Closed loop bi-directional broadband Doppler compensation and channel equalization for single carrier high-speed underwater acoustic communication

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***Abstract*—In this paper, we propose a broadband Doppler estimation and compensation receiver, which combines a bi-directional decision feedback equalizer (DFE). Compared with the existing receivers, the proposed closed loop Doppler estimation and compensation receiver combined with a bi-directional DFE can not only estimate and compensate the broadband Doppler symbol-by-symbol, but also reduce the error propagation effect caused by DFE. Experimental results show that the performance of the proposed receiver can be improved in terms of output signal-to-noise ratio (SNR) and bit error rate (BER). Compared with the closed loop Doppler estimation and compensation receiver combined with the adaptive DFE, the performance of the proposed receiver can be improved by $1.17\ dB$ in terms of output SNR at $1\ kbps$ with the platform moving at up to $6\ knots$.**

Keywords*—Doppler effect; closed loop Doppler compensation; bi-directional DFE; single carrier modulation

I. INTRODUCTION

Underwater acoustic channel is the largest obstacle which makes the underwater acoustic communication system lag far behind the terrestrial mobile telecommunication system. Moreover, underwater acoustic channel is very severe due to the high frequency attenuation, and low velocity of acoustic waves, typically $1500\ m/s$. Broadband data transmission characterised by Doppler spread is much greater than those experienced in EM transmission. In [1], decision feedback equalizer (DFE) with a second order phase locked loop (PLL) embedded was used in the coherent underwater acoustic communication system. However, the receiver cannot work effectively when there exists broadband Doppler effect. In [2], an open loop Doppler estimation and compensation algorithm was proposed. A PLL was also embedded in this algorithm. However, this algorithm needs to assume that the whole data packet has experienced the same Doppler effect. In [3], [4], an adaptive closed loop Doppler estimation and compensation algorithm was proposed. In [4], the Doppler-tracking schemes was incorporated within a DFE to mitigate both Doppler and multipath effects. Moreover, the closed loop Doppler compensation algorithm can compensate Doppler effect symbol-by-symbol. However, the conventional DFE in the closed loop Doppler has the error propagation effect. In [5], [6], the authors proposed a bi-directional DFE in wireless channels for packet based communication systems. In [7], a selective time reversal DFE was proposed, in which decided whether to operate in a normal mode or time reversal mode under the criteria of smaller mean square error (MSE). The authors of [8], [9] proposed a bi-directional arbitrated decision feedback equalization (BAD) algorithm according to a local maximum a posteriori (MAP) criterion. In [8], the BAD algorithm can reduce the error propagation effect and improve the performance of the conventional DFE by combining two parallel DFE structures, i.e., normal mode and time reversal mode. In [10], the authors applied the BAD algorithm into the underwater acoustic communication system.

In this paper, a closed loop Doppler estimation and compensation algorithm combined with a bi-directional DFE is proposed. The proposed algorithm can not only compensate the broadband Doppler symbol-by-symbol by using a closed loop Doppler estimation and compensation algorithm, but also reduce the error propagation effect by using a bi-directional DFE in the time varying underwater acoustic channel. The proposed algorithm can effectively improve the output SNR, suppress the intersymbol interference (ISI), and reduce the BER under at-lake experiment.

The paper is organized as follows. In Section II, we propose a closed loop Doppler estimation and compensation algorithm combined with bi-directional DFE. In Section III, we provide experimental results. Finally, in Section IV, we summarize the conclusions about this work.

Notation: in the following parts of the paper, vectors are denoted by boldface lowercase letters. Elements of vector $\mathbf{x}$ is denoted as x_n. $(\cdot)^H$, $(\cdot)^*$ denote the Hermitian transposition, and the complex conjugate operation, respectively.

II. SYSTEM MODEL

A. Broadband Doppler estimation and compensation algorithm with conventional DFE

For broadband signals, the Doppler effect can not only cause frequency shift, but also cause the expansion or compression of the signal waveform in the time scaling [12]. Therefore,

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the received signal can be expressed as

$$r(t) = s[(1+\Delta)t] + w(t) \tag{1}$$

where $r(t)$ is the received signal, $s(t)$ is the transmitted signal, Δ is the Doppler factor, which is defined as $\Delta = v/c$, v is the relative radial velocity between the transmitter and receiver, c is the underwater sound speed. $1+\Delta$ is the Doppler interpolation factor. When the radial velocity is positive, the Doppler factor is positive. It means that the transmitted signal is expanded. On the contrary, the transmitted signal will be compressed. $w(t)$ is the adaptive white Gaussian noise (AWGN) with the zero mean and variance of σ_w^2.

In the representation of discrete time signal, (1) can be rewritten as

$$r(nT_s) = s[n(1+\Delta)T_s] + w(nT_s) \tag{2}$$

where n is an integer and T_s is the sample period.

To reconstruct the transmitted signal from the received signal $r(nT_s)$, we have

$$s(nT_s) = r(\frac{nT_s}{1+\Delta}). \tag{3}$$

In order to eliminate the influence of the Doppler effect, the sampling rate should be

$$f_s^{'} = (1+\Delta)f_s \tag{4}$$

where f_s is the sampling rate, $f_s^{'}$ is the sampling rate to eliminate the influence of the Doppler effect.

There are two parts for the closed loop Doppler estimation and compensation combined with conventional DFE in the receiver. The first part is a closed loop Doppler estimation and compensation part, and the second part is a DFE part. First, the Doppler shift is estimated from the received signal to obtain the Doppler interpolation factor $1+\Delta$. An interpolator is used to perform a sampling rate conversion on the received signal sampled at f_s. Second, the resampled signal is processed by the adaptive DFE. The overall system structure is shown in Fig. 1.

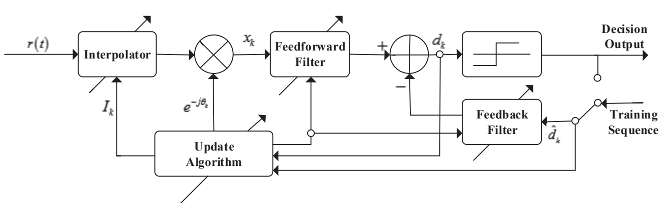

Fig. 1. Block diagram for closed loop Doppler compensation.

For the *k*-th time interval, the DFE output is given by

$$d_k = \mathbf{h}_k^H \mathbf{x}_k - \mathbf{g}_k^H \hat{\mathbf{d}}_k \tag{5}$$

where $\mathbf{h}$ and $\mathbf{g}$ are tap-weight vectors for the feedforward filter and feedback filter. $\mathbf{x}$ is the received signal vector. $\hat{\mathbf{d}}$ is the training sequence vector or the symbol decision vector for the feedback filter.

If the normalized least mean square (NLMS) adaptive algorithm is adopted [11], the tap-weights of the filters are updated as follows

$$\mathbf{w}_{k+1} = \mathbf{w}_k + \mu/(\mathbf{x}_k^H \mathbf{x}_k + \varepsilon) e_k^* \mathbf{x}_k \tag{6}$$

where μ is the step-size, ε is a very small constant, $\mathbf{w}_k = [\mathbf{h}_k^T \ \mathbf{g}_k^T]$ is the tap-weight coefficients vector, and e_k is the decision error, i.e.,

$$e_k = \hat{d}_k - d_k \tag{7}$$

If the recursive least square (RLS) adaptive algorithm is adopted [11], the tap-weights of the filters are updated as follows

$$\mathbf{w}_{k+1} = \mathbf{w}_k + \mathbf{\Psi}_k^{-1}/(\lambda + \mathbf{x}_k^H \mathbf{x}_k \mathbf{\Psi}_k^{-1} \mathbf{x}_k) e_k \tag{8}$$

where λ is the forgetting factor, the $\mathbf{\Psi}_k^{-1}$ updating equation can be obtained as

$$\mathbf{\Psi}_{k+1}^{-1} = \lambda^{-1}(\mathbf{\Psi}_k^{-1} - \mathbf{\Psi}_k^{-1}\mathbf{x}_k/(\lambda + \mathbf{x}_k^H \mathbf{\Psi}_k^{-1} \mathbf{x}_k)(\mathbf{x}_k^H \mathbf{\Psi}_k^{-1})) \tag{9}$$

The variation of phase error indicates the variation of Doppler. The Doppler interpolation factor can be updated as

$$I_{k+1} = I_k + K_p \theta_k \tag{10}$$

$$\theta_k = \arg[\mathrm{d_k \hat{d}_k^*}] \tag{11}$$

where θ_k is the estimation of the maximum likelihood (ML) phase, K_p is the tracking constant, and I_k is the Doppler interpolation factor.

Doppler frequency and the relative velocity can easily be written as

$$f_d = f_c(I_k - 1) \tag{12}$$

$$v = (I_k - 1) \times c \tag{13}$$

where f_c is carrier frequency, c is the underwater sound speed.

B. Proposed broadband Doppler estimation and compensation algorithm with bi-directional DFE

Conventional DFE suffers from error propagation caused by the feedback of incorrect decisions. To mitigate error propagation, a bi-directional DFE was proposed in [8]. In this paper, a novel broadband Doppler estimation and compensation receiver structure which combines a bi-directional DFE is shown in Fig. 2. In Fig. 2, the upper block illustrates a normal mode operation of the receiver involving closed loop Doppler estimation and compensation and an adaptive DFE. On the other hand, the lower block operates on the time-reversed version of the received signal. The other operations are the same as the normal mode operation. The proposed receiver can not only suppress the error propagation by taking advantage of the different statistical properties of the bi-directional noise, but also compensate the broadband Doppler effect symbol-by-symbol.

III. Experimental Results

A single carrier communication experiment was carried on in the SongHua Lake on Nov. 2013. The modulation format is QPSK. Symbol rate is $1\ kbps$. The 48-element vertical array is moored on the bottom of the lake. The sound source is fixed at broadside of the boat with the depth of $1\ m$. We process the received signals from 20-th element of the vertical array at $41\ m$ depth. The measured sound speed profile is shown in Fig. 3. The trajectory of the source ship in the universal transverse mercator (UTM) grid system is shown in Fig. 4.

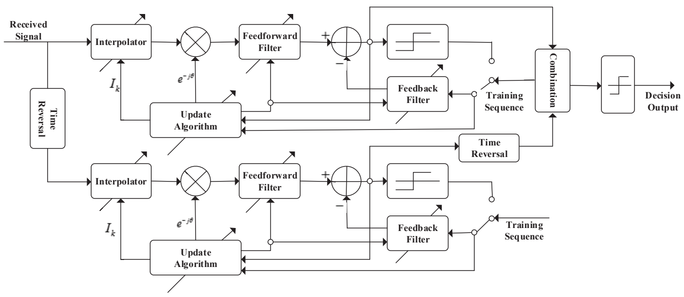

Fig. 2. Block diagram for the proposed receiver.

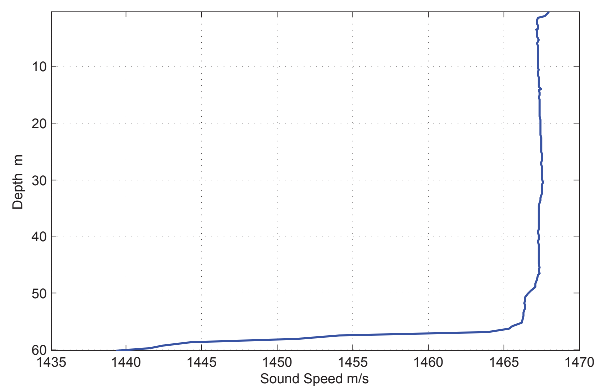

Fig. 3. Measured sound speed profile at receiver array location.

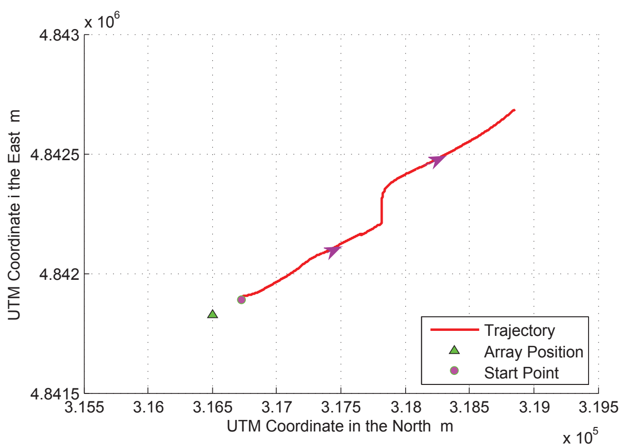

Fig. 4. Trajectory of source ship.

The transmitted data packet structure is shown in Fig. 5. Hyperbolic frequency modulated (HFM) signal at the beginning of the data packet is used as the synchronization signal. The time guard is 150 ms. In order to compare the proposed broadband Doppler estimation and compensation algorithm with the open loop Doppler estimation and compensation algorithm, HFM signals at the beginning and the end of the data packet are used for open loop Doppler estimation. The training sequence 1 and training sequence 2 are used for bi-directional DFE.

The order of the feedforward filter and feedback filter in the conventional DFE are 15 and 60, respectively. The order of the feedforward filter and feedback filter in the reversal DFE

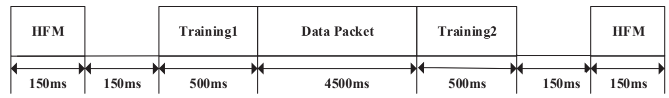

Fig. 5. The frame structure of transmitted data.

TABLE I. THE OUTPUT SNR AND BER OF THE RECEIVERS

The type of the receiver	SNR_{out}/dB	BER
Closed Loop + Conventional DFE	10.4839	0.11%
Closed Loop + Reversal DFE	10.0909	0.08%
Closed Loop + Bi-directional DFE	11.6529	0.01%
Open Loop + PLL + Conventional DFE	5.7246	8.73%

are 30 and 50, respectively. The tracking coefficients K_{f_1} and K_{f_2} in the second order PLL are set to 0.0001 and 0.00001, respectively [4]. The output SNR and BER are demonstrated in Table I.

In Table I, compared with the closed loop Doppler estimation and compensation with conventional DFE and the closed loop Doppler estimation and compensation with reversal DFE, it can be seen that the performance of the closed loop Doppler estimation and compensation is better than the performance of the open loop Doppler estimation and compensation algorithm embedded a second order PLL in terms of output SNR and BER. It is because the closed loop algorithm can estimate and compensate the broadband Doppler effect symbol-by-symbol. Moreover, compared with the closed loop algorithm with conventional DFE, reversal DFE and the bi-directional DFE, the bi-directional DFE receiver has a better performance in terms of output SNR and BER. It is because the bi-directional DFE can reduce the error propagation effect compared with the conventinoal DFE. From Table I, it can be seen that the output SNR can be improved by 1.17 dB compared with the closed loop Doppler estimation and compensation receiver combining with conventional DFE. Moreover, BER can be reduced from 0.11% to 0.01%. The open loop Doppler estimation and compensation receiver combing with an open loop Doppler estimation and compensation algorithm and a second order PLL achieves the worst performance, i.e., the lowest output SNR and the biggest BER. The proposed broadband Doppler estimation and compensation receiver combing with a bi-directional DFE has the best performance in terms of output SNR and BER. It can also be seen in Fig. 6 that the proposed broadband Doppler estimation and compensation receiver combining with a bi-directional DFE has the most aggregate constellation when compared with other receivers.

In the lake experiment, we process 12 epoches in 6 min when the source ship moves along the trajectory shown in Fig. 4. In Fig. 7, the red line is the source velocity we calculated from the GPS and the blue line is the source velocity we estimated from the proposed broadband Doppler estimation and compensation algorithm with a bi-directional DFE. It can be clearly seen from Fig. 7 that the estimated relative radial velocity is consistent with the projection velocity calculated from the GPS. It means that the broadband Doppler can be estimated and compensated. In Fig. 8, the BER can be got from the 12 epoches. We compare the BER performance among the open loop Doppler estimation and compensation with conventional DFE, the closed loop Doppler estimation and compensation with conventional DFE and the closed loop

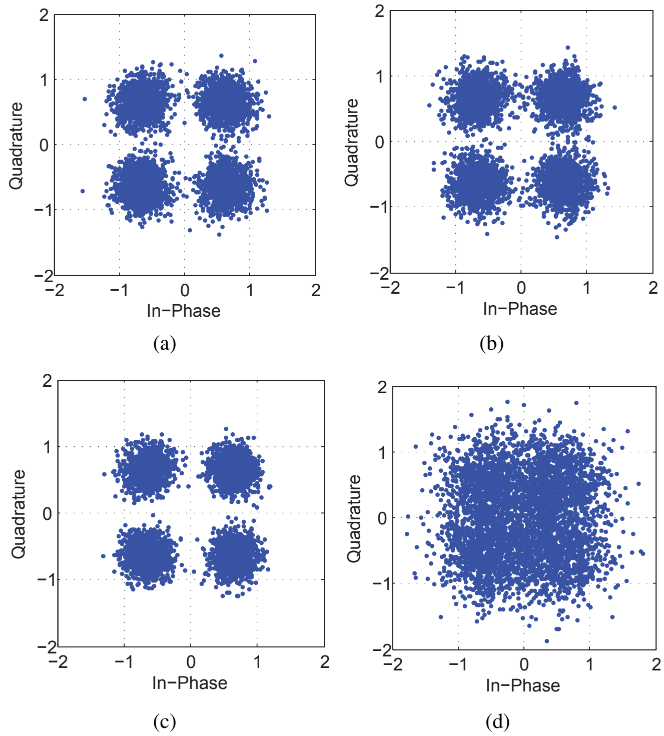

Fig. 6. Constellation from different receivers: closed loop Doppler estimation and compensation with (a) conventional DFE, (b) reversal DFE, (c)bi-directional DFE and (d)open loop Doppler estimation and compensation with conventional DFE embedded with a second order PLL

Doppler estimation and compensation with bi-directional DFE. From the 12 epoches, it can be clearly seen that compared with the other two receivers the proposed receiver can achieve a better performance in terms of BER.

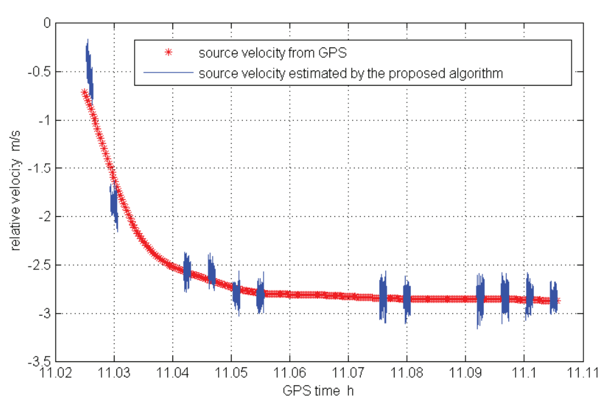

Fig. 7. Source velocity estimated by the proposed algorithm.

IV. Conclusions

In this paper, we proposed a novel bi-directional DFE receiver, which combines closed loop Doppler compensation algorithm. The proposed receiver can not only compensate the Doppler effect symbol-by-symbol, but also reduce the error propagation effect in time varying underwater acoustic channel. We have demonstrated by lake experiment results that

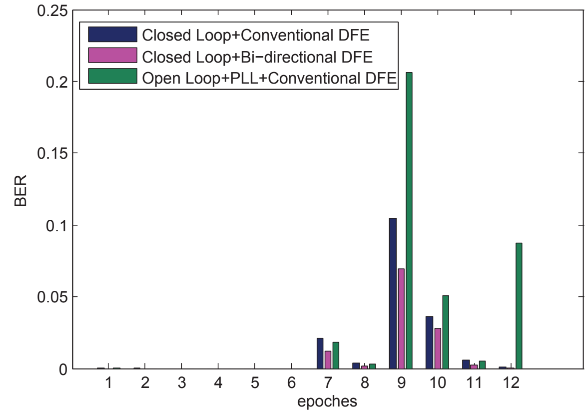

Fig. 8. BER for different receivers.

the proposed receiver has a higher output SNR and a lower BER.

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