Differential-OOK System for Underwater Visible-Light Communications

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Abstract

Underwater wireless optical communication (UWOC) can provide higher-data-rate communication over moderate distances for new underwater applications. However, high-speed data transmission in UWOC is mainly limited by spectral attenuation in water and background noise. In this study, we propose an analytical underwater daylight noise model that incorporates the daylight simulation model SPCTRAL2 with an upwelling solar radiance model for the practical analysis of background light for UWOC. Moreover, we also consider a differential on-off-keying (DOOK) system in our simulation model. This DOOK system was proposed to reduce the effect of background noise in free-space optical communications. It was found that the effectiveness of the DOOK system can be verified by our new underwater daylight noise model. For example, for coastal water and harbor water, the DOOK system can improve BERs compared with an OOK system with a fixed threshold. In addition, the DOOK system can achieve a BER of less than 10^{-6} in coastal water during daylight hours.

1. Introduction

Underwater wireless optical communication (UWOC) has attracted much attention recently as it utilizes the visible-light spectrum. UWOC can support a higher data rate by using a blue-green LED for optical communications [1],[2], although the propagation distance of UWOC is limited compared with that of acoustic underwater communications [3]. By using blue-green optical laser communications, Gb/s rates can potentially be achieved over distances of up to 100m order in clear water [4].

High-speed data transmission in UWOC is mainly limited by spectral attenuation in water and background noise. In underwater optical communication, an optical carrier with wavelength λ experiences exponential total attenuation ($c(\lambda)$) due to two optical effects, photon absorption $a(\lambda)$ and photon scattering $b(\lambda)$, where $c(\lambda) = a(\lambda) + b(\lambda)$, all in units of m^{-1} . Photon energy is lost as a result of the interaction with

water molecules or other particles via a thermal process (absorption). Also, the path of photons is changed as a result of the interaction with particles (scattering). These two effects reduce the practical communication range to 100m order in clear, open ocean water, and to 10m order in more turbid, harbor water [5]. Light propagation in water is wavelength-sensitive with comparatively attenuation in the blue-green wavelength range. Therefore, the transmitter in [2] was designed to choose between a green LED and a blue LED in response to changes in the spectral attenuation of water by estimating the optimum wavelength in a preamble packet. In [6], R optical signal outputs from a convolutional encoder with a code rate of $1/R$ were represented by the variation of multicolor LEDs (blue, green, and red) to improve the error-correcting capability. The bit error rate (BER) performances of these systems using multicolor LEDs are better than those of conventional systems using a single-color LED. To further improve the transmission rate, the background noise cannot be ignored in visible-light communication systems in outdoor environments [7]. However, to the best of the authors' knowledge, there has been no practical analysis on background light in UWOC. The effect of ambient-light noise, which varies considerably from as early as 7:00 a.m. to as late as 7:00 p.m. because of daylight, has not been considered in conventional underwater channel models.

In this study, we propose an analytical underwater daylight noise model that incorporates the daylight simulation model SPCTRAL2 [8] with an upwelling solar radiance model for underwater optical communication systems [7]. Analysis shows that our underwater daylight noise model allows us to determine the background noise power as a function of the time of day and the depth of the sea. We also consider a differential on-off keying (DOOK) system in our simulation model. This DOOK system was proposed to reduce the effect of background noise in free-space optical communications [9]. To verify the practical effectiveness of the DOOK system for underwater communication, we analyze and evaluate the BER performance of the DOOK system taking into account the spectral attenuation of water and the background noise obtained from our underwater daylight noise model.

2. System Model

Figure 1 shows the system model of the DOOK system [9] and Fig. 2 shows the transmitter and receiver positions as below.

Figure 1: System model

Figure 2: Positions of transmitter and receiver

We assume that the UWOC system is aligned with a line-of-sight (LOS) link and that the optical axes of the transmitter and receiver coincide to simplify the calculations. At the transmitter, a differential encoded signal is transmitted. For example, the source data '1,0,1,1' is converted to '1,1,0,1' by the differential encoding. This signal is converted to an optical signal and transmitted in accordance with a generalized Lambertian law. Then, the optical signal propagates through an underwater channel and attenuates. In our analysis, the underwater environment is assumed to be ideally isotropic and homogeneous water without waves or turbulence. This means that the UWOC system can be regarded as a linear time-invariant system [10].

We discuss the properties of the underwater channel in detail in the next section. At the receiver, the transmitted signal is received by an avalanche photo diode (APD). The received signal passes through a delay detection circuit to reduce the effect of background noise. For example, when the received signal is '1,1,0,1', it is converted to '1,0,-1,1' by the delay detection circuit. Finally, the original data '1,0,1,1' can be obtained from the absolute value of the delay detection output. At the receiver, we take into account photodiode shot noise and thermal noise, which are modeled as additive white Gaussian noise (AWGN) [11].

3. Theoretical Analysis

3.1 Optical properties

In this subsection, we present the optical channel model [12]. At the transmitter, we use an LED that spreads perfectly diffusing light (i.e., the transmitter semiangle at half power is 60°). In the underwater channel, we consider a spherical spreading model and an attenuation model. This means that we take the square attenuation of distance and Beer's law into account. At the receiver, we simply consider the effective area of the APD and the incident angle of the light. Thus, the UWOC channel is modeled as

$$P_r = \frac{P_t}{\pi} \cos(\phi_t) \times \frac{\exp(-c(C_C, \lambda)r)}{r^2} \times A_d \cos(\phi_r) \quad (1)$$

where r is the distance [m], C_C is the concentration of chlorophyll, λ is the wavelength of the LED, $c(C_C, \lambda)$ is the attenuation coefficient, ϕ_t is the angle of the receiver position viewed from the transmitter, ϕ_r is the incident angle of the light to the receiver, A_d is the light-receiving area, P_t is the transmittance power [W/sr], and P_r is irradiance received at distance r [W/m²].

3.2 Water properties

In the underwater channel, we also consider a spherical spreading model and an attenuation model. The spherical spreading model represents the loss of light intensity due to spreading. The attenuation model represents the loss of light intensity due to absorption and scattering. The absorption in water is a process where the light is converted into another form such as heat due to the vibration of molecules or particles. In the scattering in water, molecules or particles cause photons to change direction. These molecules and particles include water molecules and dissolved particles such as chlorophyll and a yellow substance. These effects are characterized by the absorption coefficient $a(C_C, \lambda)$ [m⁻¹] and the scattering coefficient $b(C_C, \lambda)$ [m⁻¹] whose sum is defined as the attenuation coefficient $c(C_C, \lambda)$ [m⁻¹].

$$c(C_C, \lambda) = a(C_C, \lambda) + b(C_C, \lambda) \quad (2)$$

These coefficients are affected by the concentration of chlorophyll and the wavelength. These parameters affect the light in accordance with Beer's law. In this paper, we use the Smith and Baker method [13] to derive $a(C_C, \lambda)$ and $b(C_C, \lambda)$. From [14], we determine the values of these parameters for water molecules and other particles such as the yellow substance.

The water properties are divided into four categories, as pure sea, clean ocean, coastal, harbor, on the basis of the concentration of chlorophyll [15].

3.3 Background noise

Generally, it is impossible to neglect the effect of sunlight in the sea and the effects caused by the time of day and the

depth of the sea. The incident background noise into the receiver, N_{back} [W/m²sr], can be written by [7]

$$N_{back} = \frac{E_{total} R L_{fac}(\theta) \exp(-KD)}{\pi} \quad (3)$$

where E_{total} [W/m²] is the downwelling irradiance incident on the surface of the water, R is the underwater reflectance of the downwelling irradiance [7], $L_{fac}(\theta)$ is a factor describing the directional dependence of the underwater radiance [16], θ is the incident angle of the background noise to the receiver, K [m⁻¹] is the diffuse attenuation coefficient, and D [m] is the receiver depth.

The amount of sunlight incident to the water surface E_{total} , which is calculated by SPCTRAL2 [8], is used as the daylight simulation model. SPCTRAL2 is a simulation model developed by Bird and Riordan [8] that incorporates improvements to their previous work and an algorithm for calculating spectral irradiance on tilted surfaces under different atmospheric conditions. The sunlight at the water surface in units of W/m² can be expressed by

$$E_{total} = \int E(\lambda) d\lambda \quad (4)$$

where $E(\lambda)$ is the illuminance of sunlight of wavelength λ obtained from SPCTRAL2. In SPCTRAL2, we can set the parameters of the latitude and longitude of the position, and the date.

4. Numerical Analysis and Results

Table 1 shows the parameters used in the numerical analysis. In this paper, we evaluate the BER performance of the DOOK system over a LOS model. Moreover, we assume that the diffuse attenuation coefficient K is the same value as $c(C_C, \lambda)$ and that the concentration of chlorophyll C_C is 0.83 (i.e., coastal water) and 5.9 (i.e., harbor water). Note that harbor water has lower quality than coastal water [14], [15].

Figure 3 shows the optical power received from the sun against the time of day when the receiver depth d is 2m and 7m. From this figure, we can confirm that the background noise varies considerably from as early as 7:00 (in the morning) to as late as 18:00 (in the evening) in our simulation model. Moreover, it is also found that the background-noise becomes large when the receiver is deep and that the effect of the background noise in coastal water is larger than that in harbor water because the attenuation of optical power is large in the harbor water.

Next, we show the BER performance of the DOOK system with the weak-daylight model (Fig. 4) and strong-daylight model (Fig. 5). Figure 4 shows the BER performances of the DOOK system versus the receiver depth, d , where C_C is 5.9, the time of day is 12:00, r is 1.5m, and θ is 0° and 90°. In this figure, we also compare the DOOK system with OOK with an adaptive threshold (i.e., an ideal threshold level) and OOK with a fixed threshold. Here, the fixed threshold is set

Table 1: Numerical parameters

Latitude of position	19
Longitude of position	155
Date	March 1
R [7]	1.25%
L_{fac} [16]	1 ($\theta = 0^\circ$), 0.026 ($\theta = 90^\circ$),
Transmittance power	1.3W
Wavelength	530nm
Quantum efficiency	1.0A/W
Receiver aperture	1.5mm
Average APD gain	50
Boltzmann's constant	$1.38 \times 10^{-23} \text{JK}^{-1}$
Receiver noise temperature	1100K
Receiver load resistor	50Ω
Excess noise factor	2.99
Surface leakage current	$91.7 \times 10^{-12} \text{A}$
Bulk leakage current	$18.3 \times 10^{-12} \text{A}$

as half the received power without background noise. From this figure, the BER performances of DOOK are better than those of OOK with a fixed threshold because the OOK system with a fixed threshold is significantly affected by sunlight at 12:00, although the effect of sunlight is relatively small compared with that in the strong-daylight model. When the effect of sunlight is small or the transmittance power is the large, we also confirm that the BER performance of the DOOK system is worse than that of OOK with a fixed threshold because the effectiveness of the DOOK system becomes low. Moreover, the DOOK system can achieve the asymptotic BER performance of the OOK system with an ideal threshold. The difference in the performances of DOOK and OOK with an ideal threshold is caused by the signal-to-noise ratio (SNR) of DOOK being degraded by 3dB by the delay detection circuit compared with that for the conventional OOK system.

Figure 5 shows the BER performance versus the time of day, where C_C is 0.83, the receiver depth is 2.0m, θ is 0°, and r is 5.0m. We found that the BER performances of DOOK are lower than those of OOK with a fixed threshold from 8:30 to 16:30 because DOOK system is effective for reducing the effect sunlight in the strong-daylight model.

5. Conclusion

In this paper, we have presented a practical underwater daylight noise model for UWOC systems taking into account the time-varying background noise and the receiver depth. We have also analyzed and evaluated a DOOK system that can reduce the effects of sunlight in our simulation model. Using our simulation model, we can evaluate the effects of the time of day and the receiver depth of the DOOK system on reducing background noise. It was found that in the cases of harbor and coastal water, the BER performances of the DOOK system are better than those of the OOK system

Figure 3: Optical power received from sunlight versus time of day

Figure 4: BER performance versus receiver depth when the time of day is 12:00 and r is 1.5m (harbor)

Figure 5: BER performance versus time of day when d is 2m, θ is 0° , and r is 5.0m (coastal)

with a fixed threshold because the OOK system with a fixed threshold is significantly affected by sunlight under these sea conditions. In particular, in the weak-daylight mode (i.e., harbor water), the DOOK system can achieve the similarly BER performance of the OOK system with an ideal threshold.

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