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A Novel Receiver Design of Non-Orthogonal FDM Systems in Underwater Acoustics Communication

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Abstract— While Orthogonal Frequency Division Multiplexing (OFDM) has been studied for a decade, the study of Non-Orthogonal Frequency Division Multiplexing (NOFDM) in underwater acoustics (UWA) communication has never been reported, to the best of our knowledge. Therefore, we investigate NOFDM technique for UWA communication considering the doubly-dispersive channel. The main feature of NOFDM is that it involves more closely packed subcarriers compared to OFDM, which results in higher spectral efficiency. However, this transmission suffers from severe Inter-Carrier-Interference (ICI). Since, we are considering doubly-dispersive channel, Inter-Symbol-Interference (ISI) is also encountered due to multipath propagation. Therefore, traditional receiver of NOFDM system in UWA channel, tends to have high computational complexity. Considering this problem, we design a receiver for NOFDM system, where Basis Expansion Model (BEM) is used along with Compressed Sensing (CS) channel estimation technique i.e., Orthogonal Matching Pursuit (OMP), which can effectively reduce the computational complexity. However, while implementing this technique in the real sea environment, the problem of long delay / Doppler spread is encountered due to guard intervals. Therefore, we propose the use of time domain equalizer, to mitigate the effect of long delay / Doppler spread. Simulation and experimental results based on Bit Error Rate (BER) demonstrate performance degradation due to severe interference in our proposed receiver. On the contrary, Mean Square Error (MSE) performance shows that our proposed receiver with OMP channel estimation outperforms OFDM receiver. Similarly, higher spectral efficiency gain is attained due to closely packed subcarriers.

Index Terms— Basis Expansion Model (BEM), guard intervals, Inter-Symbol Interference (ISI), Inter-Carrier Interference (ICI), Non-Orthogonal Frequency Division Multiplexing (NOFDM).

NOMENCLATURE

$E(.)$	Expectation
$(.)^T$	Transpose
$(.)^H$	Hermitian Transpose
$\mathbf{I}$	Identity Matrix
β	Bandwidth Factor

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I. INTRODUCTION

Spectral Efficiency [1],[2],[3] is a significant parameter, which can measure the transmission rate in a limited bandwidth. In recent years, this parameter has been discussed for bandwidth efficient transmission in underwater acoustics (UWA) channel.

Many techniques have been used for UWA communication such as, conventional Time Division Multiplexing (TDM) or Frequency Division Multiplexing (FDM) techniques. However, these techniques are not suitable because it needs allocation of time and frequency respectively, for each user to transmit and receive signals. Hence, these methods are not bandwidth efficient and can have low spectral efficiency. Similarly, OFDM has also been extensively studied and investigated for better spectral efficiency and to implement reliable high data rate in UWA channel. Conventionally, OFDM is based on the orthogonally spaced subcarriers, which support interference-free transmission. For orthogonality condition, OFDM systems must satisfy, $T\Delta f = 1$, where T is symbol duration and Δf is sub-carrier spacing [4]. With this condition, signals can be transmitted without interference from other sub-carriers through additive white Gaussian noise (AWGN) channel. If $T\Delta f < 1$, it will create interference in between symbols and subcarriers, which results in Inter-Symbol-Interference (ISI) / Inter-Carrier-Interference (ICI) [5],[6]. These interferences result in serious performance degradation. Some techniques have been applied, such as cyclic prefix and zero-padding to mitigate the effect of interferences [7]. While, these techniques can mitigate the effect of ISI / ICI, with the expense of reduced bandwidth and spectral efficiency.

Prior work mentioned in [5],[8],[9],[10] proposed a technique termed as overlapped time division multiplexing (OVTDM), to compromise this interference through gaining better spectral efficiency for the wireless communication system. This technique is also studied in [2],[8],[3], where overlapping of symbols results in spectral efficiency. The more symbols overlap, the higher spectral efficiency can be obtained [5],[11]. Similarly, in [12],[4],[13],[14], the technique of NOFDM system is proposed for wireless communication. This interesting technique features non-orthogonality/overlapping of symbols/subcarriers, as can be seen in [15],[16],[17]. This overlapping results in ISI / ICI. Instead of discarding ISI / ICI, NOFDM technique exploits ISI / ICI in improving the bandwidth efficiency. Mathematically, NOFDM adopts $T\Delta f < 1$. This inequality results in ISI/ICI and necessitates complex receiver processing. However, there is no work can be found regarding NOFDM in UWA communication.

From the literature [18],[19],[20] it is known that the

performance of UWA communication is strongly dependent on propagation environment. Signal transmission in UWA channels is considered difficult, due to fast-time varying environment. Similarly, in real sea environment, channel impulse responses calculations can show the effect of UWA channel on the signal propagation. Since, the signal propagation in UWA channels is a hot topic for recent few years. Therefore, researchers discuss two important phenomena which directly affect the performance of UWA communication, multipath propagation and the Doppler effect [21],[22]. Thus, UWA communication is often characterized as a time-varying doubly-dispersive communication system [23]. Due to doubly-dispersive nature of UWA channel, we have to keep in mind that there is time dispersion due to multipath propagation and frequency dispersion due to Doppler spread. Therefore, our research primarily focuses on both time and frequency dispersion in UWA channels, where symbols and subcarriers spread out in time and frequency domain, respectively. Therefore, severe ISI / ICI is encountered due to time dispersion while, long delay spread is introduced due to frequency dispersion. Considering the real sea environment, these problems are important to be discussed.

In this paper, we focus on applying NOFDM technique in UWA channels. So, in this case, we have implemented NOFDM receiver by applying: 1) pre-processing and resampling, 2) Basis Expansion Model (BEM) based Compressed Sensing (CS) channel estimation and 3) Time-Domain Equalizer. After receiving the signal with the sampling rate of $f_s = 1/2T$, where f_s is the sampling frequency. We should keep the same sampling rate by applying resampling, to maintain the condition for non-orthogonality / overlapping. Due to the overlapping behavior of the signal, it is quite clear that complexity is introduced on the receiver side. To avoid this problem, we have implemented channel estimation. While considering the sparse signal, CS [24] estimation technique like Orthogonal Matching Pursuit (OMP) [25] has been discussed. Similarly, when we are investigating NOFDM in UWA channels, the problem of long delay spread is also unbearable. Several studies such as [26],[27] improve the spectral efficiency by using time-domain equalizer, while lowering the effect of channel delay spread without using guard intervals. This equalization method considerably suppresses the influence of long delay spread through compensating different time-varying multipath delays. Therefore, inspired from the previous work [26],[27], we used time-domain equalizer for our proposed receiver. Simulation and experimental results show that Bit Error Rate (BER) performance of proposed NOFDM receiver is degraded, while, MSE performance is better when compared to OFDM system. Similarly, results based on real sea environment depict that NOFDM achieves higher spectral efficiency when compared with state-of-the-art OFDM system.

The rest of this paper is organized as follows: Section II introduces the NOFDM transmitted signal in doubly-dispersive UWA channels. Section III proposes receiver based on NOFDM system for UWA communication, which comprises of signal pre-processing and resampling, BEM based channel estimation and equalization in time-domain. Section IV demonstrates simulation and the sea experimental results. Finally, in Section V, we have provided conclusions based on the proposed receiver.

II. NOFDM TRANSMITTED SIGNAL IN DOUBLY-DISPERSIVE UWA CHANNELS

A block of data with N symbols, $s = [s_0, \dots, s_{N-1}]^T$ is transmitted. This data is passed through the pulse shaping filter, which results in rectangular pulse shape. The transmitted signal is:

$$x(t) = \frac{1}{\sqrt{T}} \sum_{l=-\infty}^{\infty} \sum_{i=0}^N s_{l,i} \exp\left(\frac{j2\pi i \beta (t-lT)}{T}\right) \quad t \in [0, \tau] \quad (1)$$

where $s_{l,i}$ is the symbol modulated on i^{th} subcarrier in the l^{th} NOFDM symbol and τ is maximum time duration of a frame. Similarly, baseband signal is derived by sampling at T/M intervals, where $M = \delta N$, $\delta \geq 1$ is the oversampling factor, $k = [0, 1, 2, \dots, M-1]$,

$$x[k] = \frac{1}{\sqrt{M}} \sum_{i=0}^N s_i \exp\left(\frac{j2\pi i k \beta}{M}\right) \quad (2)$$

where, $\beta = \Delta f T$, if $\beta = 1$, it results in OFDM transmitted signal. While for bandwidth efficient transmission, we keep $\beta < 1$, which results in NOFDM transmission. The more symbols packed closer (overlapped), the higher the bandwidth efficiency. Former studies [15],[28] achieved 40% bandwidth efficiency compared to OFDM.

Previously, the researcher implemented multipath fading channel using Viterbi algorithm as a channel model [29]. However, many questions aroused during the study of NOFDM, still, results from the earlier work [12] show that NOFDM technique has been used to develop the system with higher spectral efficiency. Similarly, non-orthogonal pulses have been investigated in doubly-dispersive channels [4], but under no consideration of underwater environment. So in our circumstances, we have introduced this technique for UWA communication and compare it with the traditional OFDM. In underwater scenario, it is obvious that due to water current and ambient noises etc, it is nearly difficult to avoid ISI / ICI. So, this section also introduces the NOFDM transmission over doubly-dispersive UWA channels.

Therefore, as shown in Fig. 1, we suppose that $h(t, \tau)$ is the channel impulse response and $x(t)$ is the transmitted signal, where $h(t, \tau)$ describes both multipath and Doppler spreads. In a doubly-dispersive UWA channel, the received signal $y(t)$ is the convolution of transmitted signal (same as in (1)) and channel impulse response:

$$y(t) = \int_{-\infty}^{\infty} h(t, \tau) x(t-\tau) d\tau + v(t) \quad (3)$$

where $v(t)$ is the ambient noise present in the UWA environment. When we use discrete multipath components for our model, the time-varying UWA channel is derived as:

$$h(t, \tau) = \sum_{q=1}^Q A_q(t) \xi(\tau - \tau_q(t)) \quad (4)$$

where $A_q(t)$ and $\tau_q(t)$ are time-varying amplitudes and delays of length Q , while ξ is the Dirac-delta function. From (4), which is the time-varying impulse response, if there is U number of da

Fig. 1 Block diagram of NOFDM signal transmission through doubly-dispersive UWA Channel and proposed receiver using (a) Pre-processing and Resampling, (b) BEM Based Channel Estimation and (c) Time-Domain Equalizer

-ta points, then the number of UWA channel coefficients to be estimated will be $U*Q$.

In this paper, since, we are dealing with doubly-dispersive channel, this type of channel model leads to a comparatively simple signal processing at the receiver [26]. In UWA communication, it has been noticed that if the transmitter is not static, time-varying components can be used to represent the channel. Let $\bar{h}(t, \tau)$ be the channel impulse response with slow time variations. So, the time-varying impulse response can be derived as convolution of $\bar{h}(t, \tau)$ and $\xi(\tau - \tau_q(t))$.

III. PROPOSED NOFDM RECEIVER

NOFDM technique is used to make ISI / ICI valuable for communication, which has been induced through multipath effect in UWA channel. Moreover, NOFDM adopts low order modulation scheme and through overlapping implemented in FDM, not only provides high spectral efficiency, but also generates coding constraint. Meanwhile, irrespective of these advantages, there would be slight increase in computational complexity. Previous studies [12],[14],[30] depict that computational complexity increases with the increase in overlapped symbols.

Additionally, when we have implemented this technique in UWA environment, enhancement of spectral efficiency occurs due to overlapping of FDM signals. However, computational complexity still remains the same. In classical single-carrier communication systems considering doubly-dispersive channel, such multipath spreads cause severe ISI and ICI, which requires sophisticated and computationally demanding estimation techniques. To overcome computational complexity, CS channel estimation technique is investigated in Section III.B. CS has various methodologies of signal recovery. Although, in our proposed receiver design, OMP is implemented to recover sparse signals, which is quite basic and a powerful technique. Similarly, our proposed receiver experienced long delay spread due to resampling, thus, time-domain equalization is adopted.

A. Pre-processing and Resampling

Fig.1 demonstrates proposed NOFDM receiver for UWA communication, where NOFDM system proposes $T\Delta f < 1$. After receiving the signal, we have introduced pre-processing filter (refer to Fig. 1). Pre-processing comprises of analog bandpass filtering (BPF), analog-to-digital conversion (ADC) and lowpass filter (LPF). Normally, for OFDM transmission, we use sampling rate $f_s = 1/T$ Hz, while in our proposed NOFDM receiver, after BPF, we use ADC with the sampling rate of $f_s = 1/2T$ Hz. After sampling through ADC, LPF is added. The resultant discrete-time signal through ADC first downshifted and then, forwarded to LPF. Therefore, the received signal for NOFDM after pre-processing in UWA channel can be described as:

$$r'(t) = \int_{-\infty}^{\infty} h(t, \tau) y(t - \tau) d\tau + v(t) \quad (5)$$

In order to maintain the non-orthogonal condition, sampling rate still remains the same for NOFDM receiver. Hence, our proposed scheme make use of resampling for non-orthogonal subcarriers to be demodulated at the receiver. The discrete-time signal received after resampling is derived as:

$$r'(n) = \sum_{l=0}^{L-1} h(n, l) y(n - l) + v(n) \quad (6)$$

where, $L-1$ is the maximum delay. Before resampling, we have subcarriers more closely packed due to transmission of non-orthogonal symbols, which causes serious complexity. However, more complexity added, when our proposed receiver introduces lowpass filter and resampling. To combat complexity, we implement BEM based channel estimation technique, i.e., OMP, which results in less complexity.

The following section discusses the BEM based channel estimation, as in previous work [36], basis expansion model is used and tested in doubly-dispersive UWA environment.

B. BEM Based Channel Estimation

At present, the most accurate approximations of doubly-dispersive UWA channels with large delay and Doppler spreads are obtained via the BEM [31],[32]. Consequently, we assume in this paper that the channel estimation is represented in terms of a BEM, which approximates the channel taps by linear combinations of prescribed basic functions [33][34][35]. Prior work proposes successful implementation of BEM for time domain oversampled channel estimation [36]. The time varying channel tap with fixed delay l is modelled by Z-order BEM as:

$$h(n, l) = \sum_{z=0}^{Z-1} b_{z,l} P_z(n) \quad (7)$$

where $P_z(n)$ is the z th order base function and $b_{z,l}$ is the corresponding model coefficient. By putting (7) into (6), we have received signal due to effect of BEM is:

$$r'(n) = \sum_{l=0}^{L-1} \left(\sum_{z=0}^{Z-1} b_{z,l} P_z(n) \right) y(n-l) + v(n) \quad (8)$$

Therefore, after rearranging summation order in (8), we obtain:

$$r'(n) = \sum_{z=0}^{Z-1} P_z(n) \left\{ \sum_{l=0}^{L-1} b_{z,l} y(n-l) \right\} + v(n) \quad (9)$$

Since, UWA signal is sparse signal, using CS theory along with BEM can effectively take advantage of its sparse characteristic to estimate the underwater acoustic channel. CS technique has been investigated and exploited sparse nature in underwater acoustics environment. Also, in doubly-dispersive environment, while recovering the signal, two conditions must be satisfied through which optimization is achieved; firstly, the non-orthogonal signal must be k -sparse, when projected onto a certain basis or dictionary matrix, and secondly, the measurement matrix $\mathbf{A}$ must be incoherent due to BEM effect.

By considering an NOFDM system with total number of closely packed N subcarriers and selected α subcarriers from N indexed with pilots at positions $P_1, P_2, \dots, P_\alpha$ from the set $1 \leq P_1 < P_2 < \dots < P_\alpha \leq N$. It is obvious from the fact that, there is an inter-carrier and inter-symbol interferences in the NOFDM system transmission. Transmitted pilot signals are represented as $\mathbf{R}(P_1), \mathbf{R}(P_2), \dots, \mathbf{R}(P_\alpha)$, while, received pilots are characterized as $\mathbf{Y}(P_1), \dots, \mathbf{Y}(P_\alpha)$. Thus, the received signal in matrix form can be derived as:

$$\begin{bmatrix} \mathbf{Y}(P_1) \\ \vdots \\ \mathbf{Y}(P_\alpha) \end{bmatrix} = \begin{bmatrix} \mathbf{R}(P_1) & 0 & 0 & 0 \\ 0 & \mathbf{R}(P_2) & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \mathbf{R}(P_\alpha) \end{bmatrix} \mathbf{D}_{\alpha \times L} \begin{bmatrix} \mathbf{h}(1) \\ \vdots \\ \mathbf{h}(L) \end{bmatrix} + \begin{bmatrix} \mathbf{w}(P_1) \\ \vdots \\ \mathbf{w}(P_\alpha) \end{bmatrix} \quad (10)$$

where $\mathbf{h} = \{\mathbf{h}(1), \mathbf{h}(2), \dots, \mathbf{h}(L)\}^T$ is the sparse Channel Impulse Response (CIR), which consists of limited number of non-zero channel taps with length L . $\mathbf{w} = \{\mathbf{w}(P_1), \mathbf{w}(P_2), \dots, \mathbf{w}(P_\alpha)\}^T$ is the ambient noise and $\mathbf{D}_{\alpha \times L}$ is the discrete Fourier transform (DFT) sub matrix selected from $\{P_1, P_2, \dots, P_\alpha\}$ and $\{1, 2, \dots, L\}$ rows and columns, correspondingly, and it is defined as:

$$\mathbf{D}_{\alpha \times L} = \frac{1}{\sqrt{N}} \begin{bmatrix} e^{-j2\pi P_1 \cdot 0/N} & e^{-j2\pi P_1 \cdot 1/N} & \dots & e^{-j2\pi P_1 \cdot (L-1)/N} \\ e^{-j2\pi P_2 \cdot 0/N} & e^{-j2\pi P_2 \cdot 1/N} & \dots & e^{-j2\pi P_2 \cdot (L-1)/N} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j2\pi P_\alpha \cdot 0/N} & e^{-j2\pi P_\alpha \cdot 1/N} & \dots & e^{-j2\pi P_\alpha \cdot (L-1)/N} \end{bmatrix} \quad (11)$$

while the transmitted pilot signal is denoted as $\mathbf{r} = \text{diag}\{\mathbf{R}(P_1), \mathbf{R}(P_2), \dots, \mathbf{R}(P_\alpha)\}$, received signal is denoted as $\mathbf{Y} = \{\mathbf{Y}(P_1), \mathbf{Y}(P_2), \dots, \mathbf{Y}(P_\alpha)\}$, so the expression (10) is simplified as:

$$\mathbf{Y} = \mathbf{r} \mathbf{D}_{\alpha \times L} \mathbf{h} + \mathbf{w} \quad (12)$$

where $\mathbf{r} \mathbf{D}_{\alpha \times L} = \mathbf{A}$ represent the measurement matrix, therefore simplified form of (12) is represented as:

$$\mathbf{Y} = \mathbf{A} \mathbf{h} + \mathbf{w} \quad (13)$$

By observing (13), the signal reconstruction using compressed sensing is based on the constraint that $\mathbf{h}$ is k -sparse. Therefore, as long as the signal is sparse in nature in underwater acoustics communication, it recognizes the fact that received signals are not contiguous rather than isolated, so for this reason, CS is being used to improve the performance. However, for recovery of a signal, different techniques for CS are there for UWA channel.

In this article, we have investigated a greedy algorithm technique of OMP to implement NOFDM system in UWA communication. The OMP algorithm offers a powerful approach when considering doubly-dispersive environment. This technique when implemented with BEM, it does not require any prior information about channel statistics and can avoid the spectral leakage [37],[38]. Since, the greedy algorithms are fast, however, the linear combinations of base functions due to BEM results in enhanced signal recovery.

In Fig. 2, OMP algorithm is initialized, where all atoms are assumed as unity. Stage 1: in between $\mathbf{r}_1 - 1$ and $\mathbf{A}_1$, where $\mathbf{r}$ is the observation vector. The inner-product samples are calculated, where, $l = \Psi_1 - 1$, and Ψ is based on values obtained through DFT matrix. Stage 2: for orthogonality, index set is chosen. Stage 3: the channel estimation calculation is done. Stage 4: based on selected column, the algorithm updates the residual. This algorithm stops when the halting condition triggered. Considering the halting condition, algorithm termination occurs when residual value is lesser than error bound. Since, there are some limitations for OMP in OFDM systems, these limitations are removed due to non-orthogonal projection of signals onto the subspace of some particular column. OMP algorithm for NOFDM leads to an improved performance over the traditional OMP for OFDM.

Fig. 2 OMP Flow Diagram

C. Time-Domain Equalizer

The main tasks of the time-domain equalizer are to compensate for differently time-varying multipath delays and reduce the channel delay spread.

Note that it is important to select proper multipath delays corresponding to the UWA channel delays. It is especially important for sparse multipath channels, which often is the practical case in the underwater acoustics [39],[40]. However, this is also important for almost continuous multipath structures as in our simulations. The multipath selection can be viewed as a process of reducing the number of channel parameters to be estimated, and, thus, the accuracy of the estimates can be improved. Based on BEM with channel estimation, estimated channel matrix obtained from (9), where, $P_z(n)$ is diagonal matrix termed as $\mathbf{P}_z$ and $\sum_{l=0}^{L-1} b_{z,l} y(n-l)$ is the circulant matrix termed as $\mathbf{B}_z$. Therefore, channel matrix $\mathbf{H}$ in time-domain is defined as:

$$\mathbf{H} = \sum_{z=0}^{Z-1} \mathbf{P}_z \mathbf{B}_z \quad (14)$$

The received signal can be re-formulated as:

$$\mathbf{y} = \mathbf{H}\mathbf{\epsilon} + \mathbf{w} \quad (15)$$

Where $\mathbf{H} = \mathbf{I}_{\Delta T}$, so (15) is regarded as non-orthogonal based received signal. We have applied time-domain equalizer, where equalizer length is chosen to be 3-5 times of channel delay spread, results in symbol estimation of $\mathbf{\epsilon}$:

$$\hat{\mathbf{\epsilon}} = \{\mathbf{H}^H \mathbf{H} + \sigma_0^2\}^{-1} \mathbf{H}^H \mathbf{y} \quad (16)$$

where σ_0^2 is the variance for the noise mentioned in (16). In our proposed non-orthogonal FDM, symbol estimation is done by averaging the signal power when subcarrier spacing is almost half of the traditional spacing of $\Delta f = 1/T$.

IV. PERFORMANCE EVALUATION

In this section, we have detailed discussions on our simulation and sea experimental results. BER results depict that there is performance degradation due to ISI / ICI. MSE performances based on simulated results and signals acquired during sea experiments, verified that our proposed NOFDM receiver using OMP has significant gain compared to OFDM system. Moreover, higher spectral efficiency gain is attained compared to non-overlapped subcarriers and symbols.

A. Simulation Results

Table 1 NOFDM Parameters

Parameters	Values
Number of Subcarriers	1024
Modulation Technique	QPSK
Number of pilot symbols	64, 128
Guard intervals	12 ms
Channel Estimation	OMP
Channel Bandwidth	4 KHz

The parameters are chosen heuristically, while bandwidth factor (β) in non-orthogonal system should be smaller than the bandwidth factor for OFDM system. OMP channel estimation technique is a greedy pursuit algorithm, which reduces the computational complexity. So for that reason, we have implemented this technique in our simulations. We compared theoretical and simulated performance of state-of-the-art OFDM with the proposed receiver of NOFDM and NOFDM mentioned in [12]. For calculating MSE, we have taken 128 number of pilot symbols for OFDM, while 64 number of pilot symbols introduced for NOFDM. MSE obtained with the channel estimation algorithm as a function of the SNR.

Fig. 3 demonstrates decreasing MSE value with the increased value of SNR. It is obvious that our proposed receiver of NOFDM outperforms OFDM by taking the advantage of OMP. Since, UWA channel characteristics are sparse in nature, NOFDM with OMP approximates channel taps using BEM. Moreover, in the process of optimal selection of atoms, atoms are realized, removed and added. Therefore, NOFDM overcomes the shortcoming of OFDM effectively. Consequently, the MSE performance using OMP of proposed NOFDM receiver design is better than OFDM.

Fig. 4 shows that the BER performance of NOFDM using QPSK is reduced, since, subcarriers are more closely packed such that $\beta = 0.6$, compared to OFDM system. Although, OFDM has been extensively implemented in underwater acoustics. Though, in our computer simulations considering the doubly-dispersive channel environment, we have tested BER performance for NOFDM using QPSK and OFDM using 16-QAM modulation techniques, furthermore, SNR limit of 15 dB is adopted. Therefore, at the floor of 10^{-5} , performance degradation of 4.5 dB for proposed NOFDM is observed compared to theoretical values of state-of-the-art OFDM.

Fig. 3 Results based on MSE performance for proposed NOFDM receiver, NOFDM in [12] and OFDM receiver using OMP channel estimation, SNR = 15 dB

Fig. 4 Results based on BER performance for proposed NOFDM receiver, NOFDM in [12] and OFDM receiver using OMP channel estimation, SNR = 15 dB

B. Sea Experiments

The sea trials took part on the Northern coast of Xiamen City, Xiamen, China. While testing, a transmitter at the depth of 60m was towed by a ship. The ship was floating towards the acoustic receiver with the speed of 5m/s. During the experiment, the NOFDM and OFDM signals are transmitted one after another. NOFDM sequence transmitted with the symbol length of 380 and same for OFDM transmission. While on the receiver side,

Fig. 5 Experimental analysis of LFM based Correlation output at the distance of 1500m

received signals were recovered by using omnidirectional hydrophones. The receiver is stationary and received the sequence at the depth of 40m in our experiments. Here we report performance results on the basis of signals, which were acquired through sea experiments.

In this paper, the proposed NOFDM technique requires the guard interval of 12ms, while the OFDM transmission will have the guard interval of 24ms. For NOFDM transmission, we have considered the same number of pilot symbols as used in our simulations. On the receiver side, signals recovered through removing the modulation (by multiplying the output with the known transmitted sequence of binary data). This is similar to the approach suggested in [41]. Following this approach, we can investigate the performance of the NOFDM receiver through the real channel. Also while considering the subcarrier spacing, we have implemented $\Delta f = 0.5/T$ Hz for NOFDM and $\Delta f = 1/T$ Hz for OFDM. The experiments were carried out by our team of Xiamen University. During the experiments, we have received correlation output, while considering linearly-frequency-modulated (LFM) signal for the channel at the distance of 1500m (refer to Fig. 5).

Channel Responses

In our proposed receiver, the channel responses due to pre-processing, resampling and time-domain equalizer can be seen from the Figs. 6(a), 6(b) and 6(c), respectively. Due to doubly-dispersive UWA channel, it is obvious that there will be channel variations in time and frequency domain. Therefore, in Fig. 6(a), we observed that there are faster channel variations. These variations were slowed down due to resampling, (in Fig. 6(b)). However, due to these delayed variations, long delay / Doppler spread is encountered at the receiver. Hence, in our proposed receiver, we introduced time-domain equalizer. Fig. 6(c) shows channel impulse responses due to the effect of time-domain equalizer. Since our main goals are to attain low complexity using OMP, improving the spectral efficiency, similarly, the problem long delay spread is resolved through applying time-domain equalizer.

Fig. 6(a) Faster time variations before resampling, (b) Slower time variations after resampling, (c) Compensation of Doppler effect using time-domain equalizer

Fig. 7 Experimental results based on doubly-dispersive channel: BER performance for NOFDM receiver and OFDM receiver using OMP channel estimation

BER and MSE Based Receiver Performance

The BER and MSE performances of the NOFDM receiver compared to OFDM receiver are shown in Figs. 7 and 8, respectively. In Fig. 7, due to doubly-dispersive UWA channel, our proposed receiver of NOFDM has BER performance degradation due to induced ICI / ISI. However, experimental results show that proposed receiver of NOFDM has BER performance very close to OFDM, when $BER = 10^{-1}$ to 10^{-3} , since, the limit of $SNR = 15$ dB. Still, there is quite a difference compared to ideal receiver. While considering MSE performance, the Fig. 8 draws the conclusion that our proposed receiver outperforms when using OMP channel estimation compared to traditional OFDM receiver.

Spectral Efficiency

From the proposed receiver design of NOFDM discussed in Section III, spectral efficiency is introduced after getting signals from NOFDM transmitter. Assume that the effective bandwidth is defined as $B' = \frac{(L+k-1)\Delta f}{k}$ and $\tau = T$ so for this case, spectral efficiency can be determined as:

$$\eta = \frac{X \log_2 M'}{B' \tau} = \frac{X \log_2 M'}{(X+k-1)\Delta f / k T} \quad (17)$$

$$= \frac{k \log_2 M'}{\beta} \frac{X}{X+k-1} \text{ bits / (Hz. sec)}$$

where $\beta = \Delta f T$, k will be number of symbols overlapped and M' is the modulation order at the transmitting side. From this equation, it is obvious that if β is small enough, so that more subcarriers are closely packed, higher spectral efficiency can be gained.

Similarly, for achieving higher spectral efficiency using NOFDM receiver, it is obvious that more symbols to be overlapped. Therefore, we have applied limit to the value of X , which is the number of overlapped symbols. Due to more symbols overlapped, the factor of $\frac{X}{X+k-1}$ is quite negligible. Also we have set $M' = 4$, therefore, the resulted spectral efficiency is:

Fig. 8 Experimental results based on doubly-dispersive channel: MSE performance for NOFDM receiver and OFDM receiver using OMP channel estimation

$$\eta = \frac{2k}{\beta} \quad (18)$$

So, higher spectral efficiency has been achieved with the more closely packed subcarriers. The Fig. 9 below demonstrates the spectral efficiency of NOFDM receiver. It is quite clear that with the bandwidth factor of $\beta = 0.6$, we have achieved highest gain, i.e., $\eta = 22$ bits/s/Hz, compared to OFDM receiver. On the other hand, bandwidth is saved with the changing values of β . Calculating the saved bandwidth, $(1 - \beta) \times 100\%$ factor is used. Therefore, when $\beta = 0.6$, bandwidth is saved up to 40%.

Fig. 9 Spectral Efficiency Gain due to closely packed subcarriers

V. CONCLUSIONS AND FUTURE WORK

This paper investigates a novel idea of NOFDM, which is an effective, reliable, and practical technique that can enhance the spectral efficiency of underwater acoustics communication. Although, the closely packed subcarriers introduces ICI, we exploit the ICI for improving signal strength during the sea experiments.

Talking about the novelty, we have introduced pre-processing filter at the receiver side, which downshift the signal using lowpass filter. Resampling is used to maintain the non-orthogonality of received signals. Channel estimation such as compressed sensing and equalization method can be useful in many practical scenarios. Even in our experiment, the use of the OMP for channel estimation has allowed improvement in the receiver performance. Computational complexity of NOFDM demodulation can easily be reduced by applying OMP algorithm. Similarly, time-domain equalizer is introduced to overcome the delay / Doppler spread. Investigations involving simulations concluded that proposed receiver of NOFDM has better MSE performance compared to the OFDM. Performance based on BER suffers degradation due to ISI / ICI in doubly-dispersive UWA channel. Results suggest that through applying this technique in underwater acoustics, we can exploit ISI / ICI, instead of ignoring. We can improve the received signal

strength using multipath, however, there is a variety of noise (ambient noise, fish noise, etc) induced by the UWA channel. For now, we only implemented NOFDM technique for QPSK. Comparing it with the OFDM, our proposed receiver has higher spectral efficiency along with the saved bandwidth.

In future, we intend to study high order modulation for NOFDM and comparing this technique with OFDM using advanced receiver design, where Carrier Frequency Offset channel estimation and data demodulation are iteratively coupled. Moreover, the problem of high peak-to-average power ratio and performance degradation is also encountered during the implementation of proposed receiver. Hence, our future work will be based on providing necessary amendments in proposed receiver.

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