

A VLC based LoS Underwater Communication System: Design and Performance

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Abstract— Underwater wireless communications can be conducted via radio frequency (RF), optical wave, and acoustic waves. High data speeds at lower latency levels are possible with underwater optical wireless communications in comparison with the bandwidth-constrained acoustic wave and RF equivalents. Using a visible light communication (VLC) spectrum for data transmission can be a promising technology for underwater communication. In this paper, an underwater VLC based line-of-sight (LoS) communication system has been designed, and the effect of environmental factors like scattering, absorption, and dynamic water properties has been studied. The simulated received power has been compared with the theoretical received power for an underwater VLC-LoS system. Also, the effect of receiver aperture diameter having values of 20 cm, 5 cm, and 3 cm has been analyzed. According to the type of water the communication range differs. The maximum transmission ranges for pure sea has been found as 420 m.

Keywords—VLC, LoS, underwater optical communication, attenuation, received power

I. INTRODUCTION

Earlier the communication system based on radio frequency (RF) and acoustic wave has been used in underwater wireless communication, but these systems face many issues like signal distortion due to aquatic environment like turbulence, attenuation [1]. Also underwater communication based on RF and acoustic wave are affected by electromagnetic interference and are bandwidth limited. The visible light communication (VLC) and free space optic (FSO) channel provides an effective way to overcome these limitations. The only difference between VLC and FSO is that the VLC uses the visible light spectrum (typically from 380 nm to 790 nm) to transmit data, while FSO uses a focused laser beam using spectrum (780-1600 nm) [2]. A VLC brings more interest as an alternative to underwater wireless communication because of its high bandwidth, immunity to electromagnetic interference, and minimal absorption and scattering [3]. The VLC based underwater communication systems may encounter challenges such as a restricted light propagation range in turbulent water; so the requirement for the exact transceiver alignment to sustain a dependable communication link is important [4]. The VLC underwater communication is categorised into two types: line-of-sight (LoS) where there is no obstruction between transmitter and receiver; and non-line-of-sight (NLoS) where the communication link is affected by the obstructions [4]. This paper mainly focuses on LoS underwater optical communication. The communication in underwater is divided into three sections: transmitter, channel and receiver shown in Fig.1.



Fig.1 Block diagram for LoS underwater optical communication link

The transmitter is a light source, which uses blue or green part of the visible spectrum for underwater communication. In clear water, the the minimum attenuation is in the blue and green part of the spectrum (450-550 nm), therefore by maintaining the operational optical window within the blue and green spectrum will enhance the transmission of light through water [5].

While travelling through the underwater channel the transmitted light faces many obstructions. The obstructions in underwater optical communication limit the performance and range of communication link. The obstruction can be due to absorption, scattering and turbulence. As the communication is in nm, the nanoparticles in the aquatic can deviate the path of transmission light as it travel. Nanoparticles found in underwater environments are, Laminaria ochroleuca (10-20 nm), Gold nanoparticles (AuNPs), Silver nanoparticles (AgNPs), Titanium dioxide nanoparticles (TiO₂ NPs) (1-100nm), Silicates (1-10nm), dimethyl sulfide (40 nm), and Silica nanoparticles (11-900nm) [6]. The silica nanoparticles inside the underwater are most likely to affect the path of light [6]. At receiver, PIN or Avalanche Photodiode (APD) is used to convert the optical signal back to electrical signal.

In [7], the OptiSystem simulator has been used for simulating optical underwater communication, where a FSO channel of has been used as a medium for communication, but it doesn't specify the attenuation type that actually impacts the communication performance which includes the absorption and scattering coefficient rather it only provide the attenuation (in dB/Km). But in this paper LoS underwater channel in the OptiSystem simulator has been used, where the variation in the attenuation due to water type has been fed as an input parameter, which gives an appropriate power analysis to the designed system. The literature also introduces a convenient method for measuring the attenuation coefficient and proposes a method to infer the maximum communication distance. In underwater optical communication research, a practical challenge is due to the utilization of LEDs as the light source with a large beam angle. Hence, the use of reflective mirrors to redirect a collimated beam is not feasible. Therefore, it becomes crucial to theoretically infer the maximum possible communication distance. It has been found to have maximum communication distance of 25.4 m at 80 Mbps [8]. However, this paper presents a method, by using Laser Diode as a transmitter as the light from the Laser diode is

highly directional in nature and that is likely to enhance the communication distance.

According to the type of water, the theoretical and simulated received power analysis considering each water type has been compared. This paper, introduce a method for optical underwater communication using a Laser diode as a transmitter which enhance the communication range up to 420 m, whereas the prior work has used LED as a transmitter and the maximum communication range for the same is 25.4 m. The maximum transmission ranges for pure sea, clear ocean, costal ocean, harbors-I and harbor-II has been found. Also the effect of receiver aperture diameter having values of 20 cm (> than transmitter aperture diameter), 5 cm (equal to transmitter aperture diameter), and 3 cm (<than transmitter aperture diameter) has been analyzed on the received power in underwater optical communication.

This paper designs a VLC based LoS system for underwater optical communication where the transmitter is pointed straight towards the receiver, hence giving rise to a LoS path. Section II shows system model for such a system. The link budget analysis is also presented in this section. Section III gives a detailed explanation of the simulation setup for the proposed method. Section IV presents the results in terms of the received power, maximum transmission range and effect of attenuation type due to absorption and scattering of light in the aquatic communication link. A comparison is also made with the literature. Section V gives the conclusion.

II. VLC-LoS UNDERWATER COMMUNICATION

The transmitter and receiver are positioned parallel in a VLC-LoS underwater communication system. The medium of transmission between the transmitter and receiver is underwater. Data is transmitted using an optical modulator consisting of an optical source like LED/Laser as a carrier. The light from the modulator is transmitted through water to reach the APD based receiver. A suitable light spectrum used for such underwater communication is blue or green light. In such systems, both LEDs and lasers offer distinct advantages and disadvantages [9]. LEDs are easier to align due to their wider beam divergence but have lower data rates and shorter ranges compared to lasers [10]. Lasers offer higher data rates and longer ranges due to their narrow beam divergence but require precise alignment [10]. The optical beam transmitted from the optical modulator can deviate from the transmission path due to two phenomena i.e. absorption and scattering. The absorption and scattering coefficient impact the signal transmission and limits the communication range [11]. Absorption occurs when light energy is absorbed by water molecules; it converts into other forms of energy, like heat. This process decreases the light's intensity, which in turn shortens the effective distance for light-based communication. [11]. Scattering involves the redirection of light by particles in the water [11]. The particles having the same size as the transmitted wavelength produce scattering effect. Scattering leads to signal distortion and reduces the signal strength at the receiver. Both absorption coefficient and scattering coefficient are wavelength dependent and denoted as $a(\lambda)$ and $b(\lambda)$ respectively [12]. The overall attenuation in the underwater is the contribution of both $a(\lambda)$ and $b(\lambda)$, which is known as extinction coefficient and denoted as $c(\lambda)$ [12],

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (1)$$

Wavelengths within the blue and green spectrum, have lower absorption and scattering, so to improve transmission range in underwater communication it is required to use these optical window.

The variations in ocean waters are influenced by both geographic location and depth. Depending upon the clarity of the ocean, the water type is divided into five types: pure sea, clear ocean, costal ocean, harbor-I and harbor-II. The absorption, scattering and extinction coefficient for various water type for $\lambda = 550$ nm is shown in Table.1,

Table. 1 Standard values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ for different types of water [12]

Water Type	$a(\lambda)$	$b(\lambda)$	$c(\lambda)$
Pure Sea	0.0405	0.0025	0.043
Clear Ocean	0.114	0.037	0.151
Costal Ocean	0.179	0.219	0.298
Turbid harbor-I	0.187	1.913	1.1
Turbid harbor-II	0.366	1.824	2.19

After passing through the underwater, the optical beam reaches the optical receiver which is PIN or APD photodetector. The optical detector transforms the incoming optical signal into an electrical one and rapidly responds to all the photons emitted by the transmitter. For long distance transmission an APD detector is preferred in comparison to PIN detector.

The received signal power at the receiver is given by [13],

$$P_{r_LoS} = P_t e^{(-c(\lambda)d)} \quad (2)$$

where, P_{r_LoS} is the power received at the receiver, P_t is the transmitted power after the modulator, During LoS transmission, LoS loss in underwater communication occurs when there is a direct path between the transmitter and receiver is disrupted or distorted by various underwater conditions. The line-of-sight loss is given by [14],

$$L_{LoS} = \frac{A_r \cos \theta}{2\pi d^2 (1 - \cos \theta_0)} \quad (3)$$

The line-of-sight loss depends upon the A_r , θ , d , and θ_0 . The received power for LoS underwater communication is given by [14],

$$P_{r_LoS} = P_t \eta_t \eta_r e^{\left(-c(\lambda) \frac{d}{\cos \theta}\right)} \frac{A_r \cos \theta}{2\pi d^2 (1 - \cos \theta_0)} \quad (4)$$

where, θ_0 is the beam divergence angle of the transmitter which is used for computing the spreading of beam in water, η_t and η_r are the optical efficiency of the transmitter and optical efficiency of the receiver, d is the perpendicular distance between the transmitter and receiver, θ is the angle between the beam and the receiver plane normal. For direct LoS (straight-line) links, we consider $\theta = 0^\circ$, so $\cos(\theta) = 1$, A_r is the receiver aperture area.

III. PROPOSED SYSTEM

The simulations are done using OptiSystem 22.0. An underwater optical communication system consists of three main elements: the transmitter, the water medium, and the receiver. The transmitter consists of four main parts: the data source, which is the message signal. A user defined bit sequence generator has been used to generate a 10 bit data; NZR pulse generator that encodes the data: the light source, which acts as a carrier that used to carry the information Laser Diodes (LDs). The third component is the modulator, which encodes the information onto the optical signal. For this, a Mach-Zehnder Modulator has been used, to modulate the originally transmitted data. The optical signal travels through an underwater medium. The optical receiver detects the optical signal and converts it to an electrical signal. The APD detector has been used for long distance transmission. After optical to electrical conversion the signal passes through a signal processing unit that contains electrical low pass Bessel filter that emits the high frequency signal and pass the low frequency signal i.e. the message signal. The signal processing unit also contains the 3R regenerator that is used to restore the signal that has been transmitted over long distance. The term 3R refers to three key functions: reamplification, which strengthens the weakened optical signal; reshaping, which recovers the original pulse shape and minimizes signal distortion; and retiming, which adjusts timing errors and synchronizes the pulses with the original clock signal. The schematic layout of the proposed system has been shown in Fig.2.

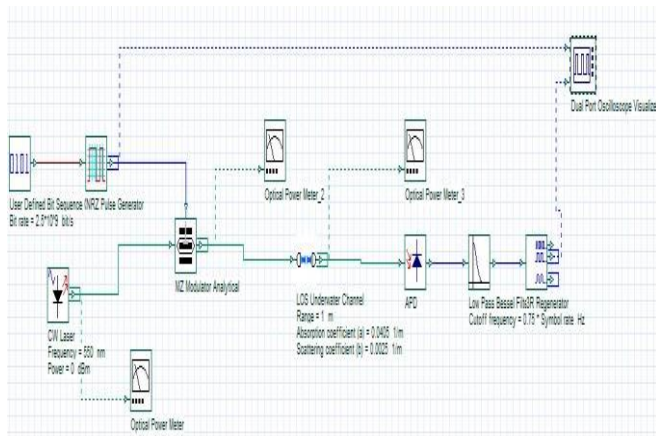


Fig.2 Schematic of LoS underwater optical communication link

The optical power meter has been used to visualize the transmitted power, power after the modulator and power received at the receiver. The Dual port oscilloscope has been used to visualize and compare the transmitted and received bits.

IV. RESULTS AND ANALYSIS

In this paper the data has been transmitted through a LoS underwater communication link using LD having wavelength of 550 nm and 0 dBm power. To get back the transmitted data APD photodiode, Low pass bessel filter, and 3R regenerator has been used. The simulation input parameters fed in OptiSystem simulator to implement the proposed schematic are given in Table.2

Table.2 Simulation Input Parameters

Parameters for Transmitter	
Parameters	Value
User defined bit sequence generator	10 bits
Laser transmitting power	0 dBm
Laser wavelength	532 nm
Parameters for LoS underwater channel	
Parameters	Value
Link type	LoS underwater
Wavelength	550 nm
Range	1 m
Attenuation type	Pure Sea
Absorption coefficient (a)	0.0405 1/m
Scattering coefficient (b)	0.0025 1/m
Transmitter aperture diameter	5 cm
Beam divergence	2 mrad
Incidence half angle	0 dB
Transmitter optics efficiency	0.9
Receiver aperture diameter	20 cm
Receiver optic efficiency	0.9
Parameters for Receiver (APD)	
Parameters	Value
Responsivity	0.65 A/W
Dark current	10 nA

The Fig. 3 shows the transmitted and received bits of a LoS underwater communication link.

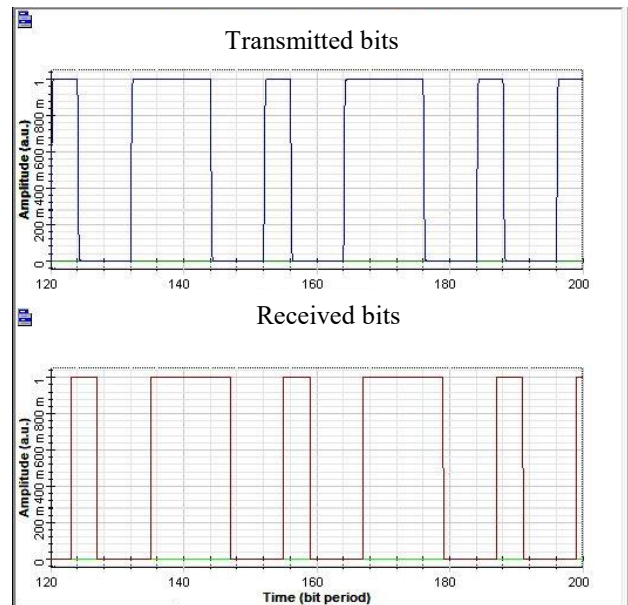


Fig. 3 Transmitted and received bits

According to the type of water the communication range differs. The maximum transmission ranges for pure sea, clear ocean, costal ocean, harbors-I and harbor-II for an input transmitter wavelength of 550 nm and transmitter power of 0 dBm are shown in Table. 3,

Table .3 Maximum data transmission range

Water type	Maximum Range
Pure Sea	420 m
Clear Ocean	140 m
Costal Ocean	92 m
Turbid harbor-I	35 m
Turbid harbor-II	18 m

The theoretical and simulated received power analysis considering each water type has been compared and shown in Fig. 4 to Fig. 8.

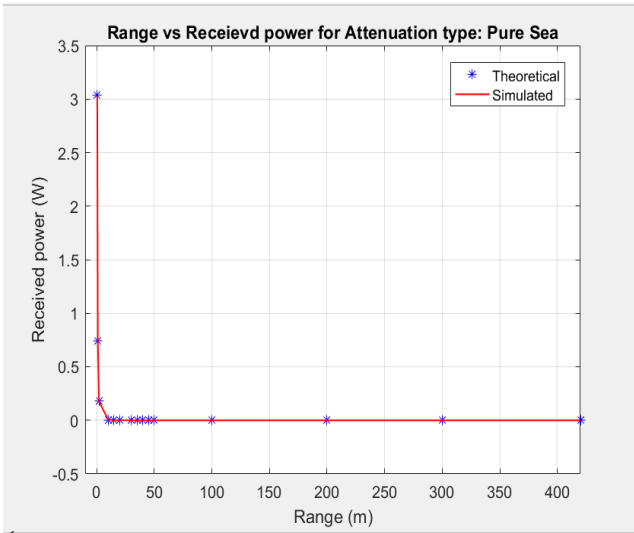


Fig. 4 Comparison of theoretical and simulated received power in pure sea

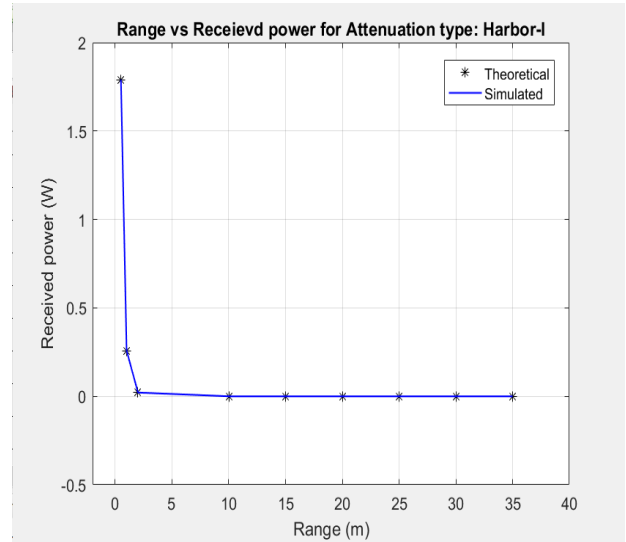


Fig. 7 Comparison of theoretical and simulated received power in Harbor-I

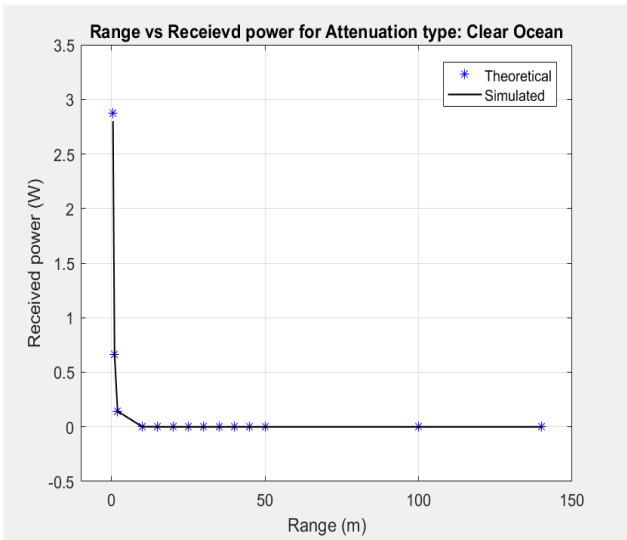


Fig. 5 Comparison of theoretical and simulated received power in clear ocean

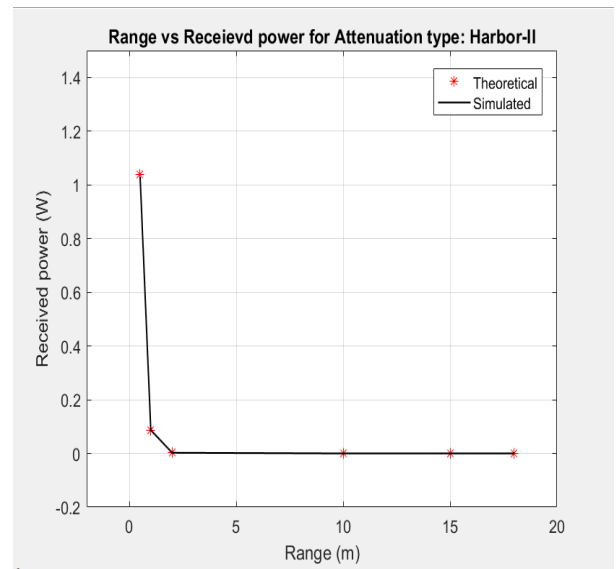


Fig. 8 Comparison of theoretical and simulated received power in Harbor-II

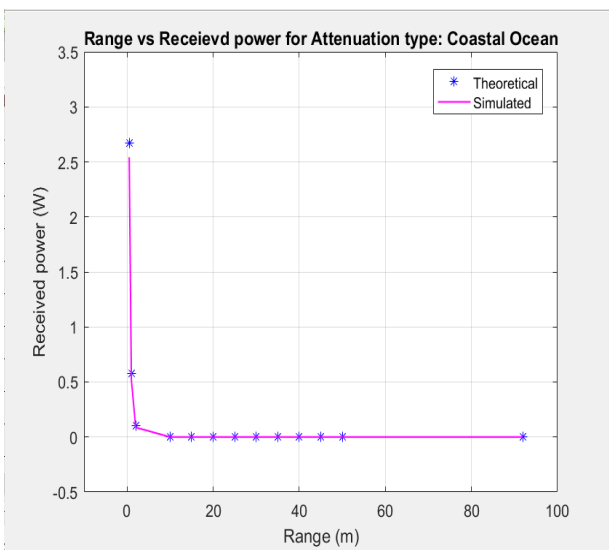


Fig. 6 Comparison of theoretical and simulated received power in coastal ocean

It has been found that for shorter distance there is an increase in the received power. The primary factor affecting the received power is the geometric spreading of the optical beam. As the light signal leaves the transmitter, it spreads out, causing the power density to decrease. From Eq. (4), the signal intensity decreases (i.e. the line-of-sight loss increases) with the increase in the square of the distance. But if the receiver's aperture is large enough to capture a significant portion of the expanding beam, the received power may still be relatively high. By keeping the $P_t=0.383$ mW, transmitter aperture diameter=5 cm and changing the receiver aperture for underwater LoS communication in pure sea, the received power has been found and shown in Table. 4.

Table. 4 Effect of received power by varying the receiver aperture diameter

Receiver aperture diameter	Range	$P_{r,LoS}$	Diff= $ P_t-P_{r,LoS} $
20 cm (> than transmitter aperture diameter)	1 m	0.743 W	0.742617
	10 m	0.005 W	0.004617
	30 m	0.0023 W	0.001917
5 cm (same as transmitter aperture diameter)	1 m	46.4 mW	0.046017
	10 m	0.315 mW	0.000068
	30 m	0.014 mW	0.000369
3 cm (< than transmitter aperture diameter)	1 m	0.016 mW	0.000367
	10 m	0.113 mW	0.00027
	30 m	0.0053 mW	0.0003777

In the literature [7], the received power analysis has presented using FSO channel for optical underwater communication. With the laser's power set to a constant value of 1, 5, or 50 mW, laser wavelength as 350 nm and the bitrate fixed at 10 Gbps, the distance was varied to study its effect on the system's performance. In Table. 5, keeping the identical input parameters as [7], the received power has been compared with the proposed work where LoS underwater channel has been used as communication medium.

Table. 5 Received power comparisons with the literature

Water type	P_t (mW)	d (m)	$P_{r,LoS}$ [7] (dBm)	$P_{r,LoS}$ (Proposed Work) (dBm)
Clear Ocean	1	103	-33.28	-78.906
	5	121	-33.34	-85.119
	50	147	-33.48	-93.860
Costal ocean	1	7.4	-33.07	-38.692
	5	8.5	-32.03	-36.008
	50	10.5	-32.86	-33.131

V. CONCLUSION

In this paper, the simulation results show that the maximum communication range for LoS underwater communication depends on water type, by considering its absorption, scattering and extinction coefficients. The theoretical and simulated received power analysis for each water type has been compared and found to be matching. The received power increases for short distance underwater communication. This can be taken care of by changing the receiver aperture diameter. Considering the transmitter aperture diameter as 5 cm and by varying the receiver aperture diameter into three type: (a) greater than transmitter aperture diameter (20 cm), (b) same as transmitter aperture diameter (5 cm), and (c) less than transmitter aperture diameter (3 cm) it has been found that, when the receiver's aperture diameter is either the same as or smaller than the transmitter's the power loss is minimum. This effect was observed over communication ranges of 1 meter, 10 meters, and 30 meters. Also by keeping the receiver aperture diameter as 5 cm and range at 10 m the received power is 0.315 mW which is nearly same as the transmitted power i.e. 0.383 mW. In prior work, the FSO channel has been used to found the received power analysis without considering the attenuation due to the water particles in different types of water. This paper has presented the received power analysis for different water types and also

considers the extinction coefficient that affects the propagation path of the transmitted light. In the literature, the FSO channel has been used as a medium of transmission in OptiSystem simulator to execute the underwater communication, but unlike underwater communication which uses water as a medium, FSO transmit the information through air. The underwater optical communication has to consider the attenuation due to the water particles that happens because of absorption and scattering so the proposed system has been designed by considering the attenuation effect in underwater which is a practical one. Creating a hybrid system with acoustic, RF and underwater optical communication can enhance the communication system which can be a promising avenue for further innovation. Also the non-line-of-sight (NLoS) underwater optical communication channel can be needed to be explored for the effect of multipath reflection in communication system.

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REFERENCES

- [1] Z. Li, W. Li, K. Sun, D. Fan, W. Cui, "Recent Progress On Underwater Wireless Communication Methods And Applications", Journal of Marine Science and Engineering, MDPI, vol. 13, no.8, pp. 2-23, August 2025.
- [2] A. A. Sabri, S. M. Hameed, W. A. H. Hadi, "Last mile access-based FSO and VLC systems" Journal of Applied Optics, vol. 62, no. 31, pp. 8402-8410, October 2023.
- [3] T. C. Yu, W. T. Huang, W. B. Lee, C. W. Chow, S. W. Chang, H. C. Kuo, "Visible Light Communication System Technology Review: Devices, Architectures, and Applications" Journal of Crystal, MDPI, vol. 11, no. 9, pp. 2-28, September 2021.
- [4] X. Zhou, J. Shi, N. Chi, C. Shen, Z. Li, "Wavefront shaping for multi-user line-of-sight and non-line-of-sight visible light communication", Optics Express, vol. 31, no. 16, pp-25359-25371, July 2023.
- [5] J.P. Xue, C.W. Cuss, T. Noernberg, M.B. Javed, N. Chen, R. Pelletier, Y. Wang, W. Shot, "Size and optical properties of dissolved organic matter in large boreal rivers during mixing: Implications for carbon transport and source discrimination", Journal of Hydrology: Regional Studies, vol. 40, no.1, pp. 1-17, February 2022.
- [6] E. Dube, G. E. Okuthe, "Engineered nanoparticles in aquatic systems: Toxicity and mechanism of toxicity in fish", Journal of Emerging Contaminants, vol. 9, no.1, pp. 1-10, February 2023.
- [7] A. Kaeib, O. A. Alshawish, M. A. Gamoudi, "Designing and Analysis of Underwater Optical Wireless communication system", IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA) Sabratha, May 2022.
- [8] M. Zhang, H. Zhou, "Real-Time Underwater Wireless Optical Communication System Based on LEDs and Estimation of Maximum Communication Distance", Journal of Sensors, MDPI, vol. 23, no. 17, pp. -15, September 2023.
- [9] M. A. A. Ali, S. K. Rahi, "Line of Sight (LoS) Underwater Wireless Optical Communication Based on LED", 9th International Symposium on Telecommunications (IST), IEEE, March 2019.
- [10] R. T. Prabu, V. Lingaraj, et al, "Light emitting diode and laser diode system behaviour description and their performance signature measurements", Journal of Optical Communications, vol. 46, no. 2, March 2024.
- [11] A. Elfikky, A. Boghdady, S. Mumtaz, et al, "Underwater visible light communication: recent advancements and channel modeling", Journal of Optical and Quantum Electronics, vol. 56, no. 10, pp. 1-45, September 2024.
- [12] T. Theocharidis, E. Kavallieratou, "Underwater communication technologies: a review", vol. 88, no.54, pp.1-27, April 2025.
- [13] I. Ramley, H. M. Alzayed, Y. A. Hadeethi, M. Chenn, A. Z. Barasheed, "An Overview Of Underwater Optical Wireless

Communication Channel Simulations With A Focus On The Monte Carlo Method”, Journal of Mathematics, vol. 12, no. 24, pp., December 2024.

- [14]C. Guo , Z. Li, L. Zha, Z. Wang, H. Jia, et.al, “Diffuse-LOS Optical Wireless Communication Across Wavy Water-Air-Interface Using UVA Light”, IEEE Photonics Society Section, IEEE Access, vol.12, pp. 1-12, August 2024.