



OCDMA transmission-based underwater wireless optical communication system: performance analysis

Somia A. Abd El-Mottaleb¹ · Mehtab Singh² · Ahmad Atieh³ · Moustafa H. Aly⁴

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Abstract

This paper introduces a novel underwater (UW) optical communication system that utilizes optical code division multiple access transmission technique using the permutation vector code. Three scenarios of water are considered, pure sea (PS), clear ocean (CL), and coastal ocean (CO). The performance is evaluated analytically in terms of bit error rate (BER), received power, signal to noise ratio for different UW links and data rates. The results show that the shortest UW range is achieved in the case of CO, achieving the highest extinction ratio compared to CL and PS. Considering a BER below the forward error correction (FEC) limit of 3×10^{-3} , the maximum UW ranges reached are 21 m for PS, 12 m for CL, and 8 m for CO at 3 Gbps with 20 dBm transmitted power. The propagation range could be increased when the transmitted power is increased to 25 dBm, achieving the ranges of 31 m, 18 m, and 9 m, for PS, CL, and CO, respectively.

Keywords Underwater optical communications (UWOC) · Optical code division multiple access (OCDMA) · Permutation vector (PV) code · Bit error rate (BER) · Signal to noise ratio (SNR)

Moustafa H. Aly: OSA member.

✉ Moustafa H. Aly
mosaly@aast.edu

Somia A. Abd El-Mottaleb
somya8839@gmail.com

Mehtab Singh
mehtab91singh@gmail.com

Ahmad Atieh
ahmad.atieh@optiwave.com

¹ Alexandria Higher Institute of Engineering and Technology, Alexandria, Egypt

² Department of Electronics and Communication Engineering, University Institute of Engineering, Chandigarh University, Mohali, Punjab, India

³ Optiwave Systems Inc, Ottawa, Canada

⁴ Arab Academy for Science, Technology and Maritime Transport, Alexandria 1029, Egypt

1 Introduction

Enabling UW wireless communications is getting more attention in the research community due to the huge interest in the marine environment. Wireless UW communication can be used in many applications including exploration of oils, monitoring pollution in sea and ocean, surveillance, studying of oceanic animals, and oceanographic research (Saeed et al. 2019; Zeng et al. 2017; Schirripa Spagnolo et al. 2020). These applications require high-speed information transmission and large bandwidth (Ghassemlooy and Popoola 2010). Acoustic communication is the most popular technology that has been used for UW communication. However, it has many drawbacks such as signal degradation due to Doppler spread, high latency, low data rates, and low bandwidth (Zeng et al. 2017; Hanson and Radic 2008; Akyildiz et al. 2005). Although, radio frequency (RF) can provide high-speed and large bandwidth transmission, it cannot be used in UW environment as it exhibits high attenuation in water which limits the transmission range (Lacovara 2008; Lanzagorta 2012). However, using optical communication for UW, also referred as UWOC, provides an effective technological solution to the above-mentioned limitations. UWOC is license free spectrum and supports high data rates, large bandwidth, and high security, with low latency (Kaushal and Kaddoum 2016). Thus, UWOC links can be used in many applications in submarine communication as shown in Fig. 1 (Zeng et al. 2017).

The optical signal attenuation in the blue-green range spectrum is significantly low (Kaushal and Kaddoum 2016; Tian et al. 2017; Liu et al. 2017). Recently, light-emitting diodes (LEDs) or laser diodes (LDs) have been developed having an emission wavelength in the range of 450–550 nm with high modulation bandwidth and high quantum efficiency, which can be used in high speed UWOC and free space communications (Chi et al. 2015; Tsonev et al. 2014).

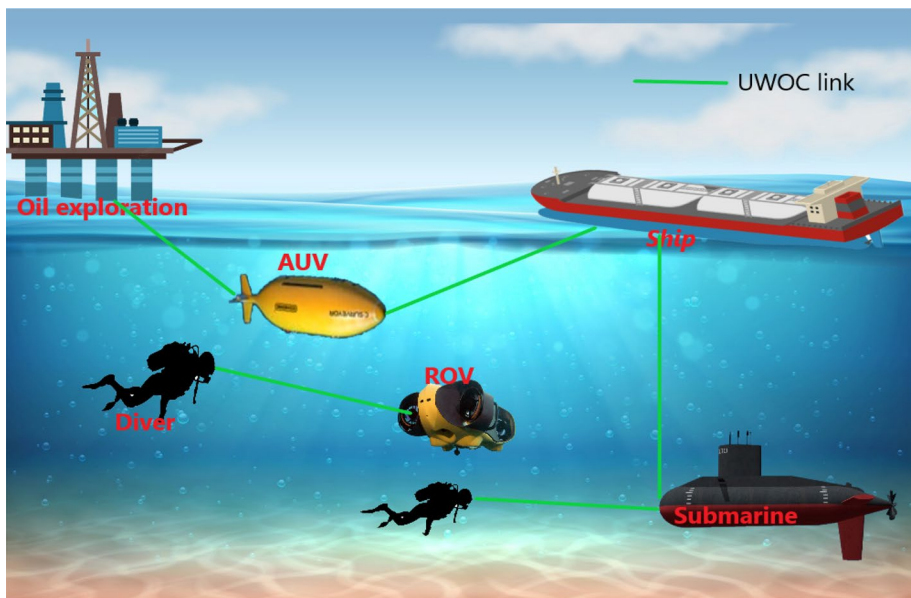


Fig. 1 Applications of UWOC systems

Despite the many advantages that UWOC systems provide, the high signal attenuation (caused by the absorption and scattering phenomenon related to the inherent optical characteristics of water) leads to degradation in the transmission ranges in the UWOC channel (Doniec and Rus 2010; Kulhandjian 2014; Lloret et al. 2012).

The OCDMA technique has gained significant attention since it offers secure information transmission. It allows transmitting many channels carrying different information while sharing the same spectrum as every channel is assigned with unique code having bits either “1” when light is present or “0” when there is no light (Aljunid et al. 2004; Stok and Sargent 2003; Abd El-Mottaleb et al. 2018). Spectral Amplitude Coding (SAC) is preferred to be used in OCDMA systems to eliminate the Multiple Access Interference (MAI) that exists in Optical Orthogonal Code (OOC) that is used in OCDMA (Abd El-Mottaleb et al. 2018). The codes used in SAC-OCDMA are of two types; the first type is characterized by having a cross-correlation greater than or equal to one and the other type is characterized by zero cross-correlation (Aljunid et al. 2004; Singh et al. 2022a, b). In this paper, we use a PV code which has zero cross-correlation and code a weight greater than one as this code can be easily detected at the receiver through using the direct detection technique and a shorter code length as compared to OOC.

Several studies have been carried out to investigate the performance of data transmission in the UWOC systems. The theoretical and simulation work in (Singh et al. 2022a, b) shows a reliable data transmission at 200 m with data rates of hundreds Gbps when using coherent detection with advance signal processing of dual polarization (DP)-16 quadrature amplitude modulation (QAM) modulated signal. The authors in (Chen et al. 2017) experimentally demonstrated that the maximum distance that can be achieved is limited to 21 m based on LDs with data rate of several Gbps. In (Hanson and Radic 2008), a UW distance of 2 m is achieved by employing LDs with data rate of 1 Gbps. A discrete pulse modulation (DPM) scheme is experimentally used in a bidirectional UWOC link in (Doniec and Rus 2010), showing a maximum transmission UW range of 50 m by employing LED at 470 nm. A 520 nm LD source operating modulated with 2.3 Gbps data using non-return to zero (NRZ) format is used in an UWOC system in (Oubei et al. 2015). In (Shen et al. 2016), an LD operating at 450 nm with 51.3 mW power is used with NRZ on-off keying (OOK) modulation to transmit a 1.5 Gbps over a distance of 20 m. The authors in (Ali and Rahi 2018) proposed an UWOC system based on using an LED source. Different modulation schemes are used like NRZ OOK and M-pulse position modulation (PPM). At a transmitted power of 100 mW, the proposed system achieved 31 m when PS is used and 14 m when CS is used. An UWOC system was proposed by authors in (Al Hammadi et al. 2020) based on using OCDMA system using optical orthogonal codes (OOC). Although results show that the system can reach UW distance of 27.9 m for PS, 17.1 m for CO, and 11.15 m for CS, its implementation was complex and costly as these codes have large code lengths. As for five users, the code length required was 409. In (Hameed et al. 2023), authors proposed an UWOC system based on using filtered orthogonal frequency division multiplexing (OFDM). At a transmitted power of 30 dBm and data rate of 1 Gbps, the suggested system reached 12 m for Harbor water.

In this work, we propose a novel UWOC transmission system employing the OCDMA technique based on using PV code, for the first time to the best of our knowledge. An LD operating at 532 nm is used to transmit three channels assigned with a PV code in OCDMA scheme with each channel transporting 1 Gbps data. Three types of water environment are considered, including PS, CL, and CO. The performance of the system is evaluated in terms of path loss, UW range, BER, received power, data rate, and SNR.

Fig. 2 Inherit optical property of water

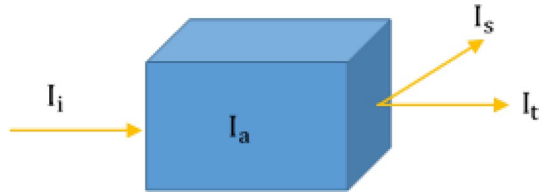


Table 1 Absorption, scattering, and extinction coefficients for different types of water (Mobely 1994; Haltrin 1999)

Types of water	$a(\lambda)$ (m^{-1})	$b(\lambda)$ (m^{-1})	$c(\lambda)$ (m^{-1})
PS	0.0405	0.0025	0.043
CL	0.114	0.037	0.151
CO	0.179	0.219	0.398

The rest of the paper is organized as follows. Section 3 describes the UWOC channel model. The explanation of the proposed UWOC-OCDMA model with a mathematical analysis is given in Sect. 4, followed by the results and discussion in Sect. 5. Finally, Sect. 6 is devoted to the main conclusion of this study.

2 UWOC channel

The UWOC channel is highly vulnerable to the adverse effects of both scattering, $a(\lambda)$, and absorption, $b(\lambda)$, which cause degradation to the optical information signal during its propagation through the channel, where λ is the operating wavelength. The values of $a(\lambda)$ and $b(\lambda)$ depend on the optical properties of the water. Figure 2 shows how the incident light is absorbed and scattered in a small volume of water (Δv). When light of power I_i is incident to water, a small amount of its power is absorbed by water denoted by I_a , and another fraction of its power is scattered denoted by I_s while the remaining power that denoted by I_t will be passed through the water without getting affected.

The extinction coefficient, $c(\lambda)$, in m^{-1} , is determined by adding both $a(\lambda)$ and $b(\lambda)$ as (Boluda-Ruiz et al. 2020)

$$c(\lambda) = a(\lambda) + b(\lambda) \tag{1}$$

In this work, we consider three types of water, PS, CL, and CO. In PS, the total signal absorption is the sum of absorption by salts and absorption of suspended particulate matter. The absorption in CL is higher than PS as CL has higher concentration of dissolved particles such as mineral components, dissolved salts, and colored dissolved organic. In CO, the concentration of the dissolved particles is the highest, so, the absorption is higher than both of PS and CL. Table 1 shows the values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ at $\lambda=532$ nm for the different water types (Mobely 1994; Haltrin 1999).

The propagation loss, P_L , in dB/km that the propagated signal experience under water is expressed as Chen et al. (2017)

$$P_L(\lambda, d) = e^{-c(\lambda)d} \tag{2}$$

3 Proposed UWOC-OCDMA model

In this section, the proposed UWOC-OCDMA transmission system is mathematically described and analyzed. Figure 3 illustrates the schematic diagram of the proposed UWOC-OCDMA system. It consists of a transmitter block, the UWOC channel, and a receiver block. At the transmitter, an LD source is used to generate optical signals according to the PV code used in OCDMA. The information data is generated using a pseudo random bit sequence generator (PRBSG), encoded using NRZ and used to modulate the LD using a Mach-Zehnder modulator (MZM). The optically modulated signal is then transmitted through the UWOC channel.

The relation between the received power, P_r , and the transmitted power, P_t , in a line-of-sight (LoS) UWOC link is given as (Saeed et al. 2019; Arnon 2010):

$$P_r = P_t \cdot \eta_t \cdot \eta_r \cdot G \cdot P_L \left(\lambda, \frac{z}{\cos\theta} \right) \frac{A_r \cos\theta}{2\pi z^2 (\cos\theta)} \tag{3}$$

where η_t , η_r , G , z , θ , A_r , and θ_z , respectively, are transmitter optical efficiency, receiver optical efficiency, beam concentrator gain, perpendicular distance between transmitter and receiver plane, angle between perpendicular to the receiver plane, transmitter–receiver trajectory, area of receiver aperture, and beam divergence angle.

The received signal is passed to the decoder of the PV code-OCDMA at the receiver block to recover the original signal. Further, the decoded signal is passed to a PIN photodetector (PD) to convert the optical signal to electrical signal. The output signal from the PD is directed to a low pass filter (LPF) to reject the unwanted signal frequencies. A BER analyzer is used to characterize the signal quality. The electrical current at the PD output in the case of PV code, I_{PD} , is given by (Singh et al. 2022a, 2022b):

$$I_{PD} = \frac{\mathcal{R}P_r w}{L} \tag{4}$$

where \mathcal{R} is the responsivity of PD, w is the code weight of PV code, and L is the code length of the PV code.

The relation between the code length, L , the code weight, W , and the number of the channels, N , is (Singh et al. 2022a, 2022b)

$$L = W \times N \tag{5}$$

The code sequence of PV code consists of $N \times L$ matrix, which is given as

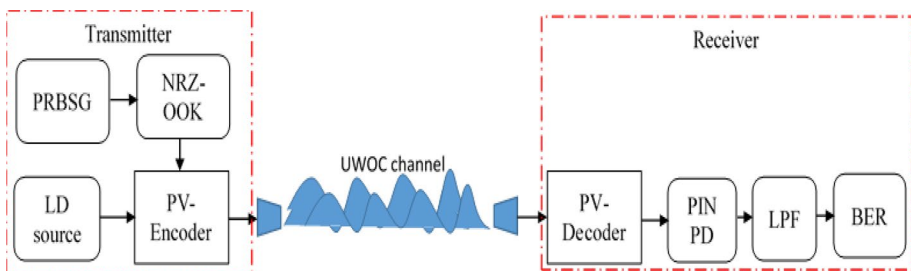


Fig. 3 Schematic diagram of proposed UWOC-OCDMA system

$$PV = (R^N|H)_{N \times L} \tag{6}$$

where R is the real number and R^N is the space of N tuples that form the one dimension vector ($1 \times N$) that having one integer of value “1”. H is a permutation vector that used to perform permutation to the columns of the matrix and it can be calculated as (Abd El-Mottaleb et al. 2023)

$$H = \frac{(WN)!}{(W!(L - W)!)} \tag{7}$$

As an example, take $N=3$, and $W = 2$, so, $L=2 \times 3=6$ and according to Eq. (7), $H=15$, so, there are 15 possibilities for the matrix of PV code, two of them can be written as

$$\begin{aligned} \text{FirstHpossibleofPVcode} &= (\mathfrak{R}^3|(1, 2, 3, 1, 2, 3)) = \begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{pmatrix} \\ \text{SecondHpossibleofPVcode} &= (\mathfrak{R}^3|(3, 2, 1, 3, 2, 1)) = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \end{aligned} \tag{8}$$

The signal to noise ratio, SNR, is (Moghaddasi et al. 2015)

$$SNR = \frac{(I_{PD})^2}{\sigma_{ST}^2 + \sigma_{Th}^2} \tag{9}$$

where σ_{ST} is the variance of the shot noise and σ_{Th} is the variance of thermal noise, respectively, given by (Moghaddasi et al. 2015; Anuar et al. 2013)

$$\sigma_{ST}^2 = 2eB_e(I_{PD} + I_D) \tag{10}$$

$$\sigma_{Th}^2 = \frac{4k_B T B_e}{R_{Ld}} \tag{11}$$

where e , B_e , and I_D are electron charge, electrical bandwidth, and dark current, respectively, k_B is Boltzmann constant, R_{Ld} is the receiver load resistance in Ω , and T is the absolute temperature of receiver noise in K.

Therefore, the SNR will be

$$SNR = \frac{(I_{PD})^2}{2eB_e(I_{PD} + I_D) + \frac{4k_B T B_e}{R_{Ld}}} \tag{12}$$

Finally, the BER in terms of SNR is given as Shen et al. (2016)

$$BER = \frac{1}{2} \text{erfc} \left(\frac{\sqrt{SNR}}{2\sqrt{2}} \right) \tag{13}$$

4 Results and discussion

The performance of the proposed UWOC-OCDMA system is discussed analytically using Matlab software in this section based on the parameters given in Table 2 (Kaushal and Kaddoum 2016; Liu et al. 2017; Singh et al. 2022a, b; Singh et al. 2022a, b). The performance of the system is studied in terms of maximum UW length achieved, received power, SNR, supported data rates, and BER.

All the calculations and the obtained results are considered for BER below the FEC limit which is 3×10^{-3} (Liu et al. 2017).

Figure 4 displays the path loss versus distance for the three different types of water considered in this work. As the link distance increases, the path loss increases. The PS exhibits the lowest path loss compared to CL and CO as expected because it has the lowest signal attenuation coefficient. As an example, the underwater distances are 50 m for PS, 15 m for CL, and 6 m for CO at a path loss value ~ -10 dB.

The BER performance of proposed UWOC-OCDMA model is depicted in Fig. 5 when three channels are used with each carries 3 Gbps. It is clear that the BER degrades as the distance between the transmitter and receiver increases. The CO achieves the smallest distance of 8 m, while the UW ranges are 21 m and 12 m, respectively, for PS and CL. These values are chosen for a forward error correction (FEC) BER limit of 3×10^{-3} and a transmitted power of 20 dBm.

The received power of the proposed UWOC-OCDMA system for different water type when 3 Gbps signal is launched with 20 dBm is shown in Fig. 6. The PS has the highest received power while CO has the lowest value as expected. The minimum received powers for PS at 21 m, CL at 12 m, and CO at 8 m, are -26.51 dBm, -28.25 dBm, and -28.04 dBm, respectively.

Figure 7 shows the SNR versus UW range for different water conditions. As the UW distance increases, the SNR decreases. The SNR is calculated as 16.54 dB for PS at 21 m, 18.36 dB for CL at 12 m, and 13.04 dB for CO at 8 m.

Table 3 summarizes the maximum ranges at acceptable FEC limit ($< 3 \times 10^{-3}$) with corresponding received powers and SNR for the different types of water.

Table 2 Simulation parameters (Kaushal and Kaddoum 2016; Liu et al. 2017; Singh et al. 2022a, 2022b; Singh et al. 2022a, 2022b)

Parameter	Value
Transmitted power (dBm)	15, 20, and 25
Data rate (Gbps)	1.5, 3, and 4
Number of channels assigned with PV code	3
PV code weight	2
PV code length	6
Transmitter optical efficiency	0.99
Receiver optical efficiency	0.99
Area of receiver aperture (mm ²)	1
Beam concentrator gain	2.1025
Beam divergence angle (mrad)	75
Responsivity of PD (A/W)	1
Electrical bandwidth (Hz)	$0.75 \times$ data rate Hz
Receiver noise temperature (K)	300
Receiver load resistance (Ω)	1030

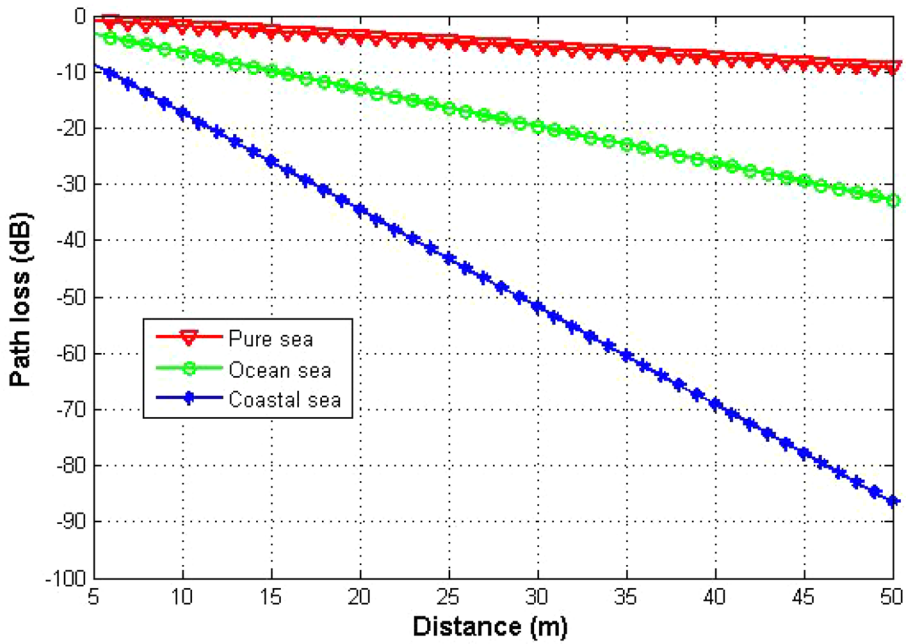


Fig. 4 Path loss versus distance for different types of water

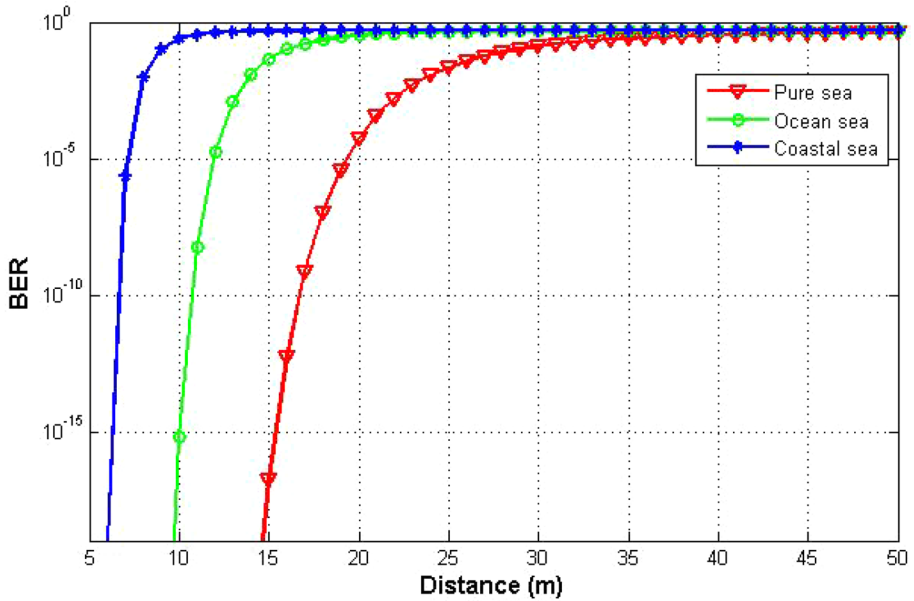


Fig. 5 BER versus UW ranges for proposed UWOC-OCDMA system in different types of water conditions when 3Gbps per channel is used

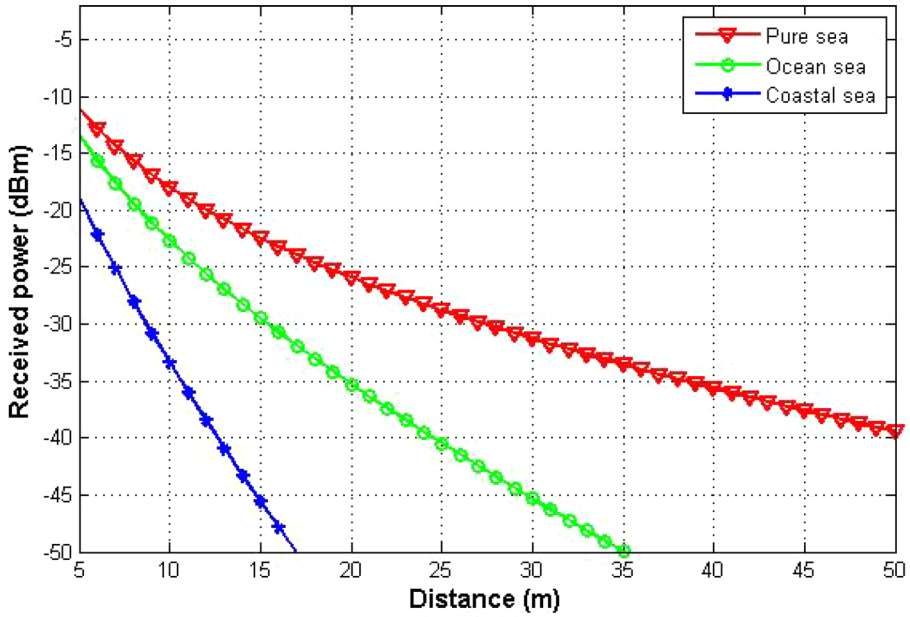


Fig. 6 Received power versus UW ranges for the proposed UWOC-OCDMA system in different types of water conditions

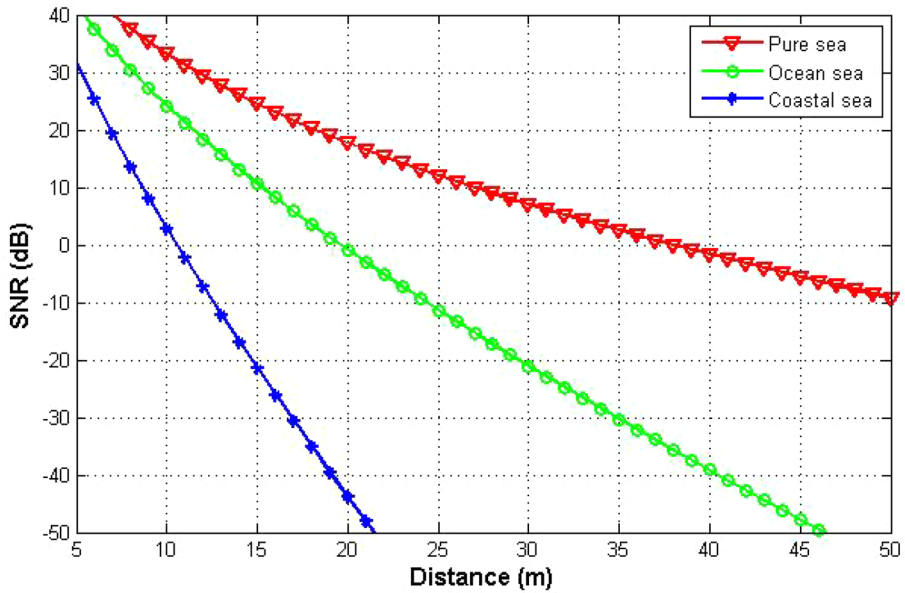


Fig. 7 SNR versus UW ranges for the proposed UWOC-OCDMA system in different types of water conditions

Table 3 Ranges, received power, SNR at BER~ 3×10^{-3}

Types of water	Range (m)	Received power (dB)	SNR (dB)
PS	21	-26.51	16.54
CL	12	-28.25	18.36
CO	8	-28.04	13.04

Additionally, the effect of the transmitted power on the performance of the proposed UWOC-OCDMA system is investigated and discussed in Figs. 8, 9, 10. Figure 8 displays this effect for the PS case. As transmitted power increases, the BER is enhanced, and the system can propagate longer distance, leading to an improved performance.

For CL environment, the BER versus UW distance for the UWOC-OCDMA system for transmitted power of 15 dBm, 20 dBm, and 25 dBm is shown in Fig. 9.

Figure 10 illustrates the BER versus UW distance for the UWOC-OCDMA system at different transmitted power: 15 dBm, 20 dBm, and 25 dBm in the case of CO environment.

Table 4 summarizes the values of maximum distance achieved for PS, CL, and CO at different transmitted power levels at BER $\sim 3 \times 10^{-3}$.

Finally, the effect of data rate on the performance of the proposed UWOC-OCDMA model is studied. Figure 11 shows the BER versus UW distance at different data rates of 1.5 Gbps, 3 Gbps, and 4.5 Gbps for 20 dBm transmitted power. It is observed, from Fig. 11, that as data rate becomes higher, the transmission range in UW channel decreases for all types of water.

Table 5 summarizes the maximum achievable UW distance at different data rates for PS, CL, and CS at BER $\sim 3 \times 10^{-3}$.

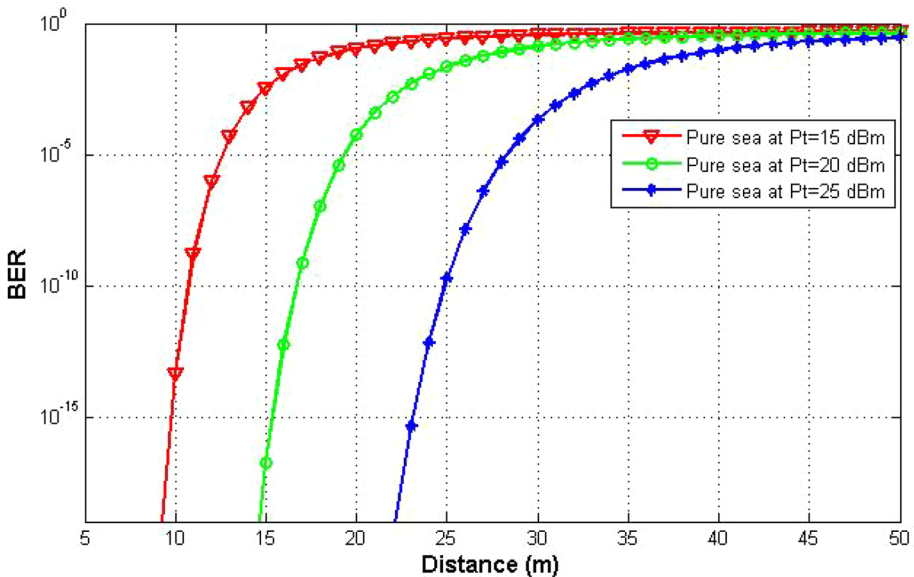


Fig. 8 BER versus UW ranges for the proposed UWOC-OCDMA system in PS at different transmitted power levels

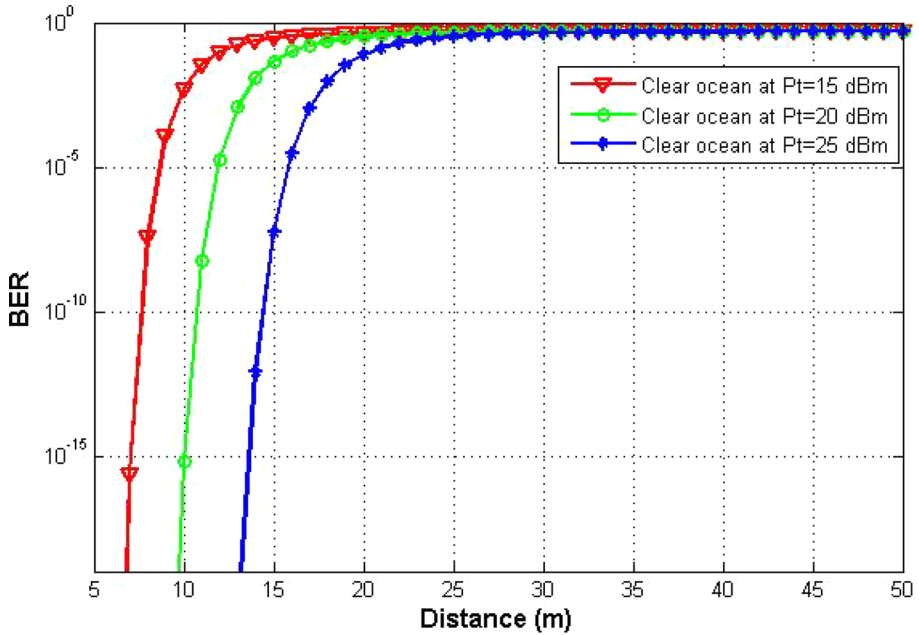


Fig. 9 BER versus UW ranges for the proposed UWOC-OCDMA system in the CL at different transmitted power levels

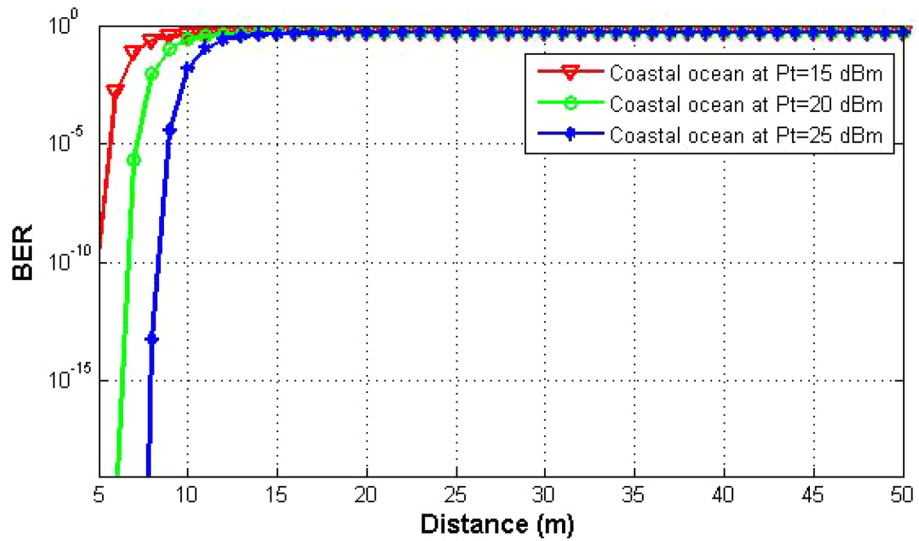


Fig. 10 BER versus UW ranges for the proposed UWOC-OCDMA system in the CO at different transmitted power levels

Table 4 Maximum UW distance achieved at $BER \sim 3 \times 10^{-3}$

Transmitted power (dBm)	UW range (m)		
	PS	CL	CO
15	15	10	5
20	20	12	8
25	31	18	9

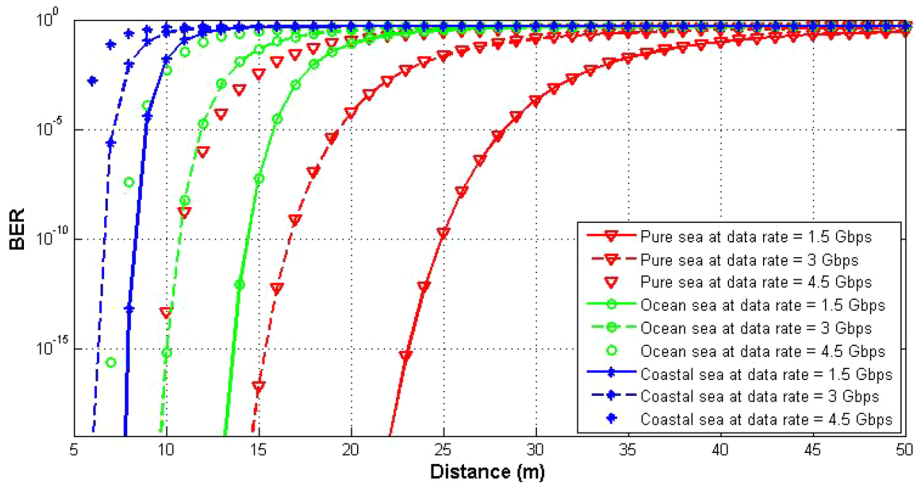


Fig. 11 BER versus UW ranges for the proposed UWOC-OCDMA system in different types of waters at different data rates

Table 5 Maximum UW ranges achieved at different data rates and $BER \sim 3 \times 10^{-3}$

Data rate	UW range (m)		
	PS	CL	CO
1.5 Gbps	31	16	9
3 Gbps	20	12	8
4.5 Gbps	15	10	5

Table 6 is a comparison between our present work and previous published work, showing a superiority for our proposed system in data rate.

5 Conclusion

An UWOC system employing OCDMA transmission of three channels using PV code is proposed, for the first time to the best of our knowledge. Three different water types: PS, CL, and CO are considered. An LD with an operating wavelength of 532 nm is used. The performance of the proposed UWOC-OCDMA model is evaluated analytically in terms of BER, received power, SNR, UW distance and different data rates. A bit rate of 3 Gbps, the maximum UW

Table 6 Comparison between present work and previous work

Work	Operating wavelength (nm)	Transmitted power (mW)	Modulation	UW range (m)	Data rate
Ref. (Liu et al. 2017)	520	100	NRZ-OOK	34.5	2.70 Gbps
Ref. (Shen et al. 2016)	450	51.3	NRZ-OOK	20	1.5 Gbps
Ref. (Hameed et al. 2023)	532	1000	OFDM	Harbor: 12	1 Gbps
Ref. (Singh et al. 2020)	532	NA	NA	PS: 30 CS: 13 Turbid: 3	500 Mbps
Ref. (Ali and Rahi 2018)	NA	100	NRZ-OOK	PS: 31 CS: 14	NA
Ref. (Al Hammadi et al. 2020)	532	500	OCDMA/OOC code	PS: 27.9 CL: 17.1 CO: 11.15	NA
Present work	520	100	OCDMA/PV code	PS: 21 CL: 12 CO: 8	3 Gbps
				PS: 15 CL: 10 CO: 5	4.5 Gbps

range achieved within FEC threshold (3×10^{-3}) is 21 m, 12 m, and 8 m for PS, CL, and CO, respectively. The CO has the highest extinction coefficient. Thus, it has the shortest UW range with SNR of 13.04 dB. Additionally, the effects of transmitted power levels and data rate on the performance of our proposed UWOC model is also investigated. It is observed that lower data rates support longer UW distances. At 1.5 Gbps, the maximum achievable UW links is 31 m, 16 m, and 9 m, respectively, for PS, CL, and CO. The achievable UW distance is 15 m for PS, 10 m for CL, and 5 m for CO at 4.5 Gbps. Consequently, we suggest our model to be used in submarine communication applications that include exploration of oils, monitoring pollution in sea and ocean.

Authors contributions S.A.A., A.M., M.S., A.A., M.H.A. have directly participated in the planning, execution, and analysis of this study. S.A.A. drafted the manuscript. All authors have read and approved the final version of the manuscript.

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Availability of data and materials The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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