



Outage analysis of relay-assisted underwater wireless optical communication systems

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ABSTRACT

In this paper, we theoretically evaluate the outage probabilities of underwater wireless optical communication (UWOC) systems. Our derivations are general as the channel model under consideration takes into account all of the channel degrading effects, namely absorption, scattering, and turbulence-induced fading. We numerically show that the UWOC systems, due to the severe channel impairments, cannot typically support longer link ranges than 100 m. Therefore, in this paper, in order to increase the transmission reliability and hence extend the viable communication range of UWOC systems, we apply decode-and-forward (DF) relay-assisted communications either in the form of multi-hop transmission, where multiple intermediate relays are serially employed between the source and destination, or parallel relaying in which multiple DF relays are distributed among the source-to-destination path to cooperate in the end-to-end transmission. Our numerical results reveal that multi-hop transmission, owing to the distance-dependency of all of the channel degrading effects, can tremendously improve the end-to-end outage probability and increase the accessible link ranges to hundreds of meter. For example, a dual-hop transmission in a 45 m coastal water link can provide up to 41 dB performance improvement at the outage probability of 10^{-9} .

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1. Introduction

Underwater wireless optical communications (UWOC) is becoming a potent solution for high-throughput and large-date underwater applications. In fact, compared to the conventional acoustic communications, UWOC benefits from by far higher data rates (on the order of Gbps), much lower time latency (due to the extremely larger propagation speed of light compared to acoustic waves), and better security (owing to the directivity of optical signals) [1,2]. Moreover, UWOC systems are more suitable with respect to the underwater echo system. These unique advantages all together have attracted many researchers, since the past few years, to design efficient and smart UWOC systems that can facilitate the underwater exploration and communication.

Extensive research activities, in the past few years, concerning on the UWOC channel degrading effects and their modeling have disclosed that the optical beam propagation through water suffers from a couple of fundamental disturbing phenomena, including absorption, scattering, and turbulence-induced fading [3–5]. These make UWOC channel a complex media that can difficultly be treated and modeled. Recent explorations have shown that, because of these severe channel impairments, the typical UWOC systems cannot support longer link ranges

than 100 m [1,6]. Short accessible link lengths of UWOC systems is their main drawback compared to the traditional underwater acoustic communication systems. Therefore, since the past few years, too many scientists have come together to, first, more accurately and generally investigate the UWOC channel model, and, second, design intelligent UWOC systems and efficient transmission and/or reception methods to extend the viable communication ranges.

Many of the recent research activities in this area have focused on the investigation of the channel degrading effects and the UWOC tractable channel modeling. In this context, [7] have used the radiative transfer theory to model the UWOC channel and evaluate its performance. Based on the experimental results reported in [3,8], Monte Carlo (MC) numerical approach have been applied in [1,4,9] to simulate the fading-free impulse response (FFIR) of UWOC channels with respect to absorption and scattering effects. In the meantime, in [1], a double gamma function (DGF) has been fitted to the aforementioned impulse response and the system bit error rate (BER) has numerically been evaluated without considering turbulence effects. Furthermore, a weighted Gamma function polynomial (WGFP) has been proposed to model the FFIR of multiple-input multiple-output (MIMO) UWOC

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links with arbitrary number of light sources and detectors [10]. Some other useful reports in the literature have concentrated on the characterization of the underwater turbulence. Based on Rytov method and the accurate power spectrum derived in [11] for the fluctuations of turbulent seawater refractive index, the scintillation index of optical plane and spherical waves propagating in underwater turbulent medium have been evaluated in [5,12]. The authors in [13] have carried out an experiment to ascertain the accordance of different common statistical distributions in predicting the intensity fluctuations produced by the presence of random air bubbles in the propagation path. In [14], the on-axis scintillation index of a focused Gaussian beam has been formulated for weak oceanic turbulence, and the average BER in the case of lognormal distribution for intensity fluctuations has been evaluated.

On the other hand, some very recent research activities have applied the aforementioned comprehensive channel modeling to smartly design robust UWOC systems capable of communication through the complex UWOC channel. In this context, the authors in [6,15] have applied MIMO transmission over both collimated laser-based and diffusive light emitting diode (LED)-based UWOC links to mitigate fading deteriorations and hence partially improve the system performance. A cellular optical code-division multiple access (OCDMA)-based UWOC networking has been proposed in [2] where a unique optical orthogonal code (OOC) is assigned to each mobile underwater user to minimize the multiple access interference between the concurrent users. In particular, in the context of relay-assisted underwater communication, the authors in [16] proposed a novel underwater acoustic cooperative communication system involving the wave cooperative transmission protocol, orthogonal frequency division multiplexing (OFDM) and the Lloyd algorithm-based limited feedback procedure. Moreover, BER performance of bit-detect-and-forward (BDF) serial relaying in a point-to-point UWOC system and chip-detect-and-forward (CDF) relaying in the aforementioned OCDMA-based UWOC network have respectively been evaluated in [17] and [18]. We should emphasize that none of these prior works do not deal with the outage probability of UWOC systems as one of the most important metrics in the evaluation of their performance, and such an important research is comprehensively carried out in this paper.

In this paper, we first treat the inter-symbol interference (ISI) effect similar to noise in order to obtain an expression for the effective signal-to-noise ratio (SNR) and derive the outage probability. We further define a new formula for the SNR of UWOC systems based on their BER formula, and then once again calculate the outage probability expressions to compare the results with the first approach. In order to effectively reduce the channel degrading effects and increase the viable end-to-end communication range, we apply decode-and-forward (DF) relay-assisted communications either in the form of multi-hop transmission, where multiple intermediate relays are serially employed between the source and destination, or parallel relaying in which multiple DF relays cooperate the source to destination end-to-end data transmission.

The rest of the paper is organized as follows. In Section 2, we overview the UWOC channel modeling and explain the system model for the DF relaying. In Section 3, we first define two formulas for the electrical SNR and derive the outage probabilities for a single-hop UWOC link with respect to all of the channel degrading effects. Using this baseline, we then extend our derivations for multi-hop and also cooperative UWOC systems with DF relaying to calculate their outage probability expressions as well. Section 4 provides the numerical results for various scenarios and Section 5 concludes the paper.

2. Channel and system models

2.1. UWOC channel modeling

When the optical beam is propagating through the UWOC channel, each photon may interact with the water molecules and particles. These interactions in ocean engineering are known as absorption and scattering. In the absorption process, the aforementioned interactions

lead to the lose of photons' energy thermally. In the scattering process, on the other hand, these interactions alter the transmit direction of each photon which also can cause energy loss, since less photons may be captured by the receiver aperture. Energy loss of non-scattered light, due to absorption and scattering can be characterized by absorption coefficient $a(\lambda)$ and scattering coefficient $b(\lambda)$, respectively, while extinction coefficient $c(\lambda) = a(\lambda) + b(\lambda)$ describes the total effect of absorption and scattering on the energy loss. Depending on the water type and the wavelength used λ , the values of these coefficients are widely variable [1]; however, the $400 \text{ nm} < \lambda < 530 \text{ nm}$ window possesses the lowest values for the absorption and scattering coefficients [3]. Therefore, UWOC systems apply the blue/green region of the visible light spectrum for data communications.

The comprehensive channel MC-based numerical simulations in [1,4,9,15] have revealed that the UWOC channel fading-free impulse response (FFIR) with respect to the absorption and scattering effects cannot simply be adopted similar to free-space optic (FSO) links. In fact, the huge amount of multiple scattering on the propagating light wave causes considerable temporal dispersion on the channel FFIR and hence on the received optical signal. Although the channel FFIR can be expressed as closed-form functions similar to [1,10], in this paper, for the sake of generality and accuracy, we denote the FFIR of the link connecting any node i to the arbitrary node j by $h_0^{(i,j)}(t)$. To obtain $h_0^{(i,j)}(t)$, we simulate the UWOC channel based on MC approach, similar to [1,4,9,15], to thoroughly include the absorption and scattering effects.

Turbulence-induced fading, on the other hand, is also amongst the channel major degrading effects that should appropriately be taken into account in our channel modeling. Optical turbulence occurs as a result of random variations of refractive index due to the fluctuations in temperature and salinity [19]. To characterize turbulence effects, similar to [6,20–22], we multiply $h_0^{(i,j)}(t)$ by a positive multiplicative fading coefficient $\tilde{h}_{i,j}$. We assume weak oceanic turbulence and model $\tilde{h}_{i,j}$ with log-normal distribution [6,14,20,23] as;

$$f_{\tilde{h}_{i,j}}(\tilde{h}_{i,j}) = \frac{1}{2\tilde{h}_{i,j}\sqrt{2\pi\sigma_{X_{i,j}}^2}} \exp\left[-\frac{(\ln(\tilde{h}_{i,j}) - 2\mu_{X_{i,j}})^2}{8\sigma_{X_{i,j}}^2}\right], \quad (1)$$

where $\mu_{X_{i,j}}$ and $\sigma_{X_{i,j}}^2 = -\mu_{X_{i,j}}$ are respectively the mean and variance of the Gaussian distributed log-amplitude factor $X_{i,j} = \frac{1}{2} \ln(\tilde{h}_{i,j})$.

The scintillation index of a light wave with intensity $I_{ij} = I_{0,ij}\tilde{h}_{i,j}$, where $I_{0,ij}$ is the fading-free intensity, is defined by;

$$\sigma_{I_{ij}}^2 = \frac{\mathbb{E}[I_{ij}^2] - \mathbb{E}^2[I_{ij}]}{\mathbb{E}^2[I_{ij}]} = \frac{\mathbb{E}[\tilde{h}_{i,j}^2] - \mathbb{E}^2[\tilde{h}_{i,j}]}{\mathbb{E}^2[\tilde{h}_{i,j}]}, \quad (2)$$

which relates to the log-amplitude variance as $\sigma_{I_{ij}}^2 = \exp(4\sigma_{X_{i,j}}^2) - 1$ [5,22]. Comprehensive studies on the characterization of the scintillation index for optical plane and spherical waves under the assumption of weak oceanic turbulence can be found in [5, Eqs. (1)–(8)].

2.2. Relay-assisted UWOC system model

As it is shown in Fig. 1, we consider a UWOC system with N intermediate DF relay nodes in both serial and parallel topologies. Hereafter, we represent the source node S as the 0th node, relay R_i as the i th node, $i = 1, 2, \dots, N$, and destination D as the $(N + 1)$ th node. In the case of intensity-modulation direct-detection (IM/DD) DF relaying with on-off keying (OOK) modulation, which is assumed in this paper, each relay decodes the received signal after direct detection, modulates it using OOK modulation, and retransmits the modulated signal to the next node if and only if the received SNR is above a given decoding threshold in order to avoid the error propagation [24]. We further assume that the transmitted power of each transmitter is designed such that guarantee a good performance for each intermediate hop; therefore, in the serial relaying each node only receives the transmitted signal of its previous

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