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Performance Analysis of SIMO-UVLC System in Mix-Water Medium

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Keywords: LED array signaling | mixed water properties | optical pointing errors | SIMO-UVLC system | underwater optical turbulence (UOT) | underwater wireless optical communication

ABSTRACT

This research endeavors to investigate the end-to-end performance metrics of a submerged AUV within the Single-Input-Multi-Output underwater visible-light communication (UVLC) system operating in moderate-to-strong turbulence channel conditions while accounting for pointing errors. In this study, the closed-form expressions of analytical work are derived by using the probability density function and cumulative density function with a specific focus on Gamma-Gamma distribution channel. The analytical framework is used to gain insight into the performance of developed UVLC system within the mixed waters. To validate the accuracy of the analytical approach under the Monte Carlo simulation methodology is used to improve the quality of service. The designed system aims to improve the reliability, practical applicability, and efficiency of the UVLC system, which is the paramount importance in emerging communication technologies.

1 | Introduction

The growing interest in an alternative optical signaling approach that employs visible light as communication in both indoor and outdoor settings. This interest has been particularly pronounced in the context of addressing the challenges posed by extremely harsh underwater communication channels [1]. Specifically, a myriad of underwater applications require the establishment of reliable and high-connectivity links to facilitate real-time data streaming, especially in the context of advancing wireless networks. Therefore, the underwater visible light communication (UVLC) has drawn the attention of a promising and potential candidate for underwater signaling. UVLC offers the distinctive advantages of extremely low latency and high bandwidth, particularly when applied to real-time data encryption/decryption scenarios. The appeal of UVLC is further heightened by the utilization of the visible light communication (VLC) framework, which leverages a free licensing spectrum at minimal cost, making it an attractive prospect for researchers and practitioners alike. The availability of a free license spectrum in the visible light wavelength range underscores its status as one of the most reliable communication media for underwater applications. In particular, the wavelength spectrum from blue to green $(450 - 532 \text{ nm})$ is noted for its exceptional suitability in establishing trustworthy wireless networks for various purposes, including underwater monitoring, observation of marine life, monitoring of water pollution, interconnecting small islands, facilitating commercial activities, and improving coastal security

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[2]. The traditional underwater wireless communication (UWC) technologies such as acoustic and electromagnetic (EM) waves in terms of radio-frequencies (RF) are widely used but with numerous drawbacks [3]. The acoustic waves propagate with very low speed, experience with frequency dependent attenuation, and high latency, while the RF waves propagate only few meters and require large size antenna in underwater environment for signal transmission [4].

Therefore, considering the above shortcomings in traditional underwater communication medias, an alternative underwater wireless communication methodology as UVLC is investigated throughout this research. Predominantly, the existing research on UVLC has been conducted under conditions characterized by weak turbulence channels without accounting for pointing errors [5]. The prior works have primarily focused on modeling the signal layer within non-mixing water, neglecting the incorporation of experimental data [6]. In the most recent study [7, 8], where the authors proposed an underwater optical communication system model by utilizing the log-nomal distribution channel for weak turbulence channels. Therefore, the necessity is to develop the most reliable UVLC communication link through this study that supports the high-data rate encryption/decryption in real-time monitoring within the moderate-to-strong turbulence channel conditions in mixed ocean waters. In contrast, this study addresses the limitations by introducing a Single-Input-Multi-Output (SIMO)-UVLC vertical model designed to vary moderate-to-strong turbulence conditions while considering the presence of pointing errors. It is noteworthy that this research utilizes the experimental data to formulate and validate the proposed SIMO-UVLC system model in the mixed-water environment [9]. This research evaluates the Bit Error Rate (BER) and outage performance of the system by employing the On–Off Keying (OOK) modulation scheme. Therefore, this study proposes a SIMO-UVLC system in kth number of vertical layers within strong turbulence channel conditions considering both in the presence and absence of pointing errors between communication nodes. In Figure 1, it is depicted that an autonomous underwater vehicle (AUV) transmits the optical signal toward a fixed floating vessel at varying depths. It is noteworthy that the floating vessel applies M-ary of LEDs for receiving information. To bridge this gap, in this study the authors derived and updated closed-form expressions for the SIMO-UVLC system employing an Mth-array of LEDs at the receiver end.

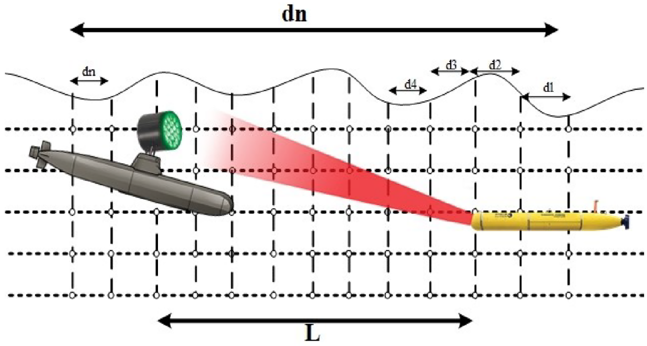

FIGURE 1 | The developed system model where an autonomous underwater vehicle (AUV) communicates with a submarine which is mounted M-ary of LEDs.

2 | Main Contribution of the Study

The developed vertical UVLC system is intended for use under conditions of the moderate-to-strong turbulence channel while considering the pointing errors. The following contributions are highlighted throughout this research:

- A novel mathematical formulation encompasses closed-form expressions designed for an array of LEDs that receive optical signals in mixed-water channel conditions. This approach enables to incorporation of successive water layers with varying physicochemical properties, providing a realistic representation of wireless communication scenarios throughout the entire year.
- This proposed research is updated by generalized Meijer-G functions that accommodate the intricate interplay of water layers within a composite channel environment. To enhance the system performance, we leverage the Gamma-Gamma (GG) distribution and exponential distribution to optimize both turbidity and the reduction of pointing errors between transceivers. Specifically, we obtain critical metrics as the average bit-error rate (ABER) and the outage probability considering the sequential arrangement of LEDs.
- This research conducts extensive simulations based on varying temperature, salinity, communication range, beam spreading angle, and the number of LED arrangements, successive changes in vertical depth, and the presence of pointing errors. Additionally, we account for the inherent optical properties (IoPs) and apparent optical properties (AoPs) in this comprehensive analytical study.

3 | Proposed System Model

This section presents the developed communication model in consideration of challenging channel conditions, encompassing variations in the physicochemical properties of mixed ocean water. In this research, we employ an AUV as the data source, responsible for transmitting oceanographic data to a fixed floating vessel as the base station (BS). This transmission occurs through successive kth vertical water layers utilizing a laser diode. It is noteworthy that in this study the BS is equipped with an array of 2^M LEDs for receiving optical signals. The proposed system model is designed within the mixed water in the Southern Indian Ocean (SIO). The whole system model is designed within the plane wave model approach (vertical layers). The performance analysis is obtained on varying vertical layers and each layer is considered 10 m for numerical and simulation results. The corresponding path loss and turbulence have been determined by associating vertical water layers. The large-scale (α), small-scale (β), and scintillation index (SI) contribute to the underwater optical turbulence (UOT) and are calculated by consideration of kth vertical layers based on the real-time experimental data for the whole year in SIO [10]. Moreover, the Monte-Carlo simulation approach is also used to validate the results and stimulation of the photon trajectories in random water flow toward the optical receiver. The designed UVLC model is illustrated by Figure 1. Additionally, the Figure 1 shows the communication between the AUV and the BS within the mixed ocean water environment. The

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PDF of strong turbulence for *k*th vertical layers can be written as follows [11];

$$f_{I_{t^k}}\left(I_{t^k}\right) = \frac{\prod_{k=1}^{K}\left(\alpha_k\beta_k\right)}{\prod_{k=1}^{K}\left(\Gamma\alpha_k\Gamma\beta_k\right)} G_{0,2K}^{2K,0} \left(\prod_{k=1}^{K}\left(\alpha_k\beta_k\right) I_{t^k} \middle| \begin{matrix} - - - \\ \alpha_1 - 1, \dots \alpha_K - 1, \beta_1 - 1, \dots \beta_K - 1 \end{matrix}\right) \tag{1}$$

The PDF of pointing errors for *k*th vertical layers [12] can be written as $I_{p^k} = A_k \exp\left(-\frac{2a_k^2}{\Omega_{d_k}^2}\right)$ where a_k defines the random radial displacement (RRD) of communication nodes, The RRD is calculated by $a_k = \sqrt{a_x^2 + a_y^2}$. In addition, the horizontal and vertical elevation axes are defined by a_x^2 and a_y^2, respectively. A_k is the power factor collected in $a_k = 0$. The equivalent beam width is represented by Ω_{d_k}. Therefore, the PDF of I_p can be written as $f_{I_p^k}\left(I_{p^k}\right) = \frac{\zeta^2}{A_0^{\zeta^2}} I_{p^k}^{\zeta^2-1}$, where $\zeta = w_{zeq}/2\sigma_s$ is the ratio between the equivalent beam radius and the pointing error displacement standard deviation.

It emphasizes that the received light intensity I_K represents the cumulative effect of multiplicative factors arising from path loss I_{l^k}, pointing error I_{p^k} and turbulence conditions I_{t^k} within the *k*th vertical mixed water layers [13]. Therefore, we define the multiplicative factor as: $I_K = \sum_{k=1}^{K}\left[\prod_{k=1}^{K} I_{l^k} I_{p^k} I_{t^k}\right]$. The received light intensity I_K at the receiver end can be further defines as $I_K = \max\left(I_1, I_2, I_3, \dots, I_n\right)$. Additionally, the instantaneous electrical SNR for *k*th layer under intensity modulation and direct detection (IM/DD) following OOK modulation scheme is expressed as $\gamma_k \triangleq (R\eta)^2 \left|I_k\right|^2/\sigma_k^2$, where η and R are present the optical conversion efficiency and photodetector responsivity within zero means and σ^2 variance. The whole system is considered in the selection combined process. The SNR for the selection combining process $\left(\gamma_{SC}\right)$ at the destination for decision making can be defined as $\gamma_{SC} = \max_{k=1,\dots,K}\left(\gamma_K\right)$. These formulations are crucial in assessing the performance of the system model in the underwater communication context.

4 | Performance Analysis of Average Bit-Error-Rate (ABER)

The proposed system employs the IM/DD-OOK modulation scheme within a selection combining framework. By plugging the values of $f_{I_t}\left(I_{t^k}\right)$ and $f_{I_p}\left(I_{p^k}\right)$, the average bit-error-rate (ABER) expression for this configuration can be represented as follows [12];

$$\overline{BER} = \frac{1}{2}\int_0^{\infty} erfc\left(\sqrt{\frac{\mu I_K}{2M}}\right) \times f_{I_t}\left(I_{t^k}\right) f_{I_p}\left(I_{p^k}\right) dI_t dI_p \tag{2}$$

where, the μ represents the average SNR, I_k is the combined light irradiance, and the M denoted the number of LEDs at the receiver. Replacing the values of $f_{I_t}\left(I_{t^k}\right)$ and $f_{I_p}\left(I_{p^k}\right)$ in (2), we can obtain the mathematical expression in Meijer-G function as in (3).

$$\overline{BER} = \frac{\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k}}{2\sqrt{\pi}\prod_{k=1}^{K}\Phi_{\Gamma(\alpha_k)\Gamma(\beta_k)}} \int_{-\infty}^{\infty}\int_0^{\infty} G_{0,2K}^{2K,0}\left[\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k} I_{t^k} \middle| \begin{matrix} \dots \\ \mathbf{a}_{arg} \end{matrix}\right] \times G_{1,2}^{2,0}\left[\frac{\mu I_{p^k}^2}{2M} I_{t^k}^2 \middle| \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix}\right] dI_{t^k} dI_{p^k} \tag{3}$$

The expression (3) is a complex integral expression that can be further integrated by using the properties of wolfram mathematical in consideration of [14, Equation 07.34.21.00084.01] and [14, Equation 07.34.21.0001.01] to obtain the closed-form expression as in (4).

$$\overline{BER} = \frac{2^{\sum_{k=1}^{K}(\alpha_k+\beta_k)-2K}}{2\pi^{\left(\frac{2K+1}{2}\right)}\prod_{k=1}^{K}\Phi_{\Gamma(\alpha_k)\Gamma(\beta_k)}} G_{4K+1,2}^{2,4K}\left[\frac{2^{(4K-1)}\mu}{M\left(\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k}\right)^2} \middle| \begin{matrix} \frac{1-\alpha_1}{2} \dots \frac{1-\alpha_k}{2}, \frac{2-\alpha_1}{2}, \dots \frac{1-\beta_1}{2}, \dots \frac{2-\beta_k}{2}, 1 \\ 0, \frac{1}{2} \end{matrix}\right] \tag{4}$$

4.1 | Outage Performance

In this section, we focus on evaluating the outage performance of the developed SIMO-UVLC system. This assessment is carried out through rigorous analytical calculations, utilizing the empirical data gathered from oceanic observations. The PDF of the combined influence of channel conditions is derived as follows;

$$F_{I_K} = \int_0^{I_{K,th}} f_I\left(I_{K,th}\right) dI_{K,th} = \frac{\left(\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k}\right) I_{K,th}}{AMI_{l_k}\prod_{k=1}^{K}\Phi_{\Gamma(\alpha_k)\Gamma(\beta_k)}} G_{2,4}^{3,1}\left[\left(\frac{\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k}}{AMI_{l_k}}\right) I_{K,th} \middle| \begin{matrix} \zeta^2, 0 \\ \zeta^2 - 1, \alpha_k - 1, \beta_k - 1, 0 \end{matrix}\right] \tag{5}$$

It is essential to note that for optimal outage performance, the instantaneous SNR should not exceed a predetermined threshold value. The analytical expressions for evaluating the outage performance are formulated in terms of cumulative density function (CDF) $P_{out} = F_I\left(I_K \le I_{K,th}\right) = \int_0^{I_{K,th}} f_I\left(I_{K,th}\right) dI_{K,th}$, and further calculated by integrating and utilizing the properties of wolfram mathematical [15] as follows;

$$P_{out} = \frac{\left(\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k}\right)\zeta^2}{AMI_{l_k}\prod_{k=1}^{K}\Phi_{\Gamma(\alpha_k)\Gamma(\beta_k)}} \sqrt{\frac{\gamma_{th}}{\mu}} G_{2,4}^{3,1}\left[\left(\frac{\prod_{k=1}^{K}\Phi_{\alpha_k\beta_k}}{AMI_{l_k}}\right)\sqrt{\frac{\gamma_{th}}{\mu}} \middle| \begin{matrix} \zeta^2, 0 \\ \zeta^2 - 1, \alpha_k - 1, \beta_k - 1, 0 \end{matrix}\right] \tag{6}$$

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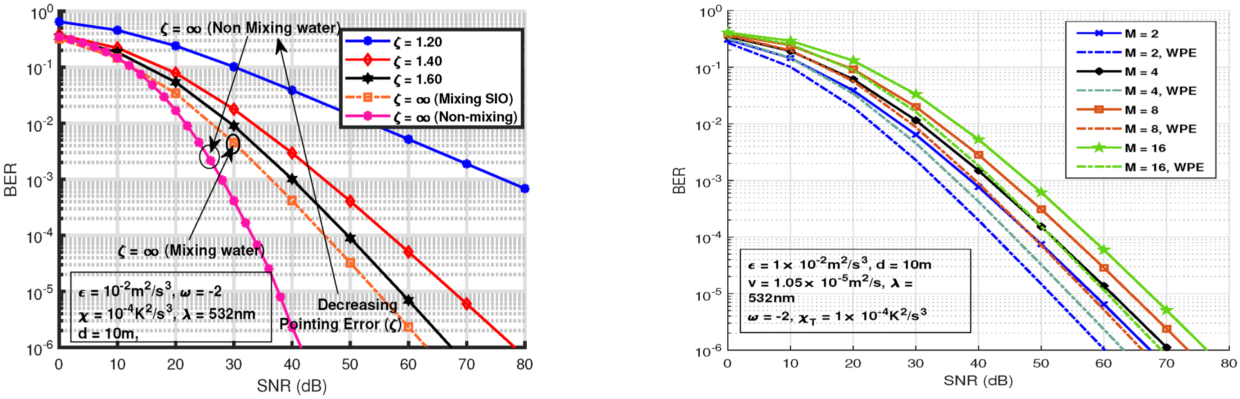
5 | Numerical Evaluation and Simulation Results

In this dedicated section, the authors conducted simulations by applying actual data sources from the SIO to validate the analytical expressions. It is crucial to emphasize that the AoPs of the water play a pivotal role in our endeavor to derive and assess the performance metrics in this study. The recorded average water surface temperature ranges from 28°C to 30°C and exhibits monthly variations, with an overall mean temperature of 27.5°C. Taking into consideration these average values for temperature, pressure, density, and salinity within the SIO [10], we evaluate system performance using the derived closed-form expressions. In our analysis, we assume the water medium to be representative of clear ocean water, characterized by an extinction coefficient of $c = 0.15$, with the transceivers placed at a distance of $d = 100$ m apart. The underwater environment is segmented into consecutive vertical layers, each with depths denoted as $d_t = 10, 20, 30,$ and 40 m while maintaining a fixed pointing error of $\zeta = 1.5^\circ$. The parameters α and β are meticulously computed to account for the varying properties of the water medium. It is important to note that at the receiver end, an array of LEDs is installed, with a fixed number of LEDs denoted as 2^M.

The pointing error plays a pivotal role in influencing the fading of the optical signal, and its impact on the BER performance is vividly illustrated in Figure 2a. The simulation results clearly indicate a decrement in the ABER as the pointing error (ζ) diminishes from 1.60 to 1.20. It is noteworthy that there is an interesting gap observed as the pointing error increases from 1.20 to 1.40. This gap arises because higher pointing errors have a more pronounced impact on accuracy in high SNR regimes. It is worth highlighting that the maximum system performance is attained at an infinite value of ζ ($\zeta = \infty$), indicating the absence of pointing errors between transceivers, while all other parameters remain constant. This observation underscores the critical role of precise transceiver alignment in optimizing system performance. It is also noteworthy that this study comprises with existing UVLC system model in non-mixing waters. The optimum performance are obtained in non-mixing water mediums while ($\zeta = \infty$) because the varying physio-chemical properties of mixing aqueous mediums [16]. The comparison offers a significant insight of the results that the implementation of the proposed system model outperform in non-mixing water rather than the mixing water channels. Therefore, the best ABER performance 10^{-6} is obtained at 41 dB SNR regimes in non-mixing water while the similar performance 62 dB in high SNR conditions.

In Figure 2b, we present the BER performance which highlights the impact of varying the number of M-ary LEDs at the receiver end. This performance evaluation is conducted within the context of strong turbulence channel conditions, where pointing errors can significantly influence signal intensity. The primary objective behind employing a higher number of LEDs, denoted as M, is to enhance the probability of successfully receiving optical photons, particularly in challenging channel conditions. In Figure 2b, the BER performances are showcased both in scenarios with and without pointing error (WPE). Remarkably, the most optimal performance outcomes are achieved when the analysis excludes the influence of pointing errors, underlining the significance of precise transceiver alignment in achieving optimal system performance.

End-to-end (E2E) outage performance is a significant metric in optimizing the proposed system model, especially in the context of mixed water mediums. Figure 3a provides a comprehensive view of the performance metrics obtained under varying conditions, including in the presence and absence of pointing error scenarios. This analysis reveals noteworthy insights into the impact of varying vertical distances underwater. We maintain consistency in our assessments by focusing on 10 m of vertical water layers. However, as the depth increases, we observe a notable decrease in outage performance. This decrement is particularly pronounced when pointing error phenomena are not considered. Similarly, the outage performance is depicted and comprises in non-mixing water at the vertical depth of 20 m [16]. The depth has been taken due to available experimental data in mixing and non-mixing waters. It can be clearly seen that the outage performance in non-mixing water is far better than in mixing water mediums. Additionally, the outage performances of the system in low SNR regimes are depicted and offers a significant impact



(a) The obtained ABER performances of the developed SIMO-UVLC system in Souther Indian Ocean.

(b) The obtained ABER performances on arrangement of M-ary LEDs at the receiver end.

FIGURE 2 | The BER performance matrics of proposed SIMO-UVLC system model in Southern Indian Ocean (SIO).

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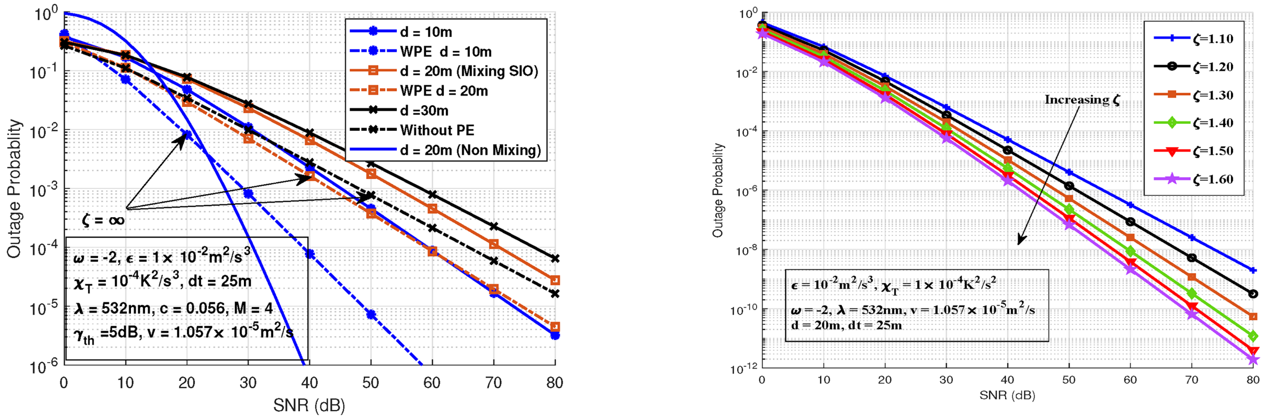

(a) Obtained outage performance of the developed UVLC system on varying vertical depth.

(b) Obtained outage performances of developed communication system model on varying pointing errors.

FIGURE 3 | The outage performance matrics of proposed SIMO-UVLC system model in Southern Indian Ocean (SIO).

of the proposed system model in immiscible and non-immiscible water types. Therefore, the importance of this study to provide the implementation scenario of the investigated UVLC model in various oceanic environments.

The misalignment phenomenon affects outage probability and provides an impressive insight on the results. The Figure 3b offers the outage performance of the SIMO-UVLC system on varying pointing errors. It is noteworthy that the outage probability decreases while increasing pointing errors on fixed physicochemical parameters. The performances in Figure 3b are obtained at fixed underwater vertical depth at 20 m.

6 | Future Directions of UVLC Link in Mix and Non-Mixing Water Mediums

The future research on UVLC has significant potential for various underwater applications, particularly in real-time data streaming and high-quality connectivity among communication nodes across both of mixing and non-mixing waters mediums. It could enhance the monitoring of oceanographic environments by enabling continuous data acquisition from sensors that track temperature, salinity, and biodiversity. In observing marine life, UVLC can facilitate real-time data transmission from underwater cameras, aiding in behavioral studies without physical interference. Additionally, for geological applications, UVLC may improve monitoring of underwater land decay and tectonic activities, enabling quicker predictions of earthquakes and volcanic events through effective data communication. The proposed communication approach also holds promise for water pollution monitoring, allowing for real-time tracking of pollution levels with integrated sensors. Moreover, UVLC can enhance the connectivity between small islands, providing access to crucial resources and information. However, challenges such as transmission range and underwater conditions will require innovative research on optimizing data streaming in varying environments. Overall, advancements in UVLC may significantly elevate our understanding and management of underwater phenomena, benefiting ecological studies and disaster response efforts.

7 | Conclusion

This study presents a comprehensive analysis of performance metrics for the SIMO-UVLC system model that operates in mixed water environments. To accurately model the channel conditions, the authors employ Gamma-Gamma distribution while optimizing the pointing errors between transceivers is achieved using the exponential distribution. Throughout this study, it is considered that the receiver is equipped with an array of M-ary LEDs to enhance system efficiency. The entire communication setup is designed and evaluated within the context of the Southern Indian Ocean (SIO), employing the IM/DD technique with the OOK modulation scheme. This study is based on analytical work that imply the experimental data of SIO. The data has collected throughout the year and offering a comprehensive understanding of the system's behavior in this challenging underwater environment. The simulation results are comprised with the existing UVLC model in non-mixing water. In addition, the results are obtained on varying pointing errors and exploring different vertical depths under mixing harsh channel conditions. Remarkably, the performances consistently excel when pointing error conditions are excluded from consideration.

Author Contributions

Mohammad Furqan Ali: conceptualization (equal), data curation (equal), formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), resources (equal), software (equal), supervision (equal), validation (equal), visualization (equal), writing – original draft (equal). **Dushantha Nalin K. Jayakody:** conceptualization (equal), data curation (equal), formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), supervision (equal), writing – review and editing (equal).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data openly available in a public repository that issues datasets. The data that support the findings of this study are openly available in

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Argo float data and metadata from Global Data Assembly Centre (Argo GDAC) at https://www.seanoe.org/data/00311/42182/, 10.1109/TWC.2015.2467386, reference number [10].

References

1. M. Elamassie and M. Uysal, "Performance Characterization of Vertical Underwater VLC Links in the Presence of Turbulence," *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)* (Budapest, Hungary: IEEE, 2018), 1–6, https://doi.org/10.1109/CSNDSP.2018.8471888.

2. A. Al-Kinani, C. X. Wang, L. Zhou, and W. Zhang, "Optical Wireless Communication Channel Measurements and Models," *IEEE Communications Surveys & Tutorials* 20, no. 3 (2018): 1939–1962.

3. M. Elamassie, C. Geldard, and W. Popoola, "Underwater Visible Light Communication (UVLC)," in *Handbook of Radio and Optical Networks Convergence* edited by T. Kawanishi, (Singapore: Springer, 2024), 1–36, https://doi.org/10.1007/978-981-33-4999-5_62-1.

4. A. Wibisono, M. H. Alsharif, H. K. Song, and B. M. Lee, "A Survey on Underwater Wireless Power and Data Transfer System," *IEEE Access* 12 (2024): 34942–34957, https://doi.org/10.1109/ACCESS.2024.3373791.

5. M. R. Biswal, T. S. Delwar, A. Siddique, P. Behera, and J. Y. Ryu, "Analysis and Investigation of a Novel Underwater Channel Model for OWC Under Log-Normal Turbulent Condition," *Photonic Network Communications* 47, no. 1 (2024): 1–8.

6. M. Elamassie, "Performance Evaluation of Pre-Equalized UVLC Links Over Outdated Lognormal Turbulence Channels," *Turkish Journal of Maritime and Marine Sciences* 10, no. 1 (2024): 19–30.

7. Z. R. Zhu, J. Zhang, R. H. Chen, and H. Y. Yu, "Autoencoder-Based Transceiver Design for OWC Systems in Log-Normal Fading Channel," *IEEE Photonics Journal* 11, no. 5 (2019): 1–12.

8. Y. Ata, Y. Baykal, and M. C. Gökçe, "Analysis of Optical Wireless MIMO Communication in Underwater Medium," *IEEE Internet of Things Journal* 11, no. 11 (2024): 20660–20672, https://doi.org/10.1109/JIOT.2024.3371112.

9. "Floats A, Southern Indian Ocean," accessed December 15, 2021, https://argo.ucsd.edu/.

10. Argo, "Argo Float Data and Metadata from Global Data Assembly Centre (Argo GDAC)," accessed July 15, 2024, 10.1109/TWC.2015.2467386, https://www.seanoe.org/data/00311/42182/.

11. M. Elamassie, S. M. Sait, and M. Uysal, "Underwater Visible Light Communications in Cascaded Gamma-Gamma Turbulence," in *2018 IEEE Globecom Workshops (GC Wkshps)* (Abu Dhabi, United Arab Emirates: IEEE, 2018), 1–6, https://doi.org/10.1109/GLOCOMW.2018.8644170.

12. M. F. Ali, D. N. K. Jayakody, S. Garg, G. Kaddoum, and M. S. Hossain, "Dual-Hop Mixed Fso-Vlc Underwater Wireless Communication Link," *IEEE Transactions on Network and Service Management* 19, no. 3 (2022): 3105–3120.

13. M. Elamassie and M. Uysal, "Vertical Underwater VLC Links Over Cascaded Gamma-Gamma Turbulence Channels With Pointing Errors," in *2019 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)* (Sochi, Russia: IEEE, 2019), 1–5.

14. Mathematica W, 2020, http://functions.wolfram.com/01.06.02.0001.01.

15. V. Adamchik and O. Marichev, "The Algorithm for Calculating Integrals of Hypergeometric Type Functions and its Realization in REDUCE system," in *Proceedings of the International Symposium on Symbolic and Algebraic Computation* (New York: ACM, 1990), 212–224, https://doi.org/10.1145/96877.969.

16. M. F. Ali, D. N. K. Jayakody, and M. V. Ribeiro, "A Hybrid UVLC-RF and Optical Cooperative Relay Communication System," in *2021 10th International Conference on Information and Automation for Sustainability (ICIAfS)* (Negambo, Sri Lanka: IEEE, 2021), 13–18.

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