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Shore-to-Undersea Visible Light Communication

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Abstract In this paper, a novel visible light based shore-to-undersea (S2US) communication is proposed. It considers various properties of both maritime and undersea environments such as wave height, wind speed, and absorption. A lighthouse transmits the signal using white light emitting diodes (LEDs) and this signal is received by a buoy that acts as a beacon to relay to the undersea receiver. The beacon employs the decode-and-forward (DF) method in such a way that green LEDs transmit the DF processed signal to the undersea receivers via the undersea optical channel. The performance of the proposed S2US system was first evaluated via simulations with the JONSWAP spectrum model representing the maritime optical channel and the Jerlov water type representing the undersea optical channel. The results show that the transmitted signal undergoes significant attenuation, particularly over the undersea optical channel. At the reference distance of 1.025 km with Jerlov water type I, a bit error rate performance of 10^{-4} is achieved with a data rate of 1 Mbps. The S2US was further verified with experiments in terms of received signal level on a laboratory scale. The comparative analysis demonstrates that the simulation and experiment results are in good agreement.

Keywords Decode-and-forward (DF) mode · Jerlov water type classification · JONSWAP (JS) spectrum model · Shore-to-undersea visible light communication

1 Introduction

Recently, many marine electronics have been utilized in an undersea environment for diverse applications, such as oceanographic and fishing surveys in marine science, pipeline route surveys in an offshore industry with remotely operated underwater vehicles, and

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military deployment [1]. In the marine industries operating various devices, a reliable communication means is a prerequisite. In particular, there is a compelling need to establish a communication link between the transmitter on the shore and the undersea receivers at a relatively high data rate, perhaps equivalent to terrestrial wireless communications. To address this need, several communication technologies have been presented using various transmission medium, i.e. acoustics based communication, radio frequency (RF) communication, and visible light communication (VLC) [2]. Among these, VLC has received much attention as an emerging technology in an undersea transmission. In an undersea environment, however, VLC has advantages as well as disadvantages, compared with both acoustic and RF communications. VLC offers the highest data rate and a moderate coverage distance of up to 100 m, considering RF supporting a distance of up to 10 m and the acoustic communication providing a maximum distance of 1 km [2, 3]. As the infrastructure of a maritime environment is well established such as lighthouse and buoy, a VLC based maritime communication link can be cost effective and practical. In addition, the standardization for the lighthouse and buoy implementation is governed by International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) [4] and there are more than 18,900 lighthouses globally, serving as a navigational aid for maritime pilots using visible light [5]. At present, more than 1354 buoys are used as sea mark and for other applications [6].

Authors have investigated visible light based shore-to-sea (S2S) communications that utilize lighthouse and buoy between shore and sea surface [7, 8]. This S2S is often affected by sea states that are represented by the JONSWAP spectrum models [8]. It supports a distance of up to 3 km using time-code diversity (TCD) scheme at a data rate of 100 Kbps [9]. Unfortunately, this scheme is only applicable for the S2S, not for the S2US. Another effort was devoted in the project proposed by the Visible Light Communication Consortium (VLCC) [10]. The project utilizes a lighthouse as the transmitter to transmit the signal towards a ship on the sea surface. Unlike the previous contribution, it is based on an image sensor to receive the signal. Although it can support a distance of 2 km, the achieved data rate is relatively very low, i.e. 1.2 and 1.022 Kbps for 1 and 2 km, respectively. Similar to the previous study, this scheme is also only applicable for the S2S.

In regard to underwater communications, a focus is mainly placed on submarine communications [11, 12]. In [11], satellite was employed as the transmitter to transmit the signal in the form of a laser beam to a submarine in an undersea environment. Even so, at the reference wavelength of 545 nm for comparison, the coverage distances attained between sea surface and undersea receiver were merely 10 m and approximately 20 m in Jerlov water type III and type I, respectively. In [12], underwater communications employing a 450 nm laser beam obtained a data rate of 2 Gbps over 12 m distance. In [13], a similar work was reported for an air-to-water VLC employing laser diodes. It obtained a data rate of up to 5.5 Gbps data rate. It assumed a static air–water channel and also good pointing accuracy. However, since these works entail laser diodes, they require accurate pointing over the transmission.

Meanwhile, a concept of hybrid communication based on both RF and acoustic communication has recently emerged [14]. The hybrid design appears to have potential for shore-to-undersea (S2US). The signal is transmitted from either shore or satellite and then received by either buoy or ship on the sea surface using RF. For the communication between the buoy (or ship) and the underwater receiver, acoustic communication technology was employed. The hybrid S2US communication system offers a competitive edge in terms of coverage distance. However, it suffers from a relatively low data rate of 500 Kbps due to the usage of acoustic communication. More importantly, however, the hybrid system requires considerably large diameter antennas, e.g. 0.5 m, and also high transmission power of up to hundreds of Watts for long-distance RF communication [2]. Another hybrid land-to-underwater optical communication based on underwater VLC was emerged employing both fibre optic communication and VLC [15]. The system utilized a passive optical network (PON) to connect between land and underwater surface. It employed VLC to connect the underwater user to the fibre optic. Unfortunately, its underwater VLC distance was limited to 1 m.

In this paper, a novel complete visible light based S2US communication is proposed. The proposed systems can support shore-to-undersea communications for vehicles, divers, and devices underwater. The proposed system utilizes existing infrastructure, i.e. lighthouse and buoy, to provide communication from the shore to the undersea receiver on the basis of visible light transmission. A lighthouse in the shore transmits the signal using white LEDs and then the signal is received by the buoy (beacon) on the sea surface via the maritime optical channel. The received signal at the buoy is then decoded using the decode-and-forward (DF) method and is relayed to the undersea receiver using green LEDs through the undersea optical channel. In the proposed system, the JONSWAP model is used to represent sea surface movement in the maritime optical channel, whereas the concentration of chlorophyll that affects communication performance in the undersea environment is represented by the absorption property in the Jerlov water type classification. Simulations were conducted on the framework of the JONSWAP spectrum model and Jerlov water type for analysis and experiments were also conducted to verify the proposed S2US. It is found that the proposed system is capable of transmitting the data at a rate of up to 1 Mbps with a bit error rate (BER) of 10^{-4}. The data rate can be further increased at the expense of BER performance. It also achieves a longer underwater transmission distance of up to 25 m than conventional RF-based transmission distance.

The rest of this paper is organized as follows. Section 2 describes the system configuration including the maritime and undersea channel models. Section 3 presents the simulation results and is followed by the experimental results in Sect. 4.

2 System Configuration

The proposed visible light based S2US is comprised of lighthouse, buoy, and undersea receiver. The undersea receiver can be any fixed infrastructure or devices. Figure 1 illustrates the proposed S2US.

The lighthouse consists of LEDs that provide coverage over a serving area and the beacon on the sea surface contains LEDs and a photodetector. The photodetector in the beacon is placed to receive the signal transmitted from the lighthouse. The transmitted signal is then relayed to the undersea receiver using LEDs. In Fig. 1, d_{m} denotes the distance between the lighthouse and the beacon, while d_{u} indicates the distance between the beacon and the undersea receiver. The total transmission distance, d, is simply expressed as the sum of both d_{m} and d_{u}.

2.1 Maritime Optical Channel Model

The transmitted signal from the lighthouse undergoes distortion, delay, and degradation in a maritime environment where sea waves are basically created as a result of wind passing over the sea surface. To model the sea surface movement, sea waves are often

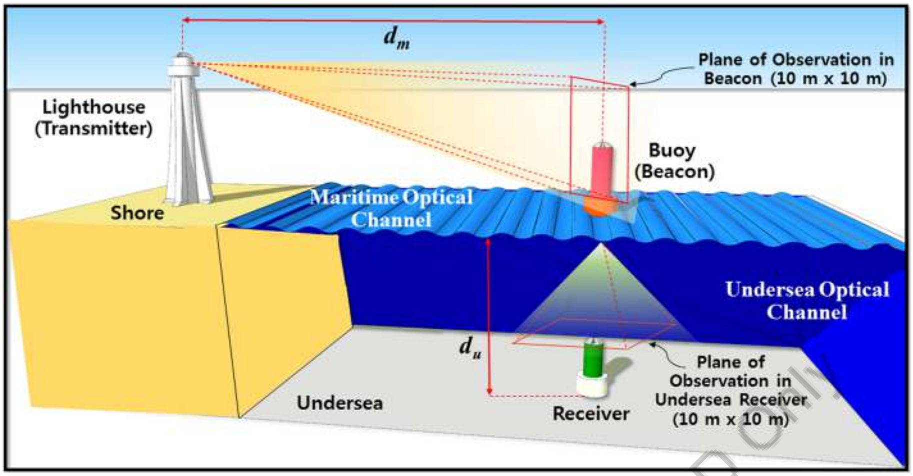

Fig. 1 Proposed shore-to-undersea VLC system

characterized in the form of wave height and wave period [16, 17]. One of the most accepted mathematical models for sea spectra analysis is the JONSWAP spectrum model as it is considered more realistic. The JONSWAP spectrum model is based on analyzing data that is collected during the joint North Sea wave observation project and is given by [8]

$$S_{JS}(f) = \frac{ag}{f^5}\exp\left[-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right]\gamma^b \tag{1}$$

$$a = 0.076\left(\frac{U^2}{gx}\right)^{0.22} \tag{2}$$

$$\mathrm{b} = \exp\left(-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right) \tag{3}$$

$$f_p = 22\left(\frac{g}{U}\right)\left(\frac{U^2}{gx}\right)^{0.33} \tag{4}$$

where g is gravity acceleration, f is wave frequency, U is wind speed, x is fetch length, and f_p is peak wave frequency. The peak enhancement function γ^b and the peak width parameter σ are called the shape parameters.

As the sea surface constantly moves, it creates an unstable optical channel behavior. As a consequence, the maritime beacon would change its position, thus causing the fluctuation of the received signal. The JONSWAP spectrum model accounts for the sea wave movement in a number of sea states [8]. For lower-numbered sea states, i.e. states of 1–3, the wave conditions are mild so that the signal distortion is negligible in the receiver, whereas the higher states are hostile with high waves and fast winds, causing the received signal to be degraded at the receiver. In [8], several sea state parameters are listed.

As a relay strategy for the beacon, amplify-and-forward (AF) and DF could be considered [18]. For the present study, since the beacon is power limited and the AF is less power efficient, the DF based relay was employed in the analysis.

2.2 Undersea Optical Channel Model

As noted earlier, the signal transmission from the lighthouse is subject to sea waves on the sea surface as well as transmission distance. The transmission path between the sea surface and the underwater receiver is largely affected by complex attenuation phenomena. The undersea attenuation coefficient $\rho(\lambda)$ is expressed as a linear combination of absorption coefficient $\rho_\alpha(\lambda)$ and scattering coefficient $\rho_\beta(\lambda)$. It is given by

$$\rho(\lambda) = \rho_\alpha(\lambda) + \rho_\beta(\lambda) \tag{5}$$

where λ is wavelength.

The scattering coefficient $\rho_\beta(\lambda)$ is regarded as negligible for wavelengths (λ) larger than 400 nm [19]. Since we employ LEDs whose wavelengths are larger than 400 nm, we consider the absorption coefficient $\rho_\alpha(\lambda)$ only in the analysis. Due to the fact that various types of absorption occur in an undersea environment, the total absorption is a combination of pure seawater absorption, chlorophyll absorption, and the two components of colour dissolved organic material (CDOM), i.e. humic and fulvic acids [2]. Hence, the total absorption coefficient $\rho_\alpha(\lambda)$ is given by

$$\rho_\alpha(\lambda) = \alpha_w(\lambda) + \alpha_{cl}(\lambda) C_c^{0.602} + \alpha_h(\lambda) + \alpha_f(\lambda) \tag{6}$$

where

$$\alpha_h(\lambda) = 3.64 C_c \exp(0.12343 C_c - 0.01105\lambda) \tag{7}$$

$$\alpha_f(\lambda) = 62.6 C_c \exp(0.12327 C_c - 0.0189\lambda) \tag{8}$$

$\alpha_w(\lambda)$ is the pure water absorption coefficient, while $\alpha_{cl}(\lambda)$ denotes the pure water absorption chlorophyll acid coefficient. In addition, $\alpha_h(\lambda)$ is the absorption coefficient of humic acid and $\alpha_f(\lambda)$ is the absorption coefficient of fulvic acid. It should be noted that the concentration of chlorophyll C_c has different values, depending upon the classification of the Jerlov water types. Table 1 shows the C_c values [20].

2.3 Optical Path Loss Model

The optical path loss model of the proposed S2US consists of two distinctive paths: maritime optical path L_M and undersea optical path L_U. Over the maritime optical channel,

Table 1 Chlorophyll concentration in Jerlov water types

Jerlov water types	Concentration of chlorophyll, C_c (mg/m^3)
I	0.03
IA	0.1
IB	0.4
II	1.25
III	3

L_M is determined by a line-of-sight (LOS) VLC link with a Lambertian source. Hence, the path loss L_M can be approximated as [21]:

$$\mathrm{L}_M = \mathrm{a}_m \frac{A_r(m_1+1)}{2\pi d_m^2} cos^{m_1}(\phi) T_s(\psi) g(\psi) cos(\psi) \tag{9}$$

where m_1 is a Lambert mode number expressing a source beam directivity. a_m is attenuation that is caused by sea state from the JONSWAP spectrum model. The detector is modeled as aperture area A_r at the field of view ψ. The gain of an optical filter at the receiver is $T_s(\psi)$. The gain of an optical lens is $g(\psi)$ that is determined by ψ and lens refractive index. Meanwhile, ϕ is half power angle.

Likewise, for the undersea link, L_U is expressed by a LOS VLC transmission. L_U is given by [22]:

$$\mathrm{L}_\mathrm{U} = \alpha_\mathrm{u} \eta_\mathrm{T} \eta_\mathrm{R} \frac{A_\mathrm{r} \cos(\theta)}{2\pi d_\mathrm{u}^2 (1-\cos(\phi))} \tag{10}$$

where

$$\alpha_u = exp\left(-\rho(\lambda)\frac{d_u}{\cos(\theta)}\right) \tag{11}$$

where η_T is optical efficiency of the transmitter and η_R is optical efficiency of the receiver. The optical efficiency defines how efficient the device is in minimizing optical loss [22]. A_r defines the receiver aperture area. θ is the angle of irradiance with respect to the axis normal to the transmitter plane.

3 Simulation Results

To investigate the performance of the S2US, simulations were conducted for the analysis of the received power and BERs. With the assumption that the transmission occurs in the LOS condition over the whole path, the data was modulated using the on–off keying (OOK) and relayed using the DF method. As described previously, the maritime optical channel is represented by the JONSWAP spectrum model with various sea states, whereas the undersea optical channel is attenuated by the absorption classified by the Jerlov water types.

The plane of observation in the beacon and the undersea receiver are both assumed to be 10 m × 10 m as shown in Fig. 1. The performance is evaluated with respect to the two distances, d_m and d_u, using the simulation parameters shown in Table 2. Figure 2 shows the received power in the beacon according to the distance, d_m, under the JONSWAP model of sea state 4. It reveals a gradual decrease in the received power as the distance increases.

On the other hand, the received power in the undersea receiver, also shown in Fig. 2, was under the conditions of the JONSWAP model of sea state 4 and Jerlov water type I. For the transmission of the green LEDs with a λ of 545 nm, the received power was measured according to different values of d_m, while d_u is fixed to 25 m. It should be noted that the green LEDs in the beacon are employed, because they have lower attenuation in the undersea communication, compared with other colour LEDs [2]. It is found that the received power in the beacon is 21.94 dBm at a d_m value of 1 km, whereas the received power in the undersea receiver at a water depth of 25 m is −12.5 dBm. The path losses

Table 2 Simulation parameters

Parameters	Values
Lighthouse transmitted power	300 W (54.77 dBm)
Number of LEDs (lighthouse and beacon)	10
Beacon transmitted power	100 W (50 dBm)
Receiver aperture area *Ar* (beacon and undersea receivers)	3 cm × 3 cm
Field of view ψ (beacon and undersea receivers)	50°
The lighthouse height	30 m
Transmitter efficiency η_T	0.9
Receiver efficiency η_R	0.9
Lens refractive index	1.5
Data rate	1 Mbps
LED half power angle ϕ (lighthouse and beacon)	60°
The gain of an optical filter $T_S(\psi)$	1
Plane of observation dimension	10 m × 10 m
Wavelength λ	545 nm
Pure water absorption coefficient $\alpha_w(\lambda)$	0.0511/m
Pure water absorption chlorophyll acid coefficient $\alpha_w(\lambda)$	0.384/m

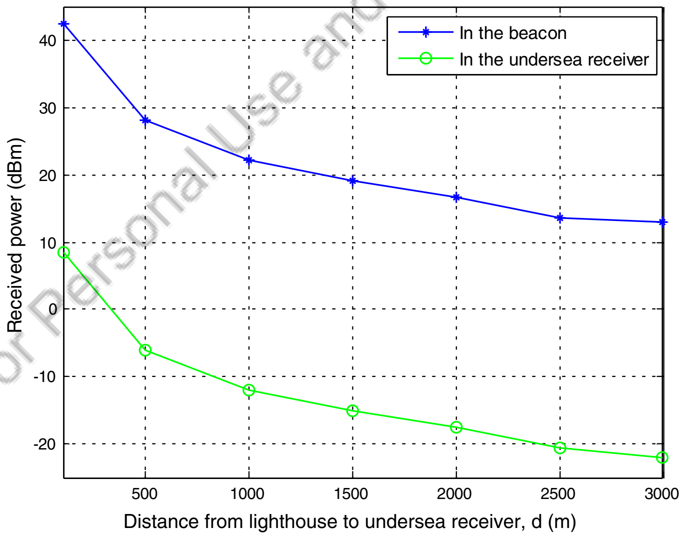

Fig. 2 Received power both in the beacon and in the undersea receiver

experienced in the maritime and undersea optical channels are 32.83 and 62.5 dB, respectively. That is, the path loss of the undersea propagation is more significant than the maritime propagation by a factor of nearly 2. In addition, it can be said that the transmitted signal undergoes a power loss of approximately 96 dB for the whole S2US path of 1.025 km long.

Figure 3 shows the BER performance of the whole S2US with various Jerlov water types under the JONSWAP spectrum model with sea state 4. It can be seen that the concentration of chlorophyll in the Jerlov water types degrades the performance significantly. With Jerlov water type I, however, a BER performance of 10^{-4} is achievable at a transmission distance of 1.025 km (1 km + 25 m). Other performance measurements were conducted with various sea states over the whole transmission path. Figure 4 exhibits the BER performance under the JONSWAP spectrum model. It is interesting to note that the performance is not significantly affected by the sea states of up to 6. Figure 5 shows performance evaluation in terms of data rate. In this evaluation, it is apparent that the proposed S2US can transmit the data at a data rate of 1 Gbps over a relatively short distance of approximately 900 m. Over a larger distance, the data rate needs to be lowered for an acceptable performance. In the proposed VLC based S2US, the transmission distance could readily be extended further with higher LED power and a larger number of LEDs. Therefore, it can be viewed that the results demonstrate the potential of the proposed S2US for a high-speed reliable maritime wireless communication based on the VLC technology.

4 Experimental Results

The proposed S2US was further put to the test for practical viability. To this end, we established an experimental setup on a laboratory scale. It was aimed at conducting measurements in terms of the received voltage (or power).

Figure 6 shows the block diagram of the experimental setup, while Fig. 7 depicts the actual experimental setup. The experiments were conducted first by generating the square

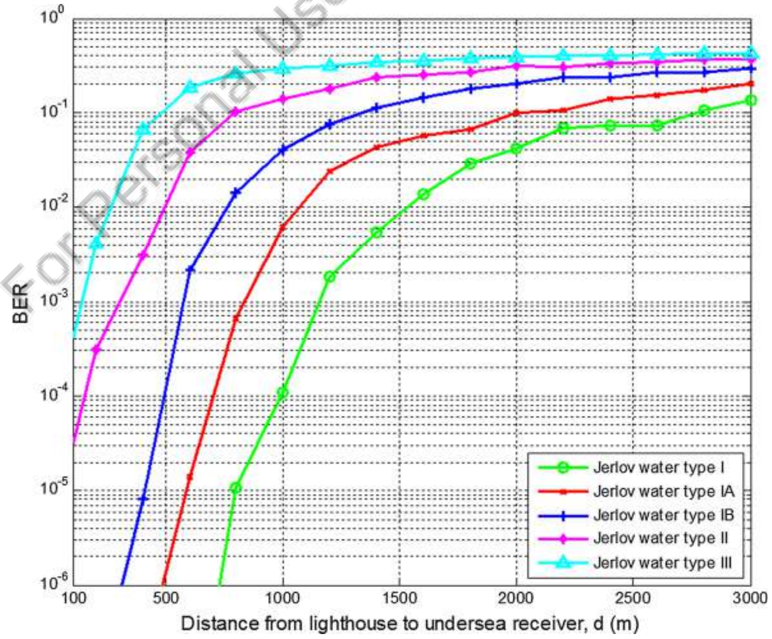

Fig. 3 Performance analysis relevant to Jerlov water type

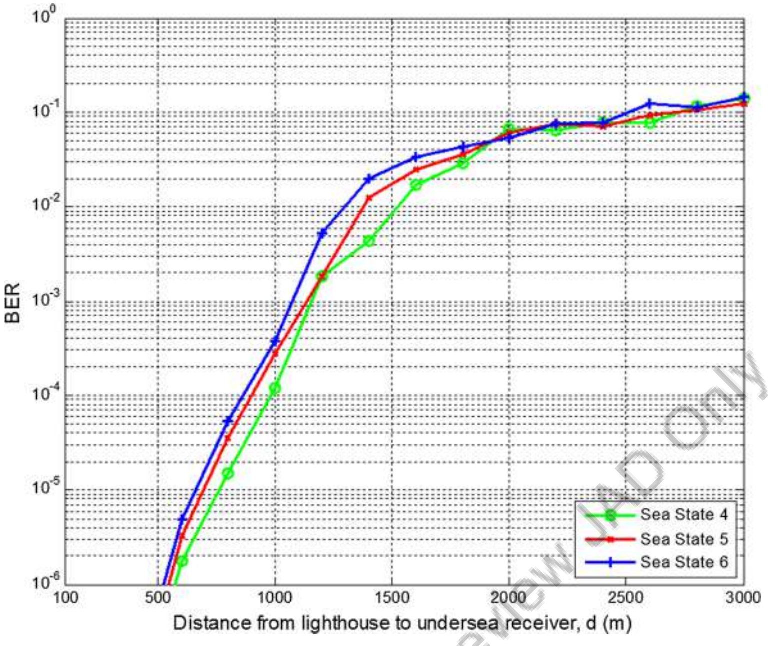

Fig. 4 Performance analysis relevant to sea state

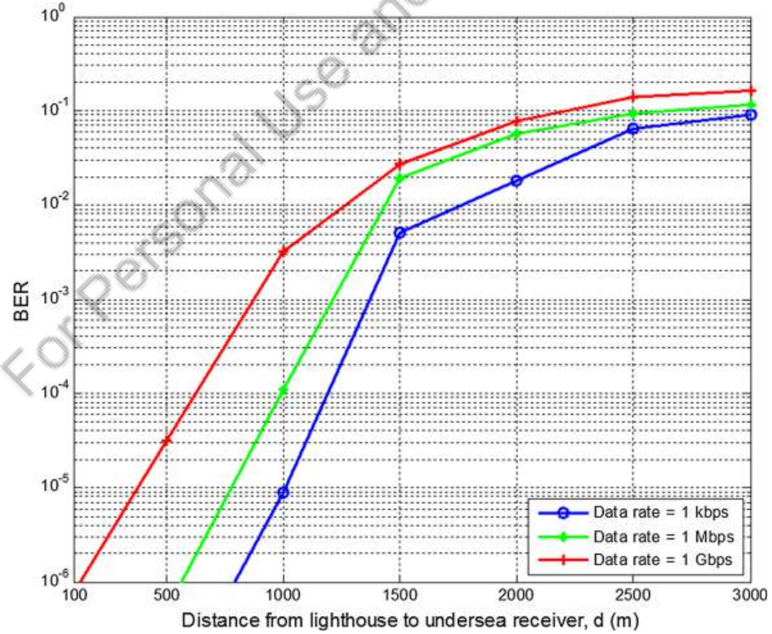

Fig. 5 Performance analysis relevant to data rate

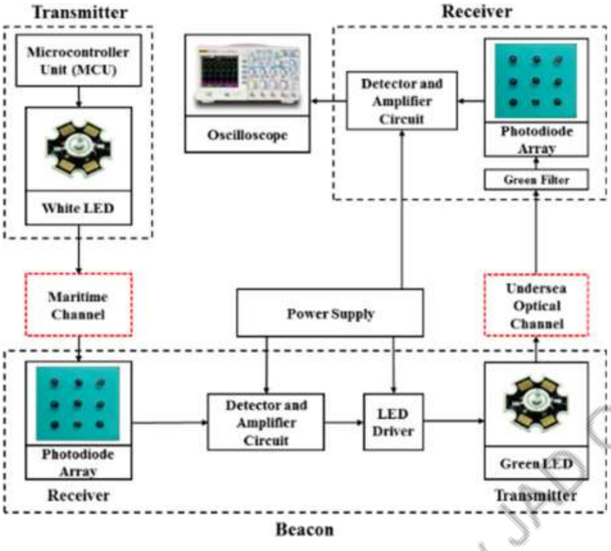

Fig. 6 Block diagram of experimental setup

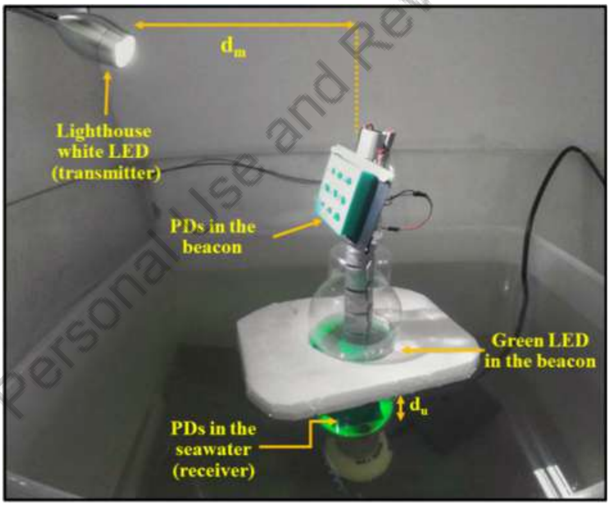

Fig. 7 Experimental setup

signal from the microcontroller unit (MCU) of ATMEGA328 at a frequency of 10 kHz and a voltage of 5 V. Then, the signal was transmitted by a 3 W white LED PHOTRON with an LED lens KBH1260PXP used as the lighthouse.

In the experiment, the maritime optical channel was represented by seawater wave movement; thus, a wave height of approximately 1.2 cm was purposely generated. For the beacon to receive the signal, we used a 3 × 3 PD array of OSRAM PIN PD SFH 213. The aperture area of this array was ensured to be equal to the one used in the simulation.

The received signal was passed to perform the AF processing with a gain of 1.6, prior to feeding to the LED driver. The detect-and-amplify circuit and the LED driver were designed for the relay, while the power was fed by the PROTEK 3033T dual power supply. In a 50 cm × 35 cm × 30 cm water tank, the coastal seawater was filled up to a height of 25 cm. For the undersea transmission, a 1 Watt PHOTRON green LED was utilized to relay from the seawater surface to the undersea receiver in the seawater tank. The undersea receiver was comprised of the 3 × 3 OSRAM PIN photodiode (PD) SFH 213 arrays in a waterproof case. The received signal at the undersea receiver was first passed into a green colour filter to mitigate ambient light interference. Finally, the received signal was detected and amplified using the detect-and-amplify circuit with a gain of 1.6 for voltage measurements at the Rigol DS12048 oscilloscope. In the measurement campaign, we recorded the received signal at different distances of d_{m} from 10 to 70 cm, while d_{u} was fixed to 25 cm, for the convenience of the measurements.

To verify the potential of the proposed S2US through comparative analysis, simulations were also conducted. It is important to note that although the simulation results were presented in the previous section, we performed separate simulations with another set of simulation parameters that must be compatible with those used in the experiments for a fair comparison. First, amplify-and-forward (AF) method was employed in the simulation, instead of the DF method described previously, because the experiment was conducted with the AF for proper measurement of the signal level. It is also necessary to determine the maritime and undersea channel parameters. For the undersea channel, the coastal seawater used in the water tank was examined in terms of attenuation and was found to be approximately Jerlov water type I. In addition, since the experiment employed a wave height of 1.2 cm on the sea surface, it is required to obtain corresponding wind speed from this wave height in order to use the JONSWAP model (Eq. 1). For the estimation of the wind speed, we utilized an approximate relationship between these two parameters, because there is no exact relationship available. The wind speed, U, is thus approximated by [16]

$$\boldsymbol{U} \approx \sqrt{\frac{g}{h}} \tag{12}$$

where h is wave height and g is gravity acceleration.

The rest of the simulation parameters for the comparative analysis are shown in Table 3. Figure 8 exhibits the comparative analysis between the simulation and the experiment results. As anticipated, the received voltage decreases as the total transmission distance (d) increases. It is observed, however, that the simulation and experimental results are in good agreement, thus validating the potential of the proposed S2US.

5 Conclusion

As an alternative to conventional maritime and shore-to-undersea communications, a novel visible light based shore-to-undersea communication has been proposed. The proposed system is comprised of lighthouse (transmitter), buoy (beacon) and undersea receiver. It was analyzed under the JONSWAP spectrum model for the maritime linkage and the Jerlov water types for the undersea linkage. It is found that the transmitted signal undergoes a severe power loss of approximately 96 dB for the whole S2US transmission path of 1.025 km long. Yet, a bit error rate (BER) performance of 10^{-4} is achievable at a data rate of 1 Mbps over that transmission path. For shorter distances, a higher data rate of 1 Gbps is found to be achievable. In addition to the simulation based performance analysis, an

Table 3 Experimental parameters

Parameters	Values
Lighthouse transmitted power	3 W
Number of LEDs (lighthouse and beacon)	1
Beacon transmitted power	1 W
Receiver aperture area A_r (beacon and undersea receivers)	3 mm × 3 mm
Field of view ψ (beacon and undersea receivers)	50°
The lighthouse height	30 cm
Distance of underwater link d_u (beacon and undersea receiver)	25 cm (± 1.2 cm)
Transmitter efficiency η_T	0.9
Receiver efficiency η_R	0.9
Lens refractive index	1.5
Data rate	20 Kbps
LED half power angle ϕ (lighthouse and beacon)	60°
The gain of an optical filter $T_s(\psi)$	1
Plane of observation dimension	10 cm × 10 cm
Wavelength λ	545 nm
Gain of amplifier (beacon and undersea receiver)	1.6
Pure water absorption coefficient $\alpha_w(\lambda)$	0.0511/m
Pure water absorption chlorophyll acid coefficient $\alpha_w(\lambda)$	0.384/m

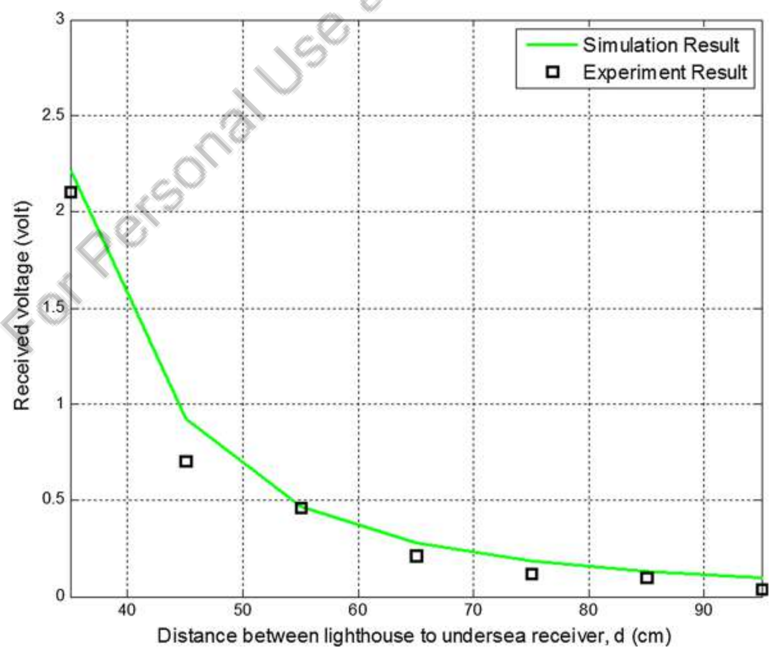

Fig. 8 Simulation and experimental results

experiment setup was established for verifying the proposed S2US. It is observed that the two results are in good agreement in terms of the received signal level, thereby proving its effectiveness of the S2US. The proposed system can be envisioned as a potential candidate for visible light based shore-to-undersea wireless communications for growing underwater applications.

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