Research and Application of Underwater Wireless Optical Communication Channel Characteristics Based on Digital Twin

Tian Song*1
*Suzhou College of Information Technology, Suzhou,Jiangsu Province 215200, China

ABSTRACT

Underwater wireless optical communication system has attracted much attention because of its high confidentiality, good security and strong defense ability against interference. However, the transmission of light under water is easily affected by various factors, resulting in the low quality of the channel. In order to reduce the energy loss in the optical transmission process of the underwater wireless optical communication system, the time consumed by the investigators for the communication channel experiment is reduced. A wireless optical communication system is developed based on the digital twin design. The system designed according to the bidirectional flow of digital twin data can adapt to the changeable channel environment, simulate the scene of the underwater communication system receiving light, and realize the test and research of the Marine underwater communication system. The experimental results show that when the underwater depth is 100m, the concentration of chlorophyll in water is about 0.23, and the attenuation coefficient of optical parameters at this time is 0.2, the absorption coefficient is 0.25, the scattering coefficient is 0.35, and the attenuation diffusion coefficient is 0.3. With the increase of the transmission distance of the light, the number of photons received by the observation surface decreases from 842,819 to 4,960. The constructed system can analyze the relationship between optical parameters and water quality in the communication channel, and the system performance is stable in the simulation test. Therefore, the Monte Carlo communication system based on digital twin proposed in this paper has application value in the study of characteristics of underwater wireless optical communication channels.

Keywords: digital twin; Wireless optical communication; Monroquart process; Photon parameters; Water quality environment; Data collection.

1. INTRODUCTION

Underwater Wireless Optical Communication (UWOC) has attracted more and more attention because of its high transmission rate, but the transmission range after absorption is limited due to the photon attenuation effect of underwater optical channels. Because the light wave is affected by the absorption, scattering and turbulence of the underwater channel in the propagation process, the signal attenuation, delay extension and fading phenomenon are caused, thus the communication distance is limited and the reliability is reduced. However, because of the high speed of underwater wireless transmission, it has great application value and development potential in underwater information transmission applications, and more and more researchers begin to pay attention to these problems. Sun X and other researchers have proposed a new solution to simplify the requirements for pointing, acquisition and tracking in order to establish robustness in underwater communication links due to the flicker and dedirection of underwater links caused by ocean turbulence. Non-line-of-sight communication mode based on light scattering, and anti-light receiver based on flicker fiber and large photovoltaic cell as light signal detector. The results show that the proposed new scheme can inhibit the influence of turbulence [1]. In order to expand the communication range that UWOC can achieve, Ye K et al. studied the performance of double-hop UOWC system with synchronous light wave information and power transmission. The system adopts time-splitting method for wireless power transmission, transmits information and energy at different stages, and minimizes the average bit error rate under the condition of energy collection and transmission rate constraints. Numerical results show that the use of relay nodes with power transmission can improve the performance of the system [2]. Uppalapati et al. studied the bit error rate performance of the underwater wireless optical communication system using m orthogonal amplitude modulation in the underwater wireless optical sensor network under the river-sea intersection scene. A recon Figureurable optical sensor network is proposed for the real-time scenario where a river flows into the sea, and a novel closed analytic bit error rate (BER) expression for the system under gamma turbulence with

1 *rainy_songpp@163.com

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attenuation effect is derived. The results show that the proposed system and its correlation analysis are of great significance for the application of optical sensor networks and underwater iot [3]. Although domestic and foreign researchers have done a lot of research on underwater wireless optical communication, there is a lack of analysis of light channels. In order to collect more ocean data, the transmission rate of light in the water is faster, increasing the defensive and security of underwater communications. A Monte Carlo wireless optical communication system based on the digital twin algorithm is studied, and most of the data about the ocean is provided by Marine optical sensors. The innovation of this study is that it builds a broad oceanographic data set by using backward inference and calculation to obtain optical parameters at different depths of the water. Then the distribution of the received light field of the underwater wireless optical communication system at different times and at different depths in the key sea area can be obtained from the data set. It is expected that the performance of most underwater wireless optical communication systems can be tested and evaluated.

2. WIRELESS OPTICAL COMMUNICATION SYSTEM BASED ON THE DIGITAL TWIN

2.1 TFramework structure of the underwater wireless optical communication simulation system based on digital twin

underwater wireless optical communication (UWOC) is concerned because of its high information transmission rate, but the channel of underwater communication is affected by environmental noise and communication distance. In contrast, digital twins generate virtual bodies corresponding to real entities in a virtual environment. Virtual bodies are spatially dynamic and can synchronize data and information changes according to the changes of entities, and the information flow between entities and virtual bodies in the twin system is bidirectional [3-4]. Therefore, the paper constructs a wireless optical communication system based on digital twin to study the underwater channel, and its simulation system framework is shown in Figure 1.

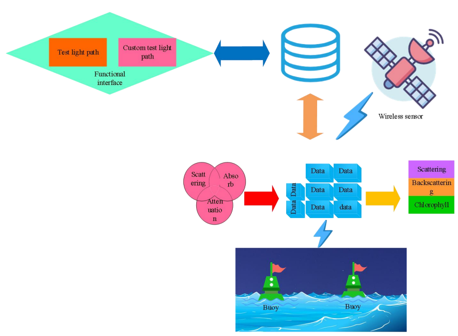

Figure 1. Frame of the wireless optical communication system.

The framework structure in Figure 1 includes three parts: data collection, storage and functional interface of the system. The collection is mainly from the monitoring data brought by the underwater optical sensor, and the water quality optical parameters of different waters and different depths can be deduced according to the reflection of the information. The contents of the parameters include absorption coefficient, scattering coefficient, weakening coefficient, diffusion coefficient, etc. The collected optical parameter information is saved in the optical database of the ocean, which is conducive to the search and acquisition of data in the future [5]. The system framework is connected with the optical database, through which the optical parameter values can be queried or the algorithm and model can be simulated and analyzed by the customized parameters, so as to realize the performance test of the underwater optical path. Before being absorbed, light will travel a certain distance in seawater, which can be expressed as equation (1).

$$s = \frac{1}{c} \ln \left(r_s \right) \tag{1}$$

In formula (1), s representsThe distance that light travels before it is absorbed, c represents seawater attenuation coefficient and r represents random number. The distance in the formula represents the distance traveled by the photon before it is absorbed, and the continuous absorption effect in the process is the reason why the photon attenuation coefficient keeps increasing. The new photon weight after attenuation can be expressed as equation (2).

$$\omega' = \omega_0 W_{th} \tag{2}$$

Formula (2), W_{th} represents the scattering albedo efficiency. If the weight of the photon is less than a specific threshold value, the photon will be judged as invalid or as ray annihilation, and this type of photon will not be tracked anymore. Based on the conservation of energy, the probability of giving such a photon inventory is to calculate the weight in reverse, so that the photon obtains the weight before annihilation, so that the photon transmission process can be simplified.

2.2 The underwater wireless optical communication system based on digital twinning accepts the light process

The communication system collects and saves the data and then connects with the functional interface to realize the framework structure, through the control of the wireless sensor, and connects the design and research of the underwater wireless communication channel. The specific flow of the communication signal receiving the light is shown in Figure. 2.

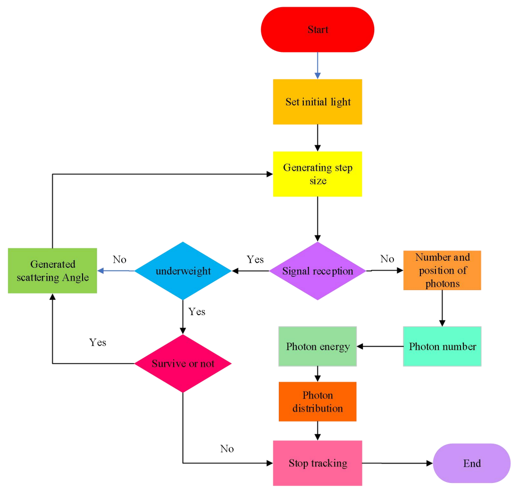

Figure 2. Specific process of receiving light for a communication signal.

In the flow chart of the wireless optical communication system receiving light shown in Figure 2, the initial state of the transmitted light should be set before the test. The initial state parameters include the starting position of the light, the Angle of the light emission, and the weight value of the light. If the light is defined as Gaussian light, it can be expressed as formula (1) The initial position is set to generate random step size. If the photon in the light is not received by the detection point in the process of free motion, the effect of absorption and scattering will occur, and whether the weight value of the absorbed photon is lower than the set threshold will be determined [6-7]. Below the threshold, the survival rule of the accent probability further determines whether the photon can survive under such rules. If it survives, the scattering Angle and scattering orientation are generated, and the motion step length is calculated again. If you don't survive, stop tracking and end the process. If the photons in the light are received by the detection point during their free movement, then the position and number of the photons are recorded by the observation point. Then, the number of photons in different radial displacement directions on different detection surfaces is obtained by statistical methods [8]. The number of photons from different radial displacements on different observation planes is calculated. It is also necessary to calculate the energy of the photons on different radial displacements on different detection surfaces, and the light field distribution of underwater wireless optical communication is completed after the energy is obtained. If the position of the photon emitted at the beginning of the process is defined by a Gaussian distribution. Then the photon expression can be expressed as equation (3).

$$p\left(r\right) = \exp\left(-r^2\right) / \left(2\sigma^2\right) \tag{3}$$

In formula (3), $p\left(r\right)$ represents the r probability of the photon leaving the center point and σ represents the width of the light wave. If the photon has been transmitted to the first detection surface and will continue to transmit, then the number of photons above the radial displacement of the next transmission detection surface needs to be counted and calculated. Finally, according to the total number of photons with different radial displacements collected on many detection surfaces, the individual photon distribution in the underwater transmission process of light can be obtained. The relationship between photon energy and number can be expressed as equation (4).

$$E = \frac{Nhc}{\lambda} \tag{4}$$

In formula (4), E represents the total energy value of photons, N represents the number of photons collected, h represents Planck's constant, and λ represents wavelength.

3. ANALYSIS OF THE APPLICATION EFFECT OF THE UNDERWATER WIRELESS OPTICAL COMMUNICATION SYSTEM BASED ON DIGITAL TWIN

3.1 Optical parameters statistics of a wireless light communication system based on digital twin underwater

Based on the digital twin, the underwater wireless optical communication system analyzes and studies the channel of the underwater wireless optical communication. It mainly collects the underwater light parameters to establish a database of related optical and Marine parameters, and analyzes the underwater optical path and communication channel through the initial photons. Optical parameter statistics for the oceans at different depths are shown in Table 1.

Table 1. Statistics of the optical parameters for the different deep oceans.

Depth of water (m)	Discount factor (m-1)	Scatter factor (m-1)	Absorption coefficient (m-1)
50	0.075	0.005	0.05
80	0.082	0.015	0.09
150	0.093	0.018	0.15
230	0.131	0.021	0.19
250	0.151	0.025	0.23
400	0.185	0.028	0.25

As can be seen from Table 1, attenuation coefficient, scattering coefficient and absorption coefficient in optical parameters also increase with the increase of ocean depth. The underwater diffusion coefficient is based on the tendency of the photon emission to change in all directions, and the attenuation coefficient is defined by the individual energy loss. When the depth of the water is 50m, the attenuation coefficient of the photon is 0.075, the scattering coefficient is 0.005, and the absorption coefficient is 0.05. When the underwater depth reaches the maximum 400m, the photon attenuation coefficient is 0185, the scattering coefficient is 0.028, and the absorption coefficient is 0.25. As the depth of the ocean increases, the coefficient of the photons gradually increases. The underwater sensor provides vertical chlorophyll and optical parameter distributions as shown in Figure 3.

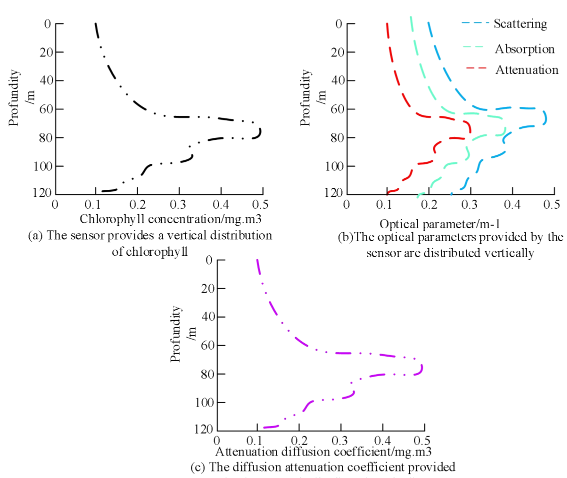

Figure 3. The underwater sensor provides a vertical distribution of chlorophyll and optical parameters.

As can be seen from Figure 3, with the change of underwater depth, the corresponding chlorophyll concentration and optical parameter value will also change, but this change is not a simple increase or decrease, and the change of coefficient value has a certain rule, but it is not uniform. When the underwater depth is 100m, the concentration of chlorophyll is about 0.23, and the attenuation coefficient in the optical parameters is 0.2, the absorption coefficient is 0.25, the scattering coefficient is 0.35, and the attenuation diffusion coefficient is 0.3. The value changes with the depth of the water. Because as the depth changes, the underwater environment will change a lot. The visibility in the water will be reduced, the turbidity will be different, the number of plant microorganisms will increase, and the complex and difficult to adapt environment will affect the construction of relationships and communication channels.

3.2 Optical properties of different water quality and different transmission distances of light

The communication system analyzes the influence of different underwater depths on the light parameters, but the optical characteristics in different water qualities are also different due to the different underwater environment. The statistics of the different types of underwater optical properties of the seawater are shown in Table 2.

Table 2. Underwater optical properties of the different types of water quality.

Water quality distribution (m)	Absorption coefficient (m-1) (m-1)	Scatter factor (m-1))	Discount factor (m-1)
Inland sea water	0.029	0.006	0.045
Ocean sea water	0.056	0.029	0.096
Far shore sea water	0.096	0.031	0.132
Near shore sea water	0.125	0.059	0.156
A single sea water	0.173	0.215	0.365
Port sea water	0.1452	1.453	1.934

As can be seen from Table 2, the optical properties differ greatly in different water quality, and the absorption, scattering and attenuation coefficients of photons are higher in nearshore seawater, pure seawater and harbor seawater. Because the water quality in these three areas is relatively simple, the underwater geology is better than that in other areas [9-10]. In inland seawater, ocean seawater and far shore seawater, the transmission parameter of light is almost less than 0.1, and the attenuation coefficient of the far shore is 0.132. Because the water quality of the inland sea is close to residential areas, the water quality will be poor due to the pollution of domestic wastewater and garbage in addition to the treatment of natural substances in seawater. The ocean water and the far shore water receive the collection of other tributaries, so the water quality situation is naturally not so pure. In addition, in the environment of ocean water and far coast water, there are some deep sea animals' sound waves on the effect of light transmission. In addition, the accumulated pollution brought by some long-sailing freighters and fishing vessels will also cause a certain degree of pollution to the water quality. Therefore, the choice of underwater communication channel must rely on a good water quality environment, and the transmission distance of light will also affect the construction of the channel. When the initial number of emitted photons is the same, the photon received by the detection plane under different transmission distance is shown in Figure 4.

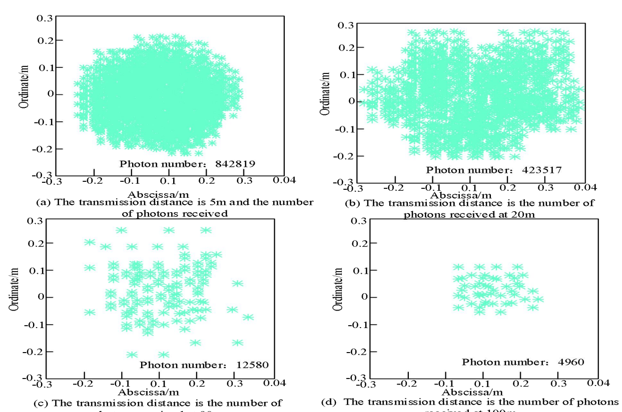

Figure 4. Photons received by the detection surface not at the same transmission distance.

As can be seen from Figure 4, when the initial photon emission number is consistent and the transmission distance is 5m, the number of photons received by the detection surface on the water is 842,819, and the distribution of photons is concentrated, and the light spots formed by photons are bright and dense. When the transmission distance of light becomes 20m, the number of photons received by the detection surface on the water is 12580, the distribution of photons begins to disperse, the brightness of the spot decreases, and the number of photons collected decreases. When the transmission distance becomes 90m, the number of photons received by the detection surface on the water becomes 125,082, the number is reduced to half of the previous transmission distance, and the light spot formed by the photons is significantly more dispersed and less bright. When the transmission distance becomes 100m, the number of photons received by the water detection surface is only 4960, the number decreases sharply, the photon distribution is extremely sparse, and the light spot is no longer bright, only dark light. It shows that with the increase of the transmission distance, the number of photons that can be received by the water observation is less, and the brightness of the spot is lower. The number of received photons is proportional to the number of initial sent photons and is inversely proportional to the transmission distance of the light.

4. CONCLUSION

Compared with ordinary underwater acoustic communication, underwater wireless optical communication has the advantages of higher bandwidth and speed, and better tightness, so it has been paid more attention. In order to analyze the underwater wireless optical communication system according to the specific channel environment, light transmission in water is easily affected by the absorption and scattering effect of seawater. This paper introduces the idea of digital twin into the field of underwater wireless optical communication, and designs and develops an underwater wireless optical communication simulation system for digital twin. The system can be applied to the unpredictable underwater communication channel, and the performance of the underwater wireless optical communication system in different areas of the ocean can be tested and evaluated. The experimental results show that when the underwater depth is 100m, the concentration of chlorophyll in water is about 0.23, and the attenuation coefficient of optical parameters at this time is 0.2, the absorption coefficient is 0.25, the scattering coefficient is 0.35, and the attenuation diffusion coefficient is 0.3. In the comparison of optical coefficients of different water quality, the attenuation coefficient of the far bank is 0.132. As the transmission distance increases, the number of photons that can be received by the detection surface changes from 842,819 to 4960. It shows that there is a positive correlation between optical parameters and underwater depth in the underwater communication channel analyzed by the system, and the transmission distance of light under water is inversely proportional to the number of photons received on the surface. To sum up, the research of underwater wireless optical communication simulation system based on digital twin has practical application value for the research of underwater communication channel. However, the beam transmission in water will be affected by ocean turbulence, which is not analyzed in the study, which is an area that can be improved in the future.

REFERENCE

[1] Sun X, Kang CH, Kong M, Alkhazragi O, Guo Y, Ouhssain M, Weng Y, Jones BH, Ng TK, Ooi BS. "A review on practical considerations and solutions in underwater wireless optical communication." IEEE Journal of Lightwave Technology 38, vol.10 no. 2,pp: 421-431.July 2020.

[2] K. Ye, C. Zou and F. Yang, "Dual-Hop Underwater Optical Wireless Communication System With Simultaneous Lightwave Information and Power Transfer," in IEEE Photonics Journal, vol. 13, no. 6, pp. 1-7, Dec. 2021.

[3] A. Uppalapati, R. P. Naik and P. Krishnan, "Analysis of M-QAM Modulated Underwater Wireless Optical Communication System for ReconFigureurable UOWSNs Employed in River Meets Ocean Scenario," in IEEE Transactions on Vehicular Technology, vol. 69, no. 12, pp. 15244-15252, Dec. 2020.

[4] Z. Rahman, N. V. Tailor, S. M. Zafaruddin and V. K. Chaubey, "Unified Performance Assessment of Optical Wireless Communication Over Multi-Layer Underwater Channels," in IEEE Photonics Journal, vol. 14, no. 5, pp. 1-14, Oct. 2022,

[5] M. Sait, Y. Guo, O. Alkhazragi, M. Kong, T. K. Ng and B. S. Ooi, "The Impact of Vertical Salinity Gradient on Non-Line-of-Sight Underwater Optical Wireless Communication," in IEEE Photonics Journal, vol. 13, no. 6, pp. 1-9, Dec. 2021.

[6] Z. Rahman, S. M. Zafaruddin and V. K. Chaubey, "Direct Air-to-Underwater Optical Wireless Communication: Statistical Characterization and Outage Performance," in IEEE Transactions on Vehicular Technology, vol. 72, no. 2, pp. 2655-2660, Feb. 2023.

[7] C. Fang, S. Li and K. Wang, "Accurate Underwater Optical Wireless Communication Model With Both Line-of-Sight and Non-Line-of-Sight Channels," in IEEE Photonics Journal, vol. 14, no. 6, pp. 1-12, Dec. 2022

[8] M. F. Ali, D. N. K. Jayakody, S. Garg, G. Kaddoum and M. S. Hossain, "Dual-Hop Mixed FSO-VLC Underwater Wireless Communication Link," in IEEE Transactions on Network and Service Management, vol. 19, no. 3, pp. 3105-3120, Sept. 2022
[9] R. Boluda-Ruiz, P. Rico-Pinazo, B. Castillo-Vázquez, A. García-Zambrana and K. Qaraqe, "Impulse Response Modeling of Underwater Optical Scattering Channels for Wireless Communication," in IEEE Photonics Journal, vol. 12, no. 4, pp. 1-14, Aug. 2020.
[10] Y. Ata and K. Kiasaleh, "Analysis of Optical Wireless Communication Links in Turbulent Underwater Channels With Wide Range of Water Parameters," in IEEE Transactions on Vehicular Technology, vol. 72, no. 5, pp. 6363-6374, May 2023