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Performance analysis of 2D optical code division multiple access through underwater wireless optical medium

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ABSTRACT

The performance of a two-dimensional optical code division multiple access (2D-OCDMA) system using an underwater wireless optical (UWO) medium is assessed in this work. The optical source is an LED with a working wavelength of 532 nm, and the optical detector is a p–i–n photodiode. When calculating the bit error rate (BER), the phase-induced intensity noise (PIIN), thermal noises, and shot sounds are taken into account. The user code address is set using 2D perfect difference (2D-PD) codes. Link distance, inclination angle, beam divergence angle, transmitter power, and the number of concurrent users are all taken into account when determining the BER performance. For various water media, such as pure sea water (PSW), clear ocean water (CLOW), and coastal ocean water (CSOW), the performance of the suggested system is examined.

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1. INTRODUCTION

In the latest times, underwater wireless optical communication (UWOC) is used in sea currents monitoring, climate forecasting, underwater vehicle operation, climate condition recording, real-time monitoring, forecasting, oceanography research, environmental research, the transmission of data between ships, linking submarines to land [1], [2]. Due to optical absorption (OA) and optical scattering (OS), as well as oceanic turbulence (OT), the shaping of UWOC is difficult, and it gets some obstacles that are very challenging to overcome. Different seawater has different levels of impurities, different values of chlorophyll concentration, and different refractive index, temperature, salinity. In contrast with terrestrial RF communications, wireless communication in an underwater medium can be seriously affected by the limitations of the channel environment, noise, and bandwidth. The underwater channel often exhibits frequency dispersion, multipath propagation effects, severe attenuation, limited bandwidth and power resources., which make the UWOC one of the most complex communication systems in nature [1]–[4].

For long distances (ranging in km) and short distances (few meters), the available data rate of existing underwater acoustic communication is up to tens of kbps and up to hundreds of kbps, respectively [5], [6]. Thus, the acoustic link can be categorized into very short, short, medium, long, and very long links [7], depending upon the transmission distance. However, putting UWOC into practice is challenging, as it is hampered by several obstacles that are tough to overcome. The fundamental disadvantage of UWOC is that the link distance is a constraint. Only a distance of less than 100 meters can be reached for a communication link [8]–[10]. An optical signal gets subjected to many hindrances, such as OA, OS, and OT while traveling through a water medium, which causes the intensity loss of the receiver power, the spreading of the optical beam, multipath interference [1], [11]. These unavoidable effects greatly degrade the quality of communication [11], [12] in the UWOC system due to the impact of the refractive index variation of sea-water, fewer impurities dissolved in seawater (i.e., salt, colored biological materials, mineral components, inorganic materials.), and changes in temperature and salinity of seawater [11], [12]. As a result, the impediment of UWOC becomes a major concern while studying the improvement of the performance of the system. Due to the lower absorption characteristics in the 400 to 600 nm, UWOC systems operate in this region to transmit data. Optical code division multiple access (OCDMA) is one optical access method that is attracting a lot of attention because of its many appealing qualities, including effective bandwidth utilization, greater security, increased robustness, and improved spectral efficiency [2], [6], [13]–[19]. OCDMA's simultaneous multi-user access to the network on the same frequency leads to multi-user interference (MUI), which is the main cause of the OCDMA system's performance decline. A common method to lessen the impact of MUI is the 2D-OCDMA system with an interference cancellation receiver. However, a code sequence with the property of a fixed in-phase cross-correlation value is used to reduce the MUI [14]. As a result, since 2D-PD codes have a unity in-phase cross-correlation value, their application will be advantageous [20]–[25]. Moreover, 2D-PDCs with spatial/spectral transceiver structures have been shown to more effectively control phase-induce intensity noise (PIIN) and lessen the impact of MUI in OCDMA [14].

2. SYSTEM MODEL

Figure 1 displays a schematic representation of the underwater wireless 2D-OCDMA. The signals from all transmitters supporting U number of simultaneous users are combined together using a combiner and then splitted to the corresponding receiver by the splitter. Here, 2D-perfect difference codes (2D-PDCs) are used to address the user code sequence. The user binary data is modulated at the transmitter using a broadband optical source and an on-off keying (OOK) modulator. The 2D-OCDMA encoder encodes the modulated signal. The fiber Bragg gratings (FBGs) array structure can be used to build the encoder's structure [14]. The signals are combined by the employment of a combiner and then transmitted through a water medium. The received signal is first decoded at the receiver by a 2D-OCDMA decoder, which is likewise built by FBGs [14]. A photodetector converts the decoded signal into photocurrent. In this system, a balanced photodetector is employed to mitigate the MUI. Finally, the threshold detector is used to retrieve the original data.

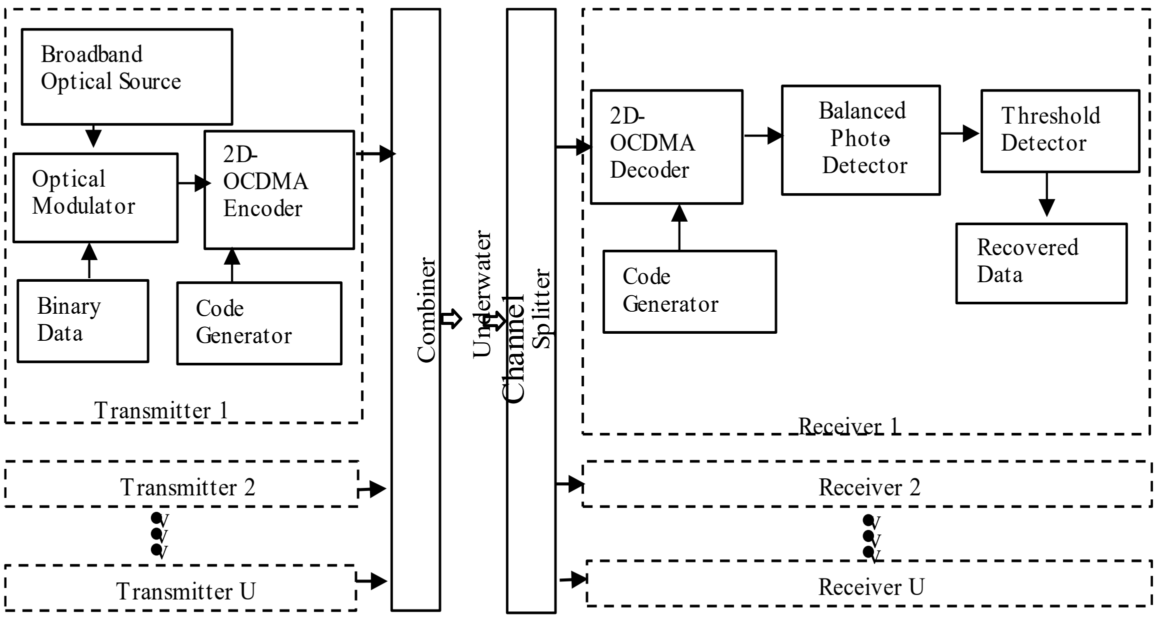

Figure 1. Schematic illustration of the underwater wireless 2D-OCDMA system

3. SYSTEM ANALYSIS

The prior consideration of designing the UWOC system is to comprehend the link budget equation, which can be given by (1) [1], [2].

$$P_{RC} = P_{TR}\eta_{TR}\eta_{RC}\frac{A_R\,cos(\phi)}{2\pi d^2[1-cos(\phi_0)]}exp\left[-c(\lambda)\frac{d}{cos(\phi)}\right] \quad (1)$$

where P_{RC} and P_{TR} are the received and transmitted optical power, respectively, η_{TR} and η_{RC} are transmitter and receiver efficiency, respectively, ϕ is the inclination angle, ϕ_0 is divergence angle, A_R is area, d is the channel length. For an underwater optical channel, the total loss coefficient $c(\lambda)$ is [2], [4].

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

where the absorption coefficient $a(\lambda)$ is given by (3) [4], [5].

$$a(\lambda) = a_x(\lambda) + a_s^0(\lambda)\left(\frac{C_c}{C_c^0}\right)^{0.602} + a_F^0 C_F\,exp(-\hbar_F\lambda) + a_H^0 C_H\,exp(-\hbar_H\lambda) \quad (3)$$

where $a_x(\lambda) = 0.0445m^{-1}$ at 532 nm, $a_s^0(\lambda) = 0.0127m^{-1}$at 532 nm, which is known as the spectral absorption coefficient of chlorophyll [6], [7]. For fulvic acid, the specific absorption coefficients are a_F^0=35.959 m^2/mg and $a_H^0 = 18.828\ m^2/mg$, $\hbar_H(= 0.01105\,nm^{-1})$ and $\hbar_F = (0.0189\,nm^{-1})$ are constants. The fulvic acid concentration [4], [5].

$$C_F = 1.74098C_c\,exp\left[1.2327\left(\frac{C_c}{C_c^0}\right)\right] \quad (4)$$

Again, the humic acid concentration [4], [5].

$$\mathrm{C_H} = 0.19334\mathrm{C_c}\,\mathrm{exp}\left[1.2343\left(\frac{\mathrm{C_c}}{\mathrm{C_c^0}}\right)\right] \quad (5)$$

Here, the value of C_c^0 is constant at 1 mg/m^3 but the total concentration of chlorophyll, C_c changes with the types of water [1], [4], [5], [8]. In this evaluation, the water types considered are coastal ocean water or CSOW ($C_c = 0.83mg/m^3$), clear ocean water or CLOW ($C_c = 0.31mg/m^3$) and pure sea water or PSW ($C_c = 0.005mg/m^3$) [8]. The scattering coefficients of sea water are the combination of various particles, which can be small or large in size, with an approximate refractive index constant of 1.15 and 1.03, respectively [9]. Therefore, the coefficient of scattering can be expressed as [4], [5].

$$b(\lambda) = b_n(\lambda) + b_{sp}^0(\lambda)C_{sp} + b_{lp}^0(\lambda)C_{lp} \quad (6)$$

where $b_n(\lambda)$ is the scattering coefficient for the case of "no particle" and $b_{lp}^0(\lambda)$ and $b_{sp}^0(\lambda)$ are the coefficients for large and small particles, respectively, causing an effective scattering phenomenon. These coefficients can be defined as (7) to (9) [4], [5].

$$b_n(\lambda) = 0.005826\left(\frac{0.4}{\lambda}\right)^{4.322}, \mathrm{m^{-1}} \quad (7)$$

$$b_{sp}(\lambda) = 1.151302\left(\frac{0.4}{\lambda}\right)^{1.7}, {m^2}/{g} \quad (8)$$

$$b_{lp}(\lambda) = 0.341100\left(\frac{0.4}{\lambda}\right)^{0.3}, \quad (9)$$

For large and small particles, the total concentrations are C_{lp} and C_{sp} respectively, which can be denoted as [4], [5], $C_{lp} = 0.76284C_c\,exp\left[0.03092\left(\frac{C_c}{C_c^0}\right)\right], {g}/{m^3}$, $C_{sp} = 0.01739C_c\,exp\left[0.11631\left(\frac{C_c}{C_c^0}\right)\right], {g}/{m^3}$.

For the estimation of system BER, noises such as PIIN, thermal noise, and shot noise are taken into account; therefore, the SNR can be calculated as (10):

$$SNR = \frac{I_r^2}{I_t^2} \quad (10)$$

where I_t is the total noise power and I_r is receiver photocurrent. The current I_r is given by (11) [6]:

$$I_r = \frac{\Re P_{RC} w_1}{M} \tag{11}$$

where w_1 is the code weight (CW) of spectral code sequence, M is the code length (CL) of spectral code sequence, and $\Re$ is the of photodetector responsivity. If the variance due to thermal noise, shot noise and PIIN are I_{PIIN}^2, I_{Shot}^2 and $I_{Thermal}^2$, respectively, then I_t can be illustrated as (12):

$$I_t^2 = I_{PIIN}^2 + I_{Shot}^2 + I_{Thermal}^2 \tag{12}$$

The thermal noise is as (13) [6]:

$$I_{Thermal}^2 = \frac{4K_b T_m B_e}{R_{Load}} \tag{13}$$

where R_{Load} is the receiver load resistance, B_e is the receiver electrical bandwidth, T_m is the receiver noise temperature and K_b is Boltzmann constant. If Δf is considered as the source bandwidth, the variance for PIIN can be expressed according to 2D-PD code by (14).

$$I_{PIIN}^2 = \frac{\Re^2 B_e P_{RC}^2}{2M\Delta f w_2^2 w_1 (MN-1)^2}\left\{\left(w_1 w_2 (MN-1) + w_2 (U-1)(M-1)\right)^2 + \frac{w_2^2 (U-1)^2 (M-1)^2}{(w_1-1)^2}\right\} \tag{14}$$

The shot noise is estimated by (15) [6].

$$I_{Shot}^2 = \frac{e B_e P_{rec} \Re}{w_2 M}\left\{w_1 w_2 + \frac{2w_1 (U-1)(N-1)}{(MN-1)} + \frac{2w_2 (U-1)(M-1)}{(MN-1)} + \frac{4(U-1)(M-1)(N-1)}{(MN-1)}\right\} \tag{15}$$

At the receiver end, the SNR can be calculated as (16) [6].

$$SNR = \frac{I_r^2}{I_{PIIN}^2 + I_{Shot}^2 + I_{Thermal}^2} \tag{16}$$

The performance of the system is defined by the BER calculation which can be written as (17) [6].

$$BER = \frac{1}{2} erfc\left(\sqrt{SNR/8}\right) \tag{17}$$

4. RESULTS AND DISCUSSION

This section provides an examination of the proposed UWOCDMA system's BER performance for various types of water. The following criteria were used to evaluate the system's performance: transmitter inclination angle (θ_i) =15°, LED beam divergence angle $(\theta_b) = 40°$, both the transmitter and receiver optical efficiency = 0.9, data rate (D_r) = 0.5 GHz, receiver aperture area (A_r) = 0.01 m^2, temperature (T) = 298 K, Photo detector responsivity $(\Re) = 0.85$, receiver load resistance (R_L) = 100 Ω, electrical bandwidth (B_{elec}) = 250 MHz, transmitter power (P_t) = 30 dBm are considered.

The plot of BER versus distance of transmission for different water is shown in Figure 2, considering the previously described parameter. It can be found from the figure that the BER increases significantly with the increasing link length. The BER of 10^{-9} is gained in PSW, CLOW and CSOW at a link distance of 14, 9.8, and 7 m, respectively. Therefore, it can be stated that in PSW, a larger area can be covered when the system is considered to be subjected to PSW maintaining a BER of 10^{-9}. However, in CSOW channel, the performance gets worse due to the scattering and the absorption of the optical signal resulting from the increasing volume of impurities.

Figure 3 refers to the plot of BER versus number of simultaneous users when the transmission distance is 6 m, and the transmitter power is 30 dBm. Since the number of simultaneous users becomes more, the effect of MUI gets aggravated which results in the degradation of the system BER performance. It can be determined that for a certain value of BER of 10^{-9}, around 250 and 244 users can be assigned simultaneously in PSW and CLOW respectively. However, the system performance diminishes in CSOW since in this medium the attenuation coefficient is dominated by scattering resulting from a great volume of impurities and considerable concentration level of chlorophyll.

Figure 4 illustrates the BER versus inclination angle curve when the link length is 7 m, beam divergence angle is 50°, and transmitter power is 30 dBm. It can be noted that the BER value degrades with the reduction of inclination angle. This is because the more the optical beam is aligned away from the axis of transmitter-receiver joining the line, the value of BER goes upward. Thus, the system undertaking CSOW channel cannot allow the beam to be inclined by a wide angle to get a targeted BER value. The results show that the inclination angle is 70° in pure sea water which must be decreased to 52° and 10° in PSW and CLOW respectively to get a fixed BER of 10^{-9}.

The plot of BER versus beam divergence angle is presented in Figure 5 assuming that the link length is 10m and the inclination angle is 10°. From the figure, it can be noted that when the beam divergence angle decreases, the BER becomes less. To achieve a target BER of 10^{-9}, the beam divergence angle must be at a value of 18° and 40° in CSOW and CLOW which is lower than that in PSW. The reason behind this is that the attenuation profile and the absorption increase majorly with the changes in the concentration of chlorophyll. In addition to that the scattering occurs due to presence of organic and inorganic particles in the water. Moreover, the volume of these particles is particularly excessive in CSOW and CLOW channel.

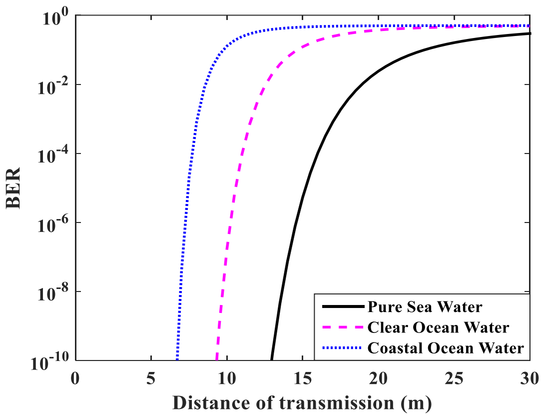

Figure 2. BER versus distance of transmission curve

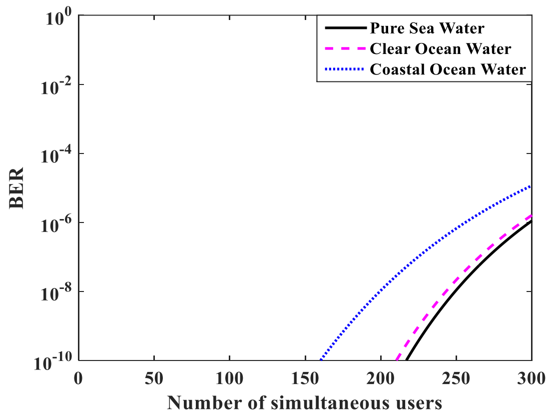

Figure 3. BER versus number of simultaneous users curve

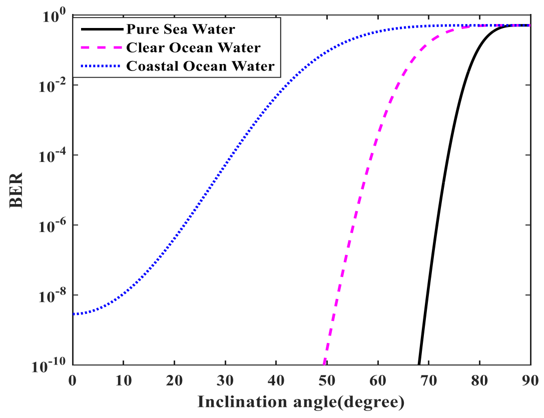

Figure 4. BER versus inclination angle curve

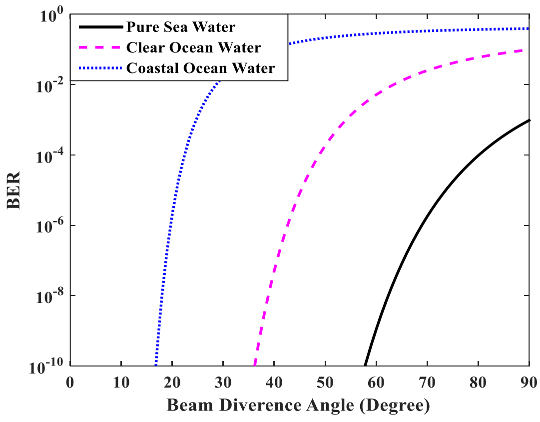

Figure 5. BER versus beam divergence angle curve

In Figure 6, the plot for the required optical power versus underwater link distance for different types of water is represented. Here, the effect of variation of underwater channel can be clearly explained. The transmitted optical power requirement increases when the number of impurity particles increase in water. The power requirement in PSW is lower CLOW than and CSOW. When the transmission link distance increases then the optical power requirement increases. At a target BER value of 10^{-9}, the system needs 38.02 dBm in CSOW channel, however, it declines to a value of 27.61 dBm in case of PSW for the same transmission length of 10 m. Figure 7 represents the characteristics curve for the required optical power versus inclination angle for different types of water considering θ_0 is 50°, d is 7 m and U is 50. It can be observed that when inclination angle increases then the required optical power is increased. This is because the inclination angle increases when the transmitted optical beam aligns away from the axis which connects the transmitter and receiver, thereby, degrading the system performance severely. As a result, the system requires more transmitted optical power when the angle of inclination rises causing more differences between the optical beam trajectory and the transmitter-receiver connecting axis. In order to get a fixed BER of 10^{-9}, the system possesses 23.78 dBm for PSW whereas it increases to 26.75 and 31.81 dBm for CLOW and CSOW channel respectively if the optical beam gets inclined by 40°.

Figure 8 shows the plot of required optical power versus number of simultaneous users for different underwater channel considering d is 10 m, θ_0 is 50°, inclination angle is 15°. The performance of the proposed system degrades with an extensive number of simultaneous users because of the impact of MUI. At a BER value of 10^{-9}, the required optical power is 39.41, 32.60 and 28.90 dBm for CSOW, CLOW and PSW respectively, when the number of simultaneous users 200. This is because in CSOW, the effect of an extensive amount of impurities and high concentration of chlorophyll result in scattering and absorption of optical signal. Thereby, the performance of the proposed system deteriorates immensely. Figure 9 presents the required optical power versus beam divergence angle curve considering d is 10 m, θ is 10° and U is 50. From the result, it can be noted that the system needs more optical power with the rising θ_0. Since the value of attenuation and absorption coefficient reaches at a maximum value when the chlorophyll concentration is maximum, the signal strength in CSOW falls down drastically. In addition to that both organic and inorganic compounds dissolved in water causes scattering of the optical signal, therefore, the system possesses more optical power to uphold the signal strength. At a fixed BER of 10^{-9} and beam divergence angle of 90°, the required power in CSOW is 33 dBm, which is reduced by 4 and 6 dB in CLOW and PSW. Hence, PSW water the performance is comparatively better than other two channels due to the less amount of total loss coefficient.

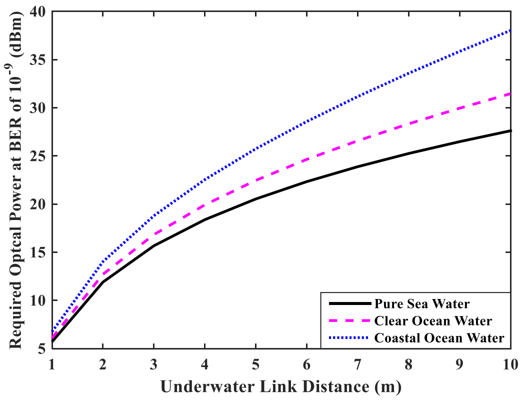

Figure 6. Required optical power at BER of 10^{-9} versus underwater link distance curve

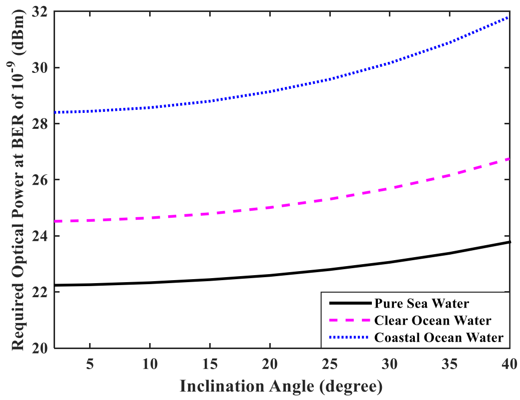

Figure 7. Required optical power at BER of 10^{-9} versus inclination angle curve

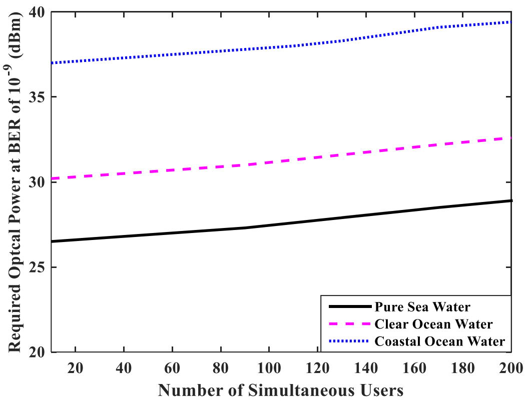

Figure 8. Required optical power at BER of 10^{-9} versus users curve

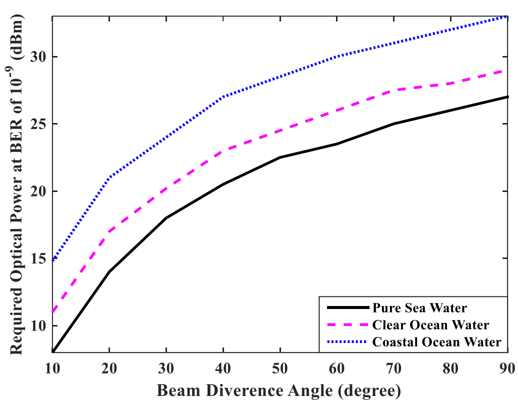

Figure 9. Required optical power at BER of 10^{-9} versus beam divergence angle curve

5. CONCLUSION

In this paper, the BER performance of 2D-OCDMA system through UWO medium is analyzed, where 2D-PDCs are implemented to set user addresses. The LED optical source with 532 nm operating wavelength is employed, and two balance detectors are used for the purpose of eliminating the effect of MUI. The thermal noise, shot noise and PIIN are considered in the calculation to investigate the system performance with respect to transmission distance, inclination angle, beam divergence angle, and number of simultaneous users. Moreover, the system performance is evaluated for different water mediums due to the fact that it greatly depends on them. The underwater medium is dissolved with a high level of impurities, and the chlorophyll concentration is affected severely due to the occurrence of scattering and absorption of the optical signal. That is why the CSOW channel gives poor performance compared with other water channels. It can be seen that when transmission link distance is increased, then the optical power requirement increases. The system performance is more affected by MUI with increasing users. At a BER value of 10^{-9}, it can be observed that approximately 250 and 244 users can simultaneously deliver signals in PSW and CLOW respectively.

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BIOGRAPHIES OF AUTHORS

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