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COMPARISON OF DIFFERENT CODES IN SAC-OCDMA FOR DIFFERENT MEDIUM

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ABSTRACT

A spectral amplitude coding optical code division multiple access (SAC-OCDMA) system has been utilized to compare its efficiency in free space and underwater using two different code families, such as the random diagonal (RD) code and the modified quadratic congruence (MQC) code. On account of a variety of ocean water properties, the efficiency of the RD code has been assessed for pure seawater and coastal water and collated with the performance of the MQC code. RD code's performance has been compared with MQC to validate that the RD code is capable of providing improved performance in underwater channels. The bit error rate (BER) evaluation regarding underwater and free space has been integrated to discern which code family exhibits higher proficiency in which atmosphere for the proposed framework. Comparative inspection amid free space and underwater using common parameters such as transmitted power and number of simultaneous users has been conducted to verify the most suitable channel for the RD code.

KEYWORDS: BER, FSO, MAI, MQC, On-off keying, RD, SAC-OCDMA, UWOC.

1. INTRODUCTION

The irresistible impulse to accumulate knowledge from inaccessible places on the planet and even from outer space within a few milliseconds is the reason for inventing high-speed communication techniques. Owing to technological breakthroughs, the ability to communicate below a deep, dark ocean has been achieved. The utilization of energy, such as photons, in expeditious data transmission has made it more reliable and secure (Xiao et al., 2022). In affluent countries, optical communication has essentially taken the place of overhead communication lines as a result of its characteristics, which include better speed for data transmission, increased bandwidth, and improved security of users' personal information (Stucchi et al., 2013). Additionally, constructing a copper wire communication system in perilous geographical locations can be exceedingly challenging, can require a very long time to be constructed, and needs an enormous financial plan allotment (Reynaert et al., 2016). For the foregoing reasons, the usage of free-space optical communication has become pervasive as it can be easily installed. Free space optical (FSO) communication is the remote transmission of information that utilizes imperceptible light emissions (Huurdeman, 2003), (Khatib, 2014). An uncomplicated on-off keying (OOK) modulation scheme is utilized to establish a free-space optical communication structure as a bandwidth and protocol-transparent physical layer connection (Gupta et al., 2014). Moreover, even in underwater transmission, this technology provides low latency and less attenuation (Alghamdi et al., 2019). When security and quick installation are prime concerns, wireless optical communication beneath the ocean is a suitable choice (Rashed and Sharshar, 2013).

OCDMA technology is an essential function for enhancing the effectiveness of FSO communication (Tseng, 2019). The spread spectrum technology in OCDMA ensures high security when multiple users try to access the system to send information simultaneously (Ahmed et al., 2020). However, as a consequence of the multiple access characteristics, multiple access interference emerges in OCDMA as a result of signal overlapping (Dang and Pham, 2012). However, this inconvenience can be diminished by spectral amplitude coding (SAC) OCDMA [(Hamza et al., 2012). SAC-OCDMA can annihilate the interference that transpires due to the transmission of signals by multiple users at the same time by using unipolar orthogonal codes (Kavehrad and Zaccarin, 1995), (Noshad and Jamshidi, 2011). Light-emitting diodes (LEDs) are prominently used in SAC-OCDMA systems because they can deliver efficiency equivalent to coherent sources and are also affordable (Smith et al., 1998).

To enhance the productivity of an SAC-OCDMA framework, different researchers have constructed different codes. One code family is the modified quadratic congruence (MQC), the transmitter and receiver structure performance using this code family for SAC-OCDMA was analyzed and compared with the performance of the Hadamard code by the authors. The comparison revealed that MQC codes can increase the system's productivity by eliminating intensity noise (Zou et al., 2001). Authors (Sahbudin et al., 2008) analyzed the performance of a hybrid scheme of subcarrier multiplexed spectral-amplitude-coding optical code division multiple access (SCM SAC-OCDMA) system utilizing a novel AND detection method based on subtraction using double weight (DW) code, and the method provided improved performance than the complementary subtraction technique by diminishing total power loss. In another research, a family of codes termed the random diagonal (RD) was constructed for SAC-OCDMA using code segment and data segment, and the article proposed a detection method termed as spectral direct detection. The strength of the RD code is that any number that has a higher value than three can be taken as code weight, and the zero cross-correlation value of the data segment helps in minimizing the effect of PIIN significantly (Fadhil et al., 2009). There are numerous studies on underwater wireless optical communication (UWOC), among them one developed three wireless optical communication links for underwater communication to deliver a high data rate, which included line of sight communication, reflective communication, and a modulating retroreflector communication link for analyzing BER performance. According to the findings, communication efficiency for the three link types decreases significantly when the water absorption rises, but in certain situations, this drop could be minimized by utilizing the scattered light. The research suggested that a high-data-rate underwater optical wireless network is an effective remedy for new applications, including unmanned underwater vehicle (UUV) to UUV links and sensor networks. By utilizing multi-hop technology enhancement of ranges in these applications could be possible (Arnon, 2010). The authors (Simpson et al., 2010) constructed a compact and inexpensive underwater optical wireless communications sensor node interface for transferring information at 5 Mbps to the external observers and increasing the endurance of the system using signal processing and error correction techniques. The researchers (Oubei et al., 2015) built a cost-effective OOK-NRZ modulation system by using a TO-9 packaged pigtailed 520 nm laser diode and an APD module as transmitter and receiver, respectively, and achieved a 2.3 Gbit/s data rate over a 7m distance. Another research analyzed an underwater wireless OCDMA framework's BER performance by utilizing optical orthogonal codes regarding various water channels, such as pure sea, coastal ocean, and clear ocean. Researchers employed a 532nm LED as an optical source which is capable of proving lower attenuation, and as an optical detector, silicon APD of gain 50 was utilized for gaining improved signal reception efficiency. This system provided the best performance in pure sea water and showed the worst performance in coastal ocean water which proved that the purity level of the underwater channel can influence the system's BER performance (Al Hammadi and Islam, 2018). One research is based on the construction of an underwater SAC-OCDMA system and an assessment of the BER performance of the framework was carried out using MQC codes in case of clear water, along with pure sea water, and coastal water. According to the analysis, the system provides desirable results when the sea water's impurity level is low and the link distance is short (Deepa and Islam, 2019). In one previous study, the inspection of the BER performance of a SAC-OCDMA structure employing the MQC code was conducted considering five types of atmospheric conditions in free space such as haze, rain, mist, snow, and fog. The assessment discovered that as the density of air increases, the efficacy of the system decreases which indicates that the best performance is gained in hazy weather and the worst is in foggy weather (Das and Islam, 2022). Another research was conducted to ascertain which code family among MQC, RD, and DEU in the SAC-OCDMA structure provides improved BER performance in adverse weather, for example, haze, rain, and fog. The BER performances of the three codes were analyzed against the transmitted power and the number of simultaneous users. This comparative assessment revealed that among the three sorts of codes, DEU is capable of minimizing MAI more effectively than RD and MQC in air medium (Das et al., 2022).

1.1. Limitations of Existing Discoveries

The performance analysis of MQC and RD codes has been conducted by many researchers; however, the functionality assessment of the RD code for a SAC-OCDMA system in aquatic environments regarding distinct degrees of impurity has not been identified yet. In the case of UWOC, dissolved contaminants and temperature fluctuations in seawater originate scattering turbulence, and absorptions which alter the orientation of the optical signal and decrease link distance (Akhoundi et al., 2016), (Diamant et al., 2017), (Vali et al., 2018). Therefore, it is necessary to find a suitable code family that will overcome the issue of limited link distance in UWOC. How the potency of RD code differs in different environments, such as free space and underwater is still undiscovered because the barriers in the case of air medium are different from those underwater. When a signal travels through the air medium, scintillation and adverse weather conditions cause disruptions (Naimullah et al., 2008).

1.2. Novelty of this Research

This research emphasizes the contribution of RD code in the effective transmission of signal in two different types of aquatic channels and reveals whether RD code is more efficient than MQC code or not in terms of enhancing the system's productivity. This paper exhibits a side-by-side comparison of the performances of the MQC code and the RD code in water medium and in free space to determine which medium is best preferred for utilizing the RD code, and that validates the authenticity of this research. The reason behind comparing the performance of the MQC code is its low cross-correlation behavior. Due to this property, this code can provide trustworthy data recovery. The development of MQC codes can be accomplished simply. It offers a significant amount of resistance to MAI, which makes it highly appropriate for optical communication systems with multiple users. MQC is capable of differentiating each user's signal from others. Thus, where reduction of interference is essential, this code might be a prudent choice (Zou et al., 2001). The researchers (Deepa and Islam, 2019) implemented the MQC code in the SAC-OCDMA system for three types of ocean water at different impurity levels, where this code showed good error correction capabilities and dealt with noise effectively while maintaining low complexity. On the other hand, in (Das and Islam, 2022) MQC code has been analyzed for hazy, rainy, misty, snowy, and foggy weather for the air medium. In this article, we have tried to discover if any code other than MQC can offer enhanced results in case of UWOC, or not, and for that, we opted for the RD code. While the MQC code has been well analyzed in both air and underwater media, the RD code has only been examined in the air medium in previous research. RD code has been selected because the encoding and decoding procedures are made simpler by the use of diagonal matrices with random elements. RD codes are more resilient in noisy circumstances. It is capable of increasing the overall efficiency of the system by supporting more users without experiencing significant deterioration of the system's performance. Its large scalability makes is simple to adjust to the specific requirements of different OCDMA systems. No need for complex mathematical algorithms in the RD code allows faster implementation than the MQC code. They are adaptable for a variety of applications where interference minimization is required because of their orthogonality traits (Fadhil et al., 2009). RD code has been compared to MQC code in the case of air medium (Das et al., 2022). In this paper, we present a novel introduction of the RD code's performance for the water medium, which has not been previously investigated. Our results offer valuable insights for differentiating the RD code's functionality over the MQC code's performance. Our article contributes by conducting a first-ever performance evaluation of the RD code against the MQC code in both air and water media. This study provides a comprehensive analysis of how these codes behave in varying environmental conditions.

This article unveils in which environment these code families perform efficiently. In the case of underwater, pure seawater and coastal water have been considered. In coastal water, due to the presence of a large number of biological particles optical signal gets absorbed more than it does in pure seawater. Whereas pure seawater provides a cleaner medium for the optical signal to travel. In contrast to earlier efforts depicted in (Deepa and Islam, 2019) using the MQC code, our work sheds light on how RD provides better results in pure seawater and coastal water than the MQC code. To the best of our knowledge, this is the first study to compare the results of pure seawater and coastal water using the RD code. The BER performance for the underwater system has been evaluated using the RD code in comparison with the performance of the MQC code for different parameters such as inclination angle, link distance, number of simultaneous users, and transmitted power. These parameters have been considered because they provide insights into how efficiently the system works when the signal faces scattering, refraction, and beam loss due to suspended sediments. For free space, adverse weather such as fog and haze has been considered for evaluating the performance. Results from the performance analysis of both code families in two different environments, such as free space and underwater, have been merged to scrutinize in which environment the code families ensure better efficiency. The following are the key contributions of this research:

- Analyze the BER performance of the RD code against link distance, transmitted power, inclination angle, and number of simultaneous users in varied aquatic environments.
- Compare the RD code and the MQC code for the SAC-OCDMA structure in two sorts of water channels.
- Verify RD code's supremacy over MQC code.
- Collect the performances of RD and MQC codes for free space and underwater channels.
- Identify in which channel, between underwater and free space RD code supports better BER results against which parameter.

The remainder of this work is categorized in such a way that the explanation of the SAC-OCDMA structure is provided in Section 2. The mathematical representation of link formation and BER evaluation is shown in Section 3. Part 4 is dedicated to result interpretation. Section 5 represents a comparison of the findings, and finally, the conclusions are highlighted in Section 6.

2. SYSTEM EXPLANATION

The procedure of transferring the signal from the sending part to the receiving section is portrayed schematically in Figure 1 for the preferred SAC-OCDMA structure, and the diagram comprises two distinct sections. The first section depicts the alignment of the components in the transmitter part that is Figure 1(a). Additionally, the second section, which is Figure 1 (b), unfolds the internal construction of the receiver section.

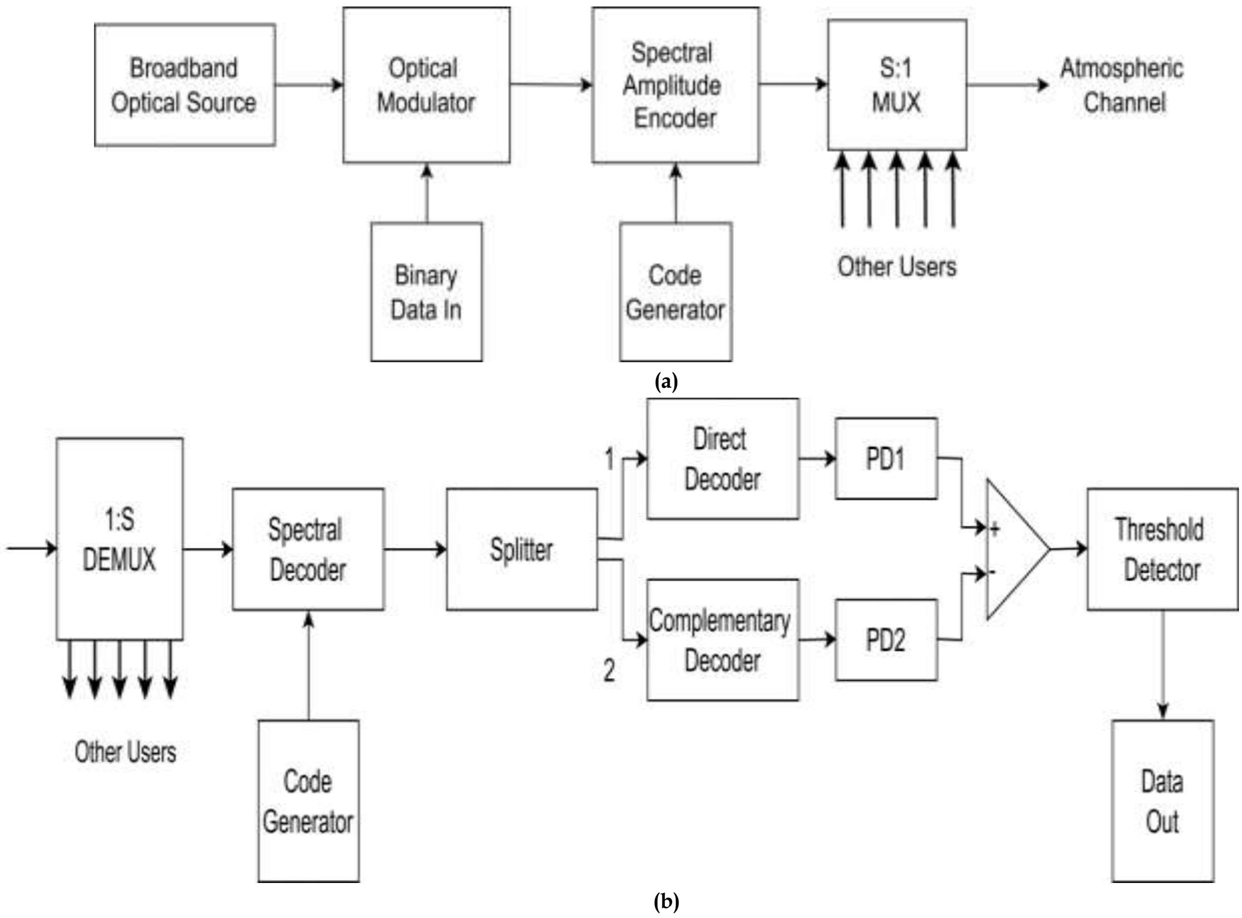

Figure 1. Diagrammatic representation of the SAC-OCDMA system (a) alignment of transmitter components and (b) receiver construction pattern.

In the transmitter portion, information that a user wishes to send is first converted into binary data, and then a broadband light source emits light pulses for modulating that binary data. The approach that has been taken for modulation in the optical modulator is termed on-off keying (OOK). Afterward, the spectral amplitude encoder, fabricated with fiber Bragg gratings (FBGs), encodes the modulated signal and is coupled with a code generator. The code generator's task is to generate a specified code that is constructed with an optical sequence of longer code weight. Then, optically encoded signals sent by S simultaneous users' receivers are merged and turned into a single optical signal via an S:1 multiplexer. Thus, here the task of the transmitter portion ends. Afterward, this signal travels through atmospheric channels such as air or water and approaches the receiver portion. When the optical signal arrives at the receiving segment, it is then detected by the 1:S de-multiplexer, which divides the multiplexed signal. These separated signals are conveyed to their particular recipients. A spectral decoder is used to correlate the signal along with a code generator. Then the correlated signal is separated into two portions using a splitter for transmitting one part to a direct decoder, whereas the other portion that is not accepted by the direct decoder is transmitted to a complementary decoder. For implementing the balance detection technique, two inversely connected photodetectors, PD1 and PD2, are used to attenuate the repercussion of MAI. The photocurrent signal then travels through a predefined threshold detector from which the authentic information that the user intends to transmit is retrieved.

3. MATHEMATICAL ANALYSIS

To establish a wireless optical model, the link budget equations for the two channels are necessary for estimating the viability of the optical link for reliable communication. The link budget equation relies on transmitted power, atmospheric absorption loss, and received power. As the signal travels through the system and medium, it can be derived at the receiving end of the system.

3.1. Link Formation

At first, the link budget formula for the air medium was represented. Then the equation of the link budget for the underwater medium has been expressed.

3.1.1. For Air Medium

To analyze the FSO system's received power, it is crucial to employ the expression of link budget that can be defined with generic empirical formulas that is equation (1) (Schuster et al., 2003);

$$P_{Re(Air)} = \left(\frac{D_{ia}}{\phi_b l_T}\right)^2 P_{Tr} e^{-\alpha l_T}, \quad (1)$$

Here, in equation (1), the optical power received is expressed with P_{Re} (watt) and for specifying this in the case of an air medium, it can be denoted as $P_{Re(Air)}$, ϕ_b indicates beam divergence angle (rad), D_{ia} (m) is employed to signify the effective diameter of a receiver; therefore, transmission length can be symbolized using l_T (m), α expresses the atmospheric absorption loss (m^{-1}), and P_{Tr} is a symbolic representation of the transmission power (watt).

3.1.2. For Water Medium

When an optical signal is intended to propagate through a water medium, particles of water tend to generate attenuation by absorbing and scattering the light pulse. Besides, the wavelength of the optical source influences attenuation. The following formula in equation (2) explains that the attenuation coefficient can be determined by adding the absorption coefficient and the scattering coefficient (Arnon, 2010).

$$A_T(\lambda) = \alpha_a(\lambda) + \beta_s(\lambda), \quad (2)$$

Here, in equation (2), the optical source's wavelength is symbolized with λ, A_T (λ) is employed to represent the coefficient of attenuation (m^{-1}). Therefore, α_a (λ) and β_s (λ) indicates the absorption and scattering coefficients successively.

Now, the link budget equation in the case of water medium for transmitting optical signal wirelessly can be explained with the formula in equation (3) (Arnon, 2010), (Kaushal and Kaddoum, 2016);

$$P_{Re(Water)} = P_{TW}\eta_{eT}\eta_{eR}\frac{A_R \cos(\phi_{inc})}{2\pi {d_w}^2[1-\cos(\phi_{bw})]} \exp\left[-A_T(\lambda)\frac{d_w}{\cos(\phi_{inc})}\right], \quad (3)$$

Here, in equation (3), for underwater, to transmit an optical signal to d_w distance, the required power can be depicted as $P_{Re(Water)}$. For representing the optical efficiency of the transmitter and receiver η_{eT} and η_{eR} has been employed respectively. A_R signifies the area of the receiver's aperture, ϕ_{bw} indicates the angle of beam divergence for transmission, and the transmitter's angle of inclination from the track, which links the transmitter and receiver, is symbolized by ϕ_{inc}.

3.1.3. Evaluation of BER

The consequences of shot noise, along with thermal noise and PIIN, have all been accommodated in this analysis to ascertain the BER of the implemented system. Therefore, the overall noise variation experienced in the photocurrent is given in equation (4);

$$\sigma_O^2 = \sigma_{Th}^2 + \sigma_{Sh}^2 + \sigma_{Pn}^2, \quad (4)$$

Here, in equation (4), σ_O^2 indicates the quantity of noise power that impacts the photodiodes. Thus, σ_{Th}^2 denotes thermal noise, σ_{Sh}^2 is employed to express shot noise, and PIIN is depicted with σ_{Pn}^2 .

Calculation of the responsivity of the photodetectors, which is denoted by R_{es} can be done using the next equation that is equation (5);

$$\Re_{es} = \frac{\eta_e E_c}{h v_c}, \quad (5)$$

Here, in equation (5), v_c is employed to represent the central frequency of the original broadband optical pulse. The electron's charge is represented by E_c. Plank's constant is denoted with hand η_e is used to symbolize the photodetector's quantum efficiency.

Equation (6) is employed to define thermal noise for MQC and RD codes (Zou et al., 2001), (Fadhil et al., 2009):

$$\sigma_{Th}^2 = \frac{4K_{Bol}T_{AN}B_{el}}{R_{Ld}}, \quad (6)$$

Here, in equation (6), T_{AN} is used as the symbol of the absolute noise temperature of the receiver, the Boltzmann constant is expressed with K_{Bol}, for the load resistance of the receiving station R_{Ld} is employed, and the electrical bandwidth is depicted with B_{el}.

For MQC Code

For evaluating the amount of shot noise for MQC, this formula is utilized with equation (7) (Zou et al., 2001);

$$\sigma_{Sh1}^2 = 2E_c B_{el} \Re_{es} P_{Re}\left[\frac{\rho_r - 1 + 2S}{{\rho_r}^2 + \rho_r}\right], \quad (7)$$

Here, in equation (7), the prime number is expressed using ρ_r , which is a prominent parameter in the MQC code. The number of simultaneous users is symbolized by S, and E_c is used to represent the charge of the electron. Here, P_{Re}will be replaced by $P_{(Re(\ Air))}$ for the air medium and $P_{(Re(\ Water))}$ for underwater.

Considering the MQC code, the PIIN can be defined with the equation (8) (Zou et al., 2001);

$$\sigma_{Pn1}^2 = \frac{B_{el}\Re_{es}^2 P_{Re}^2 S}{\Delta f(\rho_r + 1){\rho_r}^2}\left(\frac{S-1}{\rho_r} + \rho_r + S\right), \quad (8)$$

Note that the line width of the thermal source in equation (8) is expressed using Δf.

The received photocurrent's average value is determined by the following formula for the MQC code in equation (9):

$$I_M = \Re_{es}\frac{P_{Re}}{\rho_r}b, \quad (9)$$

Here, in equation (9), a specific user's bit value is indicated by b, which might be '0' else '1'.

Thus, by incorporating equations (6), (7), and (8) in equation (4), the overall noise variation for the MQC code can be expressed through equation (10) (Zou et al., 2001);

$$\sigma^2_{OMQC} = \frac{4K_{Bol}T_{AN}B_{el}}{R_{Ld}} + 2E_cB_{el}\Re_{es}P_{Re}\left[\frac{\rho_r - 1 + 2S}{\rho_r{}^2 + \rho_r}\right] + \frac{B_{el}\Re^2_{es}P^2_{Re}S}{\Delta f(\rho_r + 1)\rho_r{}^2}\left(\frac{S-1}{\rho_r} + \rho_r + S\right), \quad (10)$$

3.4. For RD Code

Again, the shot noise formula for RD code is signified by equation (11) (Fadhil et al., 2009);

$$\sigma^2_{Sh2} = \frac{2E_cB_{el}\Re_{es}P_{Re}W}{N}, \quad (11)$$

In equation (11), the code length of the RD code is represented using $N$and the code weight is expressed with W.

Thus, the equation of PIIN is derived as shown in equation (12) (Fadhil et al., 2009);

$$\sigma^2_{Pn2} = \frac{B_{el}\Re^2_{es}P^2_{Re}WS}{2\Delta f N^2}(S - 1 + W), \quad (12)$$

The formula of the average photocurrent received for the RD code is depicted in equation (13).

$$I_R = \frac{2\Re_{es}P_{Re}W}{N}, \quad (13)$$

Again, by incorporating equations (6), (11), and (12) in equation (4), the overall noise variation for the RD code can be written with equation (14) (Fadhil et al., 2009);

$$\sigma^2_{ORD} = \frac{4K_{Bol}T_{AN}B_{el}}{R_{Ld}} + \frac{2E_cB_{el}\Re_{es}P_{Re}W}{N} + \frac{B_{el}\Re^2_{es}P^2_{Re}WS}{2\Delta f N^2}(S - 1 + W), \quad (14)$$

Now, the system's signal-to-noise ratio (SNR) for MQC and RD codes can be expressed using equation (15). In the case of the MQC code, the SNR formula can be derived by incorporating equations (9) and (10) in (15). On the other hand, the SNR formula for the RD code can be derived by incorporating equations (13) and (14) in (15);

$$SNR = \frac{I^2}{\sigma^2_O}, \quad (15)$$

The following equation (16) can be used to compute the BER of the optical system by employing the SNR formula in equation (15).

$$BER = \frac{1}{2}erfc\left(\sqrt{\frac{SNR}{8}}\right), \quad (16)$$

4. RESULTS

The results have been attained by utilizing the MQC and RD code in the proposed SAC-OCDMA structure through the following steps. At first, the BER performances of the RD code in an underwater medium were analyzed by comparing it with the MQC code's performance. For that, parameter values mentioned in Table I have been incorporated with the codes to find results. Then collocated graph for the BER performance of RD and MQC code in underwater and free space has been discussed to compare the system's performance in the two channels. The selected parameters and test conditions for each finding are the ones that provide the most balanced result. After testing and analyzing multiple times, the values that consistently depicted superior results compared to others have been incorporated to ensure optimal effectiveness.

Table 1: List of Some Parameters and Their Value That Have Been Utilized to Attain the Results.

Parameter	Symbol	Value
Boltzmann constant	K_{Bol}	1.38×10^{-23}J/K
Responsivity (Deepa and Islam, 2019)	$\Re_{es}$	0.6 A/W
Electron's Charge	E_c	1.6×10^{-19}C
Load Resistance of Receiver (Das et al., 2022)	R_{Ld}	1030Ω
Receiver's Absolute Noise Temperature (Das and Islam, 2022)	T_{AN}	300K
Line Width (Deepa and Islam, 2019)	Δf	8 THz
Electrical Bandwidth (Deepa and Islam, 2019)	B_{el}	80 MHz
Prime Number (Das and Islam, 2022)	ρ_r	11
Optical Efficiency of Transmitter (Deepa and Islam, 2019)	η_{eT}	0.9
Optical Efficiency Receiver (Deepa and Islam, 2019)	η_{eR}	0.9
Divergence Angle of Beam for Transmission (Deepa and Islam, 2019)	ϕ_{bw}	40°

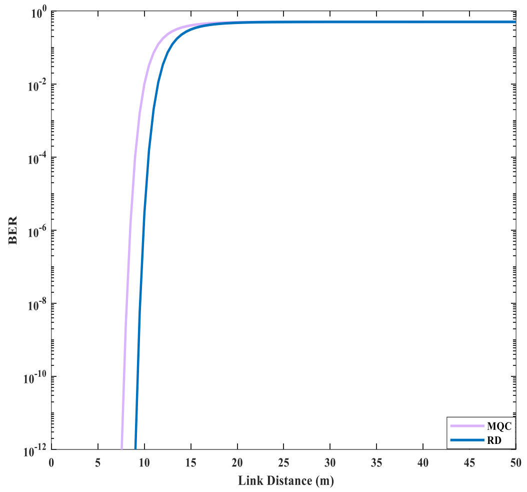

Figure 2.: Observation of BER variation according to link distance in coastal water medium for MQC and Rd codes.

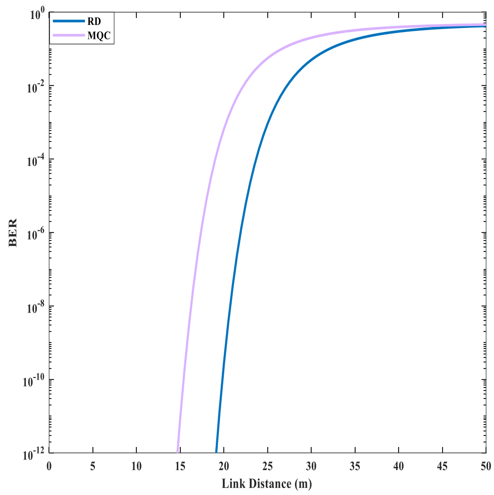

Figure 3: BER vs. link distance graph for comparing MQC and RD codes' performance in pure seawater medium.

Figure 2 denotes the alteration of BER vs link distance with respect to coastal water. Here, the inclination angle is 5°, the receiver's transmitted power is 30dBm, the number of simultaneous users is 49, and the prime number is 11. The figure depicts that with the increase of link distance, the BER increases significantly in both MQC and RD codes. So, it can be said that the performance of the system is dependent on the link distance. However, the RD code maintains a lower BER for longer distances than MQC. For the same BER at 10^(-9) the link distance achieved by MQC is 7.95 m, and for RD is 9.41 m. As the MQC code experiences the same error rate at a shorter distance than the RD code, it is less efficient than the RD code. which clearly shows that the RD code can transmit a signal at a greater range than the MQC code can.

Figure 3 represents the same graphical diagram but concerning pure seawater. By taking the same parameters as used for Figure 2, it is found that the productivity of RD is better compared to MQC. It shows the value of link distance 20.36 m for RD and 15.9 m for MQC for the 10^(-9) BER. At an equivalent error rate RD code is capable of covering a larger range than the MQC. At an equal distance of 25m MQC code shows a higher BER than the RD code. Thus, in this case, the RD code delivers better results.

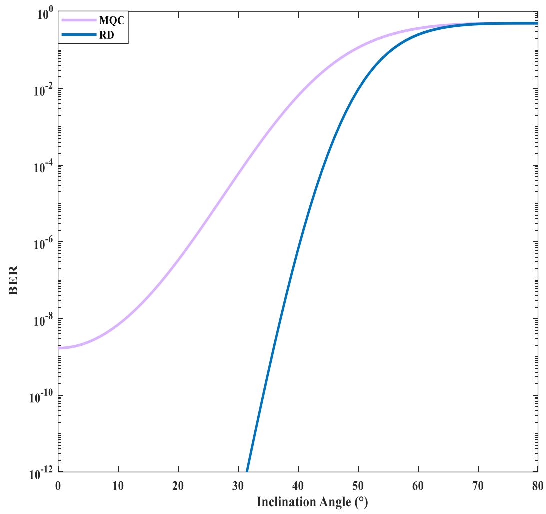

Figure 4: BER vs. inclination angle graph for comparing the MQC and RD codes' performance in coastal water.

Figure 4 shows the variation of BER vs inclination angle using both RD and MQC codes for coastal water. Here, the prime number is also 11, the transmitted power is 30dBm, the number of users is 49, and the link distance is 8m. The figure states that if the inclination angle increases, then the BER will increase in both cases. In addition, the RD code is showing a great result compared to MQC. Applying the RD code, the inclination angle is found to be 35.89° when the BER is 10^(-9) but applying the MQC code, for an 11.45° inclination angle, the BER level is 10^(-8). The graph illustrates that the RD code provides improved performance for this SAC-OCDMA structure.

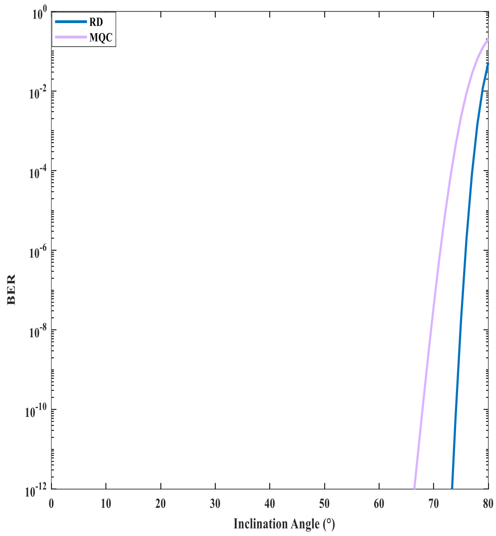

Figure 5: Observation of BER variation according to inclination angle in pure seawater for MQC and Rd codes.

Figure 5 shows the results of the same alteration based on pure ocean water. Here, all the values of the parameters are the same as in Fig. 4. The RD code is showing much better performance, i.e., the inclination angle is 74.51° when the BER is 10^(-9) on the contrary, the MQC code has a lower inclination angle, which is 68.81° for the same BER. This comparative data reveals that the RD code functions more efficiently than the MQC code for the given structure.

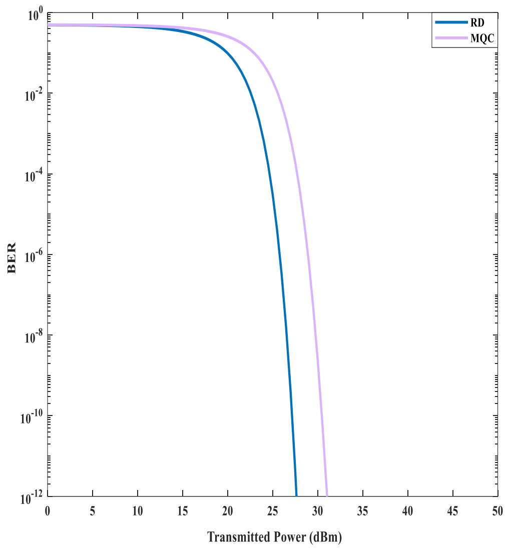

Figure 6: Analysis of BER variation according to transmitted power in coastal water for MQC and Rd codes.

Figure 6 illustrates the BER vs transmitted power curvature. The prime number is 11, the distance of the link is 8m, and the inclination angle is 5°. Here, the number of simultaneous users is 49. The figure clearly shows that the change in transmitted power is oppositely proportional to the BER. That means if the power of the transmission channel increases, the BER will be reduced. After that, the result is distinguished in both RD and MQC codes. Here, the transmitted powers are found at 26.66 dBm using the RD code and 30.12 dBm using the MQC code for the same BER of 10^(-9). So, it can be said that the efficacy of the RD code is better than the MQC code.

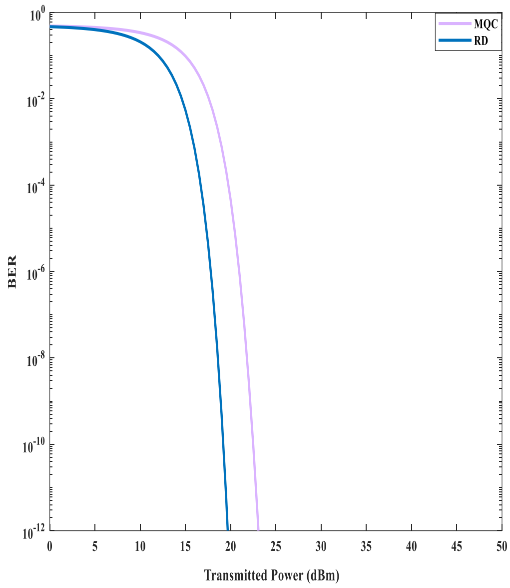

Figure 7: BER vs. transmitted power graph for comparing the MQC and RD codes' performance in pure seawater.

In Figure 7, pure seawater is taken to replace coastal water. All the parameters remain the same as in Figure 6. According to this graphical representation, it is found that the RD code is showing improved performance than the MQC code. The BER is obtained 10^(-9) at 18.87 dBm for RD and 22.12 dBm for MQC. Hence, using the RD code, less transmitted power is needed compared to the MQC code.

Figure 8 shows the variations of BER against several simultaneous users. It has taken the values of inclination angle 5°, transmitted power 30dBm, prime number 11, and link distance 8m. It is discovered that if the number of simultaneous users rises, the amount of BER rises proportionally. This problem occurred because of MAI (Multi-Access Interference). Since the system's prime number is 11, it can access a maximum of 121 simultaneous users at a time. According to the figure, the number of simultaneous users is found 94 when the BER is 10^(-9) for the RD code. But using the MQC code, the BER performance goes drastically down. The BER value is 10^(-9) for 45 simultaneous users.

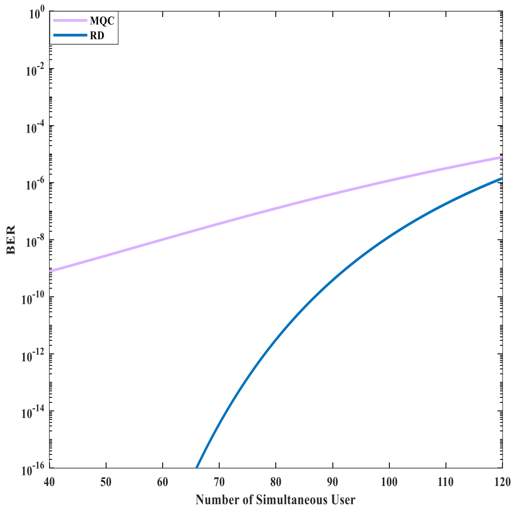

Figure 8: Assessment of BER variation according to the number of simultaneous users in coastal water for MQC and Rd codes.

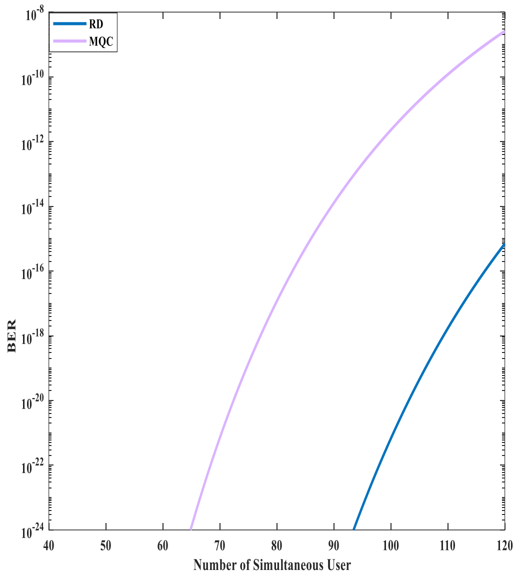

Figure 9: Assessment of BER variations regarding the number of simultaneous users in pure seawater for MQC and Rd codes.

In Figure 9, pure seawater is taken as the communication channel for examining variations in BER against the number of simultaneous users. The result highlights that the efficacy of the system for pure seawater is more effective than coastal ocean water because of impurities. Applying both RD and MQC codes for the same BER is 10^(-20). The number of simultaneous users has been evaluated at 103.5 and 72.5, respectively. Thus, the effective performance of the RD code is elucidated in this figure.

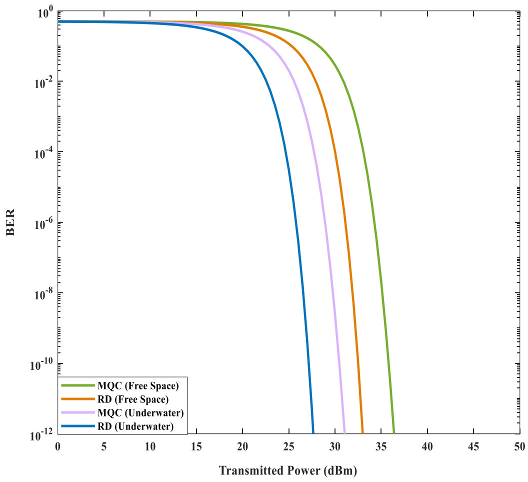

Figure 10: Comparison of BER variation according to transmitting power using MQC and Rd codes in air medium (foggy weather) and water medium (coastal ocean water).

Figure 10 showcases the alteration of BER vs. transmitted power. Here, the system performance has been tested considering two different types of communication channels: one is coastal ocean water, and the other is foggy weather in space. RD and MQC codes have been implemented to get such comparative results between them. For free space, the prime number is 11, and the link distance is 0.4m. For the underwater medium, those parameters are the same as the previous graphs. It is observed that in free space, using the RD code, the system is giving the value of transmitted power 32.17dBm when the BER is 10^(-9). By using MQC code requires 35.44 dBm transmitted power at the same BER level. On the other side, it is observed in coastal water that the system uses 26.84 dBm transmitted power at 10^(-9) BER using RD code and 30.1 dBm at the same BER using MQC code. The range covered by the signal in free space and underwater is not the same because the number of dissolved entities and the density of air and ocean water are not the same. The density of ocean water is much higher than that of air, and as a result, the wireless optical signal encounters more obstructions underwater than in the air. Though UWOC is capable of ensuring a high data transmission rate, the distance covered by the signal is limited to a few meters only. Seemingly, the figure explains that the RD code exhibits satisfactory performance when the transmitting channel is underwater.

Figure 11 represents the number of simultaneous users vs. BER curvature using both RD and MQC codes. Here, pure seawater and hazy weather for free space atmosphere have been taken as the communication channels. For free space, the prime number is 11, and the link distance is 0.1m. For the underwater medium, those parameters are the same as the previous graphs. From the illustration, it is found that in free space, the system will allow a maximum of 76.04 and 52.73 simultaneous users at the BER range of 10^(-18) using RD and MQC codes, respectively. Moving on to considering pure seawater, it is found that a maximum of 109.4 and 77.39 simultaneous users are allowed to access the system, maintaining 10^(-18) BER applies both RD and MQC codes. RD code performs better when transmitting underwater.

4. DISCUSSION AND COMPARISON

The results attained by employing the RD code and the MQC code reveal that, among pure seawater and coastal water, the pure seawater system delivers higher efficacy. In (Deepa and Islam, 2019), for the MQC code, researchers also discovered that their system provided better BER performance in pure seawater than the other two types of ocean water. Table II exhibits the comparison between the results of pure seawater and coastal water that has been attained from our analysis. As mentioned in Table II, our study indicates that, in pure sea water RD code covers a longer link distance, which is 20.36m, than it does in coastal water, which is 9.41m.

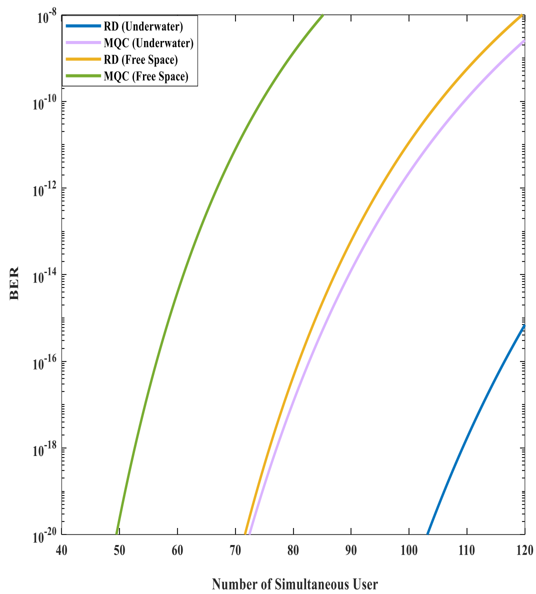

Figure 11: Comparison of BER variation according to the number of simultaneous users using MQC and Rd codes in air medium (hazy weather) and water medium (Pure Sea water).

Table 2: Comparison between results attained for pure seawater and coastal water for different parameters using the RD code at the BER level of 10^{-9} (inclination angle, link distance, transmitted power) and BER 10^{-16} (number of simultaneous users).

Parameters	Pure Sea Water	Coastal Water
Inclination Angle	74.51°	35.89°
Link Distance	20.36 m	9.41 m
Transmitted Power	18.87 dBm	26.66 dBm
No. of Simultaneous Users	117.5	66

Additionally, Table II shows that, through the implementation of RD codes, the system allows more simultaneous users, requires less transmitted power, and provides a higher inclination angle in the case of pure seawater than coastal water. Because in coastal water, the legion concentration of organic matter, such as phytoplankton, increases the possibility of scattering of the signal. Scattering is responsible for power loss, and it also leads to distortion of the signal. Furthermore, the presence of different types of dissolved salts increases attenuation in coastal water. These impurities are the reason behind the higher BER for coastal water than pure seawater (Khalighi et al., 2014). After comparing the system efficacy side-by-side for both codes in underwater and free space, it is conspicuous that in both environments RD code can deliver improved results than the MQC code. In (Das et al., 2022), the results also enumerated that the MQC code could not deliver higher efficacy than RD in free space. Turning to the details, this research examined if RD code is capable of providing higher simultaneous users using less transmitted power underwater compared to free space or not. It is explicitly observed that the RD code can give access to more simultaneous users in underwater environments than free space and needs less transmitted power to transmit a signal underwater than it needs in free space. However, the ranges covered in the two different types of channels are not the same. The overall inspection suggests that the RD code is a suitable choice over the MQC code for transmitting wireless optical signals underwater.

5. CONCLUSION

This research has scrutinized the performance of the RD code underwater through comparison with the MQC code's performance. The aim was to inspect which atmospheric channel between the underwater and free space RD code can provide satisfactory results. For measuring BER and the system's effectiveness, the influence of thermal noise, together with shot noise and PIIN noise, has been factored in. It has become clear upon examination of all the findings that our system can grant more simultaneous users with less amount of MAI, less transmitted power consumption, small inclination angle, and comparatively larger transmission distance at the implementation of the RD code, better than MQC in water medium. This is possible due to the RD code's zero cross-correlation value. Results highlight that the RD code is capable of permitting a higher number of simultaneous users when the transmitting channel is water. Additionally, for sending signals using the RD code, less transmitting power is required underwater than in free space. For coastal water, an approximately 11.5% reduction in the use of transmitted power is observed for RD code compared to MQC code, and for pure sea water, approximately 14.7% less transmitted power is needed for RD code compared to MQC code. These findings clearly demonstrates why the RD code is a preferable choice than the MQC code. The findings of this study are limited to comparing two types of code families only. Further research can be carried out by building other code families to improve the efficacy of this SAC-OCDMA system in aquatic channels, such as diagonal eigenvalue unity (DEU) codes. The DEU code is capable of dealing with an extensive number of users because of its diagonal structure, which can reduce interference. Due to its good scalability and flexible code construction, DEU shows better BER performance. It can provide optimal power efficiency and is capable of reducing loss of signal quality. DEU is a reliable code family that will possibly exhibit enhanced performance in the case of underwater wireless optical communication. Longitudinal research can be conducted considering rapid changes in the environment. Additionally, this study can be extended by building a better model employing a new detection technique for reducing MAI and attaining enhanced performance. We intend to verify the findings across different parameters in a practical environment in the near future.

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Consent to participate: All authors are contributing and agree to submit the current work.

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REFERENCES

Ahmed, H. Y., and Nisar, K. S. (2013) Diagonal Eigenvalue Unity (DEU) code for spectral amplitude coding-optical code division multiple access. Optical Fiber Technology, Vol. 19, No. 4, pp. 335–347.

Akhoundi, F., et al. (2016) Cellular Underwater Wireless Optical CDMA Network: Potentials and Challenges. IEEE Access, Vol. 4, pp. 4254–4268.

Alghamdi, R., et al. (2019) Towards Ultra-Reliable Low-Latency Underwater Optical Wireless Communications. King Abdullah University of Science and Technology Repository, Sep. 2019.

Arnon, S. (2010) Underwater optical wireless communication network. Optical Engineering, Vol. 49, No. 1, p. 015001.

Das, N., and Islam, M. J. (2022) Performance of MQC Code-Based SAC-OCDMA in FSO System. In Proc. 9th Int. Conf. on Innovations in Electron. and Commun. Engineering (ICIECE), Singapore: Springer Singapore, pp. 13-20.

Das, N., Islam, M. J., and Guho, A. (2022) Comparison of different codes on the Performance of SAC-OCDMA over FSO Link. In Proc. Int. Conf. on Recent Progresses in Science, Engineering and Technology (ICRPSET). IEEE.

Deepa, F. R., and Islam, M. J. (2019) BER Performance of Underwater Wireless SAC-OCDMA System using MQC codes. In Proc. Int. Conf. on Signal Processing, Information, Communication & Systems (SPICSCON), IEEE, pp. 9-12.

Diamant, R., et al. (2017) On the Relationship Between the Underwater Acoustic and Optical Channels. IEEE Transactions on Wireless Communications, Vol. 16, No. 12, pp. 8037–8051.

Fadhil, H. A., Aljunid, S. A., and Ahmad, R. B. (2009) Performance of random diagonal code for OCDMA systems using new spectral direct detection technique. Optical Fiber Technology, Vol. 15, No. 3, pp. 283–289.

Gupta, A., et al. (2014) A Survey of Free Space Optical Communication Network Channel over Optical Fiber Cable Communication. International Journal of Computer Applications, Vol. 105, No. 10, pp. 32–36.

Hamza, S. A., Aljunid, S., and Fadhil, H. A. (2012) Improved BER based on intensity noise alleviation using developed detection technique for incoherent SAC-OCDMA systems. Journal of Modern Optics, Vol. 59, No. 10, pp. 878–886.

Huurdeman, A. A. (2003) The Worldwide History of Telecommunications. New York: J. Wiley. [Online]. Available: https://www.wiley.com/en-sg/The+Worldwide+History+of+Telecommunications-p-9780471205050.

Kaushal, H., and Kaddoum, G. (2016) Underwater Optical Wireless Communication. IEEE Access, Vol. 4, pp. 1518–1547.

Kavehrad, M., and Zaccarin, D. (1995) Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources. Vol. 13, No. 3, pp. 534–545.

Kavehrad, M., and Zaccarin, D. (1995) Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources. Journal of Lightwave Technology, Vol. 13, No. 3, pp. 534–545.

Khalighi, M.-A., Gabriel, C., Hamza, T., Bourennane, S., Léon, P., and Rigaud, V. (2014) Underwater wireless optical communication; Recent advances and remaining challenges. In Proc. 16th Int. Conf. Transparent Opt. Netw., Graz, Austria, pp. 2–5.

Khatib, M. (2014) Contemporary Issues in Wireless Communications.

Naimullah, B. S., et al. (2008) Comparison of wavelength propagation for Free Space Optical Communications. Int. Conf. on Electron. Design, pp. 1-5.

Nisar, H. Y., et al. (2012) Improved BER based on intensity noise alleviation using developed detection technique for incoherent SAC-OCDMA systems. Journal of Modern Optics, Vol. 59, No. 10, pp. 878–886.

Noshad, M., and Jamshidi, K. (2011) Bounds for the BER of Codes With Fixed Cross Correlation in SAC-OCDMA Systems. Journal of Lightwave Technology, Vol. 29, No. 13, pp. 1944–1950.

Oubei, H., et al. (2015) 2.3 Gbit/s underwater wireless optical communications using directly modulated 520 nm laser diode. Optics Express, Vol. 23, No. 16, pp. 20743-20748.

Rashed, A. N. Z., and Sharshar, H. A. (2013) Performance Evaluation of Short Range Underwater Optical Wireless Communications for Different Ocean Water Types. Wireless Personal Communications, Vol. 72, No. 1, pp. 693–708.

Reynaert, P., et al. (2016) Polymer Microwave Fibers: A blend of RF, copper and optical communication. Sep. 2016.

Sahbudin, R., et al. (2008) Comparative Performance of Hybrid SCM SAC-OCDMA System Using Complementary and AND Subtraction Detection Techniques. Int. Arab J. Inf. Technol., Vol. 5, No. 1, pp. 61-65.

Schuster, J., Willebrand, H., Bloom, S., and Korevaar, E. (2003) Understanding the performance of Free Space Optics. Journal of Optical Networking.

Simpson, J. A., et al. (2010) 5 Mbps optical wireless communication with error correction coding for underwater sensor nodes. In OCEANS 2010, IEEE, pp. 1-4.

Smith, E. D. J., Blaikie, R. J., and Taylor, D. P. (1998) Performance enhancement of spectral-amplitude-coding optical CDMA using pulse-position modulation. IEEE Transactions on Communications, Vol. 46, No. 9, pp. 1176–1185.

Stucchi, M., Cosemans, S., Van Campenhout, J., Tőkei, Z., and Beyer, G. (2013) On-chip optical interconnects versus electrical interconnects for high-performance applications. Microelectronic Engineering, Vol.

112, pp. 84–91.
Tseng, S.-P. (2019) A New Polarization-SAC Scheme Suitable for Compact OCDMA-FSO Networks. IEEE Systems Journal, Vol. 13, No. 2, pp. 1332–1335.
Vali, Z., et al. (2018) Experimental study of the turbulence effect on underwater optical wireless communications. Applied Optics, Vol. 57, No. 28, p. 8314.
Willebrand, H., and Schuster, J. (2003) Understanding the performance of Free Space Optics. Journal of Optical Networking.
Xiao, Y., et al. (2022) Physically-secured high-fidelity free-space optical data transmission through scattering media using dynamic scaling factors. Optics Express, Vol. 30, No. 5, pp. 8186–8186.
Zou, W., Shalaby, H., and Ghafouri-Shiraz, H. (2001) Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude-coding optical CDMA systems. Journal of Lightwave Technology, Vol. 19, No. 9, pp. 1274–1281.