On the Path Loss Performance of Underwater Visible Light Communication Schemes Evaluated in Several Water Environments

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Abstract

This paper presents an in-depth study into the necessity of efficient communication systems in underwater environments, with a primary focus on Underwater Visible Light Communication (UVLC). A novel path loss model that adapts to different water types is proposed to improve existing UVLC channel models. Validation against various scenarios, including different water types and receiver aperture diameters, is carried out using Monte Carlo simulations. The results demonstrate the efficiency and accuracy of the model by carefully fitting the actual performance of the UVLC systems. The results show a considerable improvement over previous models that only considered Lambert 19s path loss and geometric path loss. Despite some variations observed at larger distances between the transmitter and receiver, the proposed model exhibits significant promise in the understanding and application of UVLC in different underwater environments. This study serves as a preliminary step toward developing more sophisticated and efficient models for UVLC systems.

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***Abstract*—This paper presents an in-depth study into the necessity of efficient communication systems in underwater environments, with a primary focus on Underwater Visible Light Communication (UVLC). A novel path loss model that adapts to different water types is proposed to improve existing UVLC channel models. Validation against various scenarios, including different water types and receiver aperture diameters, is carried out using Monte Carlo simulations. The results demonstrate the efficiency and accuracy of the model by carefully fitting the actual performance of the UVLC systems. The results show a considerable improvement over previous models that only considered Lambert's path loss and geometric path loss. Despite some variations observed at larger distances between the transmitter and receiver, the proposed model exhibits significant promise in the understanding and application of UVLC in different underwater environments. This study serves as a preliminary step toward developing more sophisticated and efficient models for UVLC systems.**

***Index Terms*—Channel modeling, Monte Carlo numerical simulation (MCNS), path loss, underwater visible light communications (UVLC).**

I. INTRODUCTION

The demand for the implementation of communication systems in underwater environments has been increasing over the years, due to the growing need of humanity to explore these remote scenarios. One of the main exploration purposes is to collect scientific data or for environmental monitoring, driven primarily by changes in global warming in ocean conditions [1]. In addition to these requirements, security and tactical surveillance of port areas or maritime territories can be included, as well as the search for oil extraction sites or other raw materials. However, to comply with the technical characteristics of these applications, robust and efficient communication systems are necessary.

In this context, in recent specialized research, several communication system models have been proposed and implemented. One of the most common implementations is related to acoustics or communication through Underwater Sensor Networks (USNs). Its main advantage lies in its monitoring capacity and that it tends to be less expensive than other communication systems [2]. However, this method does not offer high transmission rates and has significant latency in communication, making it unsuitable for real-time communication processes. An alternative communication system used to address these problems is optical communication (fiber optics), which provides high transmission rates. However, this advantage is achieved through high installation costs and logistical complexity due to the need for a cable connection. In response to the need for a technology that can operate at high transmission rates and low cost, the application of Underwater Visible Light Communication (UVLC) emerges as a possible promising alternative to provide communications in these environments.

UVLC presents several advantages, including its high transmission rates and energy efficiency [3], [4]. Despite the growing body of literature and research exploring UVLC from different perspectives, it remains an emerging field that requires a comprehensive understanding of channel modeling in underwater environments. The Radiative Transfer Equation (RTE) is the foundation for underwater communication models, which allows a thorough characterization of the propagation of light underwater [5]. However, due to its integro-differential nature, obtaining a general analytical solution poses significant challenges. Consequently, alternative numerical methods have been developed, such as the discrete ordinates method, which is limited to homogeneous bodies of water [6]. To address the need to generalize the channel, simulation techniques such as Ray-Tracing can be employed and validated through Monte Carlo methods [7], [8], [9]. Alternatively, a simpler approach involves modeling the channel through Line-of-Sight (LoS) calculations in underwater transmissions, utilizing the Beer-Lambert formula [10]. However, modifications to the Beer-Lambert formula have been proposed to account for the presence of scattered photons, such as a modification based on the weighted combination of two exponentials [11].

This paper aims to characterize the empirical path loss coefficient and develop a mathematical expression associated with different types of water, including pure water, coastal water, and harbor water. To achieve this objective, we conducted a simulation of a UVLC scenario using MATLAB. Subsequently, the simulation results were analyzed in order to derive coefficients and establish the proposed path loss expression.

The paper is structured as follows: Section II provides a comprehensive review of existing path loss models, emphasizing various approaches proposed in previous studies. Building on this foundation, Section III introduces a novel path loss model designed explicitly for UVLC. In Section IV, we present and analyze the results, accompanied by a detailed analysis using data-fitting techniques to facilitate meaningful comparisons. Finally, Section V concludes the paper by summarizing the key findings and suggesting potential directions for future research in this field.

II. STATE OF THE ART

When modeling UVLC channels, several notable works have contributed to the advancement of research. One of the fundamental models is the path loss proposed by the Beer-Lambert law. This model presents a path loss function based on an exponential relationship with parameters c and d, where c represents the coefficient of extinction for the specific type of water, and d represents the distance between the transmitter and the receiver [5]. However, this model tends to overestimate loss and overlooks other influential factors that can affect transmission. Consequently, researchers have modified the Beer-Lambert model to consider additional factors and improve its precision [5].

An exemplary work in this field is presented in [7], which introduces two combinations of path loss models for the characterization of UVLC channels. The first combination is based on the Beer-Lambert path loss, considering only the LoS component in a setup where both the transmitter and receiver are aligned. The second combination incorporates the geometric path loss, accounting for beam scattering that occurs during transmission using a configuration and diffuse/semi-collimated sources. This calculation incorporates parameters such as irradiance angle, Lambertian order, and photodetector surface area. Furthermore, the second combination includes an improvement proposed by [11] to enhance the accuracy of the path loss model. The authors perform simulations to analyze and compare both combinations, specifically focusing on the type of coastal water. The results reveal that the second proposed combination achieves a better fit to the simulation data.

Another notable path loss model is presented in [12], where the Beer-Lambert function is modified to characterize the path loss based on the angle of divergence of the beam, the diameter of the receiver aperture, and the extinction coefficient. This modification takes into account four different types of water: pure ocean water, clean oceanic water, coastal water, and harbor water. A comparative analysis between the proposed modification, the Beer-Lambert equation, and simulations demonstrates that the modified model achieves a better fit with the simulation data.

The former work represents significant contributions to the field of UVLC channel modeling, improving the accuracy of path loss estimation and considering various influential factors. However, a deeper understanding is needed in this area to develop more comprehensive and accurate models for different types of water and environmental conditions.

III. METHODOLOGY

In this section, we describe the UVLC system model and path loss models proposed in this paper.

A. UVLC System Model

The fundamental building block of a UVLC system is based on a point-to-point (LoS) link. The UVLC transmission system consists of three main elements: a transmitter, a receiver, and the UVLC channel. The transmitter includes a modulator and pulse shaper circuit, a driving circuit, and a Light-Emitting Diode (LED) for light transmission. The receiver comprises a demodulator circuit and a Photo-Diode (PD). The UVLC channel represents the medium through which the information is transmitted. These components and the layout of the system can be observed in Figure 1. In this configuration, the receiver is positioned to detect the light beam directed straight towards it from the transmitter. To obtain the appropriate UVLC channel model, we must first introduce the Direct Current (DC) channel gain model, which can be described using the general Lambertian model as follows [13], [14]:

$$H_c = \frac{A_p(m+1)}{2\pi d^2}\cos^m(\varphi)\cos(\psi)G(\psi), \tag{1}$$

where A_p represents the area of the PD or aperture diameter, m denotes the Lambertian mode, d is the distance between the transmitter and receiver, φ is the angle of irradiance, ψ is the angle of incidence, and $G(\psi)$ is the total gain, typically equal to 1. However, since the system operates underwater, the transmission is influenced by the interaction of light and water. To adapt this effect in the general channel model presented in expression (1), it is necessary to include a coefficient as follows [15]:

$$H_c = e^{-cd}\frac{A_p(m+1)}{2\pi d^2}\cos^m(\varphi)\cos(\psi)G(\psi), \tag{2}$$

where c represents the extinction coefficient, which is the sum of the absorption coefficient (a) and the scattering coefficient (b) of the medium, which can be expressed as $c(\lambda) = a(\lambda) + b(\lambda)$. Finally, the received signal expression from the new channel equation is:

$$y = H_c x + z, \tag{3}$$

where x corresponds to the transmitter output signal and z to the Gaussian noise distribution with variance σ^2.

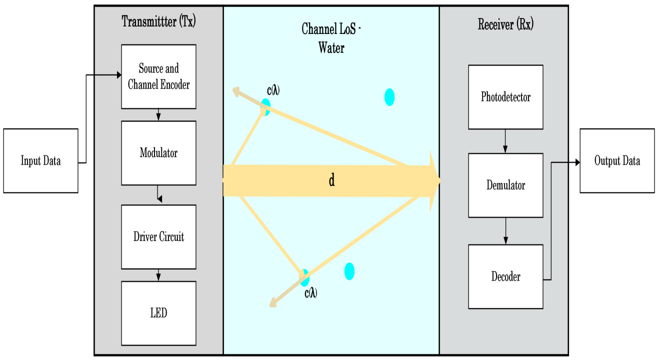

Fig. 1. UVLC System Model

B. Path loss Model

Path loss is a function that calculates signal degradation caused by attenuation and geometric effects. For power sources like laser diodes, geometric issues are negligible, so path loss depends only on attenuation. However, geometric features must be considered for diffuse and semi-collimated sources such as LEDs or diffuse laser diodes. The attenuation caused by the interaction between light and water particles can be calculated using the Beer-Lambert law [10]. In consequence, path loss can be defined as:

$$PL_{BL} = 10\log_{10}\left(e^{-c(\lambda)d}\right), \tag{4}$$

where $c(\lambda)$ represents the extinction coefficient in function of λ. However, other factors, such as geometric loss generated by LED devices, contribute to transmission loss. Consequently, The following formula can characterize:

$$PL_{GL} = 10\log_{10}\left(\frac{Ap(m+1)}{2\pi d^2}\cos^m(\phi)\right), \tag{5}$$

here, ϕ represents the angle of irradiance and $m = -1/\log_2\left(\cos(\phi_{\frac{1}{2}})\right)$. The sum of Lambertian and geometric attenuation models of the theoretical path loss of an underwater transmission channel. However, this calculation is not accurate. Consequently, we propose an enhancement to the theoretical model as follows:

$$PL_{CL} = 10\log_{10}\left(\frac{d}{e^c Ap} + \beta\right) + (c)1.15^d. \tag{6}$$

In the above equation, the value β is added, which represents a coefficient obtained through data fitting.

C. Monte Carlo Simulation

In this section, we performed numerical and graphical evaluations of path loss in underwater environments to derive an empirical model based on the general model described in Section II.B. Numerical and graphical evaluations were performed using Monte Carlo simulations in Matlab software with the model implementation proposed in [16] with some modifications tailored to UVLC scenarios. The simulation encompasses the scenario illustrated in Figure 1, where the distance between the transmitter and the receiver is set in the range of 1 and 20 m. The Field of View (FOV) is 180°, with an irradiance angle of 60° and aperture diameters ranging from 5 to 20 cm. In the simulation, we consider four types of water formula: pure seawater, clear ocean water, coastal ocean water, and turbid harbor water. The simulation parameters are presented in Table I, while the scattering values for each type of water are provided in Table II [4]. We calculate the path loss value every 1 meter for the entire distance. The coefficients obtained for each type of water are shown in Table III.

TABLE I
SIMULATION PARAMETERS

Transmitter specifications	Power: 1 Watt Angle of Irradiance: 60°
Receiver specifications	Field of view: 180° Aperture diameter: 5-20 cm
Configuration Parameters	Alpha = 10 N = 6 $\times 10^6$ Roulette Threshold = 1 $\times 10^{-4}$
Link range (m)	20
Scattering phase function	TTHG (Two-term Henyey–Greenstein)
Mean cosine of scattering angles (g)	0.924

TABLE II
WATER PARAMETERS

Water Type	$a(\lambda)$	$b(\lambda)$	$c(\lambda)$
Pure sea water	0.053	0.003	0.056
Clear ocean water	0.069	0.080	0.149
Costal ocean water	0.088	0.216	0.304
Turbid harbor water	0.295	1.875	2.170

IV. NUMERICAL EVALUATION AND DISCUSSION

In this section, we present a performance analysis of the proposed path loss model. Figure 2 illustrates the comparison between the results of the Monte Carlo simulation and the combined effect of Lambert's path loss, geometric path loss, and the proposed path loss model for an aperture diameter of 5 cm and coastal ocean water. The results demonstrate that the proposed model significantly approximates the simulation data. However, it should be noted that the proposed model exhibits slight variations starting at a distance of 12 m between the transmitter and receiver, with the maximum difference occurring at about 19 m, corresponding to approximately 4 dB of attenuation. Furthermore, Figure 2 indicates a significant improvement in the accuracy of the model compared to the theoretical model that only considers Lambert's path loss and the geometric path loss components.

Moving on to Figures 3, 4, and 5, we investigate the behavior of the proposed model for different aperture diameters and water types. Specifically, Figure 3 corresponds to an aperture

TABLE III
COEFFICIENT CALCULATION

Water Type	**Coefficient (β)**
Pure sea water	0.2442
Clear ocean water	0.4735
Costal ocean water	0.626
Turbid harbor water	0.5027

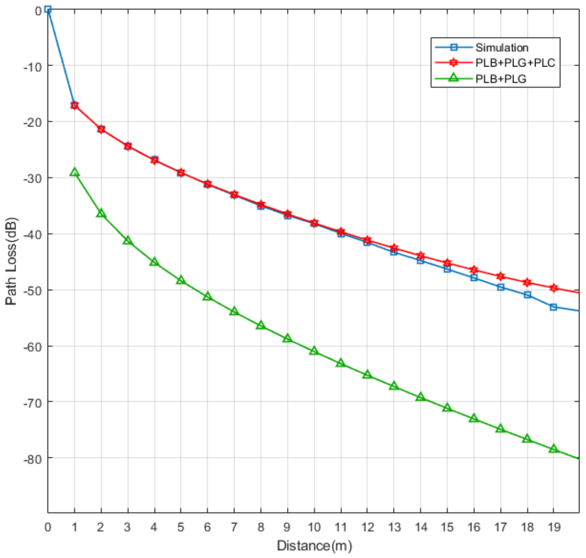

Fig. 2. Comparison of results between simulation and theoretical path loss for Ap = 5 cm

diameter of 10 cm, Figure 4 to 15 cm, and Figure 5 to 20 cm. In all cases, four different water formulas are considered: pure seawater, clear ocean water, coastal ocean water, and turbid harbor water. The results shown demonstrate that the behavior of the model aligns with the respective extinction coefficients (c) of the water formulas. As the distance between the transmitter and receiver increases, the water formula with higher extinction coefficients exhibits higher levels of signal loss. In particular, turbid harbor water generates the greatest path loss due to its significantly higher extinction coefficient compared to the other formulas. These trends remain consistent in Figures 3, 4, and 5, regardless of aperture diameter. Furthermore, we can conclude that when the receiver aperture diameter increases, the path loss decreases. This phenomenon can be attributed to the larger receiver area, which allows more light to be captured.

In summary, the proposed path loss model characterizes scenarios such as coastal ocean water with an aperture diameter of 5 cm as a function of distance. The model demonstrates good agreement with Monte Carlo simulations, capturing the impact of water type, extinction coefficient, and receiver aperture diameter on overall path loss.

V. CONCLUSIONS AND FUTURE WORK

This paper presented a comprehensive exploration of the need for efficient communication systems in underwater environments with a focus on UVLC path loss performance. We examined existing UVLC channel models and addressed the necessity for the development of a better path loss model that caters to different types of water. As a result, we proposed a novel path loss model that incorporates a series of factors, characterizing the interaction of light with various water particles and geometric features.

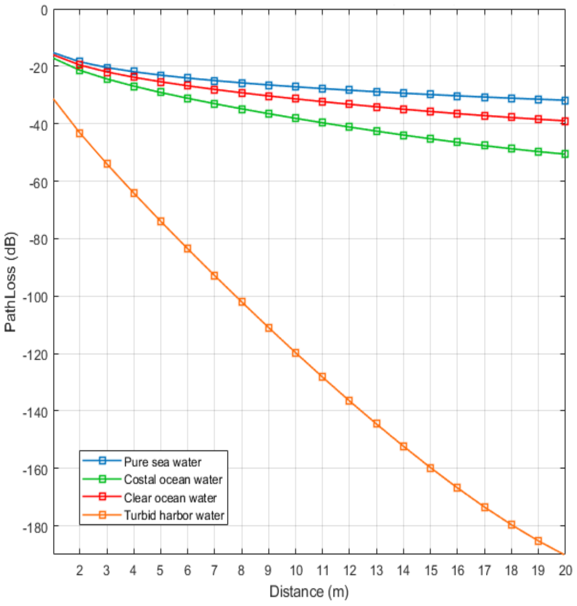

Fig. 3. Comparison of results between different water types for Ap = 10 cm

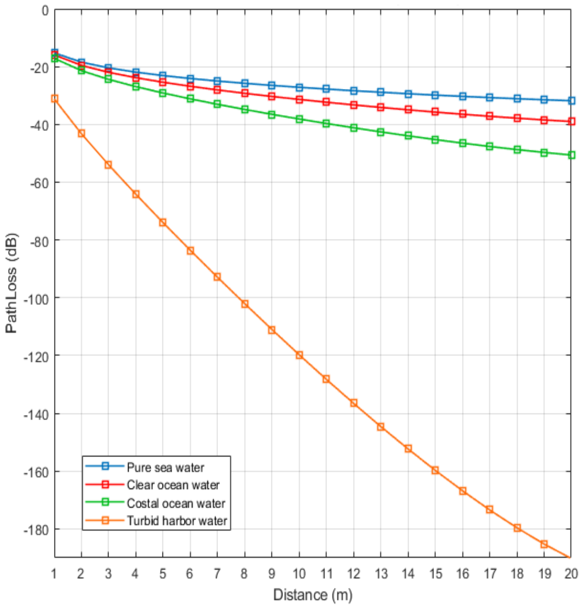

Fig. 4. Comparison of results between different water types for Ap = 15 cm

The proposed model was validated in various scenarios, considering different types of water and receiver aperture diameters, using Monte Carlo simulations. The results suggest a high efficiency and accuracy of the model in reflecting the real-world performance of UVLC systems. In particular, as the scattering index increases, we observed a corresponding increase in path loss, indicating characteristic behaviors. Additionally, our observations revealed that increasing the aperture diameter did not lead to drastic changes in the model's behavior across all water types; instead, it resulted in a slight reduction in loss values. Importantly, the proposed model represents a significant improvement over previous approaches

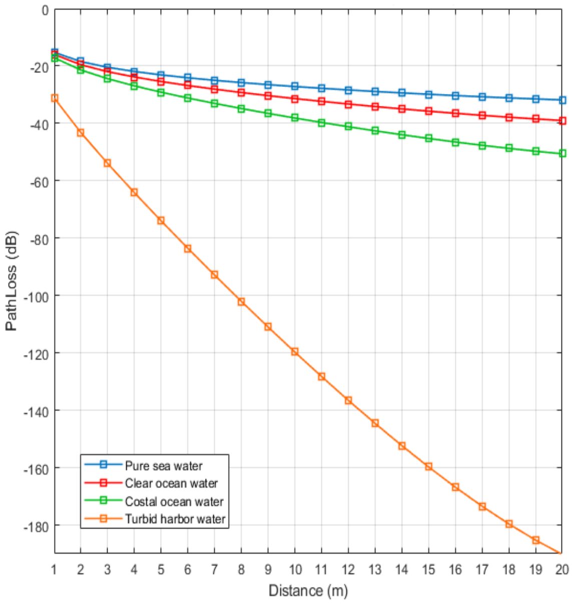

Fig. 5. Comparison of results between different water types for Ap = 20 cm

that solely account for Lambert's path loss and geometric path loss.

Despite some observed variations, especially at larger distances between the transmitter and receiver, the proposed model exhibits significant promise. It provides an essential step forward in the understanding and application of UVLC in different underwater environments.

Further research in this field could focus on refining the proposed model, enhancing its performance over longer distances, and incorporating additional environmental factors that have an impact on underwater communication. These factors may include temperature variations, pressure, salinity, water turbulence, the effects of other light sources, the Doppler effect, shadowing, and fading, among others. Our vision is that by pursuing these continuous efforts, we will advance the development of robust, efficient, and reliable UVLC systems, ultimately expanding our ability to explore and interact with underwater environments.

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