A DIRECT DECODER METHOD FOR OFDM WITH CARRIER FREQUENCY PILOT IN UNDERWATER ACOUSTIC COMMUNICATION SYSTEMS

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Abstract: **In this paper, we propose a new decoder method at the receiver of system to compensate Doppler frequency shift for OFDM-based underwater acoustic communication systems. At the transmitter, in order to save bandwidth, we do not use additional signal header (preamble) in each OFDM frame as proposed in many conventional approaches. Instead, the central sub-carrier is reserved for pilot transmission. This subcarrier is so-called as the carrier frequency pilot (CFP), which is used to detect the Doppler frequency. At the receiver, in [1], two synchronization steps are deployed. The first step, the Doppler frequency is roughly estimated on the basic of the detected carrier frequency. In the second step, we use the CFP to regulate the estimated Doppler frequency. This regulation is called as fine synchronization. The use of Doppler compensation scheme in [1] is relatively complex because in order to calculate Doppler accuracy, it is necessary to perform two steps. Therefore, I propose an algebraic computation of Doppler frequency shift with one step. The results of the Doppler frequency shift calculation will be used to re-sample the received signal using the re-sampling matrix. The advance of using this matrix is that it can be calculated with any decimal, not an integer such as using the matlab function available in [1].**

Keywords: Underwater Acoustic Communication (UAC), OFDM, Doppler Frequency Compensation.

I. INTRODUCTION

With the rapid development of technology, the underwater acoustic (UWA) communication has been attracting attention of researchers [2-3]. Compared to wireless communications, the UWA communications are more challenging. This is due to the fact that, the speed of wave propagation of about 1500m/s is much slower than that of radio waves [3]. The signal bandwidth of an UWA system is usually less than few tens of kHz.

Thus, to obtain a high data rate in UWA communications, using modulation scheme with high spectral efficiency is desirable. In this context, the Orthogonal frequency division multiplexing (OFDM) is very promising technique for an effective transmission rate in a narrow band UWA communications. The multipath propagation interference can be combated by the OFDM technique. However, the penalty of deploying the OFDM method in UAC is the sensitivity of the system to the Doppler Effect in underwater [9]. Any kind of movements in underwater will introduce an amount of the Doppler frequency shift, and thus, it will damage the received OFDM signal. Different to the wireless OFDM system, the Doppler shift in UAC can be caused by different sources, such as relative movement of the transceivers, water surface movement, dynamic chaos in underwater, etc. The relative ratio of the Doppler frequency to the carrier spacing of an OFDM-based UAC is significantly larger than that of the OFDM radio communication systems. Therefore, the orthogonally of the OFDM signal will be destroyed. It results in the ICI. To mitigate the ICI, the Doppler frequency shift must be compensated at the receiver. In literature, there are several ICI compensation approaches for the OFDM-based on UAC [4-6]. The methods proposed in [4-5] calculate the Doppler shift after the frequency synchronization. However, in a case of a large Doppler frequency shift, the synchronization technique based on a comparison of the received signal with the transmitted one do not provide a reliable synchronization result. Thus, the corresponding estimated Doppler frequency shift is

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also inaccurate. This is our motivation to propose a Doppler frequency estimation method, which does not rely on the preamble or the postamble signal as done in [4].

In the proposed method, the Doppler frequency is estimated before the OFDM signal is synchronized. In order to estimate the Doppler frequency, subcarrier is reserved to be used as a reference frequency. This subcarrier is called as the CFP (Carrier Frequency Pilot). The CFP is increased higher amplititude than the other subcarriers, and it can be used both for Doppler frequency and channel estimation.

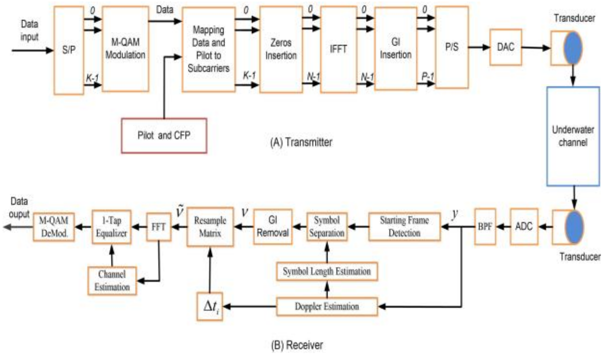


Fig. 1. The block structure of underwater system

To compensate the Doppler frequency shift, we need only one step to estimated Doppler shift. This is quite different from the other proposed method [3-5]. To estimate Doppler frequency shift, we use CFP as a carrier frequency so when we detect the CFP in receiver signal we also calculate receiver frequency therefore Doppler shift will be estimated. Compared to the technique proposed in [4], our method does not need a long frame, it can be worked with very short frame even with one or two symbol per frame, however with longer frame our method will get more accurately Doppler shift. Therefore, our approach can be applied to a very fast time-varying channel, where the relative movement speed of the transceivers is high. The drawn back of our method is increase the transmitting power of OFDM signal. In practical, compare to the case of OFDM signal without using CFP, OFDM with CFP signal makes increasing 10 percent power of OFDM transmitted signal.

This paper is organized as follows: Section I is Introduction, Section II describes the proposed architecture of an acoustic OFDM system and the proposed method for compensating the Doppler frequency shift. Section III is the experimental results of the system using our method and discussion. Section IV concludes the paper.

II. SYSTEM DESCRIPTION

A. Transmitter structure

The diagram of our proposed OFDM system is shown in Fig. 1(A), where the input data bits are split to K parallel outputs by a serial/parallel (S/P) converter. The bit stream on K parallel outputs are modulated to complex symbols by using the M-QAM scheme. The modulated symbols within an OFDM symbol are denoted by:

$$\vec{S} = [S_0, S_1, \ldots, S_{K-1}] \tag{1}$$

where K is the number of the data symbols which are modulated to an OFDM symbol. K is selected to be less than a half of the FFT length, namely: $K \le N-1$, where $N_{FFT} = 2N+1$ denotes the FFT length. This is to server later on purpose of using a data symbol with zeros mapping, as shown in Fig. 3, to avoid the use of an I/Q modulator in the UWA communication systems. In UWA communications, ones prefer to use a low carrier frequency of about several tens of kHz. This is to avoid high attenuation at high frequency [10]. Because the acoustic signal is low frequency signal, it is not necessary to use the I/Q modulator to convert the signal in baseband to bandpass.

For an example, if the desired frequency range is from $f_{\min} = 20kHz$ to $f_{\max} = 28kHz$, the sampling frequency $f_s = 96kHz$. The signal S are then inserted with $(N-1-L_2)$ zeros in the front, and in the end to form signal $\vec{X}$ of N_{FFT} samples.

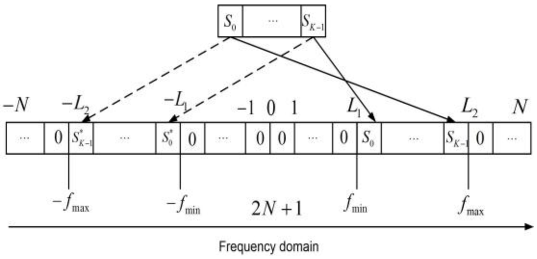


Fig. 2. Zeros Insertion

$$\vec{X} = [0,\ldots,0,S_0,\ldots,S_{K-1},0,\ldots,0,S^*_{K-1},\ldots,S^*_0,0,\ldots,0] \tag{2}$$

The distance between OFDM subcarriers: $\Delta f = f_s/(2N)$. So in Fig. 2, $L_1 = f_{\min}/\Delta f$ and $L_2 = f_{\max}/\Delta f$ are respectively the start and the end of data subcarriers to the position of S_0 and S_{K-1}. After the mapping block, signal entered an inverse fast fourier transforms (IFFT) block after mapping block, outputs composed of the real signal $x(n)$ in the time domain. The last GI samples of $x(n)$ are copied and padded in front of itself to deal with intersymbol interference (ISI). Then they are converted into the parallel to serial (P/S) converter and the last enter digital to analog converter (DAC) connect to transducer, in here the signal is carried by acoustic waves. In the receiver side, the signal will be decoded OFDM with reverse sequence. The concept of using the CFP for Doppler frequency estimation is deployed on the subcarrier at the central of the system bandwidth, which corresponds to the subcarrier index $(L_1 + K/2)$ or the subcarrier frequency:

$$F_c = \Delta f \cdot (L_1 + \frac{K}{2}) \tag{3}$$

In order to estimate channel at receiver side, Pilot will be inserted into data $\vec{S}$. Fig. 3 show Pilot and

Data are inserted together. Because this is very fast moving system so we use continuous Pilot in frequency domain. To overcome the noise and interference in UW communication, the amplitude of the CFP signal A_c should be boosted with higher amplitude in comparison with the other normal Pilot and data signal.

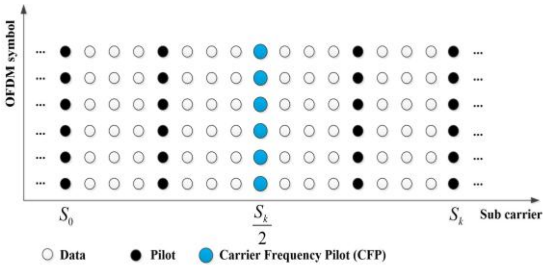


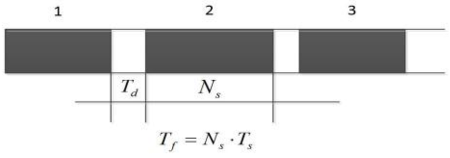
Fig. 3. Data and Pilot Insertion

The increased power when using CFP (P_{with_CFP}) compare with the case without using CFP ($P_{without\_CFP}$) can be calculated as follow:

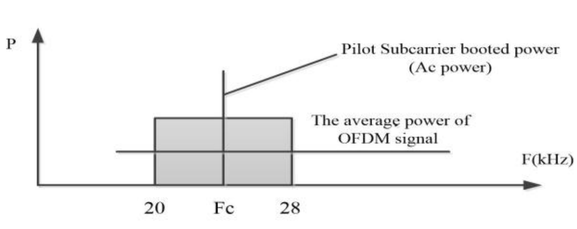
$$\eta = \frac{P_{with\_CFP}}{P_{without\_CFP}} \cdot 100\% = \left(1 + \frac{A_c^2 - A^2}{K \cdot A^2}\right) \cdot 100\% \quad (4)$$

where $A = \sqrt{2 \cdot (M-1)/3}$ is avergage amplitude of M-QAM modulation. In our experiment, $A_c = 6$, $M = 4$, $K = 174$ then the power will be increased 10 percent.

Fig. 4 show Frame Structure (a) and OFDM Transmitting Signal Spectrum (b). We organize OFDM frame contain N_s OFDM symbols, zeros gap is used to separate frames. The length of zeros is T_d show in Table I.



a. Frame structure



b. Frequency of Subcarrier Pilot

Fig. 4. Data and Pilot

B. *Receiver structure*

Fig.1(B) shows the receiver structure embedded our algorithm of Doppler frequency estimation and compensation. The discrete received signal at the receiver $y(n)$ can be represented as:

$$y(n) = h(n) * x(n) + w(n) \quad (5)$$

where $h(n)$ is the impulse response function and $w(n)$ is the additive noise.

The receiver signal in time domain is vector: $y = [y_0, y_1, ..., y_{L_F}]$ where L_F is length of receiving frame. Length of receiving frame can include all frame and zeros insertion at the head and tail of each frame. The received signal in frequency domain: $Y = [Y_0, Y_1, ..., Y_{L_F}]$ can be calculated through discrete Fourier transform FFT: $Y = F(y)$ where F is Fourier transformed. CFP F_r at the receiver is calculated based on half length of Y according to the formula:

$$F_r = \frac{\arg(\max|Y(1:L_F/2)|) \cdot f_s}{L_F} \quad (6)$$

The different sampling frequency between transmitter and receiver is:

$$\Delta f = \frac{(F_c - F_r) \cdot f_s}{F_c} \quad (7)$$

where F_c is real frequency at CFP at transmitted side.

Transmitted sampling frequency at receiver side will be recalculated:

$$\hat{f}_s = f_s + \Delta f \quad (8)$$

Based on zeros gap between two frames so we can detect the start of each frame through Start Frame detection Block in receiver scheme Fig. 1(B). So total length in samples of each OFDM frame $\hat{L}_F$ at receiver is:

$$\hat{L}_F = N_s \times \hat{N} \quad (9)$$

where N_s is number of OFDM symbols per frame.

$\hat{N}$ is length in number of samples of OFDM symbols at receiver:

$$\hat{N} = \frac{(N_{FFT} + GI) \cdot f_s}{\hat{f}_s} \quad (10)$$

All OFDM symbols in each frame will be separate individual based on its correspondent length at receiver. After remove GI, each OFDM is vector with length $\hat{N}$: $\vec{v}_{\hat{N} \times 1} = [v_0, v_1, ..., v_{\hat{N}}]$.

Those symbols will be put through resampled matrix $\mathbf{G}_{RS}$:

$$\vec{v}' = \mathbf{G}_{RS} \times \vec{v} \quad (11)$$

where $\mathbf{G}_{RS}$ is resampled matrix with size $N \times \hat{N}$.

$\mathbf{G}_{RS}$ is created from $\widehat{\mathbf{G}}_{RS}$ matrix with size $N\times(\hat{N}+2\cdot L-1)$. The rows i^{th} of $\widehat{\mathbf{G}}_{RS}$ is g_i :

$$g_i=\left[\underset{\tau-1}{0..0},\underbrace{g(LT+\Delta t_i),..,g(\Delta t_i),..,g(-LT+\Delta t_i)}_{2\cdot L+1},\underset{\hat{N}\text{-}\tau+1}{0..0}\right] \quad (12)$$

where L is length of $g(t)$ filter, $i=1..\hat{N}$

$$\Delta t_i=\frac{i\cdot f_s}{\hat{f}_s}-\tau \quad (13)$$

$$\tau=\left\lceil\frac{i\cdot f_s}{\hat{f}_s}\right\rceil \quad (14)$$

$\mathbf{G}_{RS}$ is extracted from column $L+1$ to $\hat{N}-L$ of $\widehat{\mathbf{G}}_{RS}$ matrix. Here, $g(t)$ is pulse sharping raised cosin function [12], $g(t)$ is show in equation as follow:

$$g(t)=\frac{\sin(\pi t/T)}{\pi t/T}\,\frac{\cos(\alpha\pi t/T)}{1-4\alpha^2t^2/T^2} \quad (15)$$

After resample to N length, signals $\vec{v}'$ will go through FFT block and Channel estimation to recovery data.

III. EXPERMENTAL AND RESULTS

The underwater experiments were carried out at Hotien lake at Hanoi University of Science and Technology (HUST).The experiment setup is illustrated in Fig. 5. In this experiment, the receiver is set at the fixed location beside the lake. The transmitter is on the small boat which is towed by rope from both side in right direction toward the receiver.

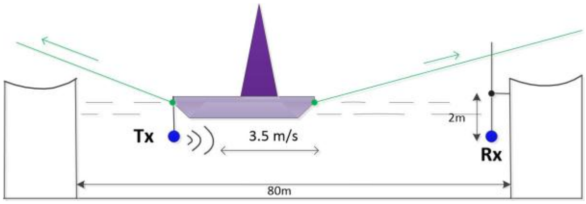


Fig.5. Illustration of the experimental setup in Hotien Lake

Then the results were processed by the software, which was developed by the Wireless Communication Laboratory of HUST. The OFDM system parameters are shown in Table I. The signals were modulated by M-QAM, with N_{FFT} = 2048, the guard interval (GI) length is: 1024. The system bandwidth is from $20kHz$ to $28kHz$. Signals are transmitted consecutive frames separated by about $0.15s$. Each frame consists of OFDM symbols N_s . In our experiment, the range of speed change maximum from $-3.5m/s$ to $+3.5m/s$. Minus sign of speed mean transmitter moves far from receiver and plus sign is in opposition direction. At maximum speed of $\pm3.5m/s$ the Doppler frequency shift is about $-56Hz$ to $+56Hz$ compare with CFP at $24kHz$, this frequency shift is greater than the width of a subcarrier of the OFDM signal is $46.865Hz$. Fig. 6 show real signal at receiver in time and frequency domain obtain from experiment in the case of moving transmitter far away from receiver and come back again. Transmitting parameter of OFDM system is showed in Table I.

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Table I. The OFDM system Parameters

Parameter	Value
1 Transmitter- 1 Receiver	SISO
Frequency sampling (kHz)	96
Bandwidth (kHz)	20-28
FFT length (N_{FFT})	2048
Guard interval length (GI)	1024
Multilever modulation	M-QAM
OFDM symbol/Frame (T_s) (ms)	32
The distance between OFDM subcarries (ΔF) (Hz)	46.865
Number of OFDM symbol/Frame (N_s)	30
Frame length (ms)	960
Roll-off factor raised cosin filter (α)	0.2
Amplitude of CFP	6
Amplitude of normal pilot	1.4142
Time gap between frames (T_d) (ms)	150
Length of $g(t)$ in sample	15

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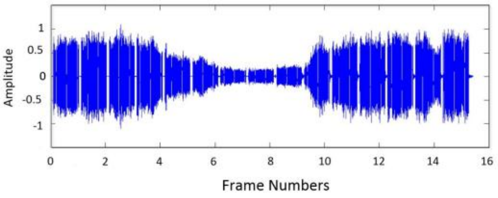
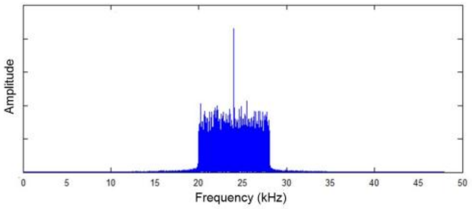


a. Receiving signal in time domain of 15 frames=16.65s



b. Spectrum of receiving signal

Fig. 6. Receiving signal in time domain and spectrum of receiving signal

In Fig. 6 the real signal at receiver in time and frequency domain obtain from experiment in the case of moving transmitter far away from receiver and come back again.

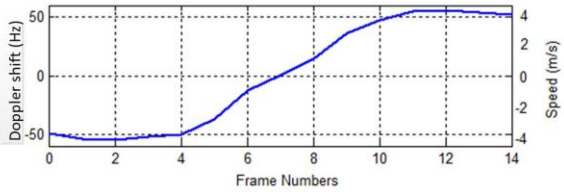


Fig. 7. Changing Doppler and equivalence Speed in experiment

Fig. 7 is estimated Doppler frequency shift and correspondent speeds obtain from experiment.

The maximum velocity is $3.5 m/s$ corresponding to a frequency offset of $56 Hz$, and the acceleration rate is about $2 m/s/s$.

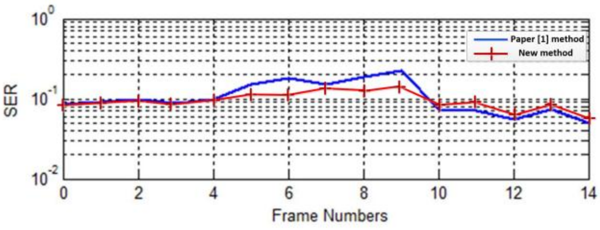


Fig. 8. Symbols Error Rate (SER) on receiving frames

Symbols Error Rate (SER) from frame to frame is shown in Fig. 8, that is obtained without using error code correction.

The results in Figure 8 indicate that the new decoding method gives a slightly better quality than the old one. However, the advantages of this method are simpler in calculation because only one step is required to accurately calculate Doppler frequency without having to round and recalculate as in the method in [1], thus saving time calculating and proactively designing programmatic systems without the need for matlab based programming.

IV. CONCLUTIONS

OFDM is promising technique in combating multipath channel and high Doppler frequency shift in Underwater communication. Proposed method has solved doppler shift problems through using OFDM Pilot as a carrier frequency pilot (CFP). Advantages of proposed method is increasing bandwidth efficiency of system because it doesn't add extra frame structure or special signals to the OFDM signal frame.

The advantage of direct decoder is simpler in calculation because only one step is required to accurately calculate Doppler frequency.

The disadvantage proposal method is increasing the transmitting power. However, using our method can solve the quick speed changing between transmitter and receiver through using short frame. So, our proposed method can handle with uniform Doppler distribution. Despite this method can apply for moving system with speed of hundreds meters per second in simulation with computer but in the experiment results just deployed on the campus of the University should be in the test speed restrictions is $\pm 3.5 m/s$.

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