Performance of different O-OFDM techniques in weak turbulence underwater Visible Light Communication

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I. Abstract

This paper is about the underwater communication system which focus on wireless networks in view of the recent advances in wireless technology and the growing need for deep ocean data mining. Underwater wireless optical communication (UWOC) has many advantages of short-distance wireless connectors due to its much higher bandwidth and data level than acoustic communication. In this Paper the two Optical Wireless Orthogonal Frequency division multiplexing (OFDM) techniques in Underwater Optical Communication are compared with their performance in different types of water. These are asymmetrically clipped optical OFDM (ACO-OFDM) and DC biased optical OFDM (DCO-OFDM). The comparison is done by the analysis of BER versus SNR of ACO-OFDM and DCO-OFDM for 4 QAM modualtion systems. DCO-OFDM is less efficient in terms of optical power than ACO-OFDM for lower SNR value. But for higher SNR values it is power efficient. This is because the DC bias used in DCO-OFDM is inefficient in terms of optical power, while the use of only half of the subcarriers to carry data in ACO-OFDM is inefficient in terms of bandwidth.

Keywords— ACO-OFDM, DCO-OFDM, Underwater Optical Communication System

II. Introduction

Underwater (UW) wireless communication refers to transmission of digital data though an underwater wireless channel using radio frequency (RF) waves, acoustic waves or optical waves as carriers. The transmission of data underwater using wired cables is not feasible in certain situations like temporary experiments, breaking of wires, and experiment over long distances. So to cope up with these situations, we require UW wireless communication. Also, as the UW operations such as oceanographic studies, offshore oil drilling, seafloor surveying, and monitoring has risen dramatically, reliable and high-data-rate UW wireless communication links are required. Some of the advantages of UW communication are,

- UW wireless communication can be used to provide early warning of tsunamis generated by undersea earthquakes,
- It avoids data spoofing and privacy leakage, and
- It is advantageous in pollution monitoring.

Acoustics, RF, and Optics are the three options for implementing UW communication. i)Acoustic UWC: This is the most widely used and proven technology for UW wireless communication. The acoustic link range is several tens of km's which is much larger than RF and optical link ranges [1]. Low data rates (in kbps) [2], severe communication delays (in seconds), costly and energy consuming transceivers are some of the limitations of this UWC method. ii) RF UWC: It has the advantage of smooth transition through air/water interface. Also RF signal can tolerate large turbulence than optical and acoustic communications [3]. But it supports short link ranges (upto few meters) and its transceivers are also costly and energy consuming. iii) UW optical communication or visible light communication (VLC): UW optical communication has the highest transmission data rate (in Gbps), high bandwidth, lowest link delay and lowest implementation cost of the three. So it can be used for real time data transmission applications as well. UW optical communication is also highly secured than RF and acoustic communication. Some of the limitations of UW optical communication are, large absorption and scattering of optical signal under water, requirement of precise alignment condition, and requirement of reliable underwater devices.

Underwater sensor networks (UWSNs) are networks that are designed to meet the growing demand for ocean exploration. Seabed sensors, relay buoys, autonomous underwater vehicles (AUVs), and remotely operated underwater vehicles (ROVs) are all part of the UW sensor network. These nodes can perform sensing, processing, and communication duties in order to perform joint monitoring of the UW environment. The UW optical communication has been substantially influenced by these UW sensor networks. In these systems, low cost light

TABLE I

UWC Technologies	RF	Acoustic	Optical
Data rate	$1-10$ Mbps for $1-2$ m $50-100$ bps for 200 m	$1.5-50$ kbps for 0.5 km $0.6-3.0$ kbps for $28-120$ km	1 Gbps for 2 m 1 Mbps for 25 m
Bandwidth	MHz	Hz	MHz
Frequency range (Hz)	$30-300$	$10-1000$	$10_{12}-10_{15}$
Communication range	Few meters (Up to 10m)	Kilometers (Up to 20 km)	Several meters (Up to 100 m)
Efficiency	medium at short range	Medium (Non-Multipath)	Highest (Non Trubid)
Latency	Moderate	High	Low

sources like light emitting diodes (LEDs) and LASER diodes are used.

III. LITERATURE SURVEY

In [4], the authors have studied about the light in the sea which may be due to sun or stars, chemical or biological process or by the man-made sources. Light is the primary source of energy which support ocean ecology. This paper discuss about the optical nature of ocean water by investigating the data from last two decades. The distribution of flux diverging from localized UW light sources, propagation of highly collimated beams of light, penetration of data light into sea and utilization of solar energy for heating, photosynthesis, vision and photography are also studied. One such case study is about the least absorption of blue-green wavelengths in UWC.[5] is about the use of RF for UW wireless communication. It provides an overview of all the three major UW transmission technologies i-e RF, acoustic and optics. Also, the comparison between these techniques is provided, indicating that RF has a great potential for UW transmission. It has been revealed that RF is the best technology for UW transmission when used along with digital technology and signal compression techniques. [6] is a survey of existing acoustic technology and its use in UW data transmission. An UW acoustic network is a network made of many sensor nodes which collect data and transfer it to an on-shore facilities. This paper mainly focus on problems faced by such kind of UW acoustic networks. Some of the problems which were focused on include severe battery power limitations, severe BW limitations, channel characteristics including long propagation times, multipath and signal fading etc. Some of the network protocols, routing algorithms and multiple access methods are also discussed.According to this paper, CDMA is the best and most robust multiple access method for UW wireless communication comparative to other multiple access methods. In [7], authors have studied about the channel modelling of UW optical communication system. Here the impact of water type, link distance and transmitter/receiver parameter over channel time dispersion is presented. In this study, a more practical system parameters, and more realistic water parameters are considered. Intensity modulation with non-coherent detection is used. It was found that the chlorophyll concentration(C) has large impact on b(scattering coefficient) than a(absorption coefficient),where a and b are related to attenuation coefficient c as

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

UW VLC employs intensity-modulation and direct-detection (IM/DD) using a basic modulation technique such as on-off keying because it is simple and cost-effective (OOK). However, the intensity-based OOK modulation's performance severely degrades even in weak turbulence.

OFDM (orthogonal frequency-division multiplexing) is a particular SC system with subcarrier spacing that is orthogonal. Because of its high spectral efficiency, resistance to ISI, and frequency-selective fading, OFDM is commonly used in the VLC system. Despite the fact that OFDM outperforms a variety of modulation methods in a band-limited channel, its performance is also influenced by the channel's bandwidth.

A. UWOC Link

1) System Model of DCO-OFDM: Figure 1 shows the system model of DCO-OFDM. The typical approach of trans-

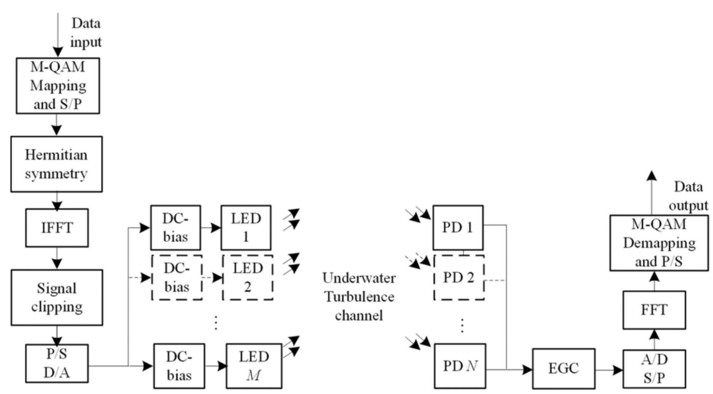

Fig. 1: The block diagram of MIMO DCO-OFDM scheme for UVLC.

lating input bits streams to L-QAM constellations (where $\log_2(L) > 0$ is an integer)is used and then serial-to-parallel (S/P) conversion is done to generate DCO-OFDM . The input symbol X_m to IFFT must then retain Hermitian symmetry, i.e., the subcarriers of the L-QAM OFDM symbol must satisfy:

$$X_m = X^*_{N_{fft-m}}, 0 < m < \frac{N_{fft}}{2}, \tag{1}$$

$$X_0 = X_{Nfft/2} = 0 \tag{2}$$

To reduce the dynamic range of DCO-OFDM signals, the IFFT signal is clipped to the upper and lower levels. A digital-to-analog (D/A) converter converts the clipped signal to an analogue signal, which is then converted to a real signal by the addition of a proper DC-bias given as

$$I_{DC} = g\sqrt{E_s} \tag{3}$$

where g is the normalised bias and E_s is the energy per symbol. The incoming optical signal is transformed into an electrical signal before being merged with equal gain combining (EGC).

2) System Model of ACO-OFDM: Figure 2 shows the block diagram of ACO-OFDM for UVLC. Only the odd subcarriers carry data symbols in ACO-OFDM, while the even subcarriers form a bias signal that ensures the transmitted OFDM signal meets non-negativity requirements.Only odd components make up the IFFT's input signal.

The ACO-OFDM transmitter's front-end is similar to that of a DCO-OFDM transmitter.The receiver's processing is similar to that of a DCO-OFDM receiver, with the exception that only the odd subcarriers are demodulated in ACO-OFDM, as these carry the data symbols.

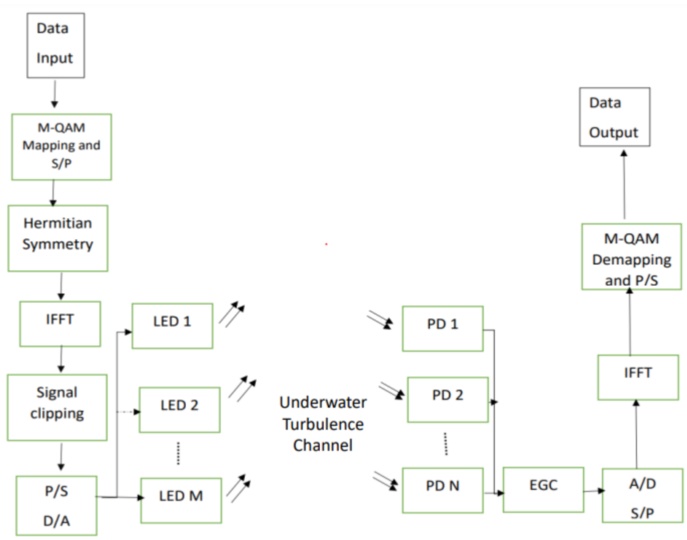

Fig. 2: The block diagram of MIMO ACO-OFDM scheme for UVLC.

3) Path loss and Fading: The path loss of the UWOC link depends upon the attenuation loss and the geometric loss [8]. The attenuation loss which depends on the type of water is modeled using well-known Beer-Lambert's law as

$$PL_{att.} = e^{-c(\lambda)d} \tag{4}$$

where $c(\lambda)$ is wavelength dependent extinction/attenuation coefficient and is the summation of the absorption coefficient (a) and scattering coefficient (b), which can be expressed as

$$c(\lambda) = a(\lambda) + b(\lambda).$$

The spread of the transmitted beam between the transmitter (LED) and receiver causes geometric loss that is dependent on the system's transceiver characteristics. It can be expressed as

$$PL_{gem.} = \frac{A_R(m+1)\cos(\theta_{1/2})^m}{2\pi d^2}, \tag{5}$$

where, A_R is photodetector (PD) area, d is the link distance $\theta_{1/2}$ is the angle of irradiance, m denotes the order of Lambertian emission given as $m = -1/\log_2(\cos(\Theta_{1/2}))$, wherein, $\Theta_{1/2}$ denotes semi angle of the light source. From (4) and (5), the total path loss (DC gain) for the underwater optical communication link can be obtained as

$$H = \left(\frac{A_R(m+1)\cos(\theta_{1/2})^m}{2\pi d^2}\right) e^{-c(\lambda)d} \tag{6}$$

Additionally, the refractive index of water changes due to change in temperature and salinity resulting in optical turbulence, which causes signal fading. To model this fading, the lognormal fading model is used as the weak turbulence is considered. The probability density function (PDF) of this lognormal fading can be given as,

$$f(\alpha) = \frac{1}{(2\alpha\sqrt{2\pi\sigma_\rho^2})} \exp\left(\frac{-(\ln(\alpha) - 2\mu_\rho)^2}{(8\sigma_\rho^2)}\right), \tag{7}$$

where, α is turbulence-induced fading coefficient and it can be expressed as

$$\alpha \sim \mathcal{N}(2\mu_\rho, 4\sigma_\rho^2),$$

where, the mean and variance of normal-distributed fading log-amplitude are denoted by μ_ρ and σ_ρ respectively, while the fading log-amplitude is denoted as $\rho = \frac{1}{2}\ln(\alpha) \sim \Omega(\rho, \mu_\rho, \sigma^2)$. The scintillation index is a measurement of turbulence strength that can be defined as

$$\sigma_I^2 = \frac{< I^2 > - < I >^2}{< I >^2},$$

where, $<>$ is the mean operator. Normalization of (11) leads to

$$\mu_\rho = \frac{-\sigma_\rho^2}{2}.$$

The following equation describes the relationship between scintillation index and log amplitude variance

$$\sigma_I^2 = \exp(4_\rho^2) - 1.$$

B. BIT ERROR RATE (BER) ANALYSIS FOR EGC

The electrical signal-to-noise ratio (SNR) (γ_{EGC}) can be derived as [9]

$$\gamma_{EGC} = \left(\frac{\eta k P_s}{MN\sigma}\right) E[x]^2 \left(\sum_{m=1}^{M}\sum_{n=1}^{N} \alpha_{mn} h_{mn}\right) \tag{8}$$

where $\alpha_{mn}$and h_{mn} represent the fading coefficient and channel path loss (or DC gain) from the mth transmitter to the nth receiver, respectively. e η denotes the photodiode (PD) responsivity, k is the modulation index, x(t) represents the OFDM signal, and n(t) is the additive white Gaussian noise (AWGN) signal where σ^2 is the AWGN variance.

Furthermore, the BER performance of L-QAM O-OFDM can be calculated using the following analytical expression:

$$p_e = \frac{4\sqrt{L} - 1}{\sqrt{L}\log_2(L)} Q\left(\sqrt{\frac{3}{L-1}\gamma_{eff}}\right) \tag{9}$$

IV. NUMERICAL RESULTS

In this section, the numerical results are shown and discussed which are obtained for channel impulse response and BER performance of 4-QAM DCO-OFDM UVLC under weak turbulence. We used the Monte-Carlo Ray tracking system to mimic the free impulse response (FFIR) and route loss (PL). Simulation parameters are given in Table II.

A. DCO-OFDM for UVLC

This section contain the results which are the implementation of the base paper (”Performance of Spatial Diversity DCO-OFDM in a Weak Turbulence Underwater Visible Light Communication Channel” Hongyan Jiang , Hongbing Qiu , Ning He, Wasiu Popoola , Senior Member, IEEE, Zahir Ahmad , and Sujan Rajbhandari , Senior Member, IEEE).All the results shown are similar to that of the paper.

TABLE II
SIMULATION PARAMETERS

Parameters		Value
Transmitter	Wavelength	532 nm
	Full beam divergence angle	10°
	No. of Transmitter	1, 2 and 4
	Transmitter separation	30 cm
Channel	Refractive index of Water, *n*	1.331
	Link distance	12 m
	Absorption coefficient	0.179 m^{-1} coastal water
	Scattering coefficient	0.219 m^{-1}
Receiver	Aperture diameter	20 cm
	Half angle FOV	90^0
	No. of receiver	1,2 and 4
	Receiver separation	30 cm
	Photon weight threshold	10^{-4}

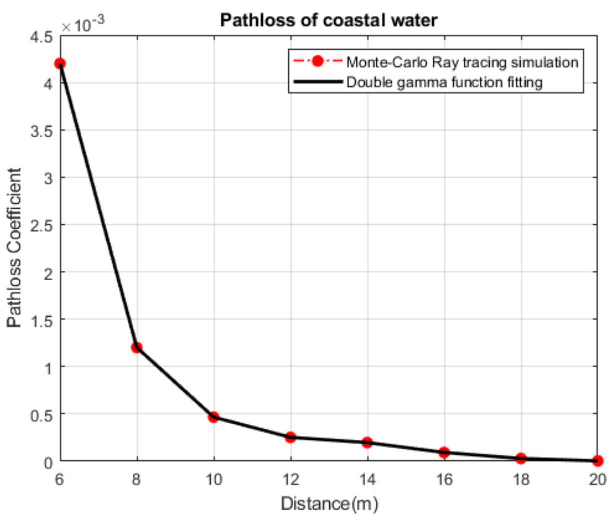

Fig. 3: DCO-OFDM - The The path loss coefficient as a function of link distance in coastalwater

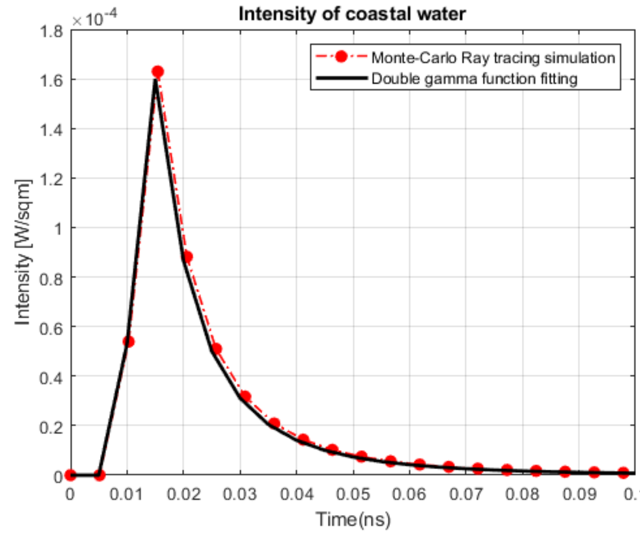

Fig. 4: The FFIR for a UVLC link with a distance of 12 m in the coastal water.

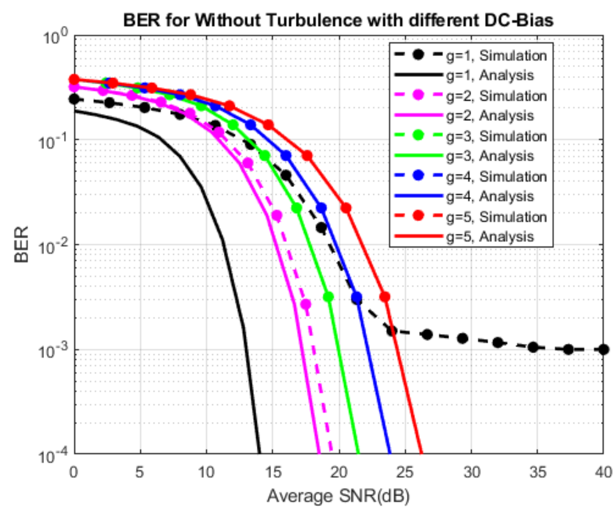

Fig. 5: The simulation and theoretical BER of 4-QAM DCO-OFDM in an AWGN channel without turbulence and with different DC-bias levels.

As can be seen from the figure(5), the theoretical prediction and simulation results match closely for the large DC-bias level of $g >= 3$ that avoids significant clipping distortion. There is a small deviation between the theoretical and simulated results for g = 2. However, at g = 1, the simulation results show that there is a BER floor of 10^3. This is due to high clipping noise. The clipping noise is not included in the theoretical prediction and hence there is a difference in the theoretical and simulated BER for g = 1 and 2. Furthermore, the figure clearly demonstrates that increasing the DC-bias level reduces the electrical power efficiency. Hence, g = 3 is selected in the rest of the study as this offers the best electrical power efficiency without any clipping noise.

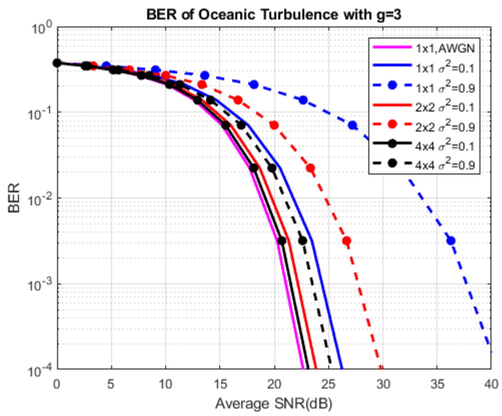

Fig. 6: The simulation BER performance of spatial diversity 4-QAM DCO-OFDM in oceanic turbulence channel with g = 3, and $\sigma^2 = 0.1, 0.9$.

Fig. 6 demonstrates a clear advantage of diversity schemes in the presence of turbulence, especially for the strong turbulence. The diversity order of 2 × 2 and 4 × 4 outperforms the BER performance of the single channel. It is also obvious that as the turbulence strength increases, the BER performance of single-channel worsens. By comparison, turbulence strength has less influence on BER performance with a large diversity order.

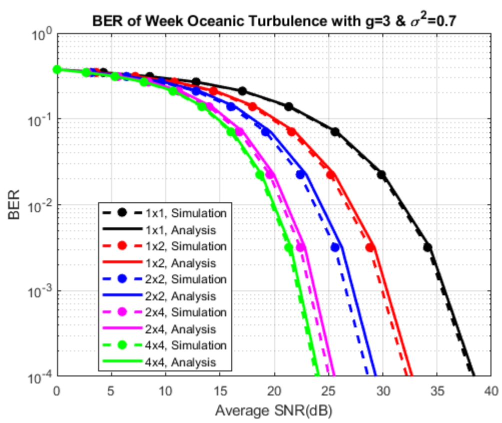

Fig. 7: The theoretical and simulation BER performance 4-QAM DCO- OFDM in a weak oceanic turbulence channel with g = 3 and a**2 = 0.7 with different spatial diversity orders.

B. Novel results

The figure 8 shows the ber performance of 4-QAM DCO-OFDM in weak turbulence channel for clear ocean water (c=0.305) and Turbid harbor water (c=2.17). From the figure it is clear that BER performance of clear ocean water is better than that of Turbid harbor water. Also, the performance of clear ocean water is better even for different spatial diversity orders as shown in figure 9.

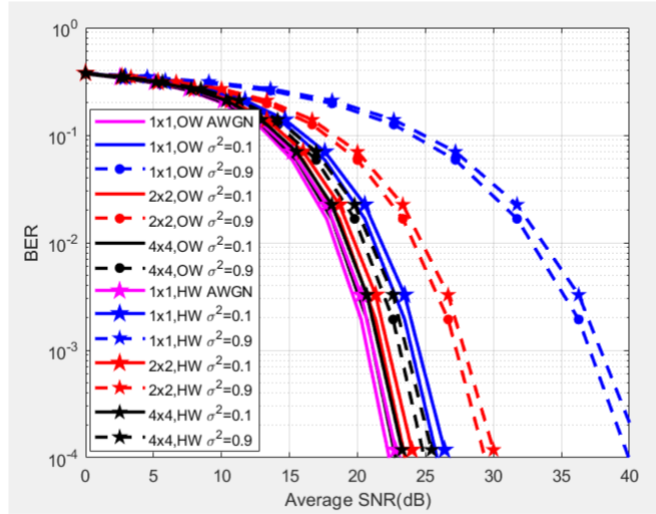

Fig. 8: The simulation BER performance of spatial diversity 4-QAM DCO-OFDM in weak turbulence channel with g = 3, and σ^2 = 0.1 and 0.9 for different water types

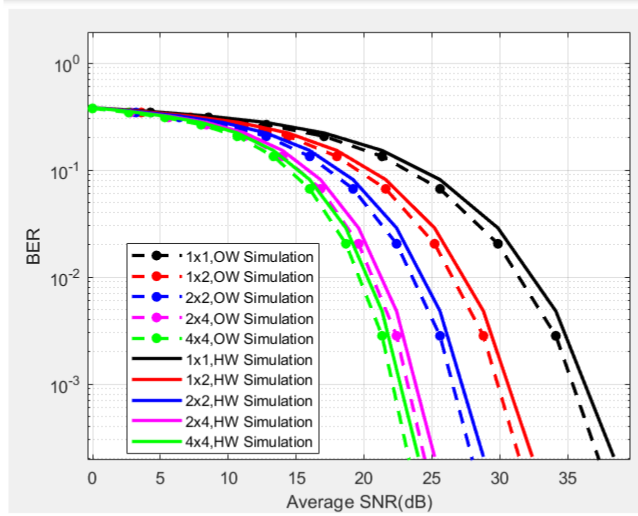

Fig. 9: BER performance of 4-QAM DCO-OFDM in a weak oceanic turbulence channel with g = 3 and σ^2 = 0.7 with different spatial diversity orders for different water types

1) DCO OFDM vs ACO OFDM: The comparison is done by the analysis of BER versus SNR of ACO-OFDM and DCO-OFDM using 4 QAM modulation systems. DCO-OFDM is more efficient as can be seen in below figure. Since there is no DC-bias for ACO-OFDM, it has significant advantages in terms of power efficiency. i.e. DCO-OFDM is less efficient in terms of average optical power in lower SNR values but for larger values it is power efficient.

Figure 10 shows the EGC diversity gain in oceanic turbulence channel for various diversity orders with different scintillation indexes for DCO-OFDM and ACO-OFDM. From this graph, we can conclude that, as the turbulence strength increases, diversity gain also increases with increasing diversity orders. This show that a larger diversity order is required to combat strong turbulence.

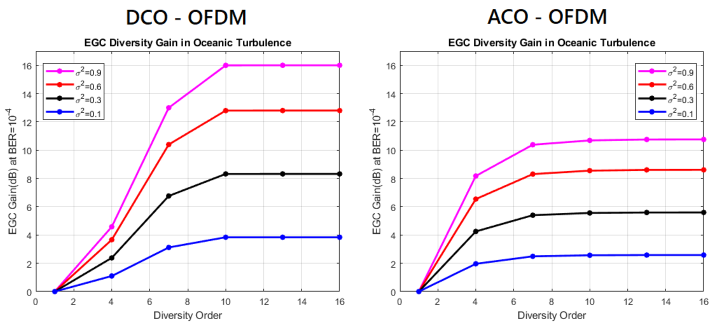

Fig. 10: EGC diversity gain in a lognormal oceanic turbulence channel against the diversity order for Both Dco-OFDM and ACO-OFDM

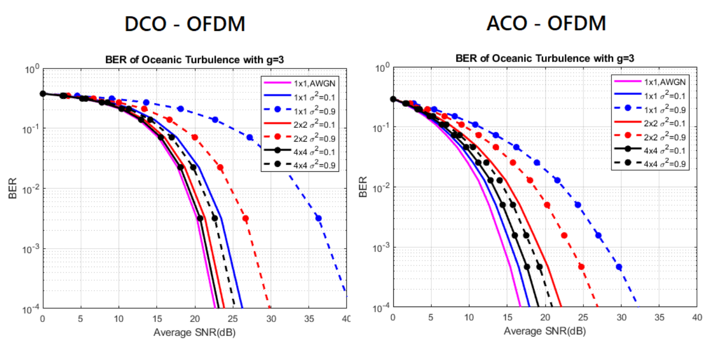

Fig. 11: The simulation BER performance of spatial diversity 4-QAM DCOOFDM in oceanic turbulence channel for both DCO-OFDM and ACO-OFDM

V. CONCLUSION

In this paper, the BER performance of the UVLC system for spatial variability in a weak marine station has been investigated based on the M-QAM DCO-OFDM version and EGC. We have found the BER accurate theory of M-QAM DCO-OFDM systems in the presence of a weak disorder that takes the wrong distribution. We used the Monte Carlo Ray tracking system to mimic route losses and power reactions to various orders. The BER of various orderings have been modeled and compared for analysis. It concludes that the high diversity system is effective in reducing the impact of chaos and the benefits of diversity increase with the intensity of the chaos. Also it was analysed that ACO-OFDM performs better than DCO-OFDM in underwater communication in weak turbulence conditions.

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