A NOVEL TWO-STEP DOPPLER COMPENSATION SCHEME FOR CODED OFDM UNDERWATER ACOUSTIC COMMUNICATION SYSTEMS

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Abstract: *The performance of orthogonal frequency division multiplexing (OFDM) is gravely affected by the Doppler induced symbol dilation. Thus, it is important to compensate for this effect before detection. In this paper, we propose a combined Doppler Effect estimation scheme for coded OFDM underwater acoustic communication systems. This scheme contains two steps; the first step is using the Fractional Fourier Transform to estimate the chirp rate change of the linear frequency modulation (LFM) signal, which is used as synchronisation probe to obtain an initial Doppler Effect estimate using the chirp rate change. In the second step, cyclic prefix (CP) correlation is used to estimate the fine Doppler factor. We compare the proposed approach with state-of-the-art, time and frequency based resampling methods. The presented numerical results show that the proposed scheme can estimate the Doppler factor precisely after the two steps and match the performance of the resampling-based approaches. However, the advantage of the two-step approach does not require the whole packet to be received, which in turn reduces the storage requirements and hardware resources, and thus, it is more suitable for the real-time implementation.*

Keywords: *Orthogonal Frequency Division Multiplexing (OFDM); underwater acoustic (UWA) communication; Doppler effects estimation; Fractional Fourier Transform*

1. INTRODUCTION

Due to the severe multipath and Doppler spread present in the underwater acoustic (UWA) environment, transmitted communication signals suffer from intersymbol interference and symbol dilation. Orthogonal frequency division multiplexing (OFDM) is a multicarrier system where all the subcarriers are orthogonal to each other. Its performance is gravely affected by inter-carrier interference (ICI) caused by the Doppler induced frequency offsets [1]. There is a high demand of accurate estimation and compensation of the Doppler frequency offset to ensure the reliability of the UWA OFDM waveforms. Thus, several techniques [2]-[6] have recently been introduced in order to estimate and compensate it. The most widely adopted method is using two synchronisation probes in form of linear frequency modulation (LFM) signals in adjacent OFDM frames to estimate the sampling point number change to obtain the Doppler factor. This method is easily applied but requires the whole received packet, which in turn increase the signal storage demands.

2. PRINCIPLE OF THE TWO-STEP SCHEME

In this paper, we propose a combined Doppler effect estimation scheme for coded OFDM underwater acoustic communication systems. This scheme contains two steps; the first step is using the Fractional Fourier Transform (FRFT) to estimate the chirp rate change of the LFM signal, which is utilized as synchronisation probe to obtain an initial Doppler effect estimate using the chirp-rate change. In the second step, cyclic prefix (CP) correlation is used to estimate the fine Doppler factor to track the Doppler changes on symbol by symbol basis. The advantage of the two-step approach is that it does not require the whole packet to be received, which in turn reduces the storage requirements and hardware resources, and thus, it is more suitable for the real-time implementation. The frame structure suitable for this two-step scheme is shown in Fig.1.

T_g T_{OFDM}

LFM Signal	Guard Interval	Cyclic Prefix #1	OFDM Symbol #1	···	Cyclic Prefix #N	OFDM Symbol #N

Fig.1: Frame structure of the UWA OFDM system

The chirp signal is always used in radar and sonar communication systems as a synchronisation probe, and the expression can be determined by the following equation.

$$s(t) = A\exp[j(2\pi f_0 t + \pi k t^2)]\mathrm{rect}(t/T), \tag{1}$$

where f_0 is the centre frequency, $k = B/T$ is the chirp rate, B is the bandwidth, and $\mathrm{rect}(t/T)$ represents a rectangular pulse which pulse width is T . The instantaneous frequency can be given as

$$f(t) = f_0 + kt. \tag{2}$$

The instantaneous frequency affected by Doppler can be written as

$$f_D(t) = f(\lambda t) = \lambda f_0 + k\lambda^2 t\,, \tag{3}$$

where $\lambda = 1 + \Delta = f_r / f_t$ indicates the frequency ratio between the received and transmitted signal, and the Doppler Factor is defined as $\Delta = (v/C)\cos\theta$ and C is the sound speed in the water.

The FRFT has a characteristic of energy concentration on LFM signal. There exists an optimal order of FRFT, which focuses the energy of the chirp signal [7]. The optimal order $\hat{p}$ resulting in maximum energy can be obtained by searching a certain set of orders.

Furthermore, the estimated chirp rate can be represented as

$$\hat{k} = -\cot(\frac{\hat{p}\pi}{2}) = (1+\hat{\Delta})^2 k\,, \tag{4}$$

where k is the original chirp rate, and $\hat{p}$ is the optimal order of FRFT. $|\Delta|$ is usually less than 1 because of the low speeds, so that $\hat{\lambda}$ can be estimated as

$$\hat{\lambda} = 1 + \hat{\Delta} = \sqrt{\frac{-\cot(\frac{\hat{p}\pi}{2})}{k}}\,. \tag{5}$$

After the first step using FRFT to estimate the chirp rate, we got an initial estimation $\hat{\lambda}$. In the second step, fine estimation is performed using the cyclic prefix correlation to track the Doppler factor of each OFDM symbol.

As for the received data y, the autocorrelation can be given as

$$R_y(\xi) = E\{y(mT_s)y^*((m+\xi)T_s)\}\,. \tag{6}$$

The magnitude of $R_y(\xi)$ is maximum at $\xi = 0$ and at the lag

$\xi = \xi_{peak} = NT_{s_0} / (1+\Delta)T_s$,

where T_{s_0} is the sampling interval at the transmitter, and T_s is the sampling interval at the receiver.

Assuming that $T_s = T_{s_0}$, then $\hat{\xi}_{peak} = \frac{N}{(1+\Delta)} = \frac{N}{\lambda}$, and $R_y(\hat{\xi}_{peak})$ should have the maximum magnitude except for $R_y(\xi = 0)$. So that the fine estimation of λ can be obtained by the following steps:

1. First of all, define $\lambda_{initial} = \hat{\lambda}$, which is obtained by the estimating the chirp rate change of the chirp signal.

$$\xi_{peak\_initial} = \frac{N}{\lambda_{initial}}\,. \tag{7}$$

2. Then set a search range around $\xi_{peak\_initial}$, let

$$\xi_{peak\_search} \in (\xi_{peak\_initial} - N_{search\_range}, \xi_{peak\_initial} + N_{search\_range}) . \tag{8}$$

Calculating the autocorrelation $R_y(\xi_{peak\_search})$ of all the ξ_{peak_search} , the $\hat{\xi}_{peak}$ corresponding to the maximum magnitude $R_y(\xi_{peak\_search})$ is the result we are looking for.

Finally, the fine estimation of λ can be got by formula (9).

$$\lambda = \frac{N}{\hat{\xi}_{peak}} . \tag{9}$$

3. SIMULATION STUDY

In this section, a simulation is conducted to evaluate the feasibility and the performance of the proposed two-step scheme. Multipath channels using for simulation are generated by Bellhop, with the depth of transmitter and receiver are 40 and 10 m under the sea surface, respectively. The sound velocity gradient is illustrated in Fig.2 (a). Fig.2 (b) and (c) display the channel impulse response where the distances between the transmitter and the receiver are 500 m and 2 km, respectively. The RMS delay spread of the channel with the range of 500m is 6.3ms and the coherent bandwidth is 159.05Hz. Those of the channel with the range of 2km are 6.5ms and 154.87Hz. The main simulation parameters of the coded underwater acoustic OFDM system are given in Table 1.

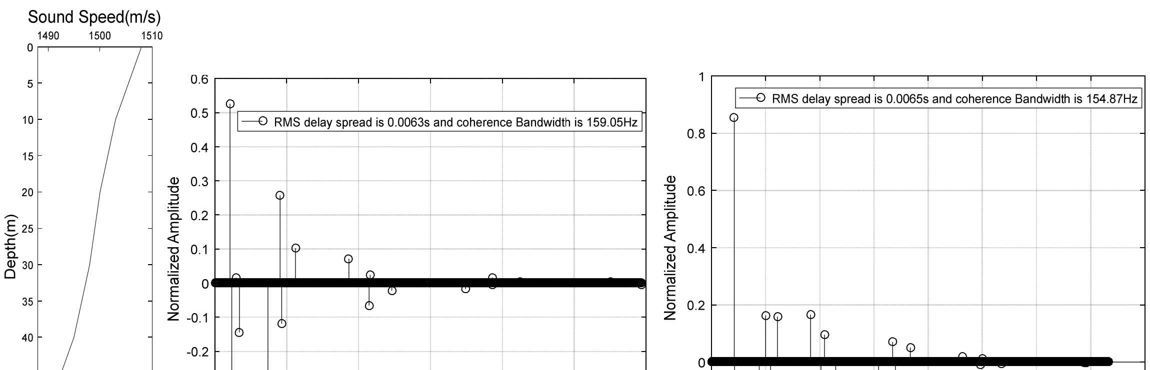

Fig.2: (a) Sound Velocity gradient, (b) channel impulse response of the distance 500 m, (c) channel impulse response of the distance 2 km.

Parameters	Value	Parameters	Value
Transmission Frequency Band	6000-12000 Hz	Guard Interval of cyclic prefix	43 ms
Bandwidth	6000 Hz	Symbol Duration	171 ms
Sampling Frequency	48 kHz	Pilot Spacing	4
Number of	1024	Coding method	Convolutional Code or

Subcarriers			Turbo Code or LDPC
Subcarrier Bandwidth	5.859375	Code Rate	1/2
Number of Bits per Subcarrier	2(QPSK modulation)	Resampling method	Time or Frequency Based method

Table 1: Simulation parameters of the underwater acoustic OFDM system.

The FRFT of a chirp signal can focus the energy in an optimal order. Chirp signals with different lengths have a different performance on focusing this energy, which results in the accuracy of optimal order estimation. This in turn affects the Doppler factor estimation. The MSE of the estimation of Doppler factor Δ with different chirp signal lengths is compared in Fig.3 (a).

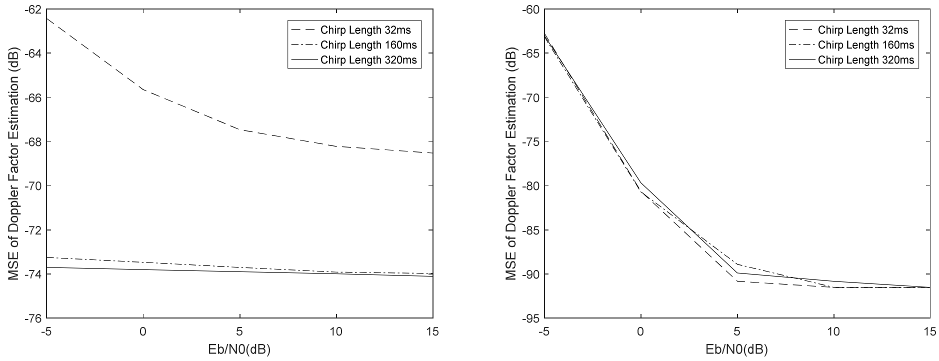

Fig.3: (a) The MSE of Doppler factor estimated by the FRFT of LFM signal, (b) The MSE of Doppler factor estimated by the proposed two-step scheme.

From Fig.3 (a), it can be seen that the MSE of Doppler Factor estimation decreased with the increase of the LFM signal length. The MSE of the signals with the length of 160 and 320 ms appears the same, but the MSE of the chirp signal with the length of 32 ms is 6~10dB larger than that of the other two signals.

Fig.3 (b) illustrates the MSE of Doppler factor estimation after the two-step approach. The chirp length has less influence than when using the FRFT approach on its own. Although the MSE of -5dB is worse than the FRFT approach, it performs better at the other conditions.

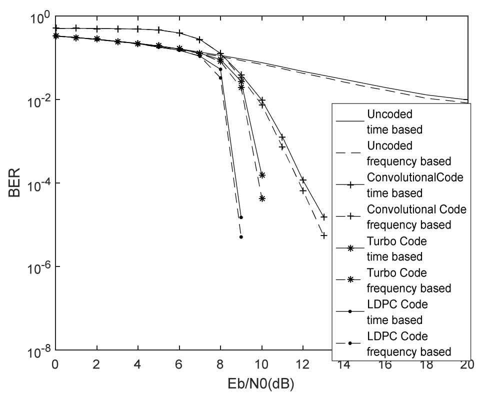

Fig.4: The comparison between the two resampling method, time based and frequency based resampling method.

After estimating the fine Doppler factor, the compensation of Doppler is performed by state-of-the-art, time and frequency based resampling methods. From Fig. 4, we can now come to a conclusion that the frequency based resampling method performs a little bit better than the time-based one.

4. CONCLUSION

In this paper, a two-step Doppler estimation method is proposed. After using the FRFT to obtain the chirp rate change of the LFM synchronisation probe, the initial Doppler is computed from the chirp-rate change estimate. Subsequently, cyclic-prefix correlation is used to estimate the fine Doppler factor of each OFDM symbol. We analyse the MSE of the estimated Doppler factor and compare the proposed approach with state-of-the-art, time and frequency-based resampling methods. The simulation results demonstrate that the proposed scheme can estimate the Doppler factor precisely using the proposed two-step method and match the performance of the resampling based approaches. The advantage of the two-step approach does not require the whole packet to be received, which in turn reduces the storage requirements and hardware resources, and thus, it is more suitable for the real-time implementation.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] **C. R. Berger, W. Chen, S. Zhou, and J. Huang,** A simple and effective noise whitening method for underwater acoustic orthogonal frequency division multiplexing, *Journal of the Acoustical Society of America*, vol. 127, pp. 2358-2367, 2010.

[2] **Byung-Chul, Kim, I. Tai Lu,** Parameter study of OFDM underwater communications system, In *OCEANS 2000 MTS/IEEE Conference and Exhibition. Conference Proceedings*, vol.2, 1251-1255, 2000.

[3] **Z. H. Wang, S. Zhou, G. B. Giannakis, C. R. Berger, and J. Huang,** Frequency-domain oversampling for zero-padded OFDM in underwater acoustic communications, *IEEE Journal of Oceanic Engineering*, vol. 37, pp. 14-24, 2012.

[4] **J. Huang, M. Ran, T. Zhang, F. Wu,** Doppler estimation based on signal phase matching principle in wideband OFDM, In *TENCON 2010 - 2010 IEEE Region 10 Conference,* 1358-1361, 2010.

[5] **A. Y. Kibangou, C. Siclet, L. Ros,** Joint channel and Doppler estimation for multicarrier underwater communications, In *IEEE International Conference on Acoustics, Speech and Signal Processing*, 5630-5633, 2010.

[6] **J. Trubuil, T. Le Gall, T. Chonavel,** Synchronization, Doppler and channel estimation for OFDM underwater acoustic communications, In *OCEANS 2014,* 2014

[7] **Xiao Zhang, Xiao Han, Jingwei Yin, Xue-li Sheng,** Study on Doppler effects estimate in underwater acoustic communication, In *International Congress on Acoustics,* 2013.