



Double the data rate in underwater acoustic communication using OFDM based on subcarrier power modulation

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Abstract

Underwater communication is one of the most important and difficult challenges facing researchers due to the high attenuation of the signal, communication with the surface because of the harsh medium of water, and data transmission performance degradation as a result of various effects. Underwater acoustic communication (UWA) has a low data rate, which describes the disadvantage of this type of communication. In addition, it has a low bandwidth range and high latency but has a long transmission range as an advantage. Multicarrier wireless transmission systems increase the data rate by sending the data using more than one carrier. We proposed a noncoherent orthogonal frequency division multiplexing (OFDM) method to increase the data rate in UWA communication systems. In addition, doubling the data rate in the OFDM using Subcarrier Power Modulation (OFDM-SPM) system can save half of the bandwidth. The MATLAB simulation program was used to implement the system in the underwater acoustic environment to increase its throughput. The proposed design uses Differential Phase Shift Keying (DPSK) with power control, and the data stream is transmitted through two-dimensional modulation schemes, the DPSK, and the power level of each subcarrier in the OFDM system with cyclic prefix (CP). The underwater channel was designed using a Rician fading multipath with a spreading loss formula as a function of distance and frequency. We designed an equalizer at the receiver side to recover the original signal as a function of three parameters which are: the channel effect as a rate between transmitting and receiving symbols, the Rician channel response, and the UWA spreading loss. OFDM-Subcarrier Power Modulation (OFDM-SPM) using the proposed equalizer performed better than the theoretical OFDM-SPM in the Rayleigh channel. The designed equalizer increased the performance of the OFDM-SPM system by 25% which helped to enhance the system's throughput and doubled the data rate compared with the OFDM system, doubling the data rate using OFDM-SPM had been validated in laboratory experiments in the Time domain.

Keywords OFDM · Cyclic prefix · Underwater acoustic · Equalization · Noncoherent · DPSK · Wireless communication · Subcarrier-power modulation

1 Introduction

Water covers more than 70% of the Earth's surface, most of which is still undiscovered. The existence of rare-earth deposits and mineral resources on the floor of the deep oceans has raised the importance of investigating and exploring these areas [1]. Autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) can access unreachable depths, which is almost impossible for divers. One of the biggest challenges when developing these vehicles is communication. Water has unique characteristics that make the design of underwater wireless communication systems an essential topic for researchers in this field.

The main three types of communication used underwater are acoustic, optical, and radio frequency. Underwater

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acoustic communication (UWA) is the most common and useful type since it can provide a long transmission distance that can be several kilometers. However, low data causes a low bandwidth range, and high latency increases the challenges of transferring a high data rate with the same bandwidth. Underwater Optical Communication (UWOC) can provide an extremely high data rate of up to Gbps, but the alignment of the transmitter and receiver, as well as the effect of the water turbidity on the signals, add more limitations to the practical use of UWOC. Radiofrequency has the advantage of free orientation over optical communication. However, the high attenuation of the electromagnetic waves causes a signal loss over a few meters [32].

Due to the high absorption of all types of communication, wireless signals have limited propagation distance through the water medium [2]. Signal Scattering affects the quality of received data. The quality of the received data is usually evaluated by the bit error rate (BER). Improving the BER performance is one of the challenges in developing underwater communication systems.

Several factors increase the error rate in the OFDM communication system, signal interference, and loss of orthogonality in the OFDM system, affecting the underwater wireless communication signal. Interfering between subcarriers in the multicarrier communication system is another challenge, which leads to difficulty in recovering the communication signal or delays of the signal copies at the destination. The interference causes a problem in synchronization between the sender and receiver. The signal energy is absorbed by the medium, which changes the signal power at each frequency, and the noise effects decrease the quality of the received signal caused by the medium channel. Thorp's formula proved the signal attenuation, which describes the mathematical relationship between absorption and frequency in a few kHz [3] [4]. Aydin et al. [7] investigated the UWA channel characteristics by simulating and comparing Thorp's and McColm's equations in different frequency ranges, and then they explained path loss as a function of frequency and distance. The results show that the absorption in McColm is less than that in Thorp in the 0–300 kHz frequency range. Researchers found that the UWA channel estimation was an interesting part of developing the communication system, the thing that needs to contribute to the development of the communication system is the underwater acoustic channel had been modeled by Kulhandjian et al. [5], the lab and the lake experiment analyzed the statistical channel characteristics in short range shallow water communication environment, the channel fading exhibits close-to Weibull or Rician distribution. Other laboratory and lake experiments describe the multipath channel in shallow water. Ultra-band underwater acoustic communication channels were used by Van Walree et al. [6], proved with two experiments that the probability density function (PDF) results are broadly consistent

with the Rician fading channel. Christhu Raj et al. [8] modeled the UWA channel using the OPNET simulation program, and they checked the propagation sound speed in an underwater environment using the Mackenzie propagation speed equation. The UWA channel was modeled by Kim, Hyeonsu, et al. [9]. To prevent the impact of shrimp noise in the OFDM system, they used 16.5 kHz and 8 kHz as carrier frequencies in their simulation model with 256 and 128 subcarriers, respectively, and then they added cyclic prefix (CP) to fend off the inter-symbol interference (ISI), using CP in the OFDM system for the underwater acoustic also in the simulation studies enhanced the performance of the system and reduce the BER [33], the performance of the OFDM system in the UWA environment had been studied using different number of Pilots to enhance the BER [34]. Improving spectral efficiency, which can help to save bandwidth or send more data streams, is also a challenge for researchers. One of the proposed methods is a multidimensional OFDM system. Sending additional data helps us to reduce the data rate as a disadvantage of underwater acoustic communication, which lies in the limited bandwidth, and to benefit from its distance range as an advantage. This development effectively contributed to improving the system's spectral efficiency by sending an additional data stream in parallel with the original data. Joint-mapping OFDM with Subcarrier Number Modulation (JM-OFDM-SNM) was proposed by Miaowen Wen et al. to enhance the spectral efficiency and error performance compared with OFDM-SNM [10]. 2-D and 3-D signal plane categories were suggested by AHMAD M. et al. [10], who presented multidimensional methods to distribute consecutive symbols [11] on the same subcarrier. Tuncay Eren et al. [12] developed a null subcarrier index modulation (NSC-OFDM-IM) technique for 6G future development, and the method showed better performance than OFDM-IM in terms of spectral efficiency and BER. Double-sided pulse interval modulation (DS-PIM) was offered by Faisal Khan et al. [13]. The method was proposed for 6G light fidelity (Li-Fi) networks, and the simulation results show performance enhancement by sending an additional stream of data in parallel with a quadrature amplitude modulation (QAM) modulation scheme. Multidimensional index modulation (IM) categorization techniques have been suggested by SD Tusha to distribute information bits through multiple domains [14]. Cai et al. [15] proposed a method that used noncoherent OFDM to improve the underwater acoustic OFDM communication system using joint energy and correlation detection. They used the activated subcarriers in the OFDM system to transmit additional bits, which helps to enhance the data rate with less energy used by subcarriers. The BER performance of the OFDM system in UWA was analyzed by Jian et al. [16], who used pilot allocation to enhance the system performance. The suggested method was simulated using MATLAB simulation software, and BER

performance reached 5×10^{-3} when 256 and 512 were used as numbers of subcarriers with pilot allocation. A live video stream was successfully transmitted in underwater environment using RF communication system with a data rate up to 6.4 Mbps [35].

In this paper, we proposed OFDM subcarrier power modulation (OFDM-SPM) as a two-dimensional system to double the data rate in underwater acoustic communication. The system provides a noncoherent modulation method to increase the throughput. In addition, we compared the BER with previous theories. The rest of this paper is structured as follows. Section 2 presents the OFDM underwater system architecture with a mathematical explanation of underwater channel estimation. Subcarrier-power modulation is presented in Sect. 3. The simulation design and the parameter setup are described in Sect. 4. Section 5 provides the results and discussion. The conclusions are given in Sect. 6.

2 OFDM system architecture

The OFDM is a frequency-division multiplexing (FDM) scheme based on the subcarrier’s spaced orthogonality to efficiently utilize the bandwidth. Series of bit streaming will

be modulated using one of the digital modulation schemes, such as BPSK, QPSK, or QAM. In the computing implementation of the OFDM system, the input bits will be gathered and mapped to source data symbols that represent the digital modulation constellation point. These complex source symbols will be handled by the transmitter in the frequency domain. Figure 1. Describes the OFDM system structure. Therefore, an inverse fast Fourier transform (IFFT) is used to convert the modulated bits from a frequency domain to a time domain.

To reduce the effect of inter-symbol interference (ISI), the system uses a cyclic prefix (CP), a copy from the tail of each OFDM symbol to their header. Finally, digital Analog (D/A) converts the signal to analog to be transmitted through the channel.

2.1 UWA channel characteristics

The underwater communication channel is negatively affected by a set of factors that reduce the quality of the received signal. These factors can be categorized into absorption (or frequency-selective attenuation), spreading loss, and noise.

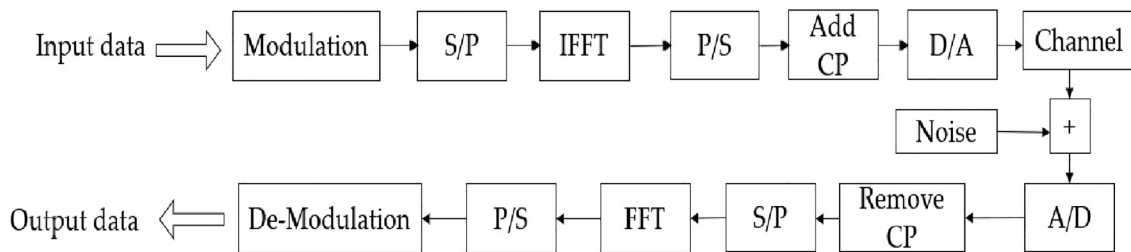


Fig. 1 OFDM block diagram

Fig. 2 OFDM-SPM underwater acoustic communication system

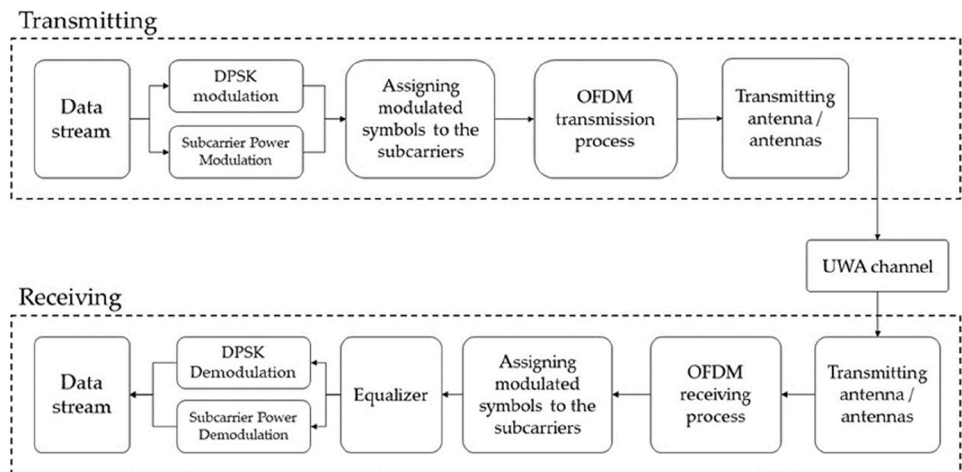


Fig. 3 UWA channel effect flow chart

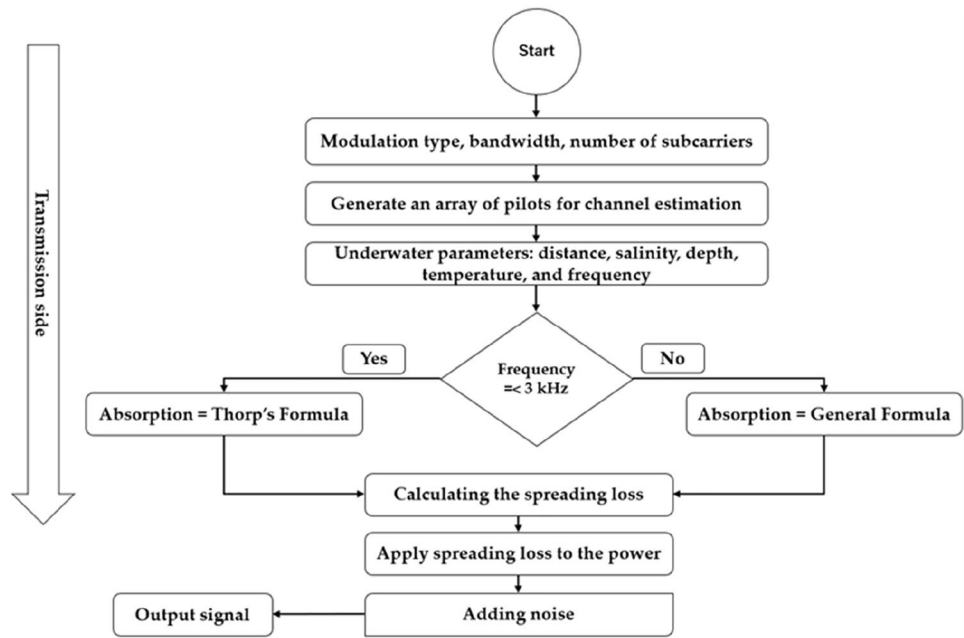


Table 1 Underwater acoustic channel parameters

Channel parameters	Value
Salinity	35 ‰
Water temperature	8 °C
Depth	100 m
Distance	0.2 to 2 km
Spreading coefficient	1.5
Frequency	200 to 400 kHz

Table 2 OFDM-SPM parameters

Symbol parameters	Values
Number of subcarriers	64
Number of used subcarriers	48
Number of unused subcarriers	12
Number of pilots	4
Modulation	DPSK, subcarrier power
Bandwidth	32, 64, 128 kHz
Distance	300 m to 2 Kilometers
Number of transmitting symbols	10 ⁴

2.1.1 Absorption

In underwater communication, the medium has a significant effect on the signal energy; thus, the acoustic signals will be absorbed gradually. This absorption is frequency-dependent, meaning that each frequency has a different absorption factor. The Mackensen formula represents the propagation of sound speed in an underwater environment as follows [18] [19]:

$$c = 1412 + 3.21T + 1.19S + 0.0167D \tag{1}$$

where c is the speed of sound, T is the temperature in Celsius (°C), S is the salinity (‰), and D is the depth (m). Thorp's Formula (1) expresses the water absorption factor of the underwater acoustic signal for frequencies less than 3 kHz [3, 4, 27].

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003 \tag{2}$$

To generalize the formula to fulfill the whole water conditions that may affect the signal absorption, Francois and Garrison developed Formula (2) to calculate the total absorption value [17], taking into consideration several variables such as salinity, depth, temperature, frequency, and pH for a frequency range between 200 Hz and 1 MHz,

$$a = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \tag{3}$$

where $A_1, A_2,$ and A_3 are the constants at atmospheric pressure [31], $P_1 = 1$ is a nondimensional correction factor for the pressure, f_1 is the relaxation frequency as given in the following, P_1, P_2, P_2 are nondimensional correction factors for the pressure, and f_1, f_2 are the relaxation frequencies for boric acid and magnesium sulfate (MgSO₄). The first part of Eq. 3 expresses the boric acid B(OH)₃ contributions to sound propagation, the second part represents the

magnesium sulfate coefficient, and the final part is the pure water coefficient.

2.1.2 Spreading loss

Signal spreading loss is affected by the geometrical shape in which the signal is propagated away from the source node of the acoustic system. Thus, the signal energy becomes less than the initialized point. The spreading coefficient (k) is the variable that can define the geometrical shape of spreading, and it can take 3 different values: 1, 1.5, or 2 [20].

In shallow water where propagation takes a cylindrical shape, the spreading coefficient is $k = 1$. In deep water, where spherical propagation dominates, $k = 2$, and $k = 1.5$ for practical propagation. The total propagation loss of the signal attenuation is connected to 3 different variables: distance, absorption, and spreading factor, as shown in Formula (12) [21].

$$10 \log A(d, f) = k * 10 \log(d) + d * 10 \log(\alpha(f)) \quad (12)$$

2.1.3 Ambient noise

The underwater ambient noise is also frequency dependent, and the total noise is a summation of multiple noise sources [19, 22]: turbulence, shipping, thermal and wind noises. Equation (13) describes the noise calculation in the range of less than 3 kHz:

$$N_{total} = N_t + N_s + N_w + N_{th} \quad (13)$$

where N_t is the turbulence noise, N_s is the shipping noise, N_w is the wind noise and N_{th} is the thermal noise. The noise can be obtained from Eqs. (14, 15, 16, 17).

$$10 \log N_t(f) = 17 - 30 \log(f) \quad (14)$$

$$10 \log N_s(f) = 40 + 20(S - 0.5) + 26 \log(f) - 60 \log(f + 0.03) \quad (15)$$

$$10 \log N_w(f) = 50 + 7.5 \sqrt{w} + 20 \log(f) - 40 \log(f + 0.4) \quad (16)$$

$$10 \log N_{th}(f) = -15 + 20 \log(f) \quad (17)$$

3 Subcarrier-power modulation

Subcarrier-power modulation (SPM) adds more dimension to the OFDM system, which allows the transfer of an additional data stream in the same OFDM symbol. OFDM-SPM enhances the spectral efficiency twice by doubling the spectral gain [23].

Since underwater acoustic communication has a low bandwidth range with a low data rate, the importance of a noncoherent OFDM system lies in doubling the data transmission rate within the same range of the available

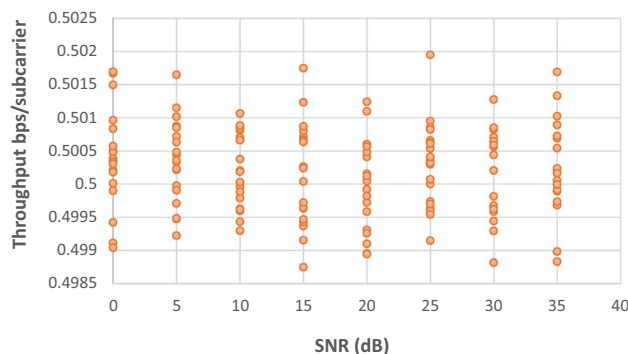


Fig. 5 Throughput of P-OFDM without equalizer for 32 kHz at 1 KM

Fig. 4 Throughput comparison between 2-DPSK, P-OFDM, and OFDM-SPM without equalizer for 32 kHz at 1 KM

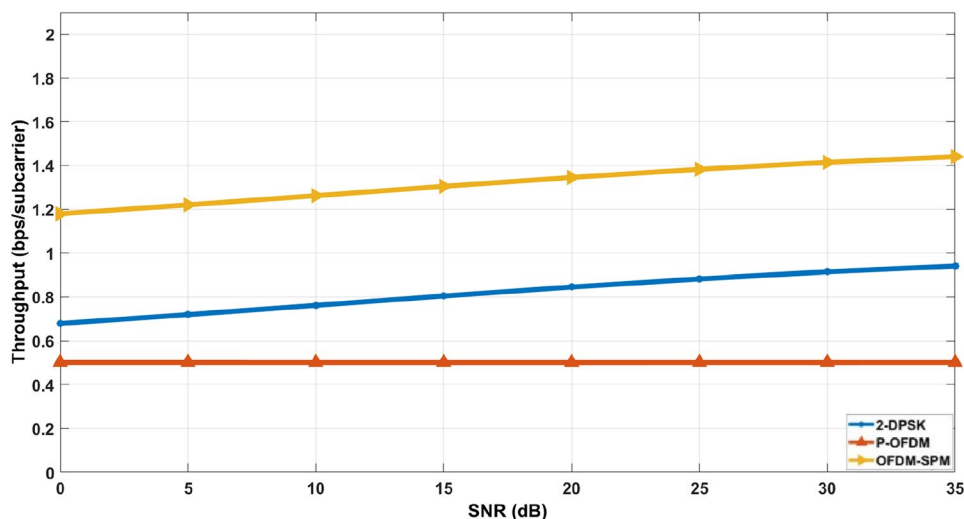


Fig. 6 Throughput comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer for 32 kHz at 1 KM

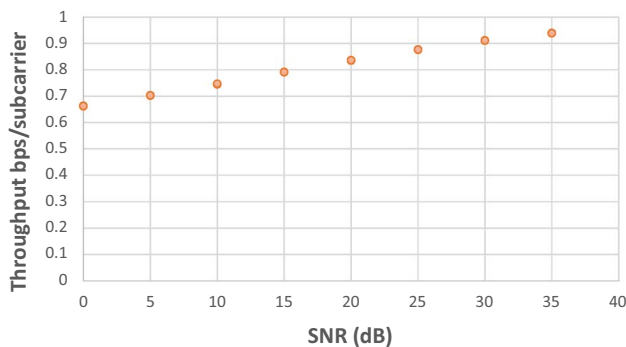
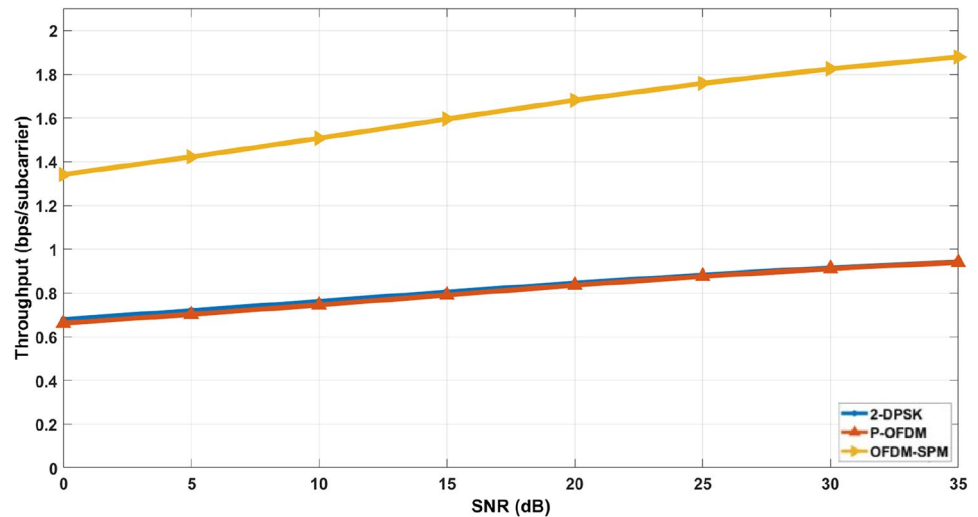


Fig. 7 Throughput of P-OFDM with equalizer for 32 kHz at 1 KM

Table 3 OFDM-SPM in UWA throughput comparison for 200 kHz with equalizer using 32 kHz as a bandwidth

Frequency = 200 kHz, BW = 32 kHz, depth = 100 m	
Distance [km]	Throughput [bps/subcarrier]
1.1	1.94
1.3	1.99
1.7	2
2.3	2
2.5	1.94
2.7	1.89

bandwidth. To enhance the underwater acoustic communication performance, the OFDM-SPM with a QPSK modulation scheme is proposed. Figure 2 shows the block diagram of the proposed underwater communication system. The underwater acoustic channel includes the following parameters: multipath fading, represented as Rician fading, spreading loss, and noise related to Eq. (17). On the receiving side, the equalizer is very important to reduce the noise

and compensate for the signal loss. Therefore, the equalizer should be designed properly. In this research, the equalizer was designed as a function of the channel response, spreading loss, and channel gain. These parameters are calculated based on sending and receiving a specific signal as pilots in this system. Figure 3 shows the flow chart of signal transmission in an underwater acoustic channel with a spreading loss effect, which is explained mathematically, and other conditions, including noise, described in Sect. 2.1.

4 Simulation setup

MATLAB software is used to design a multidimensional noncoherent OFDM system in the underwater acoustic environment. The UWA channel was designed using the mathematical formulas explained in Sect. 2.1, which includes the spreading loss as a function of distance and absorption, the multipath fading as Rician fading, and the noise. We compared the throughput and BER between 2-DPSK, Power Modulation OFDM (P-OFDM), and OFDM-SPM in the underwater acoustic environment. Table 1 illustrates the parameters of the underwater channel [26], and Table 2 illustrates the OFDM-SPM system parameters. The following coefficients have been selected based on the worst possible case for changes in salinity and temperature.

Using parameters in Tables 1 and 2, we measured the BER in different scenarios and the throughput at different distances. Furthermore, we measured the maximum distance that can be reached versus the allocated bandwidth. The values of the channel parameters were taken from the experimental results of the reference to improve the OFDM communication system [15]. The OFDM system parameters were taken from the standard IEEE 802.11 specification of wireless communication systems [28–30].

Fig. 8 Throughput comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer for 64 kHz at 1.1 KM

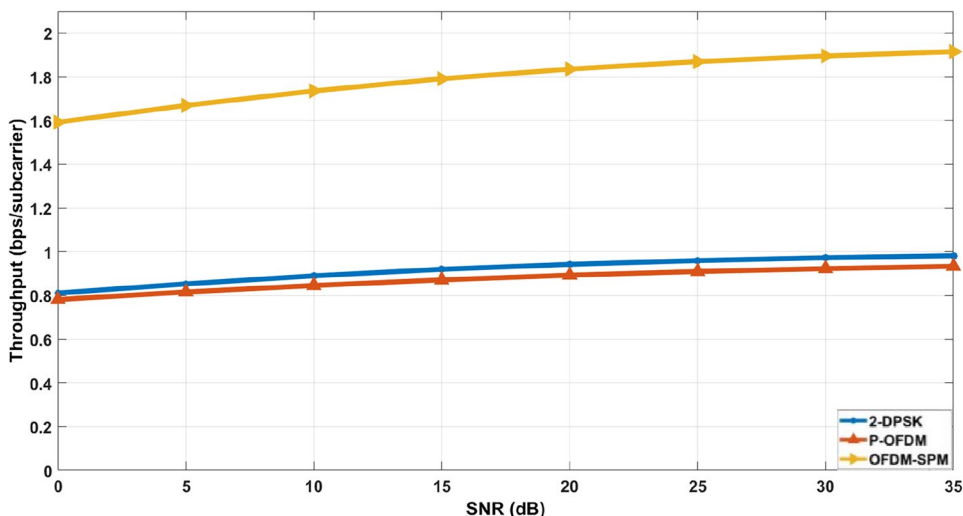


Table 4 OFDM-SPM in UWA throughput comparison for 200 kHz with equalizer using 64 kHz as a bandwidth

Distance [km]	Throughput [bps/subcarrier]
0.9	1.84
1.1	1.91
1.2	1.90
1.3	1.83
1.5	1.69

conducting a laboratory experiment.

5.1 Simulation results

The throughput and BER were studied and compared under different UWA conditions and for different frequency ranges. We used MATLAB to simulate the results 20 times for each case and then plotted the average response for each case to test the accuracy of the OFDM-SPM system response.

Figure 4 illustrates the throughput comparison between 2-DPSK, the power allocator in OFDM (P-OFMD), and OFDM-SPM in the UWA environment without adding a channel equalizer at the receiver side. The results confirmed that using the proposed method, throughput is increased gradually to 1.4 bps per subcarrier for the 32 kHz bandwidth range. When using 2-DPSK-OFDM, the throughput was 0.9 bps per subcarrier at 1 km. We can notice that increasing SNR might restore the losing bits in OFDM using 2-DPSK modulation only because we are increasing the power of the

5 Results and discussion

To study the possibility of doubling the data rate in underwater acoustic communication using OFDM-SPM we did the simulation using MATLAB, then proved the results by

Fig. 9 Throughput comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer for 128 kHz at 0.7 KM before optimization

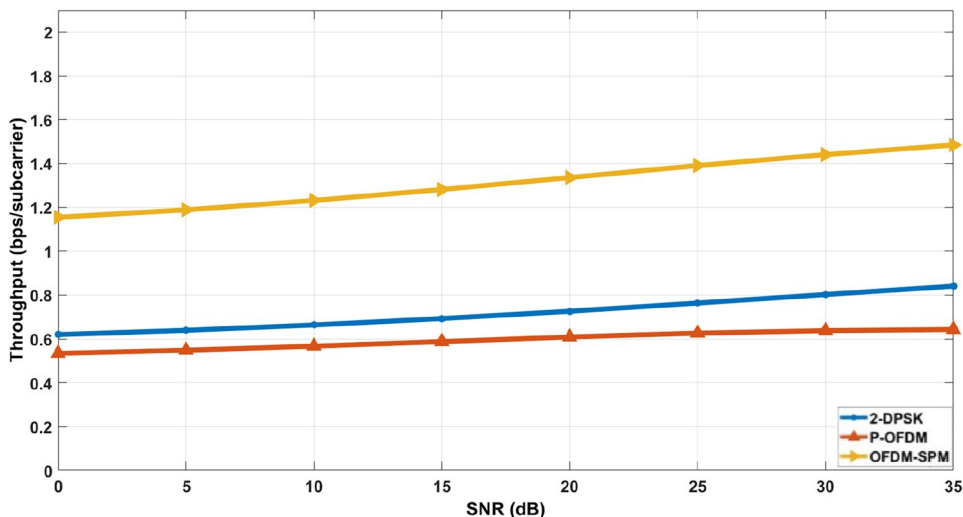


Fig. 10 Throughput comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer for 128 kHz at 0.7 KM after optimization

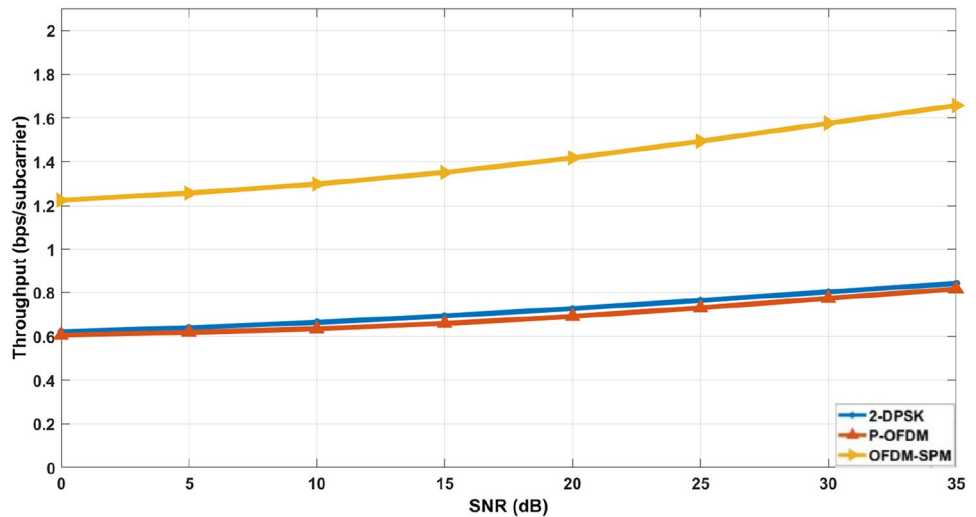


Table 5 OFDM-SPM in UWA throughput comparison for 200 kHz with equalizer using 128 kHz as a bandwidth after optimization

Frequency = 200 kHz, BW = 128 kHz, depth = 100 m	
Distance [km]	Throughput [bps/subcarrier]
0.9	1.91
1.1	1.98
1.3	1.97
1.5	1.89
1.7	1.75
1.9	1.65

Table 6 OFDM-SPM in UWA maximum distance comparison of different bandwidth ranges for 200 kHz

Frequency = 200 kHz, depth = 100 m	
Bandwidth [kHz]	Maximum distance [km]
32	2.5
64	1.3
128	1.5

Table 7 OFDM-SPM in UWA maximum distance comparison of different bandwidth ranges for 300 kHz

Frequency = 300 kHz, depth = 100 m	
Bandwidth [kHz]	Maximum distance [km]
32	1.9
64	0.9
128	1.1

Table 8 OFDM-SPM in UWA maximum distance comparison of different bandwidth ranges for 400 kHz

Frequency = 400 kHz, depth = 100 m	
Bandwidth [kHz]	Maximum distance [km]
32	1.3
64	0.7
128	0.9

bit, while it stayed at the same value of 0.5 on average for P-OFDM. Losing half the bit range in the P-OFDM system uncompensated the subcarrier power loss in the UWA channel when the bit power is increased. The suggested method used in [23] showed that the throughput should be doubled in additive white Gaussian noise (AWGN) with a Rayleigh fading multipath environment by adding an equalizer as a function of multipath, which compensates for the loss of the Rayleigh channel. Figure 5 illustrates the 20 simulation results of the throughput for P-OFDM without an equalizer. We can notice that the power attenuated even if we increased the SNR values. The reason why this occurred is because of the effect of the Rician multipath channel and the absorption. The point values that did not appear overlapped with the same value [24].

To enhance the throughput at the receiver side, we developed an equalizer based on the channel response. The proposed equalizer can establish the relationship between the spreading loss, sent and received tested data, and the multipath channel effect.

The optimization of the equalizer might vary depending on the bandwidth range but as a function of the previous three parameters. Figure 6 shows the performance of OFDM-SPM using the suggested equalizer. The throughput increases to more than 1.8 bps/subcarrier by changing SNR

Fig. 11 BER comparison between 2-DPSK, P-OFDM, and OFDM-SPM without equalizer for 32 kHz as a bandwidth, frequency = 200 kHz at 1.5 km

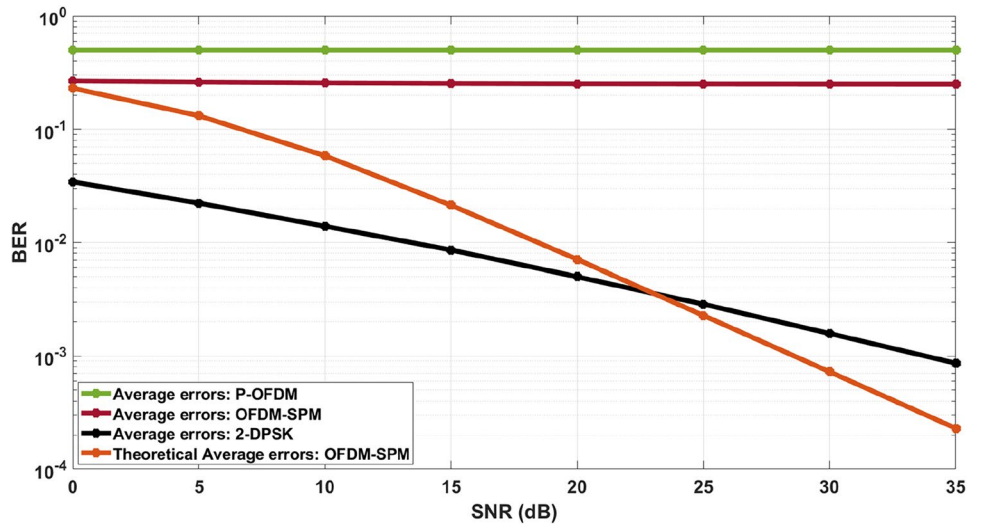


Fig. 12 BER comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer 32 kHz as a bandwidth, frequency = 200 kHz at 1.5 km

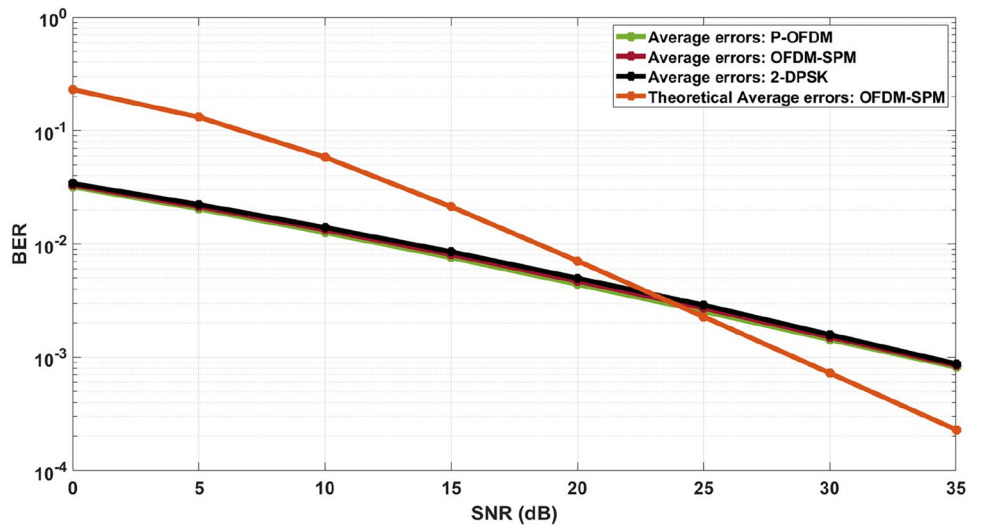


Fig. 13 BER comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer before optimization for 64 kHz as a bandwidth, frequency = 200 kHz at 1.3 km

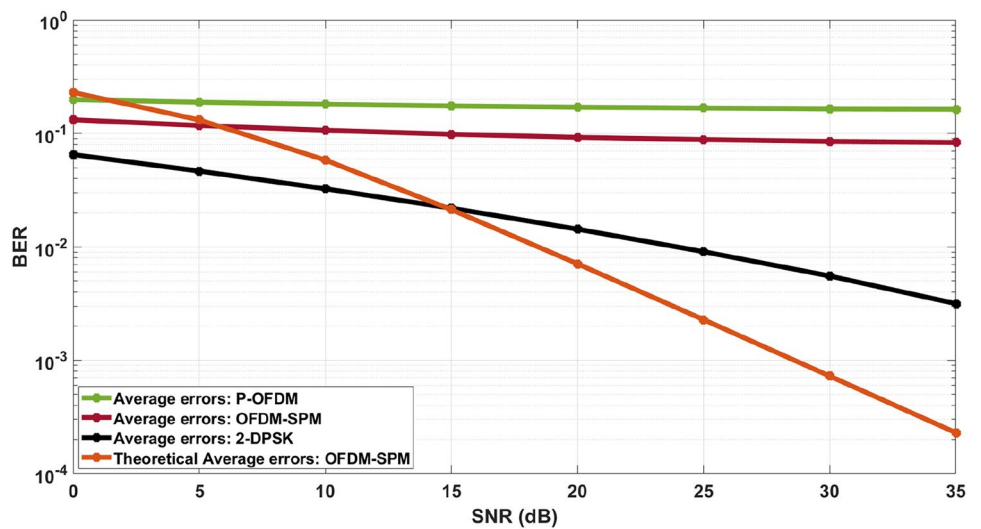


Fig. 14 BER comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer after optimization for 64 kHz as a bandwidth, frequency = 200 kHz at 1.3 km

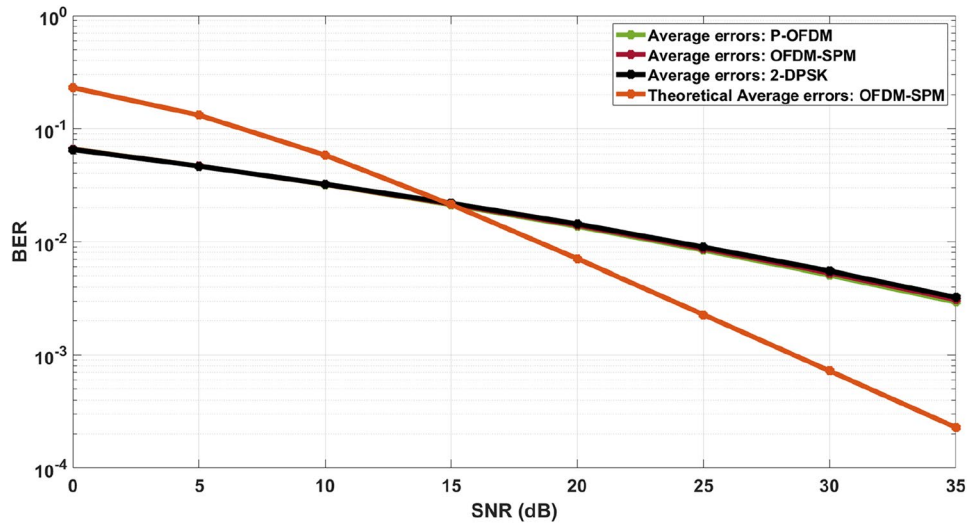


Fig. 15 BER comparison between 2-DPSK, P-OFDM, and OFDM-SPM with equalizer without optimization for 128 kHz as a bandwidth, frequency = 200 kHz at 1.4 km

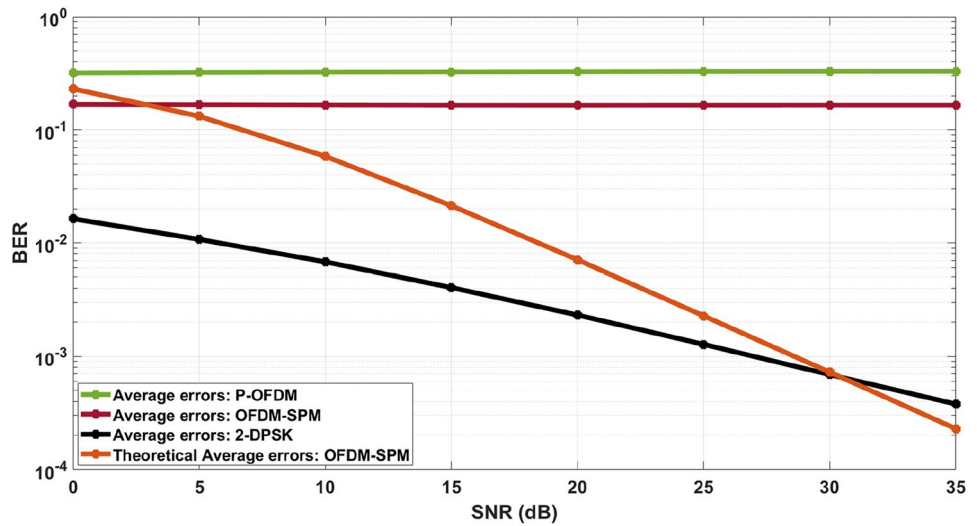
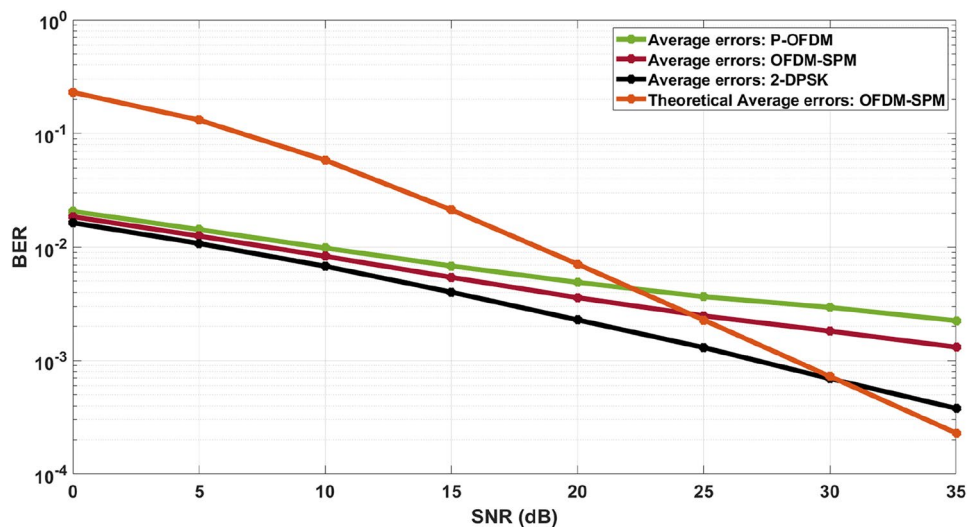


Fig. 16 BER comparison between 2-DPSK, P-OFDM, and OFDM-SPM with an equalizer with optimization for 128 kHz as a bandwidth, frequency = 200 kHz at 1.4 km



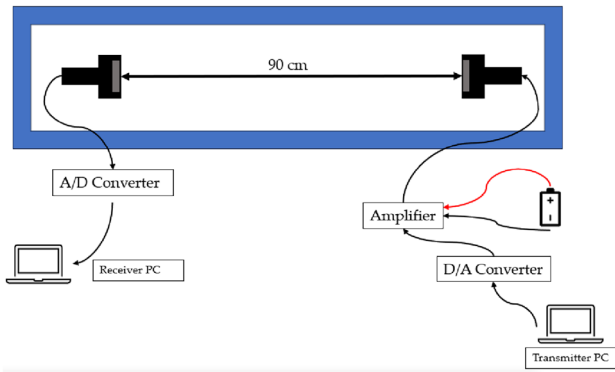


Fig. 17 Laboratory experiment setup to initialize the OFDM-SPM system

to 35 dB, as shown in Fig. 7. The throughput of P-OFDM shows the enhancement of the suggested equalizer to recover the signal. Table 3 shows the throughput versus the distance using 32 kHz as a bandwidth and 200 kHz as a carrier frequency when using the proposed equalizer. All the simulation measurements were conducted at a depth of 100 m. The results showed stable throughput values within 2.3 km; over this distance, the results showed less frequency spectrum efficiency.

Figure 8 illustrates the throughput comparison when applying a bandwidth range of 64 kHz in the OFDM-SPM system. The maximum throughput value at 1.1 km was 1.9 bps per subcarrier. The equalizer successfully recovers more than 90% of the subcarrier power when SNR is equal to or greater than 25 dB. Table 4 compares the throughput values using a frequency of 200 kHz for multiple distance values. The signal starts to be attenuated at distances over 1.3 km. Figures 9 and 10 demonstrate the throughput comparison when we tried 128 kHz as a bandwidth range in the OFDM-SPM system before and after optimization. We can see the throughput enhancement after optimizing the factor

Fig. 18 OFDM-SPM system initialization

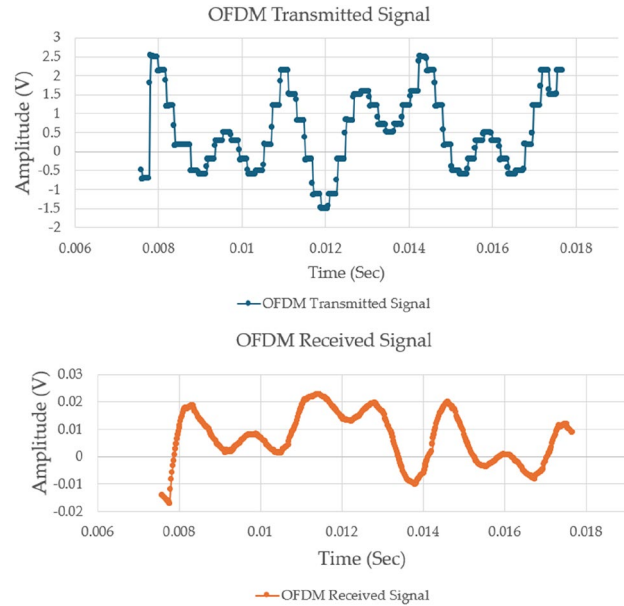
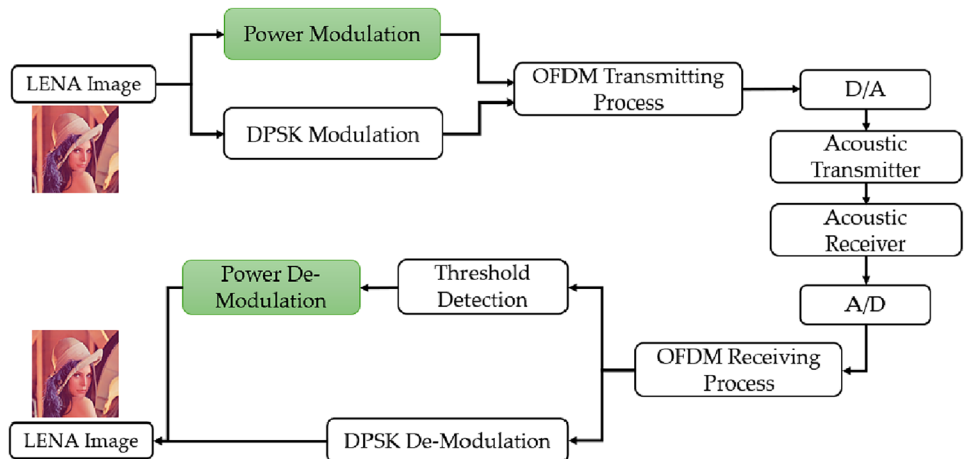


Fig. 19 OFDM transmitted and received data at a low-power level of the equalizer parameters, and the maximum throughput increased from 1.48 to 1.65 bps/subcarrier. Table 5 differentiates the throughput values for multiple distance values.

Table 5 shows that the range to get an acceptable performance for the OFDM-SPM system is up to 1.5 km.

Tables 6, 7, and 8 explain the relationship between changing the frequency with the maximum distance to reach the double data rate. We noticed that doubling the bandwidth range decreased the maximum range of distance by 52% if we used 200 kHz for both 32 and 64 kHz bandwidth ranges. In addition, Table 7 shows a similar relation but with approximately 47% if we use 300 kHz, and Table 8 describes that increasing the bandwidth will decrease the distance range by 54% when we use 400 kHz for the same bandwidth range of 32 and 64 kHz.

Fig. 20 OFDM-SPM transmitted and received data

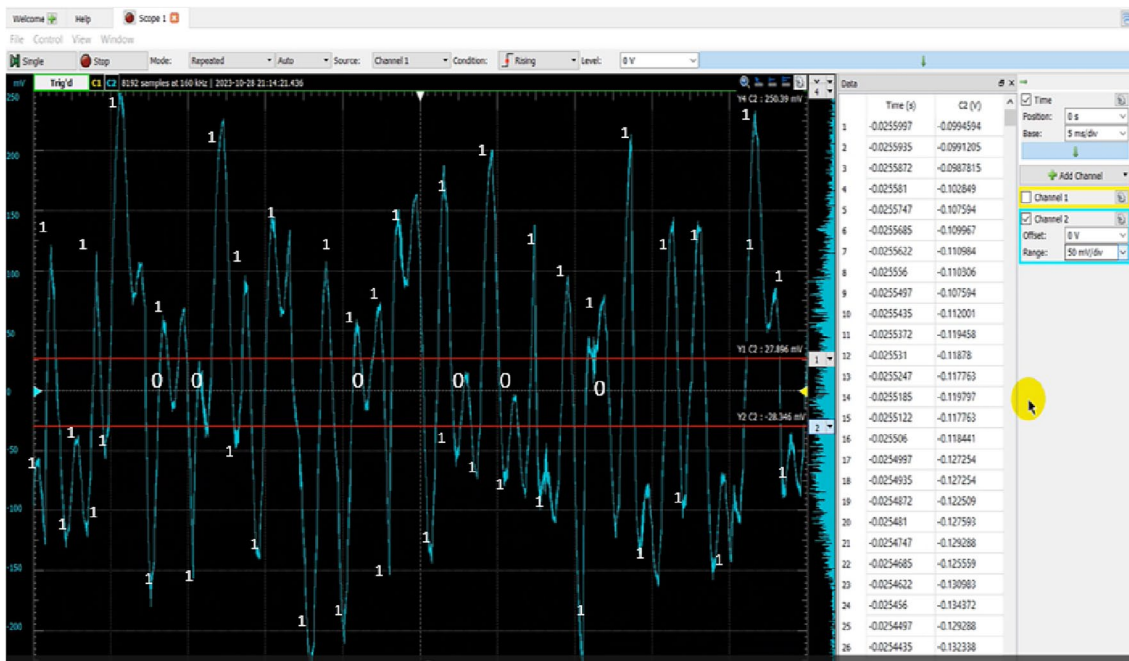
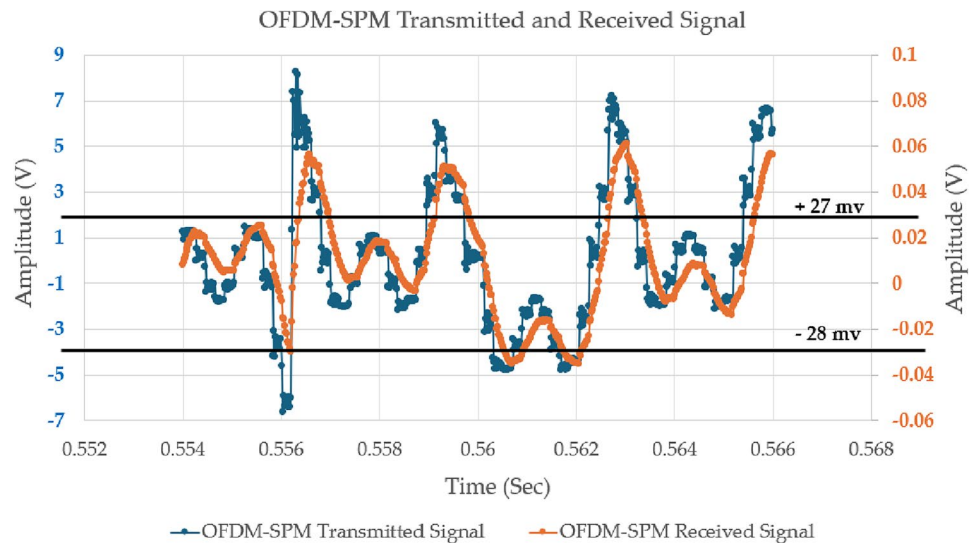


Fig. 21 OFDM-SPM signal on the oscilloscope at the receiver

Figure 11 expresses the BER performance of the system before optimizing the suggested equalizer. Figure 12 illustrates the enhancement of the BER for the OFDM-SPM after adding the equalizer, which reaches approximately 9×10^{-4} when SNR reaches 35 dB, and similar performance results with the theoretical OFDM-SPM when SNR reaches 25 dB [15] and a similar BER range compared with studies using a regular pilot-assisted OFDM system [25] or pilot allocation for OFDM system [16] in the underwater acoustic environment. The throughput had been checked for the OFDM-SPM

for 64 kHz as a bandwidth before and after equalization as shown in Figs. 13 and 14.

The performance reaches near 10^{-3} when we increase the SNR to 35 dB. We noticed the attenuation effect when we increased the distance and confirmed the reason for losing throughput accuracy, which is shown in Table 5. Figures 15 and 16 illustrate the BER comparison when the distance reached 1.4 km. The BER decreased after equalization and improved the quality of the system.

5.2 Experiment results

In order to prove that we can apply the theoretical study in the practical underwater environment, we experimented in the laboratory using an underwater acoustic transmitter and receiver as shown in Fig. 17. The distance between the acoustic devices is 90 cm, and we use an amplifier to separate the power levels which will help to initialize the OFDM-SPM system.

On transmitter and receiver PCs, we initialized the OFDM system based on the Fig. 18 box chart, LENA image had been transmitted through the system.

We started by separating the BPSK modulated bits of the LENA image into two parts. The first part is modulated with OFDM, and the second one is modulated using power levels, 0 bit means low-power level, and 1 bit means high-power level. To detect the modulated bits at the receiver, we create a threshold to demodulate the signal based on the power levels, then restore the second bit stream using OFDM demodulator. We exported the received data and then plotted the results to compare the separated power levels and prove the double data rate. First, the low-power level OFDM signal means that the OFDM carries an additional stream of zeros, and the high-power level carries an additional stream of ones. Figure 19 illustrates the OFDM transmitted and received signal, the received signal is a low-power OFDM signal, which expresses the threshold and carries bits of zeros. Any of the received OFDM signals out of the threshold-power level means that the OFDM carries bits of ones.

Using the power modulation to the second stream of data we successfully isolate each power level by amplifying the ones bits to pass the threshold at the receiver as shown in Fig. 20. Esch signal inside the threshold means that we received the OFDM signal carries a 0 bit will be extracted and demodulated from the frequency domain, because it has a low-power level, and the signal out of the threshold range carries the OFDM modulated bit, and a bit with a value 1 because it has high-power level extracted from the frequency domain too.

Figure 21 confirms the OFDM-SPM results. We can notice that the power levels were isolated and successfully transmitted an additional data stream using power control, consequently data rate had been doubled, the threshold had been created based on the samples taken from the time domain, and it can be taken from the frequency domain by measuring the threshold for all subcarriers in the OFDM.

6 Conclusion

We proposed an OFDM-SPM as a 2-D OFDM system to improve the UWA data-rate communication system. OFDM-SPM in the UWA communication system adds a subcarrier power control as a second dimension to the OFDM transmitting system, which helps to double the data stream on the transmission side and, as a result, double the data rate for the OFDM system. Throughput and BER were studied by adding an equalizer. The equalizer was designed at the receiver side as a function of the spreading loss, sent and received tested data, and multipath channel effect. We also compared the maximum distance that will be feasible to apply OFDM-SPM in a UWA environment with different carrier frequencies. In addition, the relation between the bandwidth range and the maximum distance was investigated and compared with experimental studies. The results illustrate nearly comparable results with the experimental results for bandwidth ranges of 32 and 64 kHz. BER was compared for the OFDM-SPM in different UWA conditions and different bandwidth ranges. The study has been proved by doing a laboratory experiment, and we successfully doubled the data rate by separating the power levels. The future work of this research is to expand the idea of different types of digital modulation schemes and check if we can double the data stream in UWA using OFDM-SPM for QPSK and QAM, in addition, creating a threshold strategy for the OFDM-SPM is a challenge which will be studied more deeply for different experiment environments and for different distance ranges in the laboratory and in the pool.

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Data availability The data is available only by request from the authors.

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