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Proposal for a Doppler Shift Compensation Method Using Non-Uniform FFT with Pilot Carrier Frequency for OFDM-Based Underwater Acoustic Communication Systems

Nguyen Van Duc*, Nguyen Thi Hoai Linh, Nguyen Quoc Khuong, Nguyen Tien Hoa
School of Electrical and Electronic Engineering, Hanoi University of Science and Technology, Ha Noi, Vietnam
**Corresponding author email: duc.nguyenvan1@hust.edu.vn*

Abstract

In this paper, we propose a method that uses the non-uniform Fast Fourier Transform (FFT) to compensate for Doppler frequency shifts in orthogonal frequency division multiplexing (OFDM) based underwater acoustic (UWA) communication systems. To estimate the Doppler frequency shift, the paper proposes using a pilot carrier frequency (PCF) that is identified by transmitting with greater power in the frequency domain compared to other subcarriers. This identifier helps estimate both the Doppler frequency shift and the channel. The paper proposes estimating and compensating for the Doppler frequency shift in two steps: Step 1 performs coarse frequency synchronization, where the Doppler frequency shift is determined by using PCF signal. The Doppler shift correction is obtained by re-sampling the received signal, and then interpolating re-sampled signal. However, the Doppler shift compensation in the step 1 cannot correct the phase distortion of the measured PCF signal. Therefore, performing step 2, known as fine frequency synchronization, is necessary. In this step, the correction for the phase distortion is determined based on the phase difference between the two consecutive OFDM signals in one frame. The remaining Doppler frequency shift is adjusted based on the phase deviation, using the non-uniform FFT. By using the non-uniform FFT, the complexity of the ICI compensation is significantly reduced, and the quality of Doppler shift compensation is improved. The experience results show that the transmitted text will be decoded correctly by using the proposed technique.

Keywords: Pilot carrier frequency, carrier frequency offset, inter-channel interference, non-uniform fast fourier transform.

1. Introduction

With the development of science and technology, the application of UWA communication is a rapidly growing research field in both military and civilian. Moreover, the demand for underwater communication is increasing due to human interest and activities, which is drawing more and more researchers attention [1]. In water environments, many issues must be carefully considered when designing transmission systems, such as the speed of wave propagation, which is about 1500 m/s, much slower than radio waves. Therefore, compared to radio transmission, the transmitted signal in underwater channels has different characteristics, including the Doppler effect due to receiver and transmitter movement, and environmental disturbances [2].

To overcome the multipath effect in UW channel, the Orthogonal Frequency Division Multiplexing (OFDM) technique can be applied for underwater communication system due to its high-speed transmission and ability to cope with multipath effects [3, 4]. Furthermore, the OFDM-based UWA system offers high spectral efficiency due to the overlapped spectrum of signal on subcarriers, which is allowed by the subcarrier orthogonality. However, this leads to high sensitivity of the system in terms of the carrier frequency offset (CFO). In addition, the frequency synchronization problem in the OFDM system is also more complicated than in a single carrier system. The CFO destroys the orthogonality relationship between the subcarriers, creating intercarrier interference (ICI) in OFDM systems. ICI is a frequency mismatch between the transmitter and receiver, and this frequency mismatch leads to severe performance degradation in OFDM wireless systems [5, 6]. This problem is even more serious in the OFDM-based UWA systems. Therefore, ICI minimization is one of the most important tasks to obtain satisfactory system quality of service (QoS).

Currently, there are many methods for reducing ICI in the OFDM systems, which have been extensively investigated, such as frequency-domain equalization [7], self-cancellation [8], frequency offset estimation [9, 10], correlative coding [11], minimum mean squared error (MMSE) [12], and multiple resampling [13]. Since the UWA channel is a narrow bandwidth channel [14], we don't use preamble in each OFDM frame as suggested in many common approaches [15, 16]. This is to reduce the bandwidth redundancy reserved for using the preambles. Instead, we use the PCF proposed in [17] to estimate the Doppler frequency.

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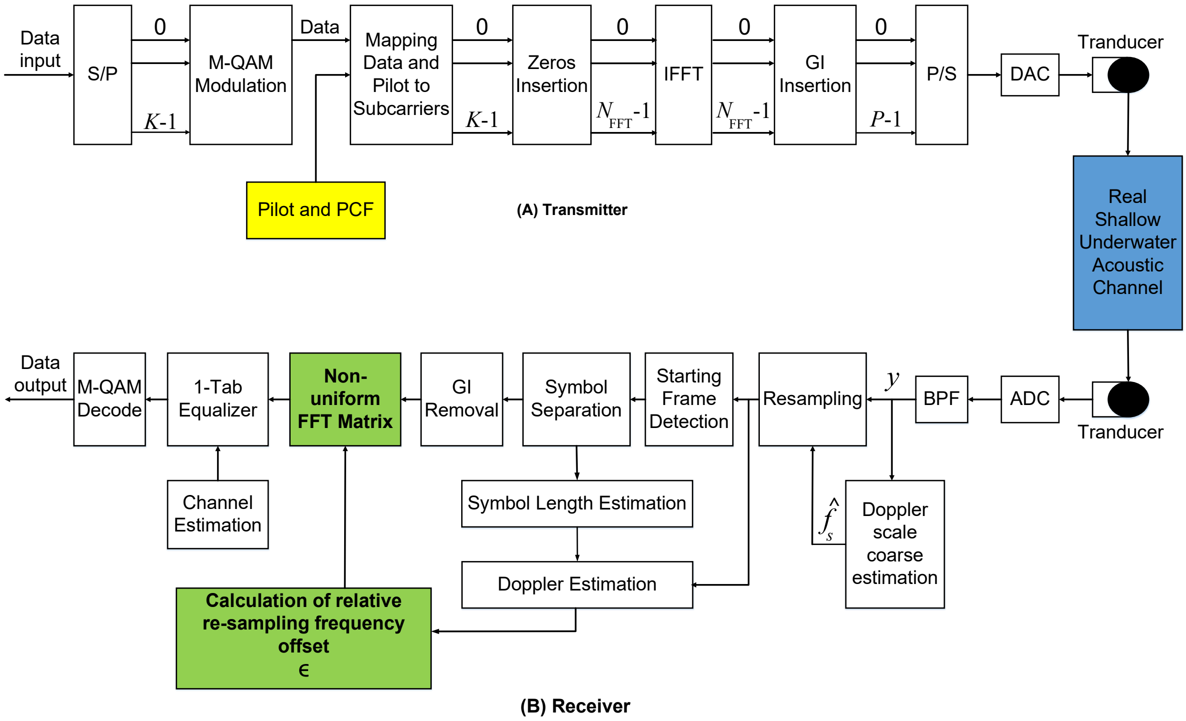


Fig. 1. The structure of the underwater acoustic OFDM system using the non-uniform FFT to compensate the Doppler shift.

As introduced in [18], Doppler compensation in OFDM-based UWA communication systems can be achieved though two-step of signal processing, namely resampling and residual CFO compensation. The novelty of our proposed method lies in the second step, where we estimate the residual CFO using non-uniform FFT and mitigate the ICI that was not fully handled in step 1. The study in [19] provides a method compensation Doppler frequency. In this study, the relative doppler frequency iscalculated by the rotate phase of the PCF pilot. Our proposal in this paper, we calculate the relative Doppler frequency based on the sampling and resampling frequency.

In this paper, we propose a two-step method for ICI minimization as follows. The first step is called coarse frequency synchronization, where the Doppler frequency shift is determined by the measured PCF signal. The Doppler shift compensation is performed by resampling and interpolating the received signal [18]. Although signal re-sampling eliminates the Doppler shift, the residual CFO can cause a loss of orthogonality between subcarriers. Therefore, the second step, called fine frequency synchronization is required. In this step, the phase distortion of the PCF signal is determined based on the phase difference between two consecutive OFDM signals in one frame. The remaining Doppler frequency shift is compensated using ununiform FFT. In the fine frequency synchronization step, the algorithm in [17] removes ICI by creating a matrix based on the pulse shaping raised cosine function and then carries out FFT. However, the complexity of the ICI compensation is high due to matrix calculation. The proposed ICI compensation method using ununiform FFT in this paper aims to reduce the complexity of the ICI canceller introduced in [17].

The rest of this paper is constructed as follows. Section 2 describes the proposed system architecture for ICI compensation caused by the Doppler shift in the UWA channels. The measurement results regarding the system performance and discussions are presented in Section 3. Finally, Section 4 draws conclusions.

2. Proposal of the System Architecture for ICI Compensation Caused by the Doppler Shift in the UWA Channels

2.1. Transmitter Structure

The architecture of the proposed OFDM-Based UWA communication system is depicted in Fig. 1, 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

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

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 $K \le (N-1)/2$, where $N_{\text{FFT}} = 2N+1$ denotes the FFT length.

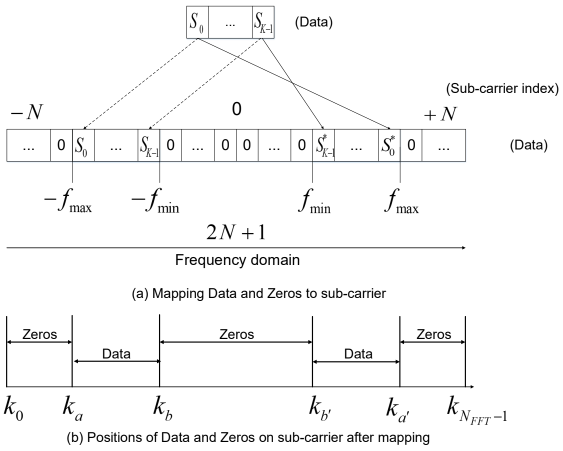


Fig. 2. Zeros insertion.

Fig. 2 shows how an OFDM symbol is organized in the frequency domain. Fig. 2a presents the mapping of the data and zero symbols on the sub-carriers, and Fig. 2b illustrates the positions of the data and zeros symbols after mapping. The purpose of this mapping is to ensure that the transmitted signal in the time domain (after the IFFT) is the real signal. This is due to the fact that we do not use the I/Q modulator to convert the signal in a high carrier frequency. In the OFDM-based UWA systems, the signal is not modulated in high frequency as in wireless communications. Instead, the signal is only modulated on each sub-carriers, which has a much lower frequency compared to wireless context. In Fig. 2b, the sub-carrier indices from k_a to k_b denote the useful data positions, while the sub-carrier indices $k_{a'}$ to $k_{b'}$ are symmetrical to the k_a to k_b, which also denote the positions of the data symbol. In other places, zero symbols are inserted. Based on Fig.2, we can represent the positions of the useful data from k_a and k_b as follows:

$$a = \left\lfloor \frac{2 \cdot f_{min} \cdot N_{\mathrm{FFT}}}{f_s} \right\rfloor, k_a = a - \mathrm{mod}(a,2) \tag{2}$$

$$b = \left\lceil \frac{2 \cdot f_{\max} \cdot N_{\mathrm{FFT}}}{f_s} \right\rceil, k_b = b + \mathrm{mod}(b,2) \tag{3}$$

After calculating the positions k_a and k_b, we can specify the positions $k_{a'}$ and $k_{b'}$.

In this work, the pilot carrier frequency (PCF) is inserted in the first sub-carrier, instead of in the middle, as introduced in [17]. The PCF is inserted for the purpose of detecting the Doppler frequency shift and estimating the channel.

Fig. 4a and Fig. 4b show the OFDM frame structure, the transmit PCF, and the data spectrum, respectively. Each OFDM frame consists of N_s OFDM symbols and T_d zero symbols, which are used to separate each OFDM frame.

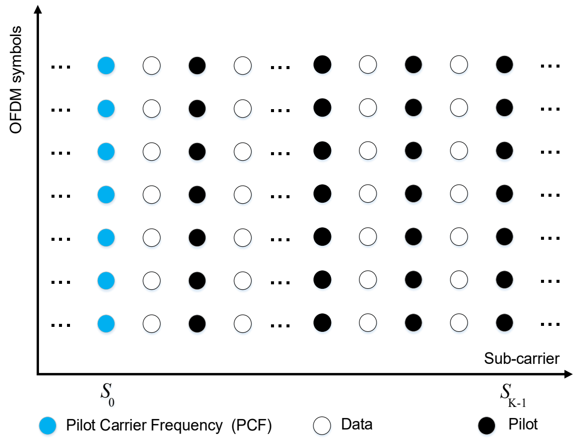


Fig. 3. Data and Pilot Insertion

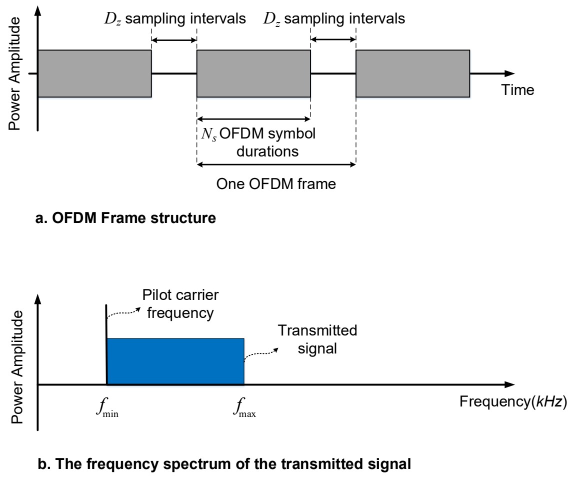


Fig. 4a) The OFDM frame structure; b) the transmit PCF and data spectrum.

Let us denote the signal after the parallel/serial (P/S) converter as $x(n)$. We can calculate the PCF frequency in the transmitter side as follows:

$$F_c = \frac{(\max |Y(1:L/2)|) f_s}{L}, \tag{4}$$

where L is the length of an OFDM frame. As the PCF is transmitted with a larger power compared to the data signal, we can easily determine the frequency of the PCF using (4).

2.2. Receiver Structure

Fig. 1b presents the receiver architecture using the proposed algorithm of Doppler frequency shift estimation and compensation.

Let us denote $y(n)$ as the received signal. The received signal after the ADC can be written as:

$$y(n) = h(n) * x(n) + w(n) \tag{5}$$

where $h(n)$ is the channel impulse response (CIR), and $w(n)$ is the additive noise. The received signal in the time domain is presented in vector form as: $y = [y_0, y_1, ..., y_{L_F}]$ where L_{F} is length of receive frame. The length of receive frame includes all frames and zero symbols inserted in the head and tail of each OFDM frame. The received signal in the frequency domain can be represented as: $Y = [Y_0, Y_1, ..., Y_{L_F}]$, which can be obtained by the discrete Fourier transform FFT, i.e., $Y = F(y)$.

Similar to the transmitter, the frequency of the PCF at the receiver side, F_r, is calculated as follows:

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

Due to the Doppler frequency shift, there is a deviation of the transmitted and received carrier frequency. This deviation is calculated by:

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

To adjust the Doppler frequency shift, the system must be re-sampled. The re-sampling frequency $\hat{f_s}$ can be determined as follows:

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

The total length of each OFDM frame $\hat{L}_F$ at receiver is calculated by:

$$\hat{L}_F = N_s \cdot (N_{\mathrm{FFT}} + GI), \quad (9)$$

where N_s is the number of symbols in a frame.

The OFDM symbol affected by the CFO is depicted in Fig. 5. In Fig. 5 the symbol $\in$ is defined as the relative re-sampling frequency offset, which is calculated by:

$$\in = \frac{f_s - \widehat{f_s}}{f_s} \quad (10)$$

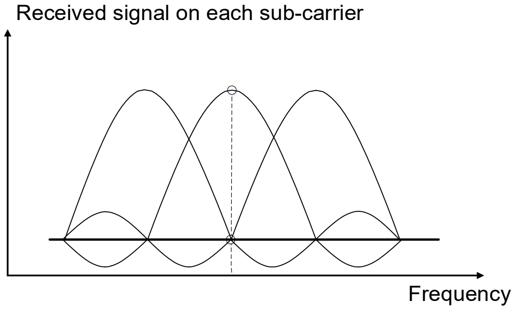
In the case depicted in Fig. 5a, the peak of one subcarrier coincides with the null of adjacent all other subcarriers. The mathematical description of the received signal is specified by

$$Y_r[k] = \sum_{n=0}^{N_{\mathrm{FFT}}-1} y_r(n) e^{-2j\pi kn/N_{\mathrm{FFT}}}; k = 0...N_{\mathrm{FFT}} - 1 \quad (11)$$

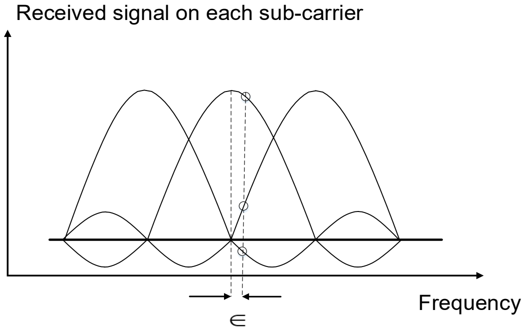
where N_{FFT} represents the total number of sub-carriers of the system.

In the case shown in Fig. 5b, the OFDM symbol is affected by the CFO, the ortho-gonality of sub-carriers is damaged. Therefore, the mathematical description of an OFDM symbol affected by the CFO is written by:

$$Y_r[k] = \sum_{n=0}^{N_{\mathrm{FFT}}-1} y_r(n) e^{-2j\pi(k+\in)n/N_{\mathrm{FFT}}}; k = 0, ..., N_{\mathrm{FFT}} - 1 \quad (12)$$



(a) Symbol is not affected by CFO Frequency



(b) Symbol is affected by CFO Frequency

Fig. 5. Illustration of a symbol affected by the CFO frequency.

To remove the ICI, we use the non-uniform FFT matrix $[\mathbf{G}_{\mathbf{RS}}]$ with the size of $N_{\mathrm{FFT}} \mathrm{x} N_{\mathrm{FFT}}$ as described in [19]. The non-uniform FFT matrix is a matrix where $(k - \in)$ is not an integer due to the influence by the CFO according to (12). In Fig. 2, the useful subcarriers are from k_a to k_b, others are unprofitable. Hence, the non-uniform FFT matrix only needs to create in the above positions. Table I shows the comparison of computations between the proposal matrix and the FFT matrix $[\mathbf{G}_{\mathbf{RS}}]$.

The results summarized in Table 1 shows that the proposed non-uniform FFT matrix reduces complexity of the ICI canceller significantly if it is compared with the conventional one.

Table 1. The total number of computations between 2 matrices

	The proposed non-uniform FFT matrix	The conventional FFT matrix
Addition	$(N_{\mathrm{FFT}} - 1).(k_b - k_a)$	$(N_{\mathrm{FFT}} - 1).N_{\mathrm{FFT}}$
Multiplication	$N_{\mathrm{FFT}}.(k_b - k_a)$	N_{FFT}^2

In our proposal, the ICI cancellation is performed by taking the nonuniform FFT of y_r as follows:

$$\overrightarrow{z_r} = [G_{\mathrm{RS}}] \times \overrightarrow{y_r} \tag{13}$$

where $\overrightarrow{y_r} = [y_{r_0}, y_{r_1}, ..., y_{r_{N_{\mathrm{FFT}}-1}}]$. After removing ICI, the ICI-cancellated signal, $\overrightarrow{z_r} = [\hat{y}_{r_0}, \hat{y}_{r_1}, ..., \hat{y}_{r_{N_{\mathrm{FFT}}-1}}]$, is fed to 1-tab equalizer that perform the channel equalization.

3. Experimental Results and Discussions

The proposed OFDM-based UWA systems is realised in a test-bed, then it will be deployed in real communication conditions in UW channel for testing. In the following, we describe the system setup, measurement results and discussions.

3.1. Measurement System

The parameters of the experimental OFDM system are shown in Table 1 including a single-input and single-output (SISO) system, the sampling frequency f_s was equal to $96000 Hz$, and the system bandwidth is from $12000 Hz$ to $15000 Hz$.

Table 2. The OFDM system parameters

Parameter	Value
1 Transmitter - 1 Receiver	1
Frequency sampling (kHz)	96
Bandwidth (kHz)	12-15
FFT length	2049
Guard interval length	1024
Multilevel modulation	QPSK
OFDM symbol length	40
Amplitude of PCF	8

The guard interval, which can be Cyclic prefix (CP), Zeros Padding (ZP), Known Symbol Padding (KSP) are inserted between transmitted symbols in the OFDM systems to combat ISI [20]. Choosing appropriate guard intervals to not only eliminate the ISI but also to limit the losses is one of most important tasks in designing UWA-OFDM systems. In this paper, the guard interval is inserted by the CP technique which is to append samples from the end to the beginning of the signal. According to [21], the outside elements' effect on CP insertion in OFDM system for UWA including the numbers of scatterers, the transmission distances, and the Tx/Rx depths.

We decided to set the guard interval length of 1024 samples when experimenting at Dong Do Lake. The total number of subcarriers is 2049. The signals were modulated by QPSK, which is commonly used in underwater environments [22]. The number of symbols in a frame and the amplitude of the PCF are thus selected to be 40 and 8.

3.2. Illustration of the Experimental System

The testbed is illustrated in Fig.6. The transmit side consists of a computer (1) and a transducer (2). The boat (TX) acts as a transmitter that is equipped with all these components. In this experiment, the receiver is static while the transmitter moves the transmitter closer to/further from the receiver. The signal will be continuously broadcasted from the transmitter.

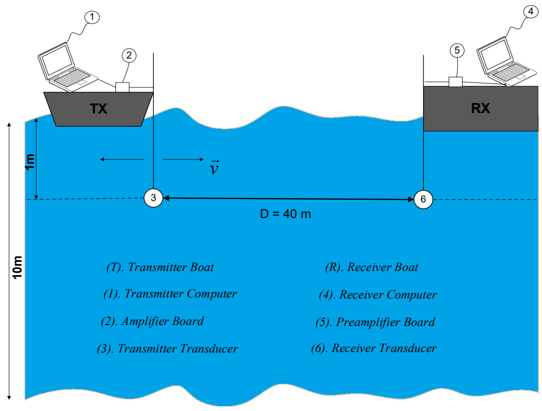


Fig. 6. Illustration of the experimental setup in Dong Do Lake

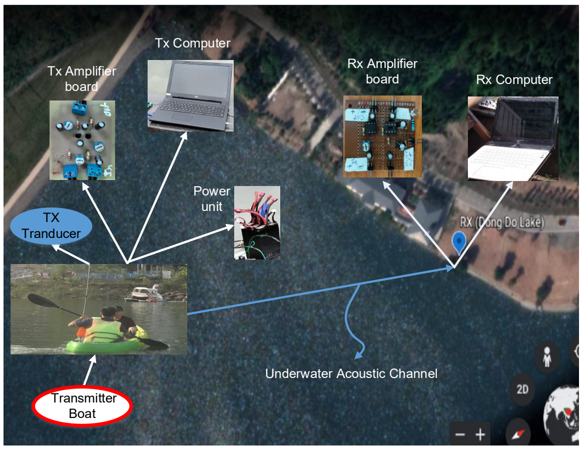


Fig. 7. Locations of transmitter and receiver units on Google Maps.

The digital signal is converted into an analog signal by a digital-to-analog converter (DAC) and transmitted through the transducer. An underwater channel in shallow water is considered, where the initial distance between the transmitter boat and the receiver boat is 40 m, and the lake depth is approximately 10 m. The receiver side consists of a transducer (4) and a receiver computer (3), which performs the OFDM demodulation.

3.3. Measurement Results

We conducted the communication experiment in December 2020 in Dong Do Lake of Minh Tan village, Minh Tri commune, Soc Son district, Hanoi City. The location of transmitter and receiver units on Google Maps is shown in Fig. 7. For the experiment, the receiver was kept stationary while the transmitter was moved closer to or further away from the receiver. The signals were transmitted in the UWA environment.

Fig. 8 shows the received text, which is readable for the user. However, there are some missing letters, which were caused by the UW channel.

Fig. 9 shows a scatter plot in 2 cases. Because the Doppler shift compensation in step 1 is not able to correct the phase distortion of the PCF signal. Step 2 - Fine synchronization: the PCF signal phase distortion correction is determined based on the phase angle difference between two consecutive OFDM signals in a frame. The remainder of the Doppler frequency shift is determined based on compensated phase angle deviation by using non-uniform FFT.

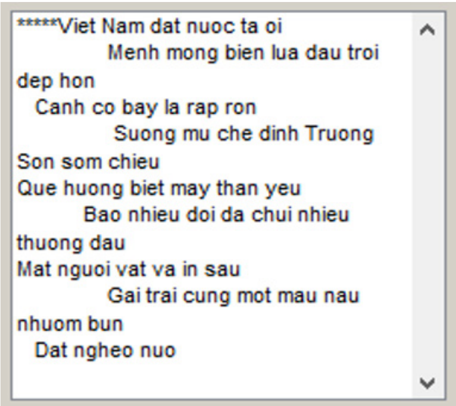


Fig. 8. The received decoded text in a communication distance of 40 m.

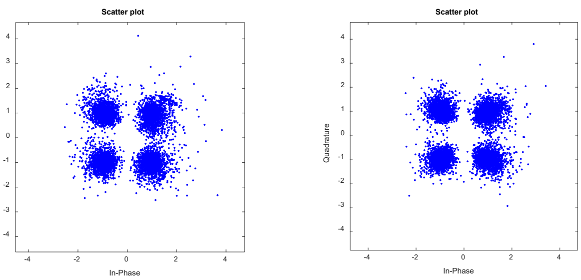


Fig. 9. (a) Scatter plot of step 1, and (b) Scatter plot both 2 steps.

4. Conclusion

This paper introduced a technique for reducing the inter-carrier interference (ICI) caused by the Doppler effect in underwater OFDM-based systems. We demonstrated the performance of the proposed method in a real testbed, where the system was able to correctly decode a received text. However, the obtained bit error rate (BER) is still relatively high compared to wireless communication. Our future work will focus on incorporating suitable channel coding techniques to overcome these difficulties.

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