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Performance Enhancement of Underwater Acoustic OFDM Communication Systems

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Abstract
The supported bandwidth of the underwater communication systems is limited to several kilo hertz, which considers as the main challenge for Underwater Acoustic (UWA) communications. Meanwhile, the Bit-Error-Rate (BER) performance of the UWA systems is degrades as a result of water temperature, water salinity, attenuation, and multi-path propagation. In this paper, we present a modification to the conventional Orthogonal Frequency Division Multiplexing (OFDM) based (FFT) using Fast Walsh–Hadamard transform (FWHT) instead of Fast Fourier Transform (FFT). Also, the proposed algorithm is encoded and decoded using Low Density Parity Check (LDPC) coding algorithm. Simulation results show that the proposed algorithm with LDPC coding can improve the BBER system performance than the corresponding traditional one.

Keywords Orthogonal frequency division multiplexing · Law density parity check matrix · Fast Walsh–Hadamard transform · Fast Fourier transform · Underwater acoustics

1 Introduction

The UWA communication systems are affected by large delay spread, which limits the achievable data rate [1]. In general, the UWA channel modeling is affected by the water properties such as; salinity, temperture, attenuation, and the PH degree. Those factors are considered as the main challenges for UWA wireless communications [2]. Meanwhile, the large delay spread causes inter symbol interference (ISI), which can mitigated by using equalization algorithm [3, 4].

The OFDM communication system can be implement a trivial equalization process after the FFT process instead of banck of demodulators to mitigate the ISI caused bby the UWA channel. In general, the equalizer can be implement into two possible formats, the post and pre

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format. There are different equalization have been used in underwater to improve the system performance. In [5] the authors only present an equalizer scheme to mitigate the impact of ISI. But, in [6], the authors present a joint equalization and carrier frequency offset compensation (CFO) for wireless communication systems. In [2, 3, 7] the authors present a joint low-complexity equalization and CFO compensation for UWA wireless communication systems to enhance the BER system perormance.

In fact, the OFDM system is affected by two performance degradation sources; the CFO, and the Peak-to-Average Power Ratio (PAPR). In this paper, we are interested in CFO problem. The CFO arises from two sources, the relative transmitter and/or reciver motios, and the Doppler shifts. Howeve, the CFO dameges the orthogonality and causes inter-carrier interference (ICI) [7, 8]. There are different algorithms are devoted for CFO estimation to preserve the BER system performance of the UWA-OFDM system [4, 9].

The implementation of the Fast Walsh–Hadamard-Transform (FWHT) requires a fewer computations (it omits the FFT's twiddle factors), and requires less complex hardware implementation than the corresponding traditional one, and gives better data transmission [10]. Really, the FWHT has one drawback that is satisfactory to damage the BER performance. This drawback is the time synchronization. In order to cope this problem, we use the Zadoff–Chu (ZC) sequences to compensate the effect of Symbol Time Offset (STO) [11] caused by the UWA channels. In fact, the ZC sequences have the ability to perform time synchronization (i.e. STO compensation) in the presence of CFO [9, 12].

As a result, the OFDM system can preserve the BER system performance if the CFO is estimated correctly and compensated and the PAPR is mitigated [13–15]. Also, the Low Density Parity Check (LDPC) codes have been used for UWA wireless communication systems that gives a superior to the BER performance compared to turbo coding and other coding schemes [16].

The LDPC codes are a special linear code, which presented by Gallager [17, 18]. The LDPC codes depend on the generator matrix (**G**) or the parity check matrix (**H**). The **H** matrix contains law number of 1's to satisfied the conditions of ($\gamma \ll m$, and $\rho \ll n$) where γ and ρ represent the number of 1's per each column and row, respectively. The code is named regular LDPC code, and irregular LDPC code if row and column weights are fixed, and infixed, respectively [16].

In this paper, we present a modified OFDM with LDPC codes for Single-Input-Single Output (SISO) UWA-OFDM systems based on FWHT and compared its BER performance with the corresponding traditional OFDM system based FFT. This paper is organized as follows: The modified SISO-OFDM system model is presented in Sect. 2. The FWHT–OFDM system versus DFT–OFDM system is reviewed in Sect. 3. The simulation results and analysis is presented in Sect. 4. Finally, the whole paper is concluded in Sect. 5.

2 Modified SISO-OFDM System Model

At the destination side, the received OFDM vector is performed to time-synchronization as mentioned in the previous section to preserve the OFDM based FWHT performance. This synchronization can be performed using the ZC sequences as [19]:

$$d_u(k) = \left\{ \begin{array}{ll} e^{\left\{-j\pi u \frac{k\times(k+1)}{63}\right\}} & 0 \le k \le 30 \\ e^{\left\{-j\pi u \frac{(k+1)(k+2)}{63}\right\}} & 31 \le k \le 61 \end{array} \right\}$$

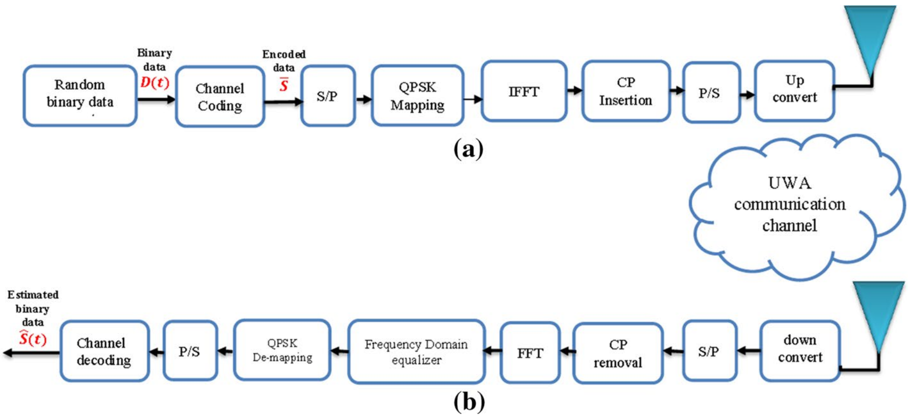

Fig. 1 Traditional UWA-OFDM system

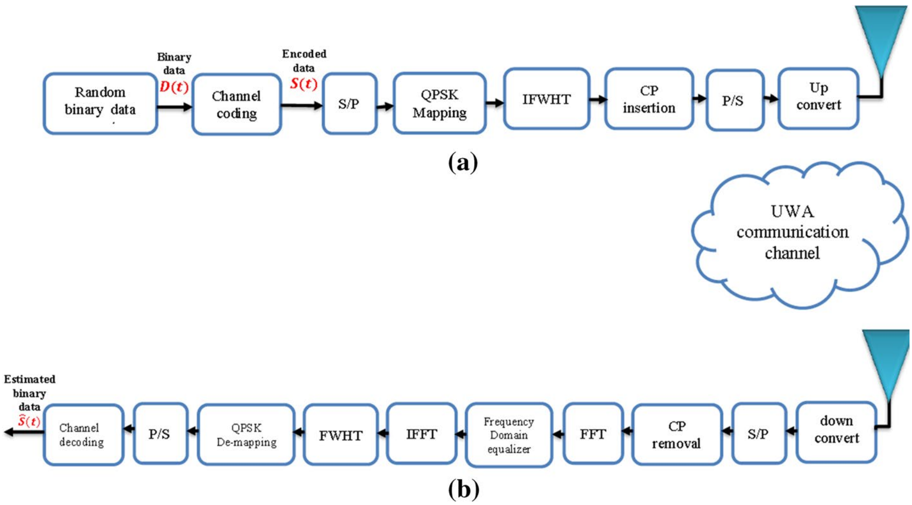

Fig. 2 Modified UWA-OFDM system

where u is the root index, typically in Long Term Evolution (LTE) standards u = 25, 29, and 34. Let us choose u = 25 for the rest of simulations.

Figure 1 illustrates the configuration of the traditional OFDM communication system, Fig. 2 illustrates the proposed OFDM based FWHT system with LDPC coding. Meanwhile, the FDE can be implemented by using any type of equalizer such as; Zero Forcing (ZF), and Minimum Mean Square Error (MMSE) equalizer, or any equalizer type to eliminate the ISI effect.

2.1 Signal Models for Transmitted and Received Data Vector

A random binary data vector U(t) are generated, then encoded as depicted in Figs. 1, and 2, then transmitted over the UWA channel. The generator matrix (**G**) can deduced from the parity check matrix (**H**) by using Gauss–Jordan elimination on (**H**) as $\mathbf{H}=[\mathbf{A}, \mathbf{I}_{\mathbf{n\text{-}k}}]$ where **A** represents $(n-k)\times k$ binary matrix and $\mathbf{I}_{n-k}$ is the identity matrix of order (n−k). The dataword vector of k length is encoded to codeword vector of n length, where $n>k$. The resulting codeword vector can be expressed using the generator matrix $(\mathbf{G})=[I_k, A^T]$ as:

$$(\mathbf{V})_{1\times n} = (\mathbf{U})_{1\times k} \cdot (\mathbf{G})_{k\times n}$$

where **G** is the generator matrix, **U** is the dataword vector, and **V** is the codedword vector. In fact, the LDPC coding concept depends on the sparsity of the parity check matrix. Sparsity reduces the computational complexity from order $O(N^2)$ operations [16] to $O(N)$ operations. Also, the FWHT reduces the computational complexity that depends on sparse matrices factorization method. The FWHT can be implemented using integrated butterfly structure via Kronecker product technique [20]. Reed–Solomon (RS) codes can be used to implement the large parity check matrix with lower-complexity. Referring to Figs. 1 and 2, the codeword is obtained by multipling the generated random binary data via the generator matrix, this is followed by a S/P converter, finally each symbol is mapped to the corresponding Quadrature Phase Shift Keying (QPSK) as $\bar{\mathbf{S}} = \left[\bar{\mathbf{S}}_1, \bar{\mathbf{S}}_2, \dots, \bar{\mathbf{S}}_N\right]^T$, where $\bar{\mathbf{S}}$ is represented the QPSK symbols of length N. The main difference between the proposed scheme (see Fig. 2) and the conventional one (see Fig. 1) at the transmitter side is the use of IFWHT instead of IFFT. The IFWHT is defined as $\left\{\mathbf{W}_{\mathbf{N}}^{-1}\right\}_{n,i} = \exp\left(-\frac{j2\pi ni}{N}\right); n = 0, 1, \dots, N-1; \quad i = 0, 1, 2, \dots, \frac{N}{4} - 1$ [20]. The output of the proposed scheme is given as:

$$\bar{\mathrm{s}} = \mathbf{W}_{\mathbf{N}}^{-1}\bar{\mathbf{S}} \tag{3}$$

The Cyclic Prefix (CP) is added to the head of each modulated OFDM symbol to mitigate the ISI, where the CP matrix is defined as $\mathbf{P} = \left[\left[\mathbf{0}_{N_C\times(N-N_C)};\mathbf{I}_{N_C}\right]^T, \mathbf{I}_N\right]^T$. Thus, the transmitted vector of Eq. (3) can be expressed as:

$$\bar{\mathbf{s}}_{\mathrm{CP}} = \mathbf{P}\bar{\mathbf{s}} \tag{4}$$

The encoded data vectors are transmitted via the transmitting hydrophones then propagate through the underwater channel and received by the corresponding hydrophones. After the supression of the CP, the resulting data vector can be expressed as:

$$\bar{\mathbf{Y}} = \mathbf{h} * \bar{\mathbf{s}} + \mathbf{n} \tag{5}$$

where, * means the convolution operator, the FFT is applied to convert the received signal to frequency-domain as:

$$\bar{\mathbf{Y}}_1 = \boldsymbol{F}_N\left(\bar{\mathbf{Y}}\right) = \mathbf{H} \times \mathfrak{z} + \mathbf{Z} \tag{6}$$

where $\mathfrak{z} = \boldsymbol{F}_N(\bar{\mathbf{s}})$.

Now, the frequency-domain equalizer can be applied to mitigate the channel effect.

The ZF, and MMSE equalizers solutions are given as [5]:

$$\mathbf{C}_{\mathbf{ZF}} = \left(\mathbf{H}^{\mathbf{H}}\mathbf{H}\right)^{-1}\mathbf{H}^{\mathbf{H}} \tag{7}$$

$$\mathbf{C}_{\mathbf{MMSE}} = \left(\mathbf{H}^{\mathbf{H}}\mathbf{H} + \frac{1}{\mathbf{SNR}}\mathbf{I}\right)^{-1}\mathbf{H}^{\mathbf{H}} \tag{8}$$

In case of ZF equalizer, the output in Eq. (6) is modified as:

$$\bar{\mathbf{Y}}_2 = \mathbf{H}^{-1}\{\bar{\mathbf{Y}}_1\} = \mathcal{s} + \mathbf{H}^{-1} \cdot \mathbf{Z} \tag{9}$$

Now, the IFFT block is applied to remove the effect of the corresponding FFT, thus Eq. (9) can be re-expressed as:

$$\bar{\boldsymbol{Y}}_3 = \boldsymbol{F}_N^{-1}\{\bar{\boldsymbol{Y}}_2\} = \boldsymbol{F}_N^{-1}\{\mathcal{s}\} + \boldsymbol{F}_N^{-1}\{\boldsymbol{H}^{-1} \cdot \boldsymbol{Z}\} \tag{10}$$

where the $H^{-1} \cdot Z$ term is the noise enhancement component. Since $\mathcal{s} = F_N(\bar{\mathrm{s}})$, thus Eq. (10) can be re-expressed as:

$$\bar{\boldsymbol{Y}}_4 = \bar{\mathbf{s}} + \emptyset = \mathbf{W}_{\mathbf{N}}^{-1}\bar{\mathbf{S}} + \boldsymbol{F}_N^{-1}\{\boldsymbol{H}^{-1} \cdot \boldsymbol{Z}\} \tag{11}$$

Now, the IFWHT is applied, hence Eq. (11) can be re-expressed as:

$$\hat{\mathbf{Y}} = \boldsymbol{W}_N\{\bar{\boldsymbol{Y}}_4\} = \bar{\mathbf{S}} + \emptyset \tag{12}$$

where $\emptyset = \boldsymbol{W}_N\{\boldsymbol{F}_N^{-1}\{\boldsymbol{H}^{-1} \cdot \boldsymbol{Z}\}\}$, $\bar{\mathbf{S}}$ represents the transmitted codedword vector.

2.2 The UWA Channel Model

The underwater channels are affected by different impairements such as, the water properties (salinity, temperture, PH degree, attenuation, and etc.). Those parameters play the core role in the channel modeling. Meanwhile, the sound waves are used instead of electromagnetic waves, this is due to the electromagentic waves are suffered from high attenuation and low effective range in the water medium [21]. There are many researchers are interested in modeling of underwater channels that helps in the use of signal processing algorithms to improve the real field experiments. In [22] the authors could predict and estimate the underwater channel impulse response in case of shallow water. The overall channel transfer function can be expressed as [22]:

$$H(f) = H_o(f) \sum_p h_p \gamma_p(f) e^{-j2\pi f \tau_p} \tag{13}$$

and

$$\gamma_p(f) = \frac{1}{h_p} \sum_{i \ge 0} h_{p,i} e^{-j2\pi f \delta_{\tau_{p,i}}} \tag{14}$$

where $H(f)$ is channel T.F, $H_o(f)$ is the T.F of direct path, $\gamma_p(f)$ is the small scale fading coefficient, $h_p, h_{p,i}$ are the gain and intra gains for the path respesitvity, and $\tau_p, \delta_{\tau_{p,i}}$ are the delay and intra delays for the path respesitvity.

According to underwater channel parameters given in Table 1, Fig. 3 illustrates the impulse response of the UWA during Mobile Acoustic Communications Experiment (MACE).

3 Modified OFDM System Verses Traditional OFDM System

The OFDM system based FWHT can increase the algorithm speed than the corresponding conventional one by replacing the FFT with FWHT, this saves about 70–36% in computer run-time up to 4096 transform length [20]. Also, the OFDM system based FWHT has a low implementation cost [20], due to lower arithmetic operations,

Table 1 The OFDM parameters

Parameter	Value	Parameter	Value
IFWHT size	256	Channel configuration	SISO
IFFT size	256	Size of the generator matrix	256 × 512
CP length	16	CFOs estimation	Perfect
Modulation	QPSK	Channel estimation	Perfect
SNR	0–20 dB	Channel model	MACE

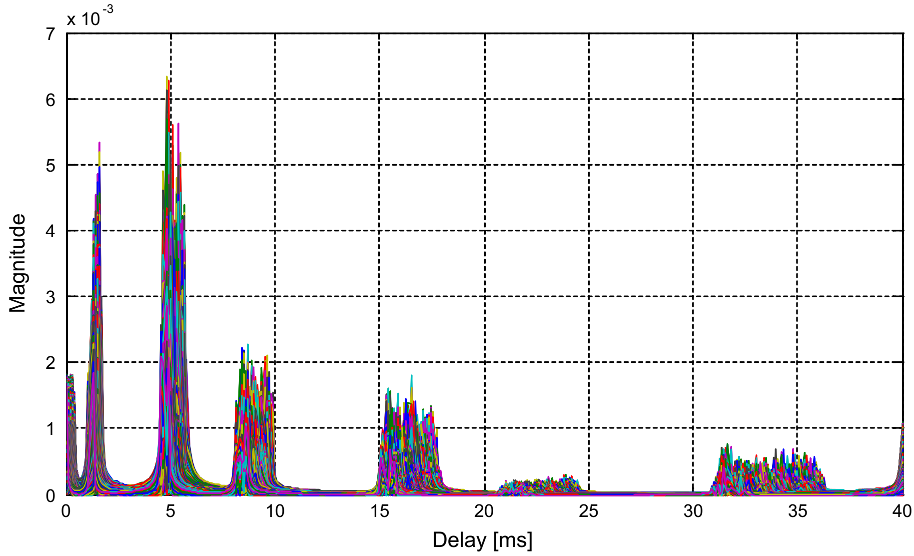

Fig. 3 Impulse response of the UWA-MACE channel

which based on the sparse matrices [20, 23]. The IFWHT can be used for OFDM modulation instead of IFFT at the transmitter side, and FWHT used instead of FFT at the receiver side to perform the OFDM demodulation instead of FFT. The main disadvantage of the OFDM system based FWHT is the need of FFT and IFFT at the receiver side to perform the equalization process in the frequency-domain. The ZF or MMSE equalizers could accomplish this task. Moreover, in case of UWA communications, the modified OFDM system based FWHT can offer a significantly improvement in the BER performance than the corresponding conventional one [23, 24].

4 Simulation Results and Analysis

This section presents a performance evaluation of the proposed OFDM based FWHT via extensive simulation. The time offset causes performance degradation especially in WHT [25]. Hence, the time offset caused by the UWA channel must be compensated correctly to avoid this problem. However, the ZC sequence is used to perform this task (time offset compensation). The main advantage of the ZC is the ability to perform time offset estimation in case of frequency offset. According to the

Table 2 The ZC parameters

Parameter	Value	Parameter	Value
ZC length	63	Normalized CFO	−1.50:0.1:1.50
Root index of ZC sequence	25	Normalized STO	Zero

Table 3 UWA-MACE channel parameters

Parameter	Value	Parameter	Value
Channel model	MACE	Central frequency	16 kHz
Water depth	100 m	Surface variance	1.125 m^2
Channel distance	1.00 km	Bottom variance	0.5625 m^2
Transmitter depth	45 m	Number of intra paths	20
Receiver depth	60 m	Mean of intra paths	25 mv
Bandwidth of the UWA channel	12 kHz	Variance of intra paths	1 μv

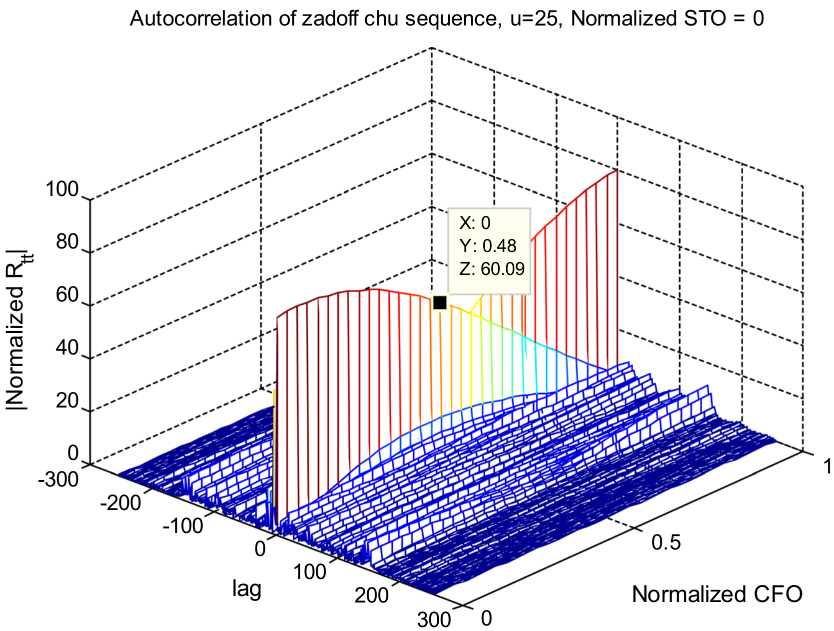

Fig. 4 Autocorrelation results with frequency offset, $|\varepsilon| \leq 1.75$

UWA-MACE channel parameters given in Table 1, and the OFDM plus ZC parameters given in Tables 2, and 3, respectively. The ZC sequences have the ability to specify the OFDM starting point in the presence of frequency offsets up to $\varepsilon \leq 0.48$ as depicted in Fig. 4. Thus, at the receiver side the OFDM starting point is specified, then the FFT is applied to convert the received vector to the frequency-domain in order to use a frequency-domain equalizer. Let us consider a MMSE for the rest of simulations. Figure 5

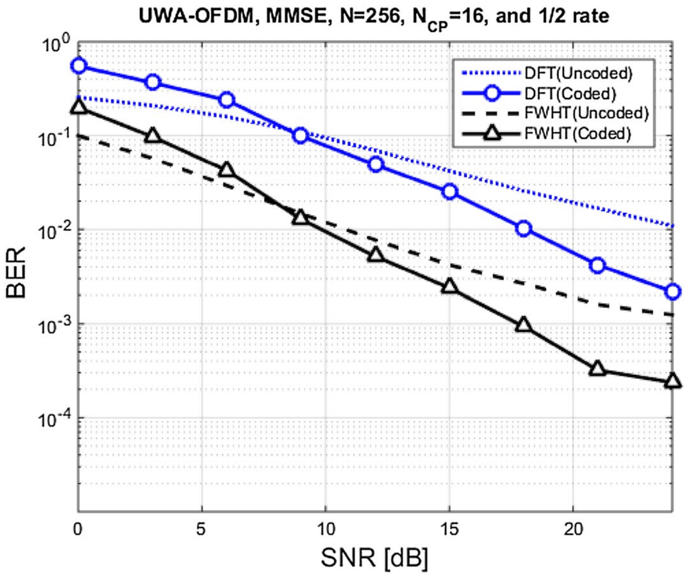

Fig. 5 BER versus SNR for the proposed algorithm and the traditional one

illustrates the performance of the proposed algorithm versus the corresponding traditional one based FFT, with LDPC coding (1024, 512) with ½ rate. It is clear that the proposed algorithm improves the UWA system performance than the corresponding traditional one, and also keep the system performance in the presence of both of STO, and CFOs.

5 Conclusion

In this paper, we propose a modified OFDM system based on FWHT with LDPC coding. The proposed algorithm can avoid the time offset associated with the FWHT by using the ZC sequences for time synchronization. Simualtion results show that the proposed OFDM system based FWHT outperforms the corresponding traditional one at the same channel conditions. Also, the proposed algorithm require a low-complexity than the corresponding traditional one.

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