

Secure Visible Light Communication Using ZCC Codes for the Underwater Communication



Ajay Yadav, Ashok Kumar, Rahul Mukherjee, Arjun Kumar, Jitendra Kumar Deegwal, and Ghanshyam Singh

Abstract In this research work, performance of spectral amplitude coding-optical code division multiple access (SAC-OCDMA) system is evaluated in presence of strong turbulence and different water types. The performance of the SAC-OCDMA system is good in presence of pure sea and clean ocean. Error probability of 10^{-3} is feasible with pure sea and clear ocean when the number of users is more than four with transmitted power of 30 dBm. For a four user SAC-OCDMA system, error probability of 10^{-3} is not feasible when the transmitted power is below 27 dBm (transmitted power eye safety limit is 27 dBm (500 mW)) in coastal water.

Keywords UWOC · 2D · ZCC · Gamma-Gamma · SAC-OCDMA

1 Introduction

With the advent of 5G communication, researchers are targeting high data rate, and low latency multiple access network in the underwater environment. Due to low data rate (10–100 kbps) and low speed (≈ 1500 m/s), acoustic communication systems will not be able to meet the requirements of 5G and 6G communication. The lower speed of acoustic signals causes high latency in the underwater long-distance communication. As a result, synchronization and decoding of multiple access techniques like optical code division multiple access (OCDMA) is affected. For 6G communication, wireless optical communication (WOC) is a promising solution in the underwater channel as compared to acoustic communication. The advantages of

A. Yadav (✉) · R. Mukherjee · A. Kumar

Department of Electronics and Communication Engineering, Bennett University, Greater Noida, Uttar Pradesh 201310, India

e-mail: ajayyadavbsz@gmail.com

A. Kumar · J. K. Deegwal

Department of Electronics and Communication Engineering, Government Mahila Engineering College, Ajmer, Rajasthan 305002, India

G. Singh

Department of Electronics and Communication Engineering, MNIT, Jaipur, Rajasthan 302017, India

WOC over acoustic communication are high data rate, better security, and very low latency. Although WOC is superior to acoustic communication in few performance parameters, it suffers from attenuation and turbulence in the underwater channel. Attenuation and turbulence affect the performance in the underwater environment by limiting the distance of communication up to few meters [1].

For the multi-user communication system, OCDMA is very useful due to asynchronous access, security, and good performance during heavy data traffic. Spectral amplitude coding-OCDMA (SAC-OCDMA) is considered for this evaluation for the underwater channel due to zero multiple access interference (MAI). Various codes like modified quadratic congruence (MQC) codes, double weight (DW) code family, Khazani-Syed (KS) code, random diagonal (RD) code, etc. have been reported in literature [2]. The performance of the code improves with increase in code-weight. Depending up on the code weight, the various codes can be used for multimedia services like voice, video, and data transmission. In this work, double weight multi-diagonal (DW-MD) code is used in SAC-OCDMA system. The performance of the SAC-OCDMA system is evaluated in the moderate and strong turbulence regimes along with the attenuation due to different water types. Pure sea, clear ocean, and coastal water have attenuation coefficients of 0.056, 0.15 and 0.305 m^{-1} , respectively [3]. The research is organized into various Sections as: Sect. 2 describes the UWOC SAC-OCDMA system. The mathematical analysis of SAC-OCDMA system and effect of various parameters on error probability is studied in Sect. 3. The results are discussed in Sects. 4.

2 SAC-OCDMA System

The block diagram of SAC-OCDMA system is shown in Fig. 1. The incoherent source like LED or broadband laser emits broad spectrum which is fed to the encoder. In the encoder, chip sequence of the DW-MD code is assigned, and different wavelengths

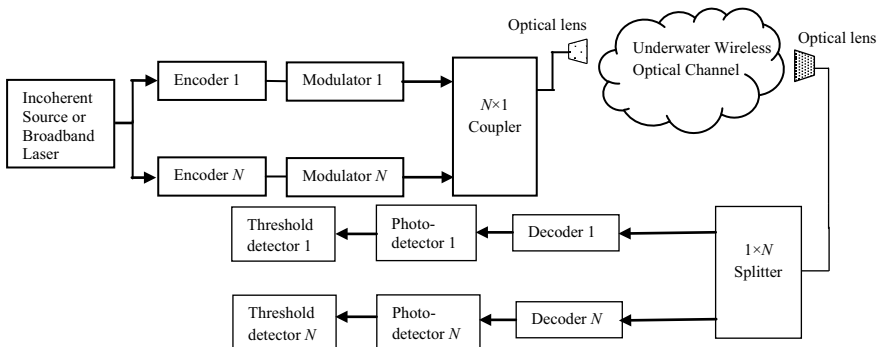


Fig. 1 Underwater wireless optical communication SAC-OCDMA system

are allocated to the chip sequence. External modulator like Mach-Zehnder modulator is used after the encoder to modulate the encoded signal [2]. Further, the modulated data bits are combined using $N \times 1$ coupler and transmitted via optical lens. The optical lens collimates the optical signal to avoid beam divergence. The transmitted signal undergoes attenuation and fading in the underwater channel. At the receiver, the data bits are recovered using splitter, decoder, photodetector and threshold detector.

3 Channel Modeling

When the optical signal is transmitted from the optical lens then the beam diverges. The spreading of the optical signal around the transmitter optical lens is called beam divergence. The optical signal absorption and scattering along with the beam divergence is well explained by Beer-Lambert's law which is given by [4].

$$\beta = \frac{A}{\pi \left(\frac{\phi_s L}{2}\right)^2} e^{-\gamma l} \quad (1)$$

where A is the receiver aperture area, ϕ_s the beam divergence angle (in radian), l the link length (meters), and γ represents the attenuation factor (m^{-1}), respectively.

In the underwater channel, the impact of turbulence is also present along with the beam divergence, absorption and scattering. At few places, the effect of turbulence is very prominent. To study the effect of strong turbulence in the underwater channel, gamma-gamma probability density function (pdf) model is used in this research work. Gamma-gamma pdf is described as

$$f_X(x) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} x^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta x}) \quad (2)$$

Here α and β are small- and large-scale eddies, respectively. $\Gamma(\cdot)$ is the gamma function, and $K_n(\cdot)$ is the modified Bessel function of second kind. For DW-MD code, when w is the code weight, and N is the number of users supported then code length (L) is wN . The received power P_R is given by [4].

$$P_R = \beta \frac{P_T w}{NL} \quad (3)$$

where P_T is the transmitted power. The number of photons absorbed per chip time is [5].

$$\lambda_s(x) = \frac{\eta x P_R}{hf} \quad (4)$$

The various parameters in Eq. (4) are quantum efficiency η , Planck's constant h and average optical frequency f . The output of APD for data bit "1" can be represented with Gaussian conditional pdf as given by

$$f_{Y1}(y|x, b = 1) = \frac{1}{\sqrt{2\pi\sigma_1^2(x)}} \exp\left(-\frac{(y - \mu_1(x))^2}{2\sigma_1^2(x)}\right) \quad (5)$$

The mean and variance for data bit "1" is defined as

$$\mu_1(x) = GT \left[w\lambda_s(x) + L \left(\lambda_b + \frac{I_b}{e} \right) + (wN - w)\lambda_s(x)/M_e \right] + LTI_s/e \quad (6)$$

and

$$\sigma_1^2(x) = G^2 FT \left[w\lambda_s(x) + L \left(\lambda_b + \frac{I_b}{e} \right) + (wN - w)\lambda_s(x)/M_e \right] + \frac{LTI_s}{e} + L\sigma_{Th}^2 \quad (7)$$

Similarly, the conditional output pdf for data bit "0" is illustrated as

$$f_{Y0}(y|x, b = 0) = \frac{1}{\sqrt{2\pi\sigma_0^2(x)}} \exp\left(-\frac{(y - \mu_0(x))^2}{2\sigma_0^2(x)}\right) \quad (8)$$

The mean and variance for data bit "0" is given by

$$\mu_0 = GT \left[L \left(\lambda_b + \frac{I_b}{e} \right) \right] + LTI_s/e \quad (9)$$

and

$$\sigma_0^2 = G^2 FT \left[L \left(\lambda_b + \frac{I_b}{e} \right) \right] + \frac{LTI_s}{e} + L\sigma_{Th}^2 \quad (10)$$

The various parameters used in the Eqs. (6, 7, 9 and 10) are APD gain G , photons due to background noise λ_b , bulk leakage current I_b , surface leakage current I_s , extinction ratio M_e , excess noise factor F_e , and thermal noise per chip σ_{Th}^2 , respectively. The intensity modulation and direct detection (IM/DD) error probability is given as

$$P_e(x) = \frac{1}{2} \left[\mathcal{Q} \left(\frac{\mu_1(x) - Th}{\sigma_1(x)} \right) \right] + \frac{1}{2} \left[\mathcal{Q} \left(\frac{Th - \mu_0}{\sigma_0} \right) \right] \quad (11)$$

The average probability of error P_E is

$$P_E = \frac{Min}{Th} \int_0^\infty P_e(x) f_X(x) dx \tag{12}$$

Gamma-Gamma pdf $f_x(x)$ and brute search algorithm is used to minimize the probability of error with respect to receiver threshold Th .

4 Results and Discussion

The performance of the SAC-OCDMA system is evaluated in the presence of strong turbulence and various water types. The receiver aperture diameter is 5 cm, link length is 20 m, and beam divergence angle is 12 mrad in the analysis. For mathematical simplicity, the average wavelength of 532 nm is used from the visible light spectrum. Also, the attenuation is less in the water at this wavelength. Figure 2 shows the variation of error probability with transmitted power in the underwater channel. The performance of four user SAC-OCDMA system is best in the pure sea and deteriorates in the clear ocean and coastal water. For $P_E = 10^{-3}$, the transmitted power P_T is 19, 27 and 40 dBm for pure sea, clear ocean, and coastal water, respectively. The increase in transmitted power decreases the error probability.

For $P_T = 30$ dBm, the error probability is varied with the number of users (N) as shown in Fig. 3. For $P_E = 10^{-3}$, 5 and 11 users are required in clear ocean and coastal water when $P_T = 30$ dBm. In presence of coastal water, it is not feasible to obtain $P_E = 10^{-3}$ irrespective of transmitted power for $N \geq 4$. The increment in

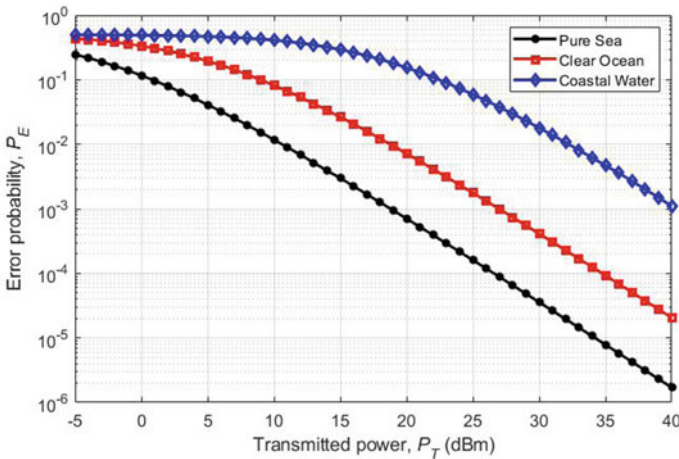


Fig. 2 Error probability versus transmitted power of SAC-CDMA system in the underwater channel

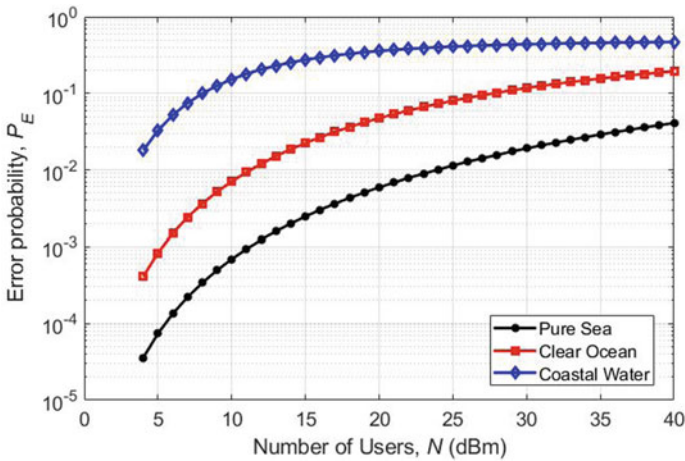


Fig. 3 Error probability versus number of users of SAC-CDMA system in the underwater channel

the number of users increases P_E . For $P_E = 10^{-3}$, the number of users should be less than 5 and 11 at $P_T = 30$ dBm. The transmitted power above 27 dBm is also not eye safe. To obtain error probability less than 10^{-6} , performance enhancement techniques like aperture averaging, diversity techniques like multiple input multiple output (MIMO), forward error correction (FEC) can be used in the SAC-OCDMA system [6, 7]. Secure visible light communication can play very important role in 5G and 6G communication. It can be used as a secure mode of communication in boats, ships, and aircraft carriers.

5 Conclusion

In the underwater environment, SAC-OCDMA system is a secure communication with low latency, and large bandwidth. The performance of the SAC-OCDMA system in presence of strong turbulence and attenuation by different water types is studied. It has been analyzed that performance is good in presence of pure sea and clear ocean. With strong turbulence and coastal water, performance of the SAC-OCDMA system is very poor. Performance enhancement techniques like space diversity, time diversity and error correcting codes can improve the performance of SAC-OCDMA system.

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