Study of Underwater Wireless Optical Communication Link Performance for Different Water Channels

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Abstract A study on the performance of underwater wireless optical communication (UWOC) system has been carried out for different water channels. Here, a mathematical expression for received optical power as a function of channel attenuation coefficient and beam propagation distance between transmitter and receiver has been proposed. The proposed expression is then incorporated for estimating the performance of the proposed system with reference to acceptable quality factor (Q factor) ($\geq$6) and bit error rate (BER) ($\leq 10^{-9}$) for varying link length and data rate through Optisystem. The performance of the proposed system is also evaluated from the eye diagram of the received signal.

Keywords Underwater wireless optical communication (UWOC) · Absorption coefficient · Scattering coefficient · Turbulence · Quality factor (Q factor) · Bit-error rate (BER)

1 Introduction

High data rate underwater wireless link is inherently needed due to recent naval applications arising from the continuous rise in the marine economy. Traditional UWOC technique mainly uses acoustic signal, radio frequency signal and optical signal for underwater wireless information transfer [1]. Acoustic signal based underwater wireless data transfer technique provides long range communication (in order of several kilometers). But data rate and propagation speed is very low in case of acoustic based communication technique. Moreover, transceiver used in this technique is bulky, expensive and energy intensive. Whereas RF based communication technique provides high data rate and high propagation speed as compared to acoustic based technique. But, RF signal is highly attenuated in marine water and hence limited to very low range communication [1, 2].

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Underwater wireless optical communication (UWOC) is a propitious technology which provides energy—efficient high data rate with low negative effects on the environment as compared to conventional underwater wireless communication techniques [3–6], whereas the reliability of UWOC system is highly affected by absorption and scattering as well as turbulence [7–10]. Attenuation due to absorption and scattering is estimated with respect to the absorption coefficient (a(λ)) as well as scattering coefficient (b(λ)) that depends on the wavelength of optical signal used. Overall attenuation due to absorption and scattering is the linear combination of a(λ) and b(λ), given as [1, 4]

$$C(\lambda) = a(\lambda) + b(\lambda). \quad (1)$$

Laser beam with blue and green wavelengths (450 and 550 nm) are the attenuation window for marine water [11]. Turbulence is caused due to change in salinity levels, alterations in temperature, air bubbles inside the underwater channel [12, 13]. To achieve robust, reliable and long range underwater wireless communication, a lot of analysis has been carried out but most of the analysis is theoretical. To characterize the underwater turbulent channel, an equation based on stochastic model has been presented in [14]. To study the propagation properties of optical signal in underwater environment, a weighted Gamma function based channel modeling is presented in [15]. Channel modeling based on lognormal function is used to investigate the performance of turbulent underwater channel in [9, 10]. Fluctuation in salinity is a major cause of turbulence inside water channel. Performance of UWOC at different salinity has been analyzed in [16]. In this paper performance analysis of UWOC is carried out experimentally as well as simulating the UWOC system for different channel conditions.

2 System Model of UWOC Link

A UWOC test-bed link is set in the laboratory environment for the analysis of the link performance in various channel conditions. Figure 1 shows the system model of UWOC link and Fig. 2 depicts experimental setup established. A monochromatic optical beam of 450 nm and transmission power of 3 mW is deployed in water present in a glass chamber of dimension: 180 cm (length), 45 cm (breadth), and 60 cm (height). A message signal, obtained from a waveform generator at transmitter (Tx), is used to modulate the laser beam using intensity modulation technique with the help of modulator and driving circuit. Semiconductor photodetector at the receiver (Rx) is connected with an optical power meter is used to receive the transmitted signal. Specification of components used in the experimental setup is listed in Table 1.

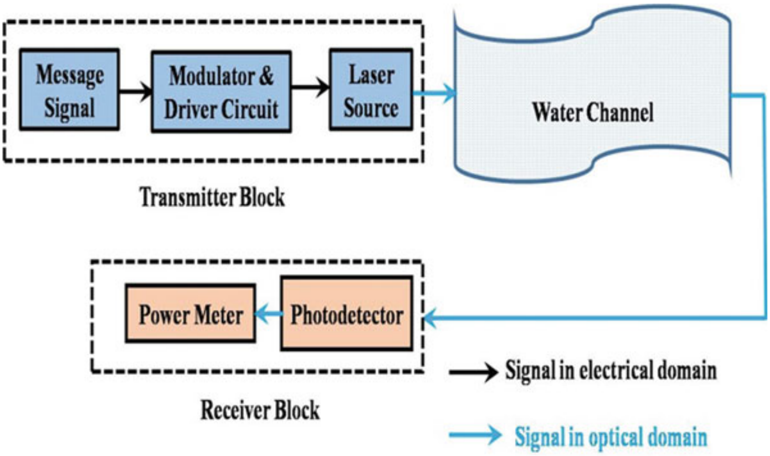

Fig. 1 System model of the proposed UWOC system

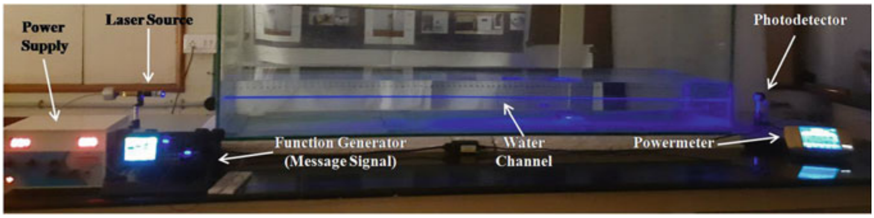

Fig. 2 Experimental setup of the proposed UWOC system

Table 1 Specifications of components used in experimental setup

Components	Parameters	Values
Laser source	Wavelength	450 nm
	Transmitted power	3 mW
Photodetector	Detection range	420 to 1080 nm
	Measurable power	6 nW to 300 mW
Powermeter	Power range	4 pW to 30 kW
UWOC channel	Glass chamber dimension	180 × 45 × 60 cm

3 Mathematical Channel Modeling

Power is received at different link length for different channels; tap water channel (TWC) as well as saline water channel (SWC) with salt concentration of 35 gm/L. The variations in received optical power with link length are illustrated in Fig. 3. Figure 3 illustrates that received power is decreased with link length for both channel

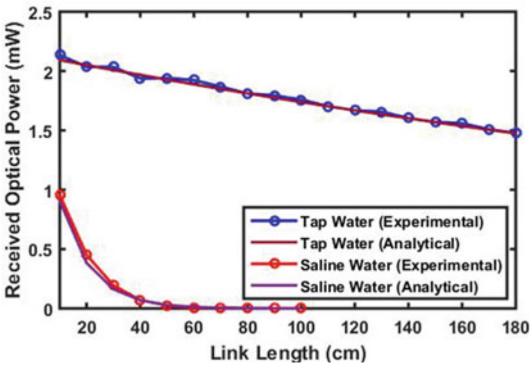

Fig. 3 Experimental and analytical fitting of optical power at receiver with link length for different channel conditions

conditions. The received power is considerably reduced in saline water based UWOC link. Optical absorption and scattering are the major reasons of decrement in received optical power. The fitting of the resultant data from the experiment with standard mathematical expression governing Beer–Lambert law [17–19], as provided in (2), is then performed.

$$\mathrm{P_r} = \mathrm{P_0} * \exp\left(-\alpha * \mathrm{x}\right), \tag{2}$$

where $\mathrm{P_r}$ represents the optical power obtained at Rx for a link length of x, $\mathrm{P_0}$ is the emitted laser power from the waterproof encasing and α is the overall attenuation coefficient, as provided in (1).

After fitting the Beer-Lambert's law, given by (2), the attenuation coefficient 'α' has been obtained. Figure 3 clearly illustrates similar values for experimental and analytical values with reference to TWC and SWC. The resultant value of α for TWC is 0.1561 m^{-1} with root mean square error (RMSE) of 0.0109. Similarly, the resultant value of α for SWC is 8.037 m^{-1} with RMSE of 0.0471. As such, (1) is the best fit, which approximately models the distribution of the data obtained through experiment with higher goodness of fit.

Apart from the optical fading due to absorption and scattering effects in the UWOC channel, the beam divergence also results to degradation in link performance. The amount of beam divergence depends on the type of UWOC link length. For smaller link lengths, it is not significant. Equation (2) is consistent for small UWOC link length, while, the negative effects of the beam divergence on link performance are higher for longer UWOC link length. Thus, (2) needs to be modified for longer UWOC link length. The amount of the optical power obtained at the Rx due to divergent beam for a link length of x is given as [17]

$$\mathrm{P_r} = \mathrm{P_0}\left(\frac{d_r}{d_t + \theta_s x}\right)^2, \tag{3}$$

where P_0 is the emitted beam power, d_t and d_r are the diameters of Tx and Rx aperture, θ_s represent beam divergence angle. By considering Eqs. (2) and (3), the analytical expression for long range UWOC communication is expressed as,

$$P_r = P_0\left(\frac{d_r}{d_t + \theta_s x}\right)^2 \exp(-\alpha * x). \quad (4)$$

4 Simulation of UWOC System

For estimating the performance of underwater wireless optical communication link with various link length, data rate and transmitted power with respect to acceptable Q factor and bit error rate, an UWOC link is simulated in optisystem. Figure 4 presents the block diagram of the simulated UWOC system.

UWOC system consists of a continuous wave laser as an optical source. The wavelength of laser source is 450 nm. According to centre for Devices and Radiological Health regulation 21 CFR and ANSI Z136.1, lasers used for underwater applications should be Class IIIa or IIIb. The range of power output of Class IIIa and IIIb are 1 mW to 5 mW and 5 mW to 500 mW respectively. At higher power levels, IIIb laser is considered as definite eye hazard. Therefore, considering safety of marine life, maximum transmitted laser power is kept at 200 mW [20]. Electrical signal is generated by electrical signal generator in accordance with pseudo random bit sequence generated by PRBS generator. Electrical signal is modulated by continuous wave laser source using amplitude modulator. A matlab component representing water channel is designed using Eq. (4). Modulated signal is fed to water channel. Transmitted signal is then received with the help of photodetector and the signal is analyzed by eye diagram analyzer. Parameters which are used in simulation are listed in Table 2.

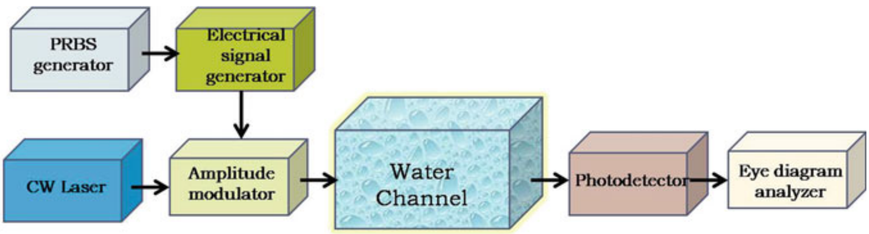

Fig. 4 Block diagram of simulated UWOC system

Table 2 Simulation parameters

Parameters	Values
Laser wavelength	450 nm
Transmitted laser power	30, 200 mW
Transmitted data rate	10, 100 Mbps, 1 Gbps
Photodetector responsivity	0.45 A/W

5 Results and Discussion

The modulation index of amplitude modulator of the proposed UWOC system is considered as unity. Similarly, the responsivity of the photo-detector is considered as 0.45 A/W. Maximum achievable link length for acceptable bit error rate ($\leq 10^{-9}$) and Q factor (≥ 6) at different data rate for 30 and 200 mW of input laser power for TWC and SWC are tabulated in Table 3 and Table 4, respectively.

Table 3 shows that the highest link length in TWC achieved for acceptable Q-Factor and bit error rate at 10 Mbps for 30 mW and 200 mW are 18 m and 21.6 m, respectively. However, the maximum achievable link lengths at 1 Gbps are reduced to 13.6 m and 17.1 m for 30 and 200 mW, respectively.

Table 4 depicts that, for SWC, maximum link length achieved for acceptable Q-Factor and bit error rate with data rate of 10 Mbps for 30 mW and 200 mW are 80 cm

Table 3 Maximum link length achieved at different data rates with various laser transition powers in TWC

Data rate	Input power (mW)	Link length (m)	Q-Factor	BER
10 Mbps	30	18	6.03	$1.55\ e^{-9}$
	200	21.6	6.25	$1.99\ e^{-10}$
100 Mbps	30	15.8	6.07	$6.19\ e^{-10}$
	200	19.4	6.01	$9.00\ e^{-10}$
1 Gbps	30	13.6	6.45	$5.30\ e^{-11}$
	200	17.1	6.01	$9.32\ e^{-10}$

Table 4 Maximum link length achieved at various data rates for different input powers in SWC

Data rate	Input power (mW)	Link length (cm)	Q-Factor	BER
10 Mbps	30	80	6.05	$7.83\ e^{-9}$
	200	91	6.43	$6.27\ e^{-11}$
100 Mbps	30	72	6.47	$4.75e^{-11}$
	200	84	6.27	$1.78e^{-10}$
1 Gbps	30	66	6.03	$4.76e^{-9}$
	200	77	6.09	$5.38e^{-10}$

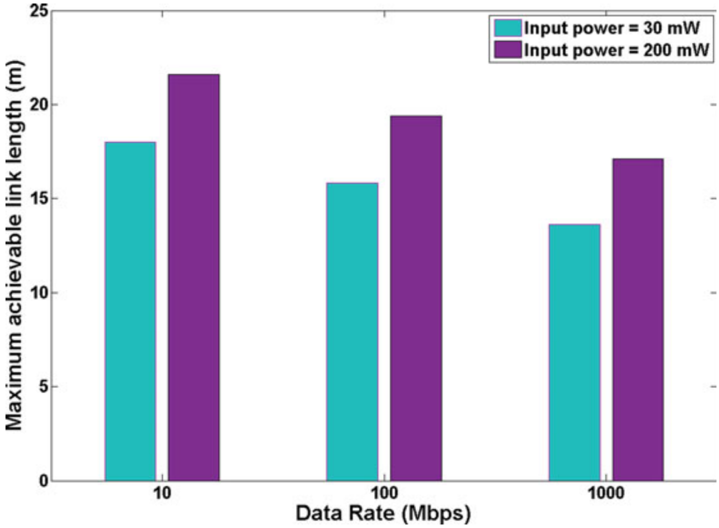

Fig. 5 Maximum achievable link lengths at different data rates for various laser transmission powers in tap-water channel

and 91 cm, respectively. However, the maximum achievable link lengths at 1 Gbps are reduced to 66 cm and 77 cm for 30 mW and 200 mW, respectively.

The variations in highest achievable link length at different data rates with input laser powers of 30 mW and 200 mW for the considered UWOC channels, i.e. TWC and SWC, are shown in Fig. 5 and Fig. 6, respectively.

It can be observed from Figs. 5 and 6 that as the input power increases, maximum achievable link length of UWOC system also increases at a fixed data rate for both TWC and SWC. However, the increments in link length are not significant when it is compared to the value by which input laser power has been increased. Also, the maximum achievable link length decreases with increased data rate at a constant laser transmission power for both water channels but again the decrement in link length is not significant. It can also be observed from Figs. 5 and 6 that maximum achievable link length of UWOC system is considerably decreased for SWC as compared to TWC. The main reason for decrement in maximum achievable link length is high attenuation of optical power in SWC as compared to TWC which reflects from the obtained very high attenuation coefficient value (8.037 m^{-1}) for SWC as compared to TWC (0.1561 m^{-1}).

Eye diagram of signal at Rx of UWOC link at 200 mW of input power for data rate of 10 Mbps at 21.6 m link length and 1 Gbps at 17.1 m link length for tap water channel are presented in Fig. 7(a) and Fig. 7(b), respectively. Figure 8(a) and (b) illustrates signal eye diagram at same laser transmission power for 10 Mbps at 91 cm link length and 1 Gbps at 77 cm link length for saline water channel, respectively.

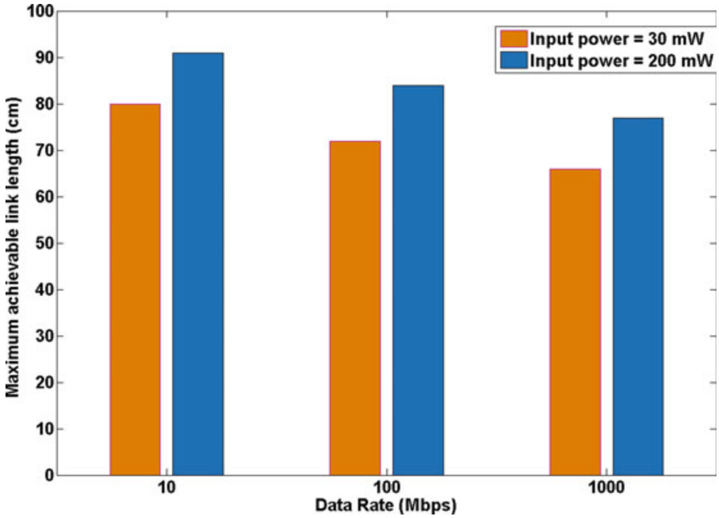

Fig. 6 Maximum achievable link lengths at various data rates for different transmission powers in saline water channel

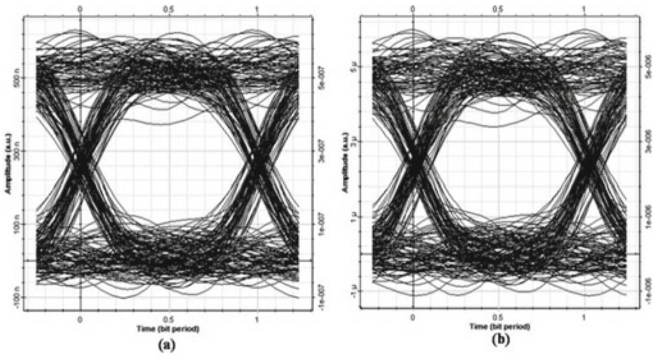

Fig. 7 Eye diagram of received signal at 200 mW input power for data rate of **a** 10 Mbps at 21.6 m link length and **b** 1 Gbps at 17.1 m link length for TWC

Quick visualization of the quality of signal is achieved by considering signal Eye diagram [21]. A clear open eye indicates minimal distortion and good signal—to—noise ratio. It is clear from Figs. 6 and 7 that eye opening is clear and hence quality of received signal is good.

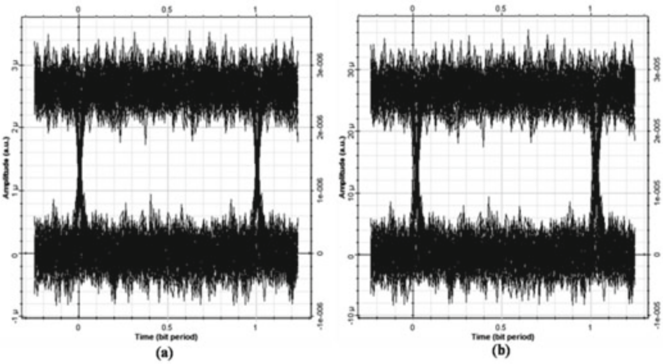

Fig. 8 Eye diagram of received signal at 200 mW input power for data rate of **a** 10 Mbps at 91 cm link length and **b** 1 Gbps at 77 cm link length for SWC

6 Conclusion

The experimental and simulation study is conducted for performance analysis of UWOC link for different channel conditions in terms of link length and data rate. On the basis of experimental outcomes, the attenuation coefficient of the UWOC channel under study is evaluated by curve fitting. The fitting is then implemented to model the water channel for further simulation. The performance of UWOC has been analyzed in terms of acceptable quality factor and bit error rate for varying link length and data rate. Maximum achievable link length of UWOC system increases with increase in input laser power at a constant data rate for both TWC and SWC but the increments in link length is not significant when it is compared to the value by which input laser power has been increased. Also, the maximum achievable link length decreases with increased data rate at a constant input laser power for both UWOC channels but again the decrement in link length is not significant. It is also observed that maximum achievable link length of UWOC system is considerably decreased for SWC as compared to TWC. Eye diagrams are used to analyze the quality of received signal.

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