based detection schemes to further improve the reliability and performance of underwater optical wireless communication systems..

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