Performance Analysis of Selective Mapping in Underwater Acoustic Orthogonal Frequency Division Multiplexing Communication System

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Abstract-Under-Water Acoustic (UWA) communication networks are commonly formed by associating various independent UWA vehicles and transceivers connected to the bottom of the sea with battery-operated power modems. Orthogonal Frequency Division Multiplexing (OFDM) is one of the most vital innovations for UWA communications, having improved data rates and the ability to transform fading channels into flat fading. Moreover, OFDM is more robust on Inter-Symbol and Inter-Carrier Interferences (ISI and ICI respectively). However, OFDM technology suffers from a high Peak to Average Power Ratio (PAPR), resulting in nonlinear distortions and higher Bit Error Rates (BERs). Saving power of battery deployed modems is an important necessity for sustainable underwater communications. This paper studies PAPR in UWA OFDM communications, employing Selective Mapping (SLM) as a tool to mitigate PAPR. The proposed SLM with the oversampling factor method proves to be less complex and more efficient. Simulation results indicate that SLM is a promising PAPR reduction method for UWA OFDM communications reducing BER.

Keywords-underwater acoustic communication; orthogonal frequency divisional multiplexing; peak to average power ratio; selective mapping

I. INTRODUCTION

Under-Water Acoustic (UWA) wireless communications are utilized in military and civil applications. For military purposes, reliable communication is needed between submarines and autonomous underwater vehicles on the battlefield [1], as the overall operations depend on fast and flexible communications. In civil applications, UWA is essential in studying the underwater environment, and investigating further oil and gas explorations [2, 3]. UWA-based networks are different from terrestrial radio-based networks due to propagation delays, transmit energy, bandwidth, and multipath effects that affect the channel drastically [4-6]. Acoustic signals have a limited propagation speed around to five orders of magnitude lower than radio signals. Therefore, the techniques used in radiofrequency cannot be directly implemented in UWA-based networks. In UWA wireless communication, OFDM is implemented over UWA channels keeping in mind channel propagation and the complexity of the medium, while multipath arrivals and Doppler shifts make it more challenging [7]. However, OFDM has several advantages as it improves the flexibility of channel conditions and data rates, and results in better bandwidth with high spectral efficiency [8-10]. However, OFDM has several drawbacks, such as high PAPR and carrier frequency offset. When the peaks of a signal move towards the nonlinear region of the Power Amplifier (PA), distortion is created, overall system's efficiency is reduced, particularly for PA, while the complexity increases sharply for Analog to Digital (ADC) and Digital to Analog Converters (DAC) [11, 12].

OFDM has become a significant standard in communication networks. Its major drawback of high PAPR

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results in low energy efficiency, hence it is very difficult to implement an OFDM system in battery-powered modems in a UWA environment. Utilizing High-Power Amplifiers (HPA) and linear converters could overcome this drawback, but would increase cost and complexity. Efficient PAPR reduction techniques could solve this problem without complex hardware, keeping in mind the linear range of the power amplifier before design to avoid the saturation of HPA [12-15]. In- and out-band distortions are created by the saturation process, which increases BER and band distortion, while it also causes adjacent channel interference [16-19]. In long-term applications of UWA communication networks, such as ocean monitoring, the PA always works in full power mode and the system becomes vulnerable due to limited powered modems. Many factors influence the performance of PAPR, including the subcarrier number, modulation types and order, constellation type, and pulse shaping. PAPR can be reduced by many methods having merits and limitations, as there is always a compromising balance between bandwidth, computational complexity, average power, etc. Many researchers introduced such techniques and classified PAPR into several classes. In terrestrial communication, clipping is the easiest way to mitigate PAPR [20-23]. Moreover, reconstruction of the lost clipped signal, iterative clipping, and filtering have been introduced [24-26]. Peak windowing is an improved clipping method [27], while a further enhancement was introduced in [28]. The concept of the envelope scaling method was suggested in [29]. In probabilistic schemes, SLM and Partial Transmit Sequence (PTS) were suggested in [30-33]. Tone Reservation (TR) following as a linear programming problem and regarded as a Projection Onto Convex Sets (POCS) was studied in [34-35]. Moreover, several types of companding techniques have been introduced [36]. An improved companding technique for UWA OFDM communication was presented in [37]. The Tone Injection (TI) method had a severe drawback, as signal power increased due to the injected signal [38]. The interleaving and active constellation extensions are also PAPR reduction techniques. This paper proposes the utilization of Selective Mapping (SLM) with an oversampling factor in OFDM UWA communications to reduce PAPR and improve BER with lesser complexity.

II. SYSTEM MODEL AND OFDM MODULATION IN UWA

A. OFDM Modulation

The summation of subcarriers is modulated separately by using Phase Shift Key (PSK) or Quadrature Amplitude Modulation (QAM) to form an OFDM signal. They are transmitted through a transducer as a data stream from the OFDM modulator. The Inverse Fast Fourier Transform (IFFT) is applied as:

$$X(t) = \sum_{n=-\infty}^{\infty}\left[\sum_{n=0}^{N-1} d_{n,k}\phi_k(t-nT_d)\right]e^{j2\pi f_k t} \quad (1)$$

$$\phi_k = e^{j2\pi f_k t} \quad t\epsilon\ [0, T_d] \qquad (2)$$
$$\varphi_k = 0 \quad \text{otherwise}$$

and:

$$f_k = f_0 + \frac{k}{T_d},\ (k = 0,....,N-1) \quad (3)$$

where f_k shows the k_{th} frequency of subcarriers, f_0 is the lowest, and T_d represents the duration of each symbol. The number of subcarriers is indicated by N when different symbols are transmitted from the OFDM signal. It can be represented by $d_{n,k}$ with n intervals of time by using k_{th} subcarrier. The orthogonality of the subcarrier $\varphi_k(\tau)$ is described as:

$$\int_0^{T_d} \phi_k(t)\phi_l^*(t)dt = T_d\delta(k-1) = \{^{T_0\ k=1}_{0\ otherwise} \quad (4)$$

The demodulator can be represented digitally due to the orthogonality relationship of the subcarriers, after it undergoes several processes such as mathematic operations IFFT to FFT and modulation to demodulation. The OFDM signal can be implemented as:

$$d_{n,k} = \frac{1}{T_d}\int_{nT_d}^{(n+1)T_d} x(T)*\phi_k^*(t)dt \quad (5)$$

Figure 1 shows the framework of the proposed UWA OFDM communication system with SLM. Successively, signals are converted from serial to parallel, mapped in Quadrature Phase-Shift Keying (QPSK), and IFFT is applied with the proposed SLM reduction method to select the minimum PAPR signal. Afterward, the Cyclic Prefix (CP) amplified by HPA is added, which reduces the ISI. At the receiver side, the CP is removed from the signal, followed by the FFT and the process of demodulation. Finally, each QPSK demodulated symbol is decoded.

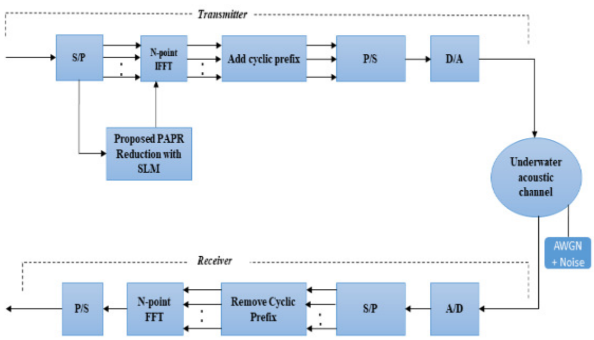

Fig. 1. The framework of UWA OFDM communication system.

B. Peak to Average Power Ratio

Peak power is always higher than the average power in an OFDM signal, as the number of subcarriers is added, resulting in high PAPR. PAPR is very important in a UWA OFDM communication system, as it affects power efficiency and PA's performance. When PAPR is high, the peak signals are shifted towards the nonlinear region of the PA, decreasing power efficiency. The PAPR of an OFDM signal is equivalent to about 12dB. ISI and ICI are due to the nonlinearity among OFDM signals. PAPR in terms of a discrete-time signal is given by:

$$PAPR = \frac{\max_n |x(n)|^2}{E_n\left[|x(n)|^2\right]} \quad (6)$$

Applying IFFT, discrete time-domain samples are given by:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{\frac{2\pi in}{N}},\ 0 \le n \le N-1 \quad (7)$$

The value of $x[n]$ is zero when the Gaussian variables are generated by increasing the value of subcarriers N. We will get Rayleigh distributed variance when the value of $x[n]$ is complex Gaussian and the phase of the OFDM signal becomes uniform. The Rayleigh distribution with a high peak value of signal exceeds nonzero digit probability. Hence, the PAPR of the digital signal exceeds the threshold value $P_0 = \frac{\sigma_0^2}{\sigma_n^2}$. The OFDM signal $x[n]$ is IDFT or IFFT of complex data symbols. We get this oversampled orthogonal frequency divisional multiplexing signal with help of QAM or PSK at N subcarriers.

PAPR increases with the subcarrier number N, if N is assumed as a Gaussian random variable distributed identically $x_n, 0 \le n \le N-1$ and assume 0 mean and unit power. As we know $E_n = (x[n])^2$ is the mean power. Then:

$$\frac{E|x_0^2|}{N} + \frac{E|x_1^2|}{N} + \ldots \frac{E|x_{N-1}^2|}{N} = 1 \quad (8)$$

By adding x_i coherently the maximum value is given by:

$$\max\left[\frac{1}{\sqrt{N}}\left(\left|x_0 + x_1 + \ldots + x_{N_1}\right|\right)\right]^2 \quad (9)$$

$$\left[\left|\frac{N}{\sqrt{N}}\right|\right]^2 = N \quad (10)$$

Equation (10) shows that the highest value of PAPR becomes N with the subcarriers (N).

III. SELECTIVE MAPPING IN UWA OFDM COMMUNICATION

SLM can be considered as the most prominent method in UWA OFDM communication systems. This process minimizes PAPR, as it transmits the signal having the least PAPR. The generated OFDM symbols are termed as candidates. Selective mapping was introduced in [39]. The signal having the minimum PAPR is transmitted from a various number of identical data blocks. The expression for the original data block $X\left[X_0, X_1, \ldots, X_{N-1}\right]^T$ is extracted by multiplying this mathematical expression with phase sequence $P^{(u)} = \left[P_0^{(u)}, P_1^{(u)}, \ldots, P_{N-1}^{(u)}\right]^T$ where $u = 0, 1, 2, 3\ldots, U-1$ is the phase sequence defined by U. IFFT is applied to each sequence to get a time-domain signal from the frequency domain, resulting in different time domains in the OFDM data blocks. The value of each data block is: $U\ X^{(u)}\left[X_0^{(u)} + X_1^{(u)} + \ldots + X_{N-1}^{(u)}\right]^T$ and will get a various number of PAPRs. Finally, the signal with minimum PAPR is selected in the transmitting transducer from the input data blocks and the candidates. The block diagram of the SLM with oversampling factor is shown in Figure 2. $\bar{X}$ is the OFDM signal candidate for actual transmission, which defined as:

$$\bar{X} = \arg\min_{0 \le u \le U}[PAPR(X^{(u)})] \quad (11)$$

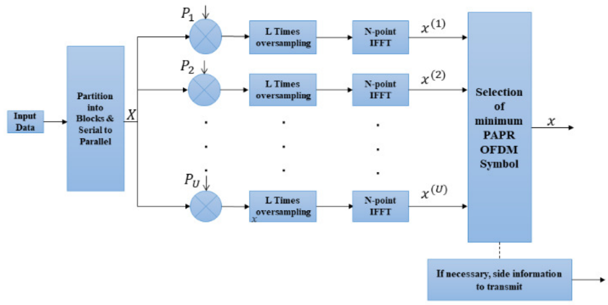

Fig. 2. The framework of selective mapping.

Using Nyquist sample rate, the complex envelope of OFDM signal having N subcarriers is regarded as:

$$x(t) = \frac{1}{\sqrt{N}} \Sigma_{I=0}^{N-1} X_i e^{j\frac{2\pi t}{N}}, 0 \le t \le N-1 \quad (12)$$

The modulated symbols are represented with X_i. Gaussian variables can be regarded when the value of $x(t)$ is zero, assuming the subcarrier number N is larger, as proved in the central theorem. With 0.5 variance in the OFDM signal which has Rayleigh distribution and the signal $x(t)$ being complex Gaussian, the signal phase remains unchanged. The nonzero probability occurs when the signal peaks have Rayleigh distribution and will surpass any value. Here we have assumed $x(t)$ average power equal to 1, and for $i.i.d$ random variables of Rayleigh, it is represented as z_n. The probability density function z_n is given as:

$$f_{z_n}(Z) = 2Ze^{-z}, n = 0, 1, 2, 3\ldots, N-1 \quad (13)$$

The PAPR value is approximated to the maximum value z_n. When the value of $z_{\max}$ follows $z_{\max} = \max_{n=0,1,2,3\ldots,N-1} z_n$ the probability of PAPR and the Complementary Cumulative Distribution Function (CCDF) of $z_{\max}$ below threshold can be given as:

$$P(PAPR \le z) = (1 - e^{-z})^N \quad (14)$$

The PAPR value can be determined by the data realization on OFDM subcarriers and is also dependent on pilot symbols. To analyze the PAPR in an OFDM signal, the CCDF is considered as a performance metric when the threshold value is large. The threshold z is exceeded then to search the probability of PAPR, assuming the CCDF as:

$$P(PAPR > z) = 1 - (1 - e^{-z})^{N} \quad (15)$$

U phase sequences are created in each data block if the mapping of each phase sequence is not statistically dependent, so the CCDF of PAPR in the SLM becomes:

$$P(PAPR > z) = (1 - (1 - e^{-z})^{N})^{U} \quad (16)$$

where z shows the threshold, N is the number of the subcarriers, and U represents the phase sequences.

From (16) and assuming the subcarrier number N of large and independent samples U by using the Nyquist sampling rate, without mentioning band limited and oversampling factor we get (17). A sampled signal doesn't need to have the highest point up to the original signal. At the same time, for getting real values of PAPR, the signal must be oversampled by an oversampling factor L. Authors in [34] first indicated the acceptable four oversampling. Then peak power distribution becomes very difficult to derive, hence the approximation of PAPR with N subcarriers and oversampling distribution with oversampling factors a and N. It was proven that a=2.8 is the better value to reach a decent PAPR by taking subcarrier number larger than 64.

$$P(PAPR \leq z) = F(z)^{N} = (1 - e^{-z})^{\alpha.N} \quad (17)$$

If the PAPR value surpasses the threshold z, the oversampling is defined as:

$$P(PAPR > z) = (1 - (1 - e^{-z})^{\alpha.N})^{U} \quad (18)$$

This equation was employed to check the performance of the UWA OFDM communication system, by adding an oversampling factor a.

IV. RESULTS AND DISCUSSION

The results and numerical analysis of the proposed system were considered with a different number of subcarriers and phase sequences. The UWA channel was established based on the Bellhop ray-tracing model. Simulations were carried out to further evaluate the performance of the SLM scheme for PAPR reduction. The simulation parameters are shown in Table I.

TABLE I. UWA OFDM SIMULATION DATA PARAMETERS

S/N	Parameters	Data
1	Sampling Frequency	100k
2	Bandwidth	6.25k
3	FFT Points	4096
4	OFDM Symbols	23
5	Number of Subcarriers	128,256,512
6	Cyclic Prefix Time	25ms
7	Modulation	QPSK
8	PA Saturation level	6
9	Sound Speed	1500m/s

The operating frequency of the transmitted signal was kept between 12 and 15k. The Bellhop ray tracing channel was created by giving a sound profile in the ENV file. The transmitting transducer was fixed at 1.5m depth, while a hydrophone was fixed at 5m depth at the receiver's side. The distance between the transmitter and the receiver was 2km, as shown in Figure 3. The signal was passed through the power amplifier, transmitted by the transducer, and underwent an underwater acoustic channel before received by the hydrophone. Figure 4(a) shows the Eigen ray of the multipath Bellhop channel. As it can be observed, the underwater acoustic channel had several multipath delays. The signal was reflected and refracted at the bottom of the tank/sea and the surface, while some signals arrived directly at the receiver. Figure 4(b) shows the sound speed profile measured while establishing the Bellhop multipath channel.

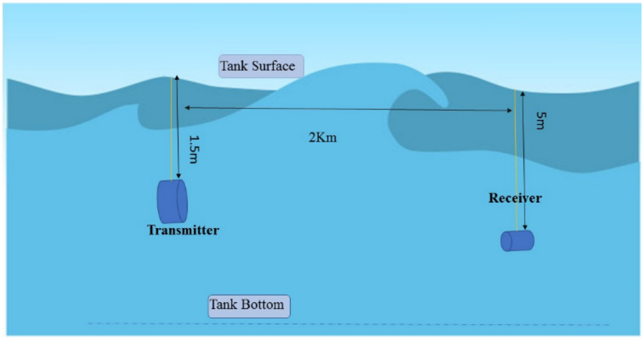

Fig. 3. Schematic layout of UWA communication with single transducer and a single hydrophone.

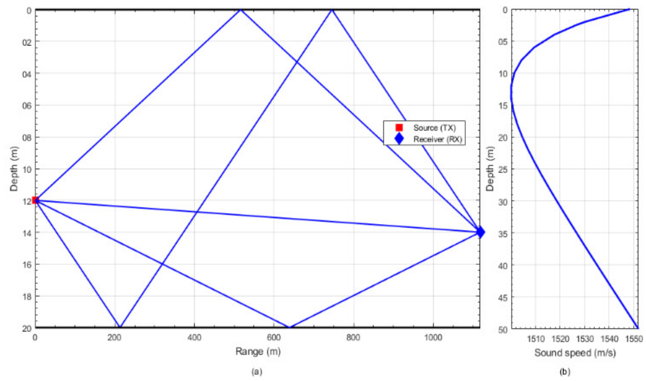

Fig. 4. (a) Multipath channel Eigen ray, (b) sound speed profile in the water.

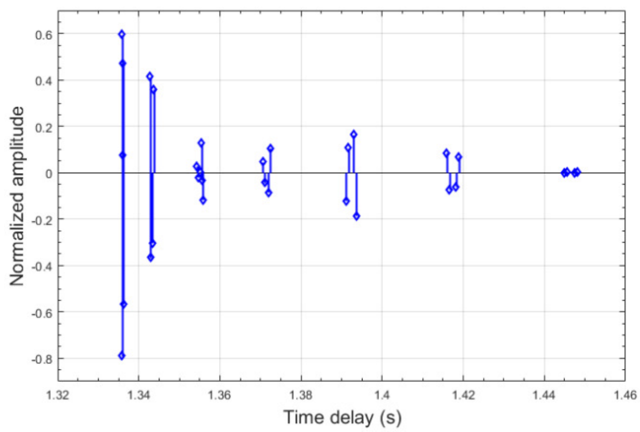

Fig. 5. Bellhop channel impulse response.

Figure 5 shows the channel impulse response of the UWA channel. The delay between two successive points can be seen with normalized amplitude. This is due to the nature of the UWA channel: the signal meets severe multipath and delays before reaching the destination. Figures 6-8 illustrate the reduction of PAPR using the SLM scheme. As it can be noted, increasing phase sequences (*U*) reduces PAPR, while increasing the number of subcarriers (*N*) increases PAPR. The least PAPR was observed with 128 subcarriers and 16 phase sequences.

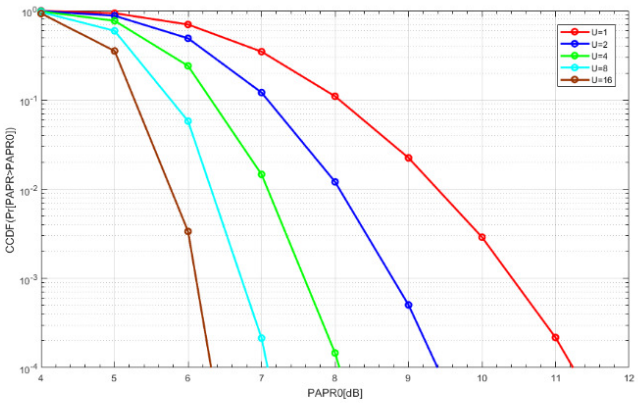

Fig. 6. PAPR of OFDM signal with SLM, *N*=128, *U*=1,2,4,8,16.

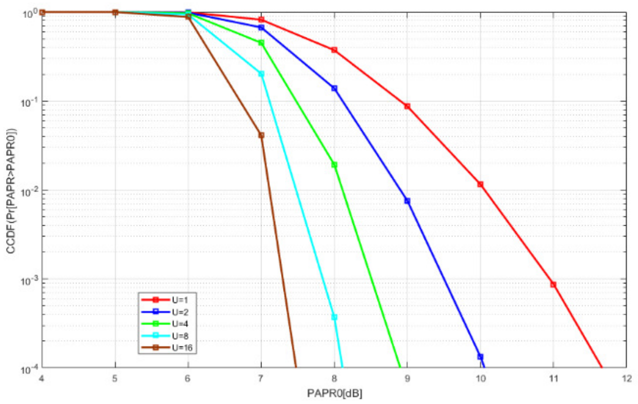

Fig. 7. PAPR of OFDM signal with SLM, *N*=256, *U*=1,2,4,8,16.

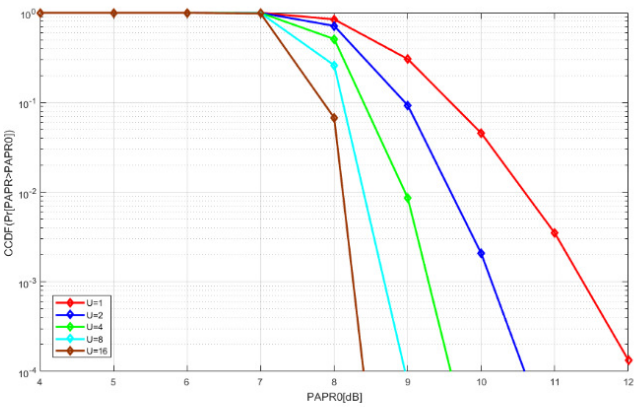

Fig. 8. PAPR of OFDM signal with SLM, *N*=512, *U*=1,2,4,8,16.

In Figure 9, the BER probability is described using the Bellhop channel in the QPSK modulation. The proposed method was compared with the original signal, clipping, and PTS. As it can be observed, the SLM outperforms the other PAPR mitigation methods at the range between 20dB and 25dB. Hence, the proposed method can be utilized in a UWA modem to design a less complex OFDM system. As it can be noted from Table II, the PAPR reduction is observed at different numbers of subcarriers and phase sequences. All data were extracted from Figures 6, 7, and 8 respectively, where the CCDF of PAPR was equal to 10^{-4}. The best performance of PAPR was 6.3dB with 128 subcarriers and 16 phase sequences. The best performance using 256 subcarriers was achieved with 16 phase sequences. Similarly, the optimum performance using 512 subcarriers was achieved with 16 phase sequences. Hence, increasing the number of phase sequences in the SLM method reduces PAPR. However, the complexity of the communication system is slightly increased.

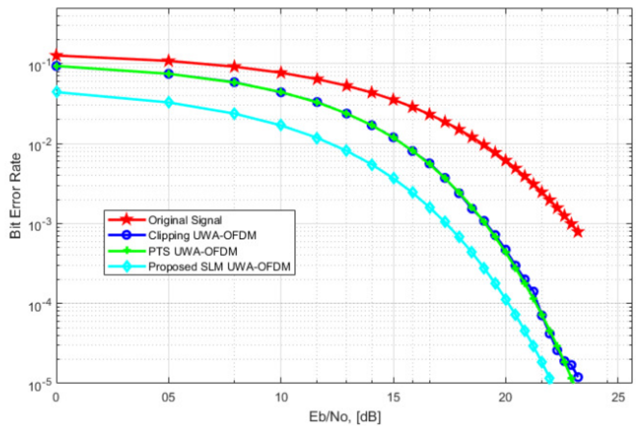

Fig. 9. BER vs signal to noise ratio for QPSK modulation in the Bellhop channel.

TABLE II. REDUCTION OF PAPR USING SLM AT VARIOUS PHASE SEQUENCES AND NUMBERS OF SUBCARRIERS

Number of phase sequences (*U*)	Number of subcarriers (*N*)	PAPR at 10^{-4}
1		11.2dB
2		9.4dB
4	128	8dB
8		7.1dB
16		6.3dB
1		11.7dB
2		10.1dB
4	256	8.8dB
8		8.1dB
16		7.5dB
1		12.2dB
2		10.6dB
4	512	9.6dB
8		8.9dB
16		8.4B

V. Conclusion and Future Work

OFDM is considered as an important modulation technique in UWA communication systems, as it can convert frequency fading channels to flat fading channels. It also has robustness over ISI and ICI, but it is very difficult to implement due to the severe environment of UWA channels. This paper focused on the study of the PAPR of a UWA OFDM communication, utilizing the SLM method to design a novel energy-efficient system. Simulation results showed that the SLM is the most promising technique to reduce PAPR. We also showed that increasing the phase sequences in SLM resulted in significant gains of the OFDM system in terms of PAPR and BER reduction. A future study could examine the improvements in the power efficiency of a UWA OFDM communication system by detecting different monomial phase sequences in probabilistic techniques. Moreover, the authors plan to continue this research by introducing some innovative, less complex, and intelligent methods for the reduction of PAPR in UWA communication networks.

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