Al-Furat Journal of Innovation in Electronics and Computer Engineering (FJIECE) is an international, open access, interdisciplinary, quarterly, and double blind peer-reviewed journal published by Al-Furat Al-Awsat Technical University/Iraq. It is dedicated to the latest advancement in Electronic Engineering, Computer engineering, and their related and subfields.

Performance Analysis of Underwater Optical Wireless Communication Systems Based on CD-Optical OFDM and Various Subcarriers Indexes

Monther Noaman Hasan[1], Ahmed Ghanim Wadday[1], Faris M. Ali[1]

[1] *Department of Communications Techniques Engineering, Engineering Technical college- Najaf., Al-Furat Al-Awsat Technical University, Najaf-Iraq*
datasun2000@yahoo.com
ahmadghw@atu.edu.iq
faris@atu.edu.iq

https://dx.doi.org/10.46649/300320-04

Abstract — **The speedy growing of communication technology and visual services, larger capacity and higher-speed transmissions are required in contemporary underwater applications, which produce the present aquatic systems finally flop to meets requirements. A recently emerging technique in the scope of wireless communication is underwater optical wireless communications (UOWC). Due to using an optical signal, we can achieve a high data rate (approximately Gbps) over medium communication link ranges because of the harsh environment in the underwater channel where optical signals are faced many difficulties in transmission such as absorption and scattering. So, the main problem in the UOWC system performance is the short link range. In this paper, a DPSK with Coherent Detection CD-Optical OFDM with a various number of OFDM subcarriers has been designed and simulated under high turbulence water. Concerning their bit error data rate (BER) achievements, the comparing bit error rate impose is corresponding to 10^{-5}. The simulation results show the achieved communication distances by the suggested system for deferent OFDM subcarriers indexes (128, 256, 512 and 1024) are 3.9m, 4.8m, 5m, and 5.9m respectively. It is clear when we increase the number of OFDM subcarriers the link rage will be increased linearly due to the combating of the inter-symbol interference (ISI) effect. The design and simulation have been accomplished using the optisystem™ tool.**

Keywords— **Underwater Optical Wireless Communications (UOWC), Differential phase shift keying (DPSK), Coherent Detection (CD), Orthogonal Frequency Division Multiplexing OFDM, optisystem™ tool.**

I. Introduction

About 73 percent of our earth's surface is wrapped by water and by the rapid technological advances, the area of underwater communications has grown rapidly and widely with comprehensive applications in trade and martial systems. Applications such as far-off monitoring in the marine oil production, pollution control, scientific oceanographic data collection, disaster detection, sensor networks for monitoring climate changes, coral reefs, autonomous drifter swarms, power plants, marine archaeology and rescue missions and early warning, national security [1]. The investigation into different wireless communication techniques in the underwater has played the most significant part in the ocean and other aquatic environments [1]. Contrary to terrestrial wireless communication, underwater wireless channels are influenced by intense conditions such as nautical milieu, restricted power, clatter, and bandwidth[2]. Thus the underwater wireless channel is the greatest complicated and tough due to many circumstances such as absorption, scattering, multipath transmission, dispersion, restricted bandwidth, and power sources. While the underwater systems confronted these exclusive circumstances, numerous recent deviances, which have not been faced in terrestrial wireless communication systems, emerge for future underwater wireless networks in Radiofrequency, acoustic and optical communication systems. Acoustics and optical, because of the possibility of extended distance of transmission and high-bandwidth network communications in dimensions, modems with power-equipped and automated systems are among these challenges. The theme of underwater wireless networks has enticed and increase the interest of investigators, not only from the academe moreover in the martial and industrial fields, based on their attractive and unique elements as well as the potential advantages of advanced underwater communications. In later years, a great deal of research has been done on underwater wireless networks, but further developments on the wireless system underwater continue to be a problem, given the previous challenges posed by the exploitation of acoustic and optical wireless channels. There are three possible methods in underwater communications [2]. RF by sending electromagnetic waves, acoustic by sending sound waves and optical

communication by sending optical waves. Each of these techniques has advantages and limitations. Optical waves are electromagnetic waves between 400 nm (blue light) and 700 nm (red light) of wavelength. Optical signals is characterized by high speed, extremely short wavelength making it capable of communicating at extremely high speeds (Beyond the 1Gbps). The optical carriers used in wireless communication, though, are usually extremely short because of strong water absorption and strong backscatter of suspended particles in the optical frequency band[3]. The author in [4] proposed and experimentally demonstrated an Intensity Modulation/Direct Detection Orthogonal Frequency Division Multiplexing (IM/DD) OFDM based underwater optical wireless communication system. The transmitter was a single compact blue LED and the receiver was a low-cost PIN photodiode. The Quadrature Amplitude Modulation (QAM) modulation with different order and subcarriers was used to evaluate the underwater optical link and bit error rate. The transmission link was 40m and performed in coastal water with negligible scattering effect. The experimental results showed that the bit data rates of 227.8Mb/s at a Bit Error data Rate (BER) of $1.46\ 10^{-3}$ using 16-QAM and 232.95Mb/s at a BER of $3.28\ 10^{-3}$ using 32-QAM respectively at 2m link range. Over a 2m underwater channel, the bit data rates were 162.46 Mb/s using 16-QAM, 167.31 Mb/s using 32-QAM, and 138.07 Mb/s using 64-QAM respectively. In [5] proposed an underwater video transmission system with the laser link. The channel performance was verified by changing the tank visibility. By using a tank of 4.6m the experiment procedure was accomplished. The distance between the transmitter and the receiver was 5m. The transmitter laser diode was 488nm and has optical power 50mw. They concluded that the underwater video transmission utilizing the underwater laser signal is achievable, even at a visibility range of 4 times visibility. Hassan M. Oubei and *et al* [6] presented a high-speed underwater wireless optical communication using non-return-to-zero on-off keying (NRZ-OOK) modulation scheme. The experiment was tested in a 7m water pool. The transmitter was a 520 nm laser diode (LD) with 1.2 GHz bandwidth and an avalanche photodiode (APD) module as the receiver. The result of the measured BER from the experiment was 2.23×10^{-4}.In [7] proposed and experimentally examined the repetition coding OFDM (RC - OFDM), Alamoutii-OOFDM and MISO - OOFDM systems in high turbulence water, The outcomes validate the diversity gain of MIMO and that the Alamoutii-OOFDM system is further unaffected by delay than the RC - OFDM system.

In this paper, we have proposed a differential phase shift (DPSK) using coherent detection-Optical orthogonal frequency division multiplexing (CD-Optical OFDM) and examine the proposed system with various number of OFDM subcarriers (128,256,512 and 1024) to find out the performance optimization such as BER and transmission range of the UOWC system under turbid conditions.

The rest of the paper is organized as follows. The key principles are described in Sect. 2. The system design is described in Sect. 3. In Sect. 4 channel modeling is described. In Sect. 5. The simulation results are demonstrated the. Finally, conclusions are discussed in Sect. 6.

II. Theoretical Principles

In this section we will demonstrate the key theoretical principles such as OFDM technique and optical coherent detection.

A. *OFDM*

Nowadays, OFDM is considered always as a strong candidate to use in most systems. OFDM is a type of multicarrier modulation (MCM) in which a data flux at one rate is split into many parallel lower rate streams, the streams are separately modulated onto different frequency carriers' waves, or subcarriers, for transmission over the same channel. OFDM has been applied only recently to optical communication, however, in many optical systems including wireless optical, single-mode fiber, multimode optical fiber, and plastic optics, there is a growing quantity of documents on the hypothetical and practical act of OFDM which is considered an amended copy of Frequency Division Multiplexing (FDM) [8]. OFDM uses many carriers per a given spectrum that are very close to each other, however, they remain orthogonal at an exact distance of each other. The use of the Fast Fourier Transform (FFT) and Inverse FFT aid to demodulate and construct the earliest signal until if there is interference between the subcarriers. OFDM signals are generated from a summation of sinusoids, with each matching to a subcarrier. Subcarriers can be mathematically represented as [9]:

$$H_k(t) = \begin{cases} \sin(2\pi k \Delta f t) & 0 < t < T = 1,2,3,\ldots..N \\ 0 & otherwise \end{cases} \qquad (1)$$

Where Δf is the subcarrier spacing, N is the number of subcarriers, and T is the data symbol period. Since the highest frequency component is $N\Delta f$, the transmission bandwidth is approximately $N\Delta f$. Signals are orthogonal if they are mutually independent of each other. These subcarriers are orthogonal to each other because they satisfy the following condition [9]:

$$\int_0^T H_i(t) H_j(t) dt = \begin{cases} c, i = j \\ 0, i \neq j \end{cases} \qquad (2)$$

The orthogonality property of OFDM signals is to look at its spectrum. The orthogonality of the transmission is a consequence of the peak of each subcarrier equivalent to the nulls of wholly neighboring subcarriers [9].

A. *CD- Optical OFDM*

Coherent detection Optical OFDM was first proposed by Shieh and Athaudage [10], it offers superior performance in terms of receiver sensitivity, spectral efficiency, tolerance to chromatic and polarization dispersion and

therefore offers greater system capacity-reach performance if compared with DD-Optical OFDM. However, this performance requires high transceiver complexity which results in higher cost compared to a DD-Optical OFDM based system. Fig.1 depict the block diagram of an ordinary CD-Optical OFDM system, consisting of OFDM transmitter, RF to Optical Up convertor (RTO) unit, channel, Optical to RF downconverter (OTR) and OFDM receiver [11]. CD-Optical OFDM employs modulation of the optical field therefore it can support complex time domain signals therefore both positive and negative frequency subcarriers can be used to carry data.

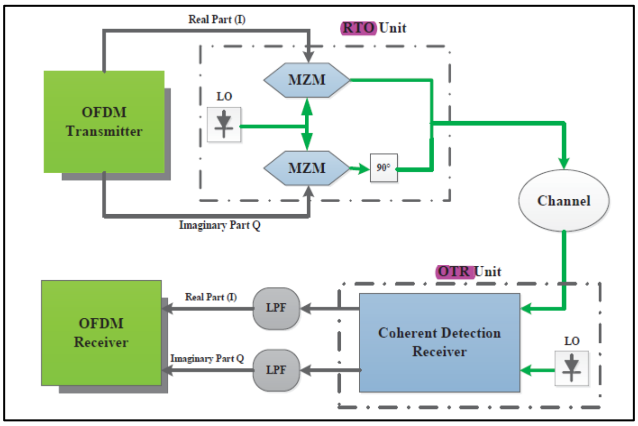


Fig. 1 CD-Optical OFDM Block Diagram [10]

The demodulation of an optical signal which needs phase, frequency and polarization control requires a coherent detection receiver. To satisfy the growth in bandwidth demand and capacity, high order modulation formats and advanced multiplexing techniques are proposed. The coherent detection receivers are capable to detect various modulation formats. However, the direct detection receivers have a limited sensitivity compared to the coherent detection receivers. The coherent detection receivers were first used in the field of radio communications. This type of receiver is based on the between the phase of the received signal and the LO (Local Oscillator) laser signal. To down-convert the received signal to the baseband, the received signal is mixed with the LO laser signal. There are many types of coherent detection receivers such us: single coherent, single balanced coherent receiver and balanced quadrature coherent receivers [12].

I. Attenuation in UOWC

In wireless communication systems, the optical signal can be used as a carrier wave, the limitation of these waves correlated to short transmission distances due to heavy absorption and scattering. The major drawbacks of utilizing visible waves in sea channels are large absorption and optical diffusion. Though, the ocean water shows decreased absorption in the section of the visible spectrum between blue and green. High-speed connection can be achieved depending on the type of water (from 400-500 nm for clear water up to 300- 700 nm for turbid water conditions) using appropriate wavelength, for example in a blue / green region. The minimum attenuation is concentrated in clear waters at about 460 nm for dirty waters near 540 nm in mid waters and shifts to higher values, as shown in Fig. 2 [14]. The propagation loss factor as a function of wavelength and distance d is given by [15]:

$$L(\lambda, d) = e^{-z(\lambda)d} \qquad (3)$$

Where z(λ)(m^{-1}) is the extinction coefficient stating the entire attenuation happened by the transmission underwater and we take the extinction coefficient value equal to 2.195 for turbid water as [16]. The total attenuation is the sum of absorption and diffusion. The total attenuation coefficient in Eq. (4) which is used in a fully absorbing or scattering medium. The absorption coefficient (A) or the dispersion coefficient (S), respectively may be replaced:

$$Z(\lambda) = A(\lambda) + S(\lambda) \qquad (4)$$

Where A(λ) is the absorption coefficient, S(λ) is the scattering coefficient, and λ is the wavelength.

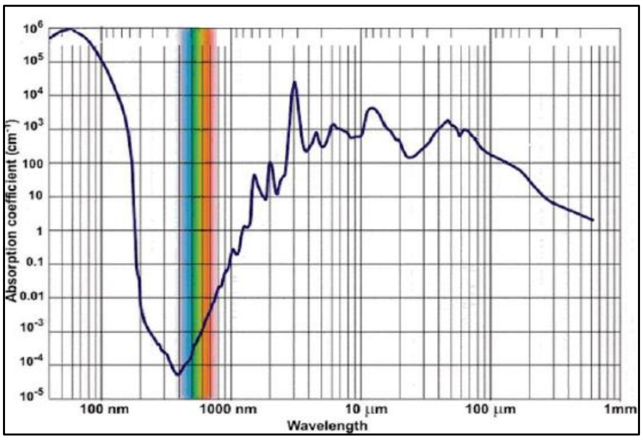


Fig. 2 The absorption coefficient versus wavelength for the Light spectrum[16].

I. System Design

The proposed CD-Optical OFDM system is described in Fig. 3. The system of CD-Optical OFDM has the main components, namely RF to optical unit (RTO) at the transmitter and optical to RF unit (OTR) which contains coherent detection (CD) at the receiver, as shown in Fig. 4 (a) two Mach-Zahnder modulators (MZM_S), X-coupler and an optical combining unit are used to build the RTO unit. In the output ports which will feed to the MZM_s, the (I) and (Q) carry components are displayed as shown in Fig. 4 (a) on the 1st input port of the coupling coupler. The dual-drive lithium Niubate MZM is used. At each MZM one of the baseband OFDM (I or Q) signal components at the two inputs of the $\text{MZM}_\text{'s}$ modulation signal is supported by positive and negative signals. The output signals of both MZMs are combined into the complex optical OFDM signal to be amplified and transmitted with the optical combiner. The input data sequence length is set to 2^{15} - 1and it is assembled with a pseudo-random binary sequence (PRBS) generator to produce a bit sequence which is then applied to the DPSK generator to make array sequences. The output of the encoder is coupled to an OFDM modulator with a 128 subcarrier to 1024 Fast Fourier Transform points. The in-phase (I) and quadrature (Q) of the subsequent signals from the OFDM modulator is then fed to the RTO unit. The RTO unit architecture is shown in Fig. 4 (a).

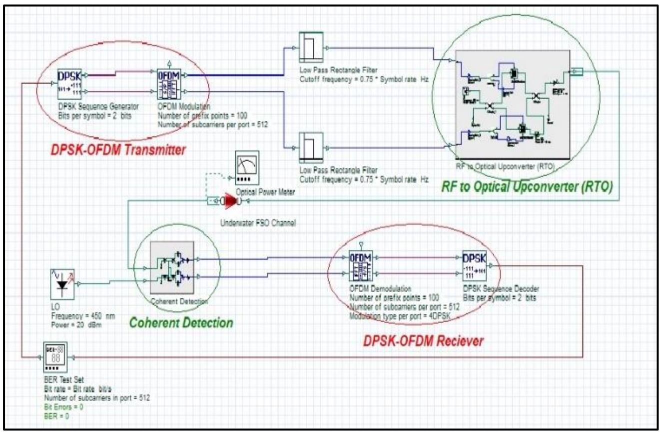
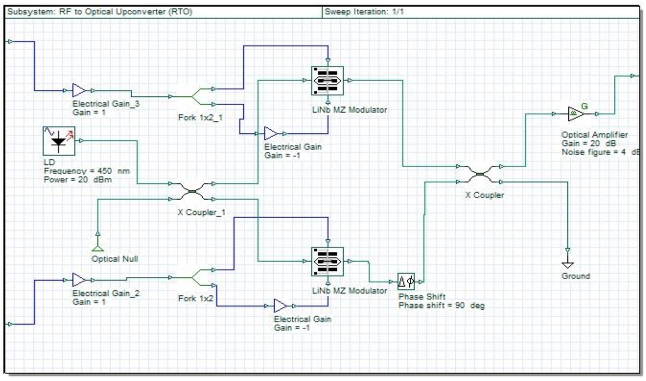
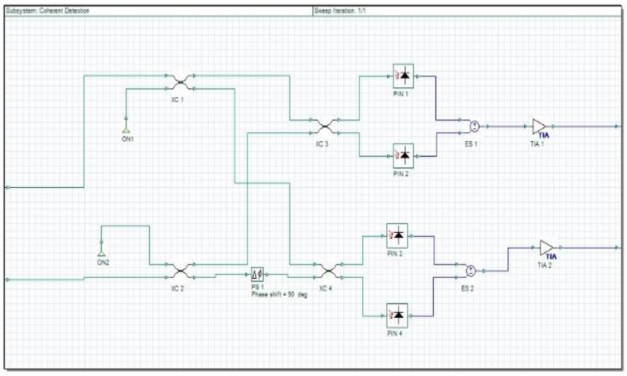


Fig. 3 The system design for the Proposed DPSK-CD-Optical OFDM System

At the receiver, the OTR unit is combined utilizing four X-couplers, a 90° phase shifter, four PIN photodetectors with a responsivity of 1A/W, and two electrical sub-tractors, as demonstrated in Fig. 4 (b). This OTR device uses stable noise detectors. To separately extract the (I) and (Q) modules in the OFDM, the first coupler splits the incoming Optical OFDM complex signal into two parts. Likewise, the second coupler is utilized to break apart the local oscillator (LO) signal into two portions to be blended with the Optical OFDM signal in the (I) and (Q) divisions.



a



b

Fig. 4 The subsystem design for: (a) RTO, (b) Coherent Detection.

TABLE I
Main Parameters of the Proposed CD-Optical OFDM System.

Parameters		*Value*	*Notes*
1	Data rate	10 Gbps	High
2	Modulation scheme	DPSK	low PAPR [17]
3	Wavelength	450nm	Low absorption and scattering
4	Chanel type	water	High turbulence
5	LD and LO power	20dBm	Low power consumption[16]
6	Photodetector	PIN	
7	OFDM subcarriers	128,256,512 and 1024	$N_{FFT/IFFT}$ =256,512,1024 and 2048
8	Coupling ratio	0.5	
9	Thermal noise	$1\text{x}10^{-22}$ W/H$_Z$ [18]	
10	Dark current	10nA	

I. Channel Modeling

Early underwater channel studies often used simple models such as Beer Lambert's law to simulate the propagation of light in underwater. Despite the modification, still, Beer Lambert's law cannot completely define the channel features of UOWC systems because of the focusing on link range and neglecting the spatial and temporal features[19]. Underwater turbulence can be divided into three channels, namely weak (clear water), mid-water, and strong turbulence (turbid water) based on the value of the beam scintillation index (σ_I^2). The beam scintillation index is determined as the variance of the laser irradiance. It's a measure of turbulence strength. Mathematically, scintillation index is defined by[20]:

$$\sigma_I^2 = \frac{E[I^2] - E^2}{E^2[I]} \tag{5}$$

Where I_0 is the fading-free intensity, and E[x] denoted the expected value of the random variable x. A scintillation index of high value indicates a strong turbulent channel while a scintillation of low value describes a weak turbulent channel. Weak turbulence channel is defined for $\sigma_I^2 \ll 1$. Moderate turbulence channel is designated as

$\sigma_I^2 \sim 1$. Strong fluctuations, also known as the saturation channel is achieved when $\sigma_I^2 \gg 1$. The Gamma Gamma (G G) distribution model as a model of turbulence was used. The Gamma-gamma scintillation model is built on Doubly Stochastic idea and it has weak to strong turbulence circumstance so the PDF (Probability Density Function) of its light intensity (L) is a product of two gamma random variables which represents fluctuations from small and large turbulence. The two random variables are Z and M and the received intensity L, is [21]:

$$L = ZM \tag{6}$$

The PDF of (L) is:

$$p(L) = \frac{2(ab)^{\frac{a=b}{2}}}{\Gamma(a)\Gamma(b)} \times L^{\left(\frac{(a=b)}{2}\right)-1} \times K_{A-B}\left(2\sqrt{abL}\right)\ , L > 0 \tag{7}$$

Where: L is irradiance, г (.) is gamma function, and K (a, b) is Bessel function of second order.

II. Simulation Results

Fig. 5 clarify the diagram of BER of DPSK based on different OFDM subcarriers indexes in turbid water. The simulation result shows the BER of DPSK-CD-Optical OFDM in turbid water. The simulation result shows the BER is 9.25×10^{-5} at 3.8m for 128 subcarriers, and linearly increase the range to 5.8m with BER equal to 8×10^{-5} for 1024 subcarriers.

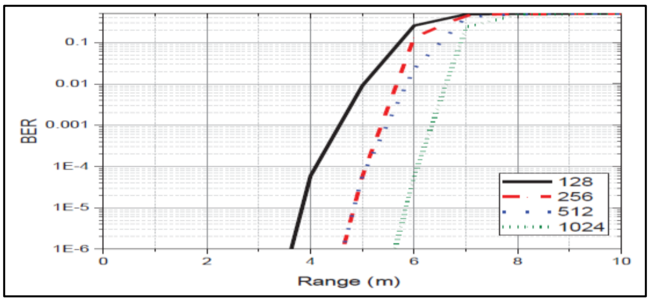


Fig. 5 BER vs. Range of DPSK-CD-OOFDM for various subcarriers indexes in Turbid Water.

Fig. 6 shows the RF spectrum of the CD-Optical OFDM transmitter and receiver. The RF transmitted power is measured at almost -10dBm, as shown in Fig. 6 (a). The RF OFDM spectrum of CD-OOFDM at the receiver is shown in Fig. 6 (b).

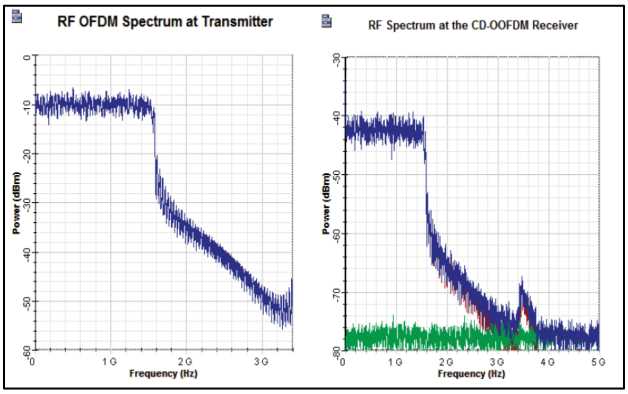
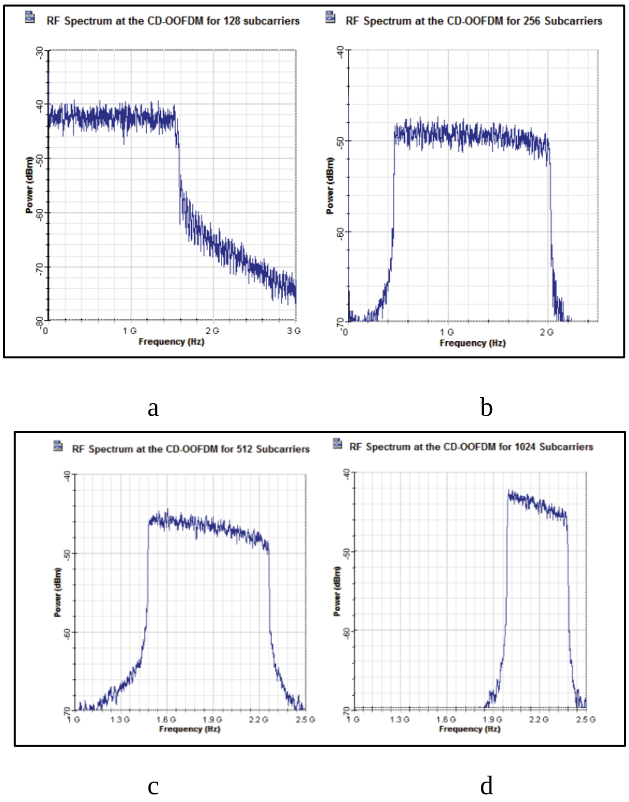


Fig. 6 RF OFDM Spectrum at the CD-Optical OFDM: (a) Transmitter, (b) Receiver

To demonstrate the impact of OFDM subcarriers on received power, Fig. 7 illustrates the influence of growing the OFDM subcarriers on the received power level. It can be noticed that the received power increased as increasing OFDM subcarriers due to increasing in subcarriers numbers.



a b

c d

Fig. 7 Signal after Detector using: (a) 128 subcarriers, (b) 256 subcarriers, (c) 512 subcarriers, (d) 1024 subcarrier.

I. Conclusions

In this paper, a proposed underwater optical wireless communication system (UOWC) which is characterized by the use of a DPSK-coherent detection of orthogonal frequency division multiplexing (CD-Optical OFDM) based on a various number of subcarriers under high turbulence water channel, the results demonstrate that when increasing the subcarriers number the transmission distance and received power will be significantly increased due to combating the inter-symbol interference (ISI) effect. The simulation results illustrate that the distance (link range) increased by using coherent detection CD-Optical OFDM based on various of subcarriers indexes (128, 256, 512 and 1024) are 3.9m, 4.8m, 5m, and 5.9m respectively, at the objective bit error rate (BER) is equal to 10^{5}.

References

[1] X. Zhang, J. H. Cui, S. Das, M. Gerla, and M. Chitre, “Underwater Wireless Communications and Networks: Theory and Application: Part 2 [Guest Editorial],” *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 30–31, 2016, doi: 10.1109/MCOM.2016.7402257.

[2] J. Oliver, “DESIGN AND DEVELOPMENT OF AN LED-BASED OPTICAL COMMUNICATION SYSTEM,” *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2013, doi: 10.1017/CBO9781107415324.004.

[3] R. Mouffage, “Real Time Evaluation of Swimmers Performance Based on an Optical Wireless Communication System Author,” 2014.

[4] B. Tian, F. Zhang, and X. Tan, “Design and development of an LED-based optical communication system for autonomous underwater robots,” *2013 IEEE/ASME Int. Conf. Adv. Intell. Mechatronics Mechatronics Hum. Wellbeing, AIM 2013*, pp. 1558–1563, 2013, doi: 10.1109/AIM.2013.6584317.

[5] M. Sun, B. Zheng, L. Zhao, X. Zhao, and F. Kong, “A design of the video transmission based on the underwater laser communication,” *2014 Ocean. - St. John’s, Ocean. 2014*, pp. 2–5, 2015, doi: 10.1109/OCEANS.2014.7003241.

[6] H. M. Oubei, C. Li, K.-H. Park, T. K. Ng, M.-S. Alouini, and B. S. Ooi, “2.3 Gbit/s underwater wireless optical communications using directly modulated 520 nm laser diode,” *Opt. Express*, vol. 23, no. 16, p. 20743, 2015, doi: 10.1364/oe.23.020743.

[7] Y. Song *et al.*, “Experimental demonstration of MIMO-OFDM underwater wireless optical communication,” *Opt. Commun.*, vol. 403, no. July, pp. 205–210, 2017, doi: 10.1016/j.optcom.2017.07.051.

[8] A. Khaled, “High Data Rate Coherent Optical Ofdm System for Long Haul Transmission,” *Thesis*, no. November, 2013.

[9] A. S. AL SHANTTi, “Optical Orthogonal Frequency Division Multiplexing Direct Detection for Improving Capacity of Radio over Fiber Transmission System,” 2015.

[10] W. Shieh, H. Bao, and Y. Tang, “Coherent optical OFDM: theory and design,” *Opt. Express*, vol. 16, no. 2, p. 841, 2008, doi: 10.1364/oe.16.000841.

[11] A. Y. Fattah and F. H. Abdul-baqi, “Polarization Division Multiplexing Coherent Optical OF DM Transmission Systems,” *IJCCCE*, vol. 15, no. 3, pp. 64–76, 2015.

[12] J. A. Salehi, B. M. Ghaffari, and M. D. Matinfar, *Wireless optical CDMA communication systems*, vol. 9780521197. 2012.

[13] H. Ali, “Modeling and Simulation of High Speed Optical Fiber Communication System with OFDM,” College of Physical Science & Technology Central China Normal University, 2015.

[14] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, “A Survey of Underwater Optical Wireless Communications,” *IEEE Commun. Surv. Tutorials*, vol. 19, no. 1, pp. 204–238, 2017, doi: 10.1109/COMST.2016.2618841.

[15] C. M. G. Gussen, P. S. R. Diniz, M. L. R. Campos, W. A. Martins, F. M. Costa, and J. N. Gois, “A Survey of Underwater Wireless Communication Technologies,” *J. Commun. Inf. Syst.*, vol. 31, no. 1, pp. 242–255, 2016, doi: 10.14209/jcis.2016.22.

[16] H. Kaushal and G. Kaddoum, “Underwater Optical Wireless Communication,” *IEEE Access*, vol. 4, pp. 1518–1547, 2016, doi: 10.1109/ACCESS.2016.2552538.

[17] W. Liu, “The End-to-End BER Analysis of Two Simulated OFDM-RoF Systems by,” 2015.

[18] M. F. Ahmed, A. H. Bakry, and F. T. Albelady, “High-Speed Modulation of Multiple Quantum Well Laser Diodes,” *Int. J. ofNew Horizons Phys.*, vol. 7, no. 1, pp. 1–7, 2014.

[19] H. M. Oubei, “Underwater Wireless Optical Communications Systems : from System- Level Demonstrations to Channel Modeling,” King Abdullah University of Science and Technology, 2018.

[20] M. Sharifzadeh and M. Ahmadirad, “Performance analysis of underwater wireless optical communication systems over a wide range of optical turbulence,” *Opt. Commun.*, vol. 427, no. May, pp. 609–616, 2018, doi: 10.1016/j.optcom.2018.07.029.

[21] K. Kaur, R. Miglani, and J. S. Malhotra, “The Gamma-Gamma Channel Model - A Survey,” *Indian J. Sci. Technol.*, vol. 9, no. 47, pp. 10–13, 2016, doi: 10.17485/ijst/2016/v9i47/106796.