The Effect of Medium Inhomogeneity in Modeling Underwater Optical Wireless Communication

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Abstract —This paper introduces a stratified approach to modeling underwater optical wireless communication (UOWC). The influence of medium inhomogeneity, which many researchers ignore, was considered in modeling the UOWC channel to achieve an accurate model. The Monte Carlo technique to simulate the photon propagation was adapted to include medium inhomogeneity to estimate the received power, channel bandwidth, and delay spread of the proposed model. We use the depth-dependent chlorophyll profile that was established in Kameda empirical model to constitute the medium inhomogeneity. The empirical model used 0.5 mg m^{-3} and 2 mg m^{-3} of surface chlorophyll concentration to represent clear and coastal water. Besides, the comparison between collimated and diffused links was also studied to highlight the effect of the medium inhomogeneity on both links. Our findings indicate that the homogeneous model produces an underestimation result compared to the stratified model. The stratified model estimated significant increases in received power, lower delay spread, and higher bandwidth, which indicates the medium inhomogeneity is important for a realistic channel model.

Index Terms—Monte carlo, underwater wireless communication, depth dependent attenuation, channel modeling, chlorophyll concentration

I. Introduction

Underwater Wireless Communications (UWCs) are considered a new means in solving the increasing requirements of real time high-speed connectivity in various fields such as deep sea exploration, marine species science, oil mining, emissions and climate change research [1]. UWCs are commonly implemented using acoustic, Radio Frequency (RF) and visible light communications system. The visible light communication used in Underwater Optical Wireless Communication (UOWC) for short and medium ranges can provide higher data rates with an order of tens of Mbps and lower latency than communication systems based on RF and acoustics [2]. Moreover, the seawater exhibits a window of decreased attenuation within the range of 450 and 550 nm (blue/green region) in the visible spectrum which make UOWC a promising one compared to RF and acoustics-based communication system [3].

Several research studies have been carried out to model the UOWC channel using the assumption of homogeneous medium where the composition of the ocean has uniform properties throughout its volume [4]-[6]. The notion of a homogeneous medium may be applicable for the communication link that is parallel to the surface of the ocean. However, for the vertical link, the properties of the ocean changes according to depth, which causes medium inhomogeneity [7]. The medium inhomogeneity is mainly caused by the variation of chlorophyll concentration, salinity, temperature and ocean turbulence with depth [8].

Therefore, in this work, we focus on incorporating the medium inhomogeneity due to chlorophyll concentration in modeling the UOWC channel. The Monte Carlo technique is used to generate the path loss profile and the channel impulse response (CIR) of the line-of-sight (LOS) communication link.

The remainder of the paper is organised as follows. The background theory of the channel model is outlined in Section II. Section III explains the simulation model approach together with the simulation parameters. Section IV discusses the findings of the simulation and Section V concludes the paper.

II. Theory

A. Absorption and Scattering

According to [9], when photons propagate through water, they are prone to be absorbed and scattered upon the composition and condition of the water medium. The interactions can be expressed as an attenuation coefficient $c(\lambda)$, which corresponds to the absorption and scattering coefficients; $a(\lambda)$ and $b(\lambda)$, as follows:

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$$c(\lambda) = a(\lambda) + b(\lambda) \tag{1}$$

A lot of literature typically expressed $c(\lambda)$ with a single value at a given wavelength, ignoring the variations of $a(\lambda)$ and $b(\lambda)$ with depth. This assumption only extends for the open oceans, where scattering is not noticeable [8] and the composition of the ocean (e.g. chlorophyll concentration) changes considerably with depth, which makes it very unlikely that the attenuation of a vertical link would be consistent [7]. Thus, the depth dependent chlorophyll model will be employed in the calculation of the absorption coefficient a, and scattering coefficient b where (1) can be rewritten to include the depth z, such that

$$a(\lambda, z) = a_w(\lambda) + a_f^0 C_f(z)exp(-k_f\lambda) + a_h^0 C_h(z)exp(-k_h \lambda) + a_c^0(\lambda, z)(C_c(z))^{0.602} \tag{2}$$

$$b(\lambda, z) = b_w(\lambda) + b_s^0(\lambda)C_s(z) + b_l^0(\lambda)C_l(z) \tag{3}$$

where a_w is the pure water absorption coefficient in unit m^{-1}, a_f^0 is the specific absorption coefficient of fulvic acid (a_f^0 = 35.959 m^2/mg), a_h^0 is the specific absorption coefficient of humic acid (a_h^0 = 18.828 m2 /mg), a_c^0 is the specific absorption coefficient of chlorophyll in unit m^{-1}, C_f is the concentration of fulvic acid in mg/m^3, C_h is the concentration of humic acid in mg/m^3, C_c is the concentration of chlorophyll in mg/m^3, k_f is the fulvic acid exponential coefficient (k_f = 0.0189 nm^{-1}), k_h is the humic acid exponential coefficient (k_h = 0.01105 nm^{-1}), b_w is the pure water scattering coefficient in m^{-1}, b_s^0 is the scattering coefficient for small particulate matter in m^2/g, b_l^0 is the scattering coefficient for large particulate matter in m^2/g, C_s is the concentration of small particles in g/m^3, and C_l is the concentration of large particles in g/m^3.

Note that the coefficients in (2) and (3) can be found in [7]. For the values of chlorophyll concentration $C_c(z)$, we adapted the empirical model of chlorophyll vertical profiles from [10] and the one-parameter attenuation model from [11]. Additionally, Beer's model is used to express the light attenuation effects in UOWC due to its simplicity and commonly used scenario. The received intensity of light is defined as [12]

$$I = I_0 \, exp(-c(\lambda)\, d) \tag{4}$$

where I is the intensity of light after the light pass through the media, I_o is the initial light intensity of incident light, and d is the distance of light travel in media.

III. Simulation Methodology

The similar Monte Carlo (MC) method used in [13]-[15] to track the propagation of the photons is reconstructed to include the medium inhomogeneity through stratification. The main parts involved in the process of sending and tracking the photons in the simulation are photon transmission, interfaces, and photon reception.

A. Photon Transmission

The photons are moving with the geometric path length s, in (5)

$$s = -ln(q) / c \tag{5}$$

where q is a uniformly distributed random number between 0 and 1. Sequentially, after the moving process, an algorithm to examine the weight and scattering direction of photon were deployed. The weight of photon is updated by multiplying with the single scattering albedo ω, given as (6)

$$W_{n+1} = W_n\, \omega = W_n\, (b / c) \tag{6}$$

Note that λ and z in (5, 6) are omitted from b and c for brevity purpose. If the photon weight W_{n+1} falls below the predefined threshold, then the photon will be terminated or boosted by the roulette [16]. When the photon survives the rouletting process, the new scattered direction must be updated using the angles computed from the scattering phase function [13], [17].

B. Interfaces

The stratification method used is the arrangement of the water column into layers with different attenuation coefficients [18]. The photon that passes the transmission process will be examined if they intersected with another layers of water column simply through intersection equations of a line and the boundary. If the photon passes, the attenuation coefficient c will be updated with the associated layer of c.

C. Photon Reception

The last layer of the stratified water column would be the position of the receiver. The photon that is captured within the area and field-of-view (FOV) of the receiver will be updated to the number of photons received. The process was repeated from the photon transmission to photon reception according to the predefined number of photons involved in the simulation.

D. Simulation Parameters

TABLE I: ATTENUATION COEFFICIENTS OF TWO WATER TYPES IN HOMOGENEOUS AND STRATIFIED MEDIUM ADAPTED FROM [10]

Medium type	Homogeneous	Stratified
Water type	Attenuation coefficient c (m^{-1})	
Clear water	0.241	0.188 ~ 0.270
Coastal water	0.775	0.708 ~ 0.809

TABLE II: SIMULATION PARAMETERS

Parameter	Value	
Wavelength	530 nm	
Link range	5 ~ 25 m	
Beam waist	1 mm	
Beam divergence	Collimated	1.5 mrad
	Diffused	15 °
Receiver aperture	10.16 cm	
FOV	180 °	
Number of photons	10^6	
Distance between layer	1 m	

In the simulation, we only consider the LOS communication link using collimated (Laser) and diffused (LED) beams. Clear and coastal water types were also considered and Table I shows the attenuation coefficients of the two types of water used. The effects of turbulence, reflection and background scattering were ignored throughout the simulation. Other simulation parameters are set as shown in Table II.

The 530 nm wavelength for both collimated and diffused sources, is chosen to map the attenuation coefficient c and single scattering albedo ω as the absorption by sea water is minimal within this wavelength [3]. The attenuation coefficient c is predominantly determined by the surface chlorophyll concentration adapted from the empirical model of chlorophyll vertical profiles in [10] and the one-parameter attenuation model in [11]. The surface chlorophyll concentrations of 0.5 and 2.0 mg m^{-3} are used to characterize the clear and coastal water, which then can be seen to have a similar trend for both vertical chlorophyll concentration and attenuation coefficient as shown in Fig. 1. Furthermore, these profiles are then implemented in the simulation to represent the medium inhomogeneity by the stratification method as described in Section 3B. Specifically, for stratified medium, the range of attenuation coefficients used are 0.188 - 0.270 m^{-1} and 0.708 - 0.809 m^{-1} for clear and coastal water respectively. For the homogenous medium, the average attenuation coefficient c from the similar profiles is computed for clear and coastal water, which are 0.241 m^{-1} and 0.775 m^{-1} respectively.

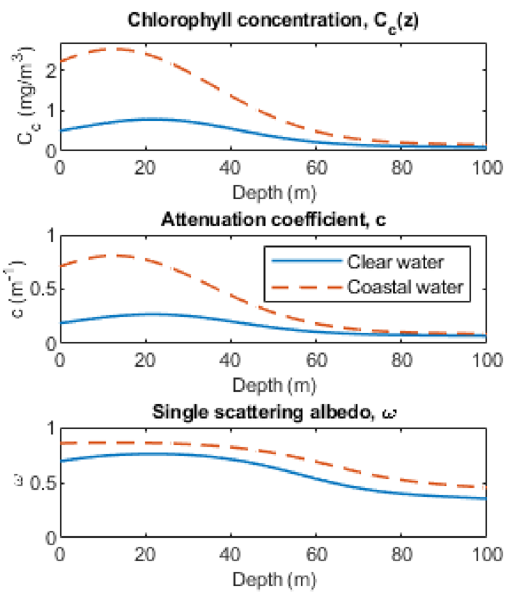

Fig. 1. Depth profiles of chlorophyll concentration C_c (z), attenuation coefficients c, and single scattering albedo ω.

IV. Result and Discussions

A. Power Estimation

Fig. 2, and Fig. 3, shows the normalised received power for collimated and diffused links of both homogeneous and stratified channel model in clear and coastal water with respect to the depth. The comparison between homogeneous and stratified channel models indicated a notable difference between clear and coastal water. Fig. 2, depicts the clear water scenario where the observed differences for collimated link are 0.88 dB, 1.94 dB, 3.05 dB, 4.11 dB, and 5.26 dB meanwhile, 0.53 dB, 0.83 dB, 1.26 dB, 1.57 dB, and 1.62 dB for diffuse link at depth of 5 m, 10 m, 15 m, 20 m and 25 m respectively. The observed differences show a significant increase in power estimated by the stratified medium than the homogeneous medium.

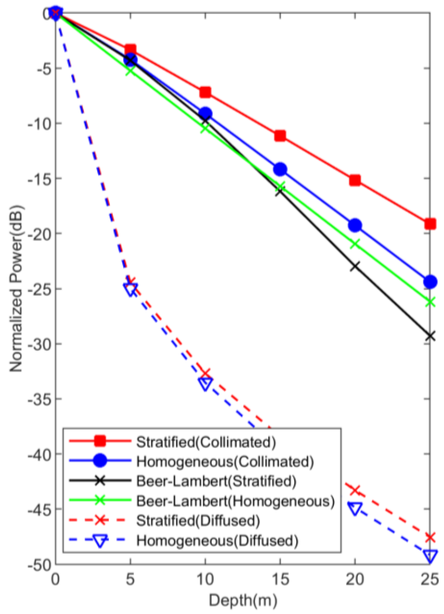

Fig. 2. Normalised power with respect to the depth in clear water.

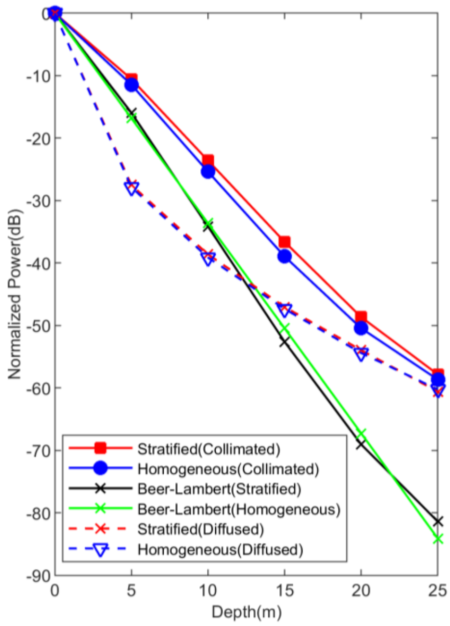

Fig. 3. Normalised power with respect to the depth in coastal water.

Specifically, in coastal water as shown in Fig. 3, there are 0.89 dB, 1.78 dB, 2.33 dB, 1.79 dB and 0.93 dB increase for power estimated in the collimated link of the stratified medium compared to the homogenous medium, while 0.36 dB, 0.51 dB, 0.33 dB, 0.45 dB and 0.35 dB for the diffused link observed at 5 m, 10 m, 15 m, 20 m and 25 m respectively. The observed differences increased slightly, suggesting a similar probability of scattering in a stratified medium with the homogeneous medium. This is because the scattering albedo graph shows a flatten trend at 0 - 40 m as illustrated in Fig. 1.

The Beer's model is also shown alongside the power estimation of homogeneous and stratified models in Fig. 2 and Fig. 3. The Beer's model is plotted by considering the similar conditions as stratified and homogeneous models. According to Fig. 2, in clear water, the diffused link of homogeneous and stratified models exhibits a significant loss than predicted by Beer's model due to the higher geometric loss caused by beam divergence [5], [19]. Next, in Fig. 3, both models of diffused link show little difference with Beer's model because of the higher scattering probability and multiple scattering effects associated with the coastal water, where Beer's model considers scattered photons as a complete loss [20]. In short, the power estimation by the homogeneous model on both links and water types show a significant underestimation relative to the stratified model where the latter model displays a better estimation due to higher accuracy achieved by the implementation of the medium inhomogeneity.

B. Channel Impulse Response and Frequency Response

Fig. 4-Fig. 7 show the channel impulse response (CIR) and frequency response (FR) for the collimated and diffused links in clear and coastal water at 5 m and 25 m depths. The frequency response plotted alongside CIR is to estimate the supported channel bandwidth. It can be observed from Fig. 4 and Fig. 6, that the bandwidth in the order of GHz is supported by both links in both models in clear water except for the link range of 25 m of the diffused link which only supported the bandwidth in the order of hundreds in MHz. In Fig. 5 and Fig. 7, both stratified and homogeneous models suffer the lower bandwidth supported in order of tens of MHz where both links operating in the multiple scattering region for 25 m depth.

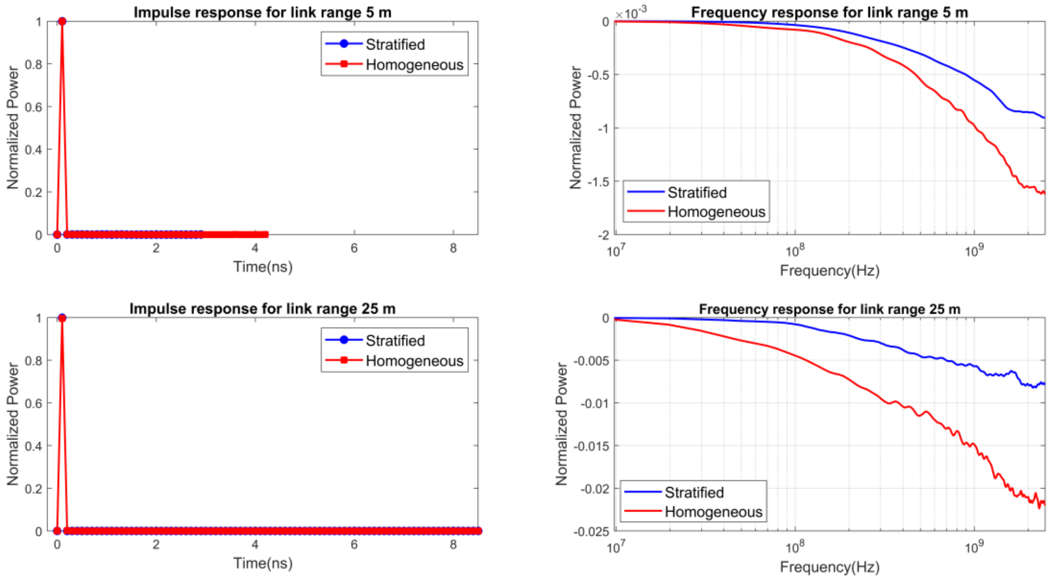

Fig. 4. CIR and FR of collimated link in clear water at 5 m and 25 m of link range.

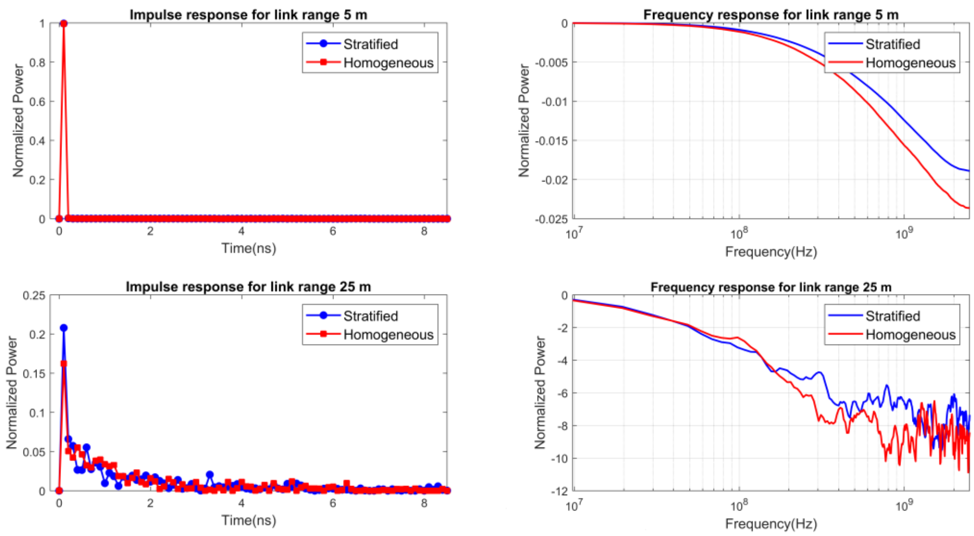

Fig. 5. CIR and FR of collimated link in **coastal** water at 5 m and 25 m of link range.

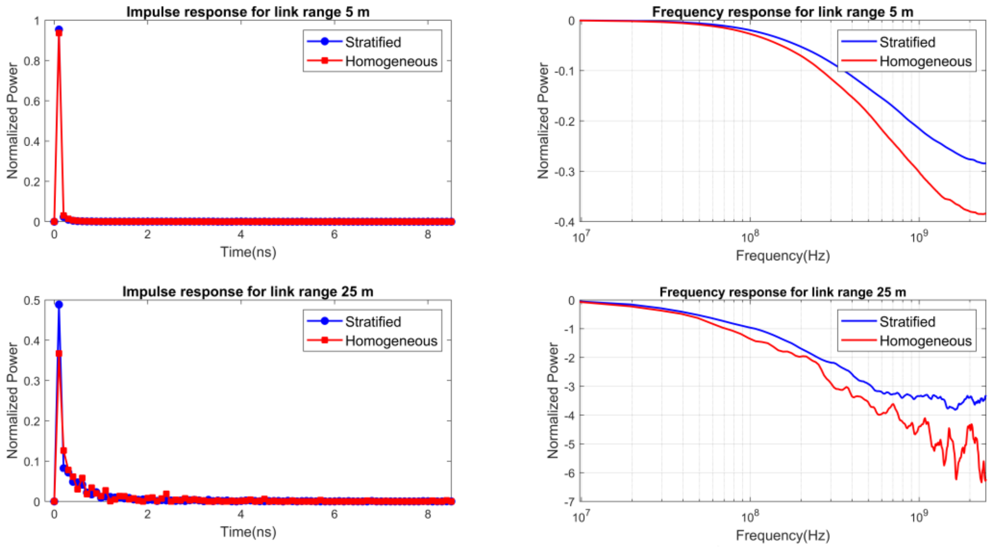

Fig. 6. CIR and FR of diffused link in clear water at 5 m and 25 m of link range.

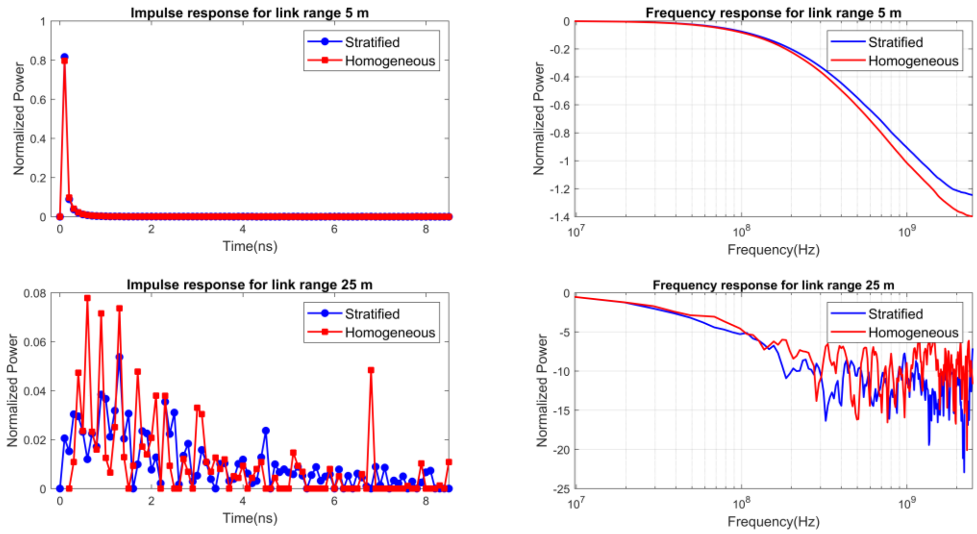

Fig. 7. CIR and FR of diffused link in coastal water at 5 m and 25 m of link range.

TABLE III: DELAY SPREAD (S) OF THE COLLIMATED LINKS FOR CLEAR AND COASTAL WATERS

Model	Homogeneous		Stratified	
Link range (m) / Type of water	5	25	5	25
Clear	2.11×10^{-14}	4.79×10^{-13}	1.13×10^{-14}	1.86×10^{-13}
Coastal	2.91×10^{-13}	1.26×10^{-9}	2.32×10^{-13}	8.44×10^{-10}

TABLE IV: DELAY SPREAD (S) OF THE DIFFUSED LINKS FOR CLEAR AND COASTAL WATERS

Model	Homogeneous		Stratified	
Link range (m) / Type of water	5	25	5	25
Clear	5.65×10^{-12}	2.85×10^{-10}	4.00×10^{-12}	1.38×10^{-10}
Coastal	2.09×10^{-11}	3.22×10^{-9}	1.84×10^{-11}	2.28×10^{-9}

Additionally, from the CIR, the estimated delay spread of collimated and diffused links of the homogeneous and stratified medium are tabulated in Table III and Table IV for 5 m and 25 m depth. It can be inferred that the delay spread of the collimated link increases rapidly at 25 m for coastal water in the homogeneous model relative to the stratified model, which implies that a highly dispersive environment occurred in the former model.

For the diffused link, a similar increasing trend occurs in delay spread, which signifies the homogeneous medium to have a higher multipath propagation due to the use of a single average attenuation coefficient to simulate the entire link range depth, thus causing underestimation to occur.

Moreover, the performance of the diffused beam relative to the collimated beam from Fig. 4– Fig. 7 and

Table III and Table IV shows that the latter source provides a better performance in term of delay spread and bandwidth. For instance, the collimated link has a lower delay spread below 10^{-10} s and a higher supported bandwidth in the order of hundreds of MHz than the diffused link for both water types. But the diffused beam can provide a wider coverage area [21] compared to the collimated beam, indicating that a suitable choices of beam source are needed before deploying the system.

The stratification of a UOWC channel can provide a better estimation at each depth where different absorption and scattering coefficients are implemented compared to the homogeneous model. The estimation of channel characteristics by the stratified model results in a lower delay spread and a higher supported bandwidth, which the homogeneous model would have neglected.

V. Conclusion

In this paper, the medium inhomogeneity due to the variation of chlorophyll concentration was considered in modeling the UOWC channel. This is performed by the stratification of the underwater channel into many layers of different absorption and scattering coefficients. By doing so, more accurate path loss estimates were possible compared to the simplified homogeneous model. Additionally, other channel characteristics namely channel impulse response and frequency response were also simulated. It can be seen that the homogeneous channel model underestimates the path loss, channel bandwidth, and delay spread. Apart from that, an analysis to compare the performance of collimated link and diffused link was also presented. This comparison is useful for system designers when implementing underwater diffused links in order to choose appropriate data rate to avoid inter symbol interference (ISI). Therefore, these results will be beneficial for an in-depth understanding of future work in order to optimise the performance of underwater optical wireless communication.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Our research team jointly conducted the presented study, performed the simulation work and analyzed the results. All authors discussed the results and contributed to the final manuscript.

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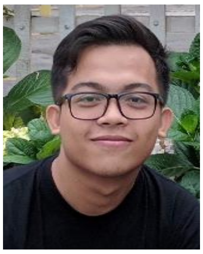

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