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PERFORMANCE ANALYSIS OF OPTICAL MODULATION IN UNDERWATER SLANT TRANSMISSION

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Abstract. *Currently, the modulation performances of underwater wireless optical communication are analyzed in horizontal optical transmission link. However, the methods cannot be used in vertical optical transmission link. In order to solve the problem a model of sea attenuation coefficient is proposed. The model is based on the Gaussian distribution model of chlorophyll concentration and the "seawater stratification idea". The attenuation coefficients in different depths of water can be calculated by this model. In this paper, the characteristics of bit error rate (BER) of four kinds of optical modulation modes are analyzed. The modes include OOK, PPM, FSK, and PSK. The results show that the performance of PPM is better than the others, and it is more suitable for the underwater wireless optical communication.*
Keywords: Underwater communication, Blue-green laser, Slant transmission, Optical modulation performance

1. **Introduction.** Blue-green laser underwater communication has the following advantages: High data transfer rate, strong anti-interference ability, and good security. Owing to the advantages the applications of underwater blue-green laser communication have got more and more attention in marine monitoring and military application. However, the underwater communication performance and the application of blue-green laser are limited by the characteristics of oceanic channel. It is a key problem to be solved in developing underwater blue-green laser communication [1]. Studying the oceanic channel characteristics and selecting an appropriate modulation mode for underwater optical communication are two of the problems urgently to be solved presently.

At present, the modulation performances of the underwater optical communications are studied in many references. The characteristics of optical pulse position modulation (PPM), such as average transmit power bandwidth requirements, transmission rate, and channel capacity are analyzed in [2]. The average power consumption, average bandwidth requirements and packet error rate of the different modulations are analyzed by Wang [3]. In reference [3], the modulations include on-off keying (OOK) modulation, PPM, differential pulse position modulation (DPPM), pulse interval modulation (PIM), and dual header pulse interval modulation (DH-PIM). However, the previous modulation performance of the optical communication is analyzed without referring to the oceanic channel environment. Therefore, these studies are lack of effective guidance in practical applications.

The relationships of different modulation among the BER, transmission distance and water quality environment are analyzed in [4]. The modulation modes include OOK, PPM, differential phase shift-keying (DPSK), and L-PPM (L is the modulation levels). The method is based on the model of the oceanic channel and is used to analyze the horizontal transmission links. The method can provide the basis for designing the system of the underwater optical communication. However, the method is only used in horizontal transmission links. The attenuation coefficient is analyzed by Jeffrey, and the attenuation coefficients in different depths are shown in [5], but the optical power attenuation is not solved. According to the method of Monte Carlo, the spot distribution of underwater optical communication is calculated by E. Zhan [6]. However, the absorption effect is not considered in this method. So, the simulation result is smaller than the theoretical estimation. The performance of underwater optical communication is not accurately reflected by the result.

To resolve the problems in references [4-6], an oceanic channel model is built which is based on the Gaussian distribution model of chlorophyll concentration and "seawater stratification idea". Using the model, the optical power attenuation and optical modulation performances in the vertical transmission direction can be analyzed according to the actual environment of the oceanic channel.

2. **Seawater Attenuation Coefficient Calculation Model.** Sea water can be divided into the case I water and the case II water. The optical property of case I water is only determined by the phytoplankton and its companions. So the optical property can be approximated by the chlorophyll concentration. The typical region of case I water is the open ocean area. When the case I water is analyzed, only the impact of the pure seawater and the chlorophyll concentration need to be considered.

According to the seawater bio-optical model [7-9], when the beam is transmitting in the case I water, the total attenuation coefficient of seawater can be calculated as:

$$K(\lambda) = A_w(\lambda) + A_c^0(\lambda)\left(\frac{C_c}{C_c^0}\right)^{0.602} + B_w(\lambda) + \left(\frac{550}{\lambda}\right) 0.3C_c^{0.62} \tag{1}$$

where λ is the wavelength of light (m), $A_w(\lambda)$ is the pure water absorption coefficient (m^{-1}), $A_c^0(\lambda)$ is the chlorophyll spectral absorption coefficient (m^{-1}), C_c is the total chlorophyll concentration (mg/m^3), C_c^0 is a constant, and $B_w(\lambda)$ is the scattering coefficient of pure water (m^{-1}). Equation (1) can be applied for the analysis of attenuation characteristics of horizontal transmission links.

The characteristics of absorption and scattering in different depths are different. It is difficult to describe the attenuation coefficient by using a fixed value when communicating along the vertical direction underwater.

Some researches have shown that the distribution of chlorophyll concentration in seawater follows the Gauss Distribution. The chlorophyll concentration can be expressed as follows [7]:

$$C_c(z) = c_0 + \frac{h}{\sigma\sqrt{2\pi}} \exp\left[\frac{(z - z_{\max})^2}{-2\sigma^2}\right] \tag{2}$$

where z is the depth of sea water (m), c_0 is the background of biomass (mg/m^3), $z_{\max}$ is the depth with the maximum chlorophyll concentration (m), σ is the standard deviation (m), h is the total biomass above the background biomass (mg/m^2), $h/(\sigma\sqrt{2\pi})$ is the peak height above the baseline. When $c_0 = 0.025$, $\sigma = 20$, $z_{\max} = 70$, $h = 30$ [10], the vertical distribution of chlorophyll concentration in the South China Sea is shown in Figure 1.

The "**seawater stratification idea**" is introduced in this paper. The attenuation coefficients of different depths can be calculated according to this idea. Assuming that the sea is divided averagely into N layers and the depth of each layer is z_0, the chlorophyll concentration of the layer i $C_c(z_i)$ ($z_i = iz_0$) can be calculated according to the vertical

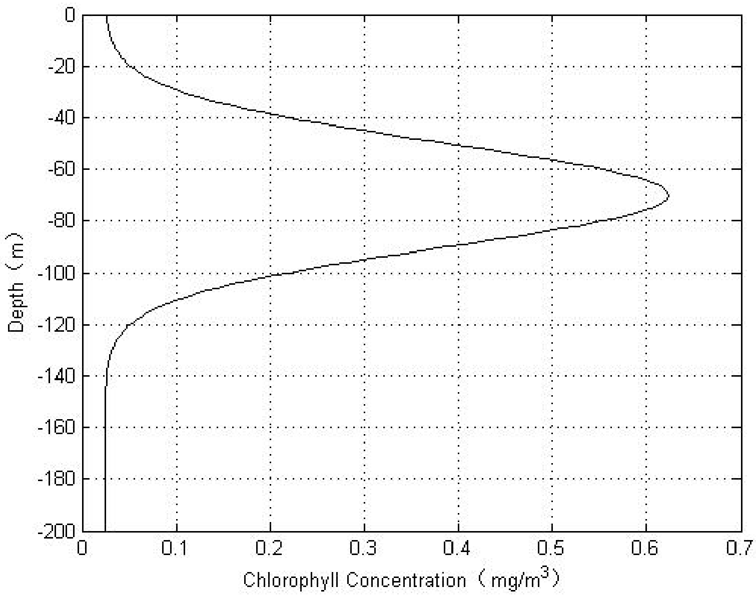

FIGURE 1. The vertical distribution curve of the chlorophyll concentration in the South China Sea

distribution model of chlorophyll concentration. Then, the attenuation coefficient of the layer i can be calculated by:

$$K_i(\lambda) = A_w(\lambda) + A_c^0(\lambda)\left(\frac{C_c(z_i)}{C_c^0}\right)^{0.602} + B_w(\lambda) + \left(\frac{550}{\lambda}\right) 0.3\left(C_c(z_i)\right)^{0.62} \tag{3}$$

3. Optical Modulation Performance Analyses with Simulation.

3.1. Optical modulation method and BER.

The performance of the pulse digital receiver is usually measured by the BER. BER is defined as the probability of code errors during transmission. For the digital optical receiver the BER is usually required less than 10^{-9}.

Currently, there are four methods of optical modulation in wireless optical communication, namely OOK, 2FSK (Frequency Shift Keying), 2DPSK (Differential Phase Shift Keying), and the L-PPM. The formulas of the BER can be expressed as follows [4]:

(1) BER of the OOK

$$P_{e(OOK)} = \frac{1}{2} erfc\left(\frac{S}{2\sqrt{2}}\right) \tag{4}$$

(2) BER of the 2FSK

In the additive white Gaussian noise channel, the 2FSK coherent modulation BER:

$$P_{e(FSK)} = \frac{1}{2} erfc\sqrt{\frac{S}{4}} \tag{5}$$

(3) BER of the 2DPSK

$$P_{e(DPSK)} = erfc\sqrt{\frac{S}{2}}\left(1 - \frac{1}{2} erfc\sqrt{\frac{S}{2}}\right) \tag{6}$$

(4) BER of the L-PPM

$$P_{e(L-PPM)} = \frac{1}{L}\left[\frac{1}{2} erfc\left(\frac{1-k}{2\sqrt{2}}\sqrt{L\cdot S}\right) + \frac{L-1}{2} erfc\left(\frac{k}{2\sqrt{2}}\sqrt{L\cdot S}\right)\right] \tag{7}$$

where S is the signal to the noise ratio, L is the modulation levels of the PPM, and k is the threshold (is usually taken as 0.5).

To calculate the BER of the four modulation modes, S should be calculated first. When the light is transmitting underwater, the transmission distance can be calculated by:

$$z = \frac{2.303}{K(\lambda)} \log_{10} \frac{P_t}{NEP \cdot S} \tag{8}$$

where NEP is the noise equivalent power of the light detector; P_t is the transmission power.

Therefore, if the NEP and the P_t are given, the signal to noise ratio of the layer i can be calculated according to the vertical distribution model of chlorophyll concentration and the attenuation coefficient $K_i(\lambda)$ of the sea. Then, the BER characteristics of different modulations can be analyzed. The formula can be expressed as:

$$S_i = 10^{-\frac{K_i(\lambda)}{2.303} z_0} \cdot \frac{P_{t_i}}{NEP} \tag{9}$$

where $P_{t_i} = P_{t_{i-1}} \cdot \exp(-K_i(\lambda) \cdot z_0)$.

3.2. **The analysis of simulation results.** The performances of different modulations are compared in three situations. The performance of horizontal optical transmission (i.e., chlorophyll concentration is a fixed value) is analyzed in deep-sea water and coastal water. The performance of the optical vertical transmission is analyzed in South China Sea.

The simulation conditions are set up as follows:

- Chlorophyll concentration: The chlorophyll concentration in the deep water is 0.011 mg/m^3, the chlorophyll concentration in the coastal water is 0.1mg/m^3, and the changes of chlorophyll concentration in the sea of southern China are related to the depth, the chlorophyll concentration distribution is shown in Figure 1 which ranges from 0.025 to 0.62mg/m^3. In Formula (3), the C_c^0 is 1mg/m^3.
- Modulation: The BER performance of five different kinds of modulation modes have been analyzed in this paper by simulation, including OOK, FSK, 2DPSK, 4PPM, and 8PPM.
- The parameters of optical communication system: The 470nm Blu-ray LXHL-PB09 as an emission source is selected for simulating; the transmitting power is about 2.59×10^{-3}W, the NEP is 0.19×10^{-12}W.

3.2.1. *Optical modulation characteristics in the horizontal transmission.* In terms of the horizontal transmission, the optical modulation characteristics are analyzed by simulation in deep-sea water and coastal water. The simulation results are shown in Figure 2 and Figure 3.

Comparing Figure 2 and Figure 3, the conclusion can be got that the chlorophyll concentration distribution has large effects on the BER performance. Chlorophyll concentration is varied in seawater. The chlorophyll concentration changes severely when the light is transmitting along the vertical direction. So the modulation performance of the actual situation cannot be analyzed by this method.

3.2.2. *Optical modulation characteristics in the vertical transmission.* Figure 4 is the simulation results of BER performance of different modulations in optical vertical transmission; the distribution of the chlorophyll concentration is shown in Figure 1 which ranges from 0.025 to 0.62mg/m^3. From Figure 4 we can see that the depth of the light transmission underwater can reach 55$\sim$60m if the BER is under 10^{-9}.

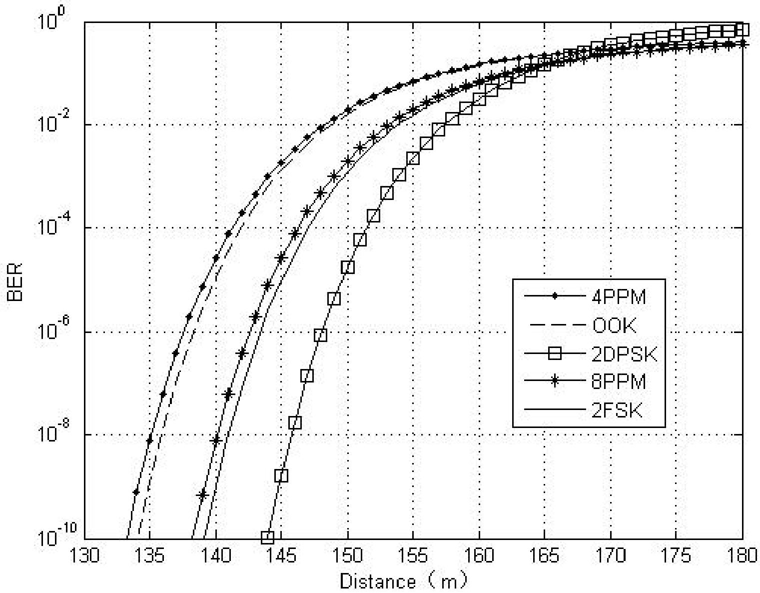

FIGURE 2. The changes of BER in the deep-sea waters at different transmission distances

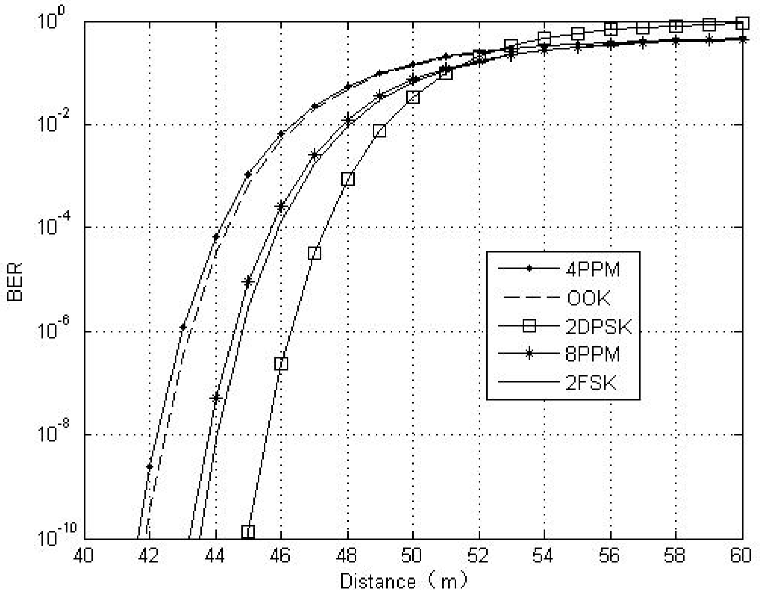

FIGURE 3. The changes of BER in the coastal waters at different transmission distances

From these three simulation diagrams the conclusion can be got that the 2DPSK has better BER performance than the others. The sensitivity receiver of 2DPSK is higher than 8PPM and 2FSK. The BER performance of OOK is poor, and the BER of 4PPM is similar to OOK. However, as the L increasing, the BER performance of L-PPM will significantly improve; for example, the BER performance of 8PPM is better than 4PPM.

In practical applications, the FSK and PSK are based on interference optical path. The applications of these modulation modes in seawater are limited by many factors such as the large size, the demanding environmental conditions and the adjustment difficulty of the interferometer. The OOK and L-PPM use the direct modulation. The method has

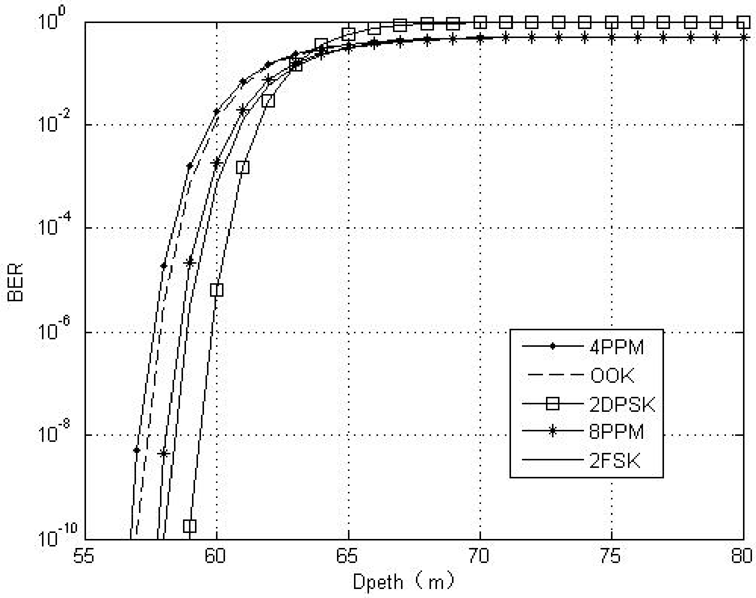

FIGURE 4. The changes of BER in the South China Sea at different transmission distances

the following advantages: simple structure, low loss, low cost, and easy to implement. It becomes the most commonly used modulation mode in optical communication. The simulation results show that the BER performance of L-PPM will gradually be better than OOK with the increase of L. The received power of PPM is $1\Big/\sqrt{L/2\log_2 L}$ of OOK in the same BER. The conclusion shows that in the same condition the PPM can improve the utilization of transmit power and increase the transmission distance. From the factors above, it can be seen that the L-PPM is more suitable for underwater optical communications than the others.

4. **Conclusions.** In this paper, a sea attenuation coefficient model is built. The model is based on the Gaussian distribution model of the chlorophyll concentration and the "seawater stratification idea". The attenuation coefficient in different depths of water can be calculated by this model. The impact of the changes in chlorophyll concentration on the communication quality is considered in this method when light transmits vertically underwater. Based on this model, the BER characteristics of the four different modulations are analyzed by simulation. These modulation modes include PPM, OOK, FSK, and DPSK. The results show that in the practical applications, the PPM has a greater advantage than the others. The chlorophyll concentrations in different seawater have notable influences on BER performance, and the existing analysis methods (chlorophyll concentration is changeless) are not suitable for the top-down optical transmission link. However, the sea attenuation coefficient model which is proposed in this paper can accurately analyze the modulation performance of the underwater communication system.

The model of sea attenuation coefficient and the analysis method of optical modulation characteristic which are proposed in this paper have the following potential applications: analyze the transmission characteristics of the underwater wireless sensor networks and underwater mobile communication of short distance, and provide basis for designing the system of the underwater optical wireless communication with high performance.

In the future study, the performance of underwater optical communication in different areas of the sea can be analyzed by using the method in this paper. And by compared with other methods it can offer better reference for designing underwater wireless optical communication system.

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