Iterative Block DFE for Underwater Acoustic Single Carrier System

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Abstract: In order to gain a better performance and reduce the computational complexity of the filter design in the underwater acoustic single carrier system, a new Iterative Block DFE (IBDFE) is proposed, which operates iteratively on blocks of the received signal, and fully implements its filtering operations by Discrete Fourier Transforms (DFTs). Two design methods are considered for IBDFE: one is HD-IBDFE, and the other is SD-IBDFE. In this paper, the first one is adopted. In this scheme, hard detected data are used as input of the feedback, and filters are designed according to the correlation between detected and transmitted data. In the simulations and experiments, the method of the HD-IBDFE is introduced, and for comparison, the performance of H-DFE is shown, as well as that of ZF, MMSE and Matched-Filter-Bound (MFB). From the results of the simulations on a Rayleigh fading channel, it is easily found that on average, the HD-IBDFE outperforms H-DFE. When the number of iteration is 4, HD-IBDFE outperforms ZF, MMSE and H-DFE by about 11dB, 5dB and 0.7 dB respectively at BER = 10^{-4}. As for MFB, the HD-IBDFE still has a degradation of 1.6 dB. In addition, the experimental results in both experiment pool and shallow water also verify the achievement. The simulation and experiment results indicate that the IBDFE outperforms other equalization schemes. What's more, it exhibits a reduction of the computational complexity.
Key words: underwater acoustic system; single carrier; IBDFE

I. INTRODUCTION

The complexity of underwater acoustic channels can be characterized as severe Doppler-drift, simultaneously limited bandwidth, time variability and excessive multipath delay spread[1-2]. Thus signals in underwater acoustic channels are very easy to be distorted without equalization technologies. To solve these problems and gain a better performance, more and more people are engaged in the study of underwater acoustic communication, especially in recent two decades [3-15].

As we all know, H-DFE significantly outperforms linear equalization in underwater acoustic channels[16]. With the help of a feedback filter, H-DFE can cancel Inter Symbol Interference (ISI) obviously. While H-DFE is attractive for its performance, the complexity is also significant, especially for very dispersive channels. Though the feed forward filtering is operated in the Frequency Domain (FD), which means that the received signals can be performed by FFT blocks, and the feedback still operates in the time domain, with the symbol detection on a per-sample basis[17]. In a sense, H-DFE does not make a simple solution for the filter design.

Next we study the Interative Block DFE (IBDFE). The transmitted symbol block is detected by a given DFE structure; in turn, the updated block of detected symbols permits the DFE to be redesigned and so on. In this scheme, both feed forward and feedback filters are operated in the FD, which results in a much lower complexity than H-DFE.

Moreover, the IBDFE configuration has a lower complexity in the filter design, because it does not need any operations of matrix inversion [18].

For IBDFE, there are two design methods. One is IBDFE with hard data detection (HD-IBDFE), and the other is IBDFE with soft data detection (SD-IBDFE). Both of them need a Minimum Mean-Square Error (MMSE) criterion for the filter design. Considering the fact that the computational complexity of HD-IBDFE is lower than SD-IBDFE[19], the first scheme is taken.

Simulation results performed on Rayleigh fading channel confirm that on average, HD-IBDFE outperforms H-DFE. Meanwhile, results from experiment pool test and shallow water experiment also verify the achievement.

The rest of this paper is organized as follows. In Section II, the structure and the algorithm of IBDFE are described. In Section III, the simulation and experiment results are given. The computational complexity of H-DFE and IBDFE is discussed in Section IV. Finally, Section V draws the conclusion.

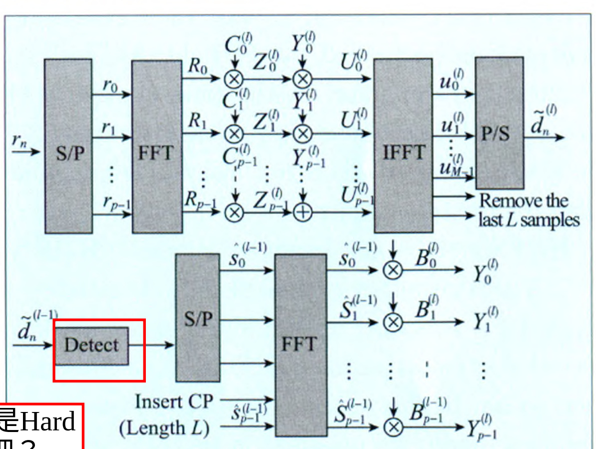
II. IBDFE

In this paragraph, the first design method of IBDFE is introduced.

Figure 1 shows the block diagram of HD-IBDFE. On the basis of Figure 1, we can get

$$\boldsymbol{U}_m^{(l)} = \boldsymbol{Z}_m^{(l)} + \boldsymbol{Y}_m^{(l)} = \boldsymbol{C}_m^{(l)}\boldsymbol{R}_m + \boldsymbol{B}_m^{(l)}\hat{\boldsymbol{S}}_m^{(l-1)} \quad (1)$$

where $0 \leqslant m \leqslant P-1$.



这个应该是Hard Desicion吧？

Fig.1 *The block diagram of HD-IBDFE*

For optimization of the coefficients $C_m^{(l)}$ and $B_m^{(l)}$, the algorithm of MMSE was chosen. Suppose that the transmitted data is $s(n)$, the channel impulse response is $h(n)$, and $v(n)$ is the additive white Gaussian noise. The received data $r(n)$ is

$$r(n) = \sum_{l=0}^{N_h-1} h(l)s(n-l) + v(n) \quad (2)$$

where, N_h is the length of the underwater acoustic channel. For Eq.(1), after FFT operation, we can get

$$R_p(k) = H_p S_p(k) + W_p(k) \quad (3)$$

And define

$$M_{S_p} = E[\,|S_p|^2\,] \quad (4)$$

$$M_{\hat{S}_p^{(l)}} = E[\,|\hat{S}_p^{(l)}|^2\,] \quad (5)$$

$$r_{S_p,\hat{S}_p^{(l)}} = E[\,S_p \hat{S}_p^{(l-1)*}\,] \quad (6)$$

where, $r_{S_p,\hat{S}_p^{(l)}}$ is the correlation function between transmitted and detected data sequences. Where * denotes the complex conjugate. The MSE of HD-IBDFE is defined as:

$$J_{HD}^{(l)} = E[\,|\tilde{d}_n^{(l)} - d_n|^2\,] = \frac{1}{P}\sum_{p=0}^{P-1} E[\,|u_p^{(l)} - s_p|^2\,] \quad (7)$$

According to the principle of Parseval, and by combining Eq. (1) and Eq. (7), we get

$$J_{HD}^{(l)} = \frac{1}{P^2}\sum_{p=0}^{P-1} E[\,|C_p^{(l)}R_p + B_p^{(l)}\hat{S}_p^{(l-1)} - S_p|^2\,] \quad (8)$$

Then unite Eqs. (4-6), and Eq.(8), we gain

$$J_{HD}^{(l)} = \frac{1}{P^2}\sum_{p=0}^{P-1}\Big\{|C_p^{(l)}|^2 M_w + |C_p^{(l)}H_p - 1|^2 M_{S_p} + |B_p^{(l)}|^2 M_{\hat{S}_p^{(l-1)}} + 2\mathrm{Re}\,[B_p^{(l)*}(C_p^{(l)}H_p - 1) r_{S_p,\hat{S}_p^{(l-1)}}]\Big\} \quad (9)$$

where, $M_W = P\sigma_w^2$ is the noise power in the FD.

Since the feedback filter does not influence the current signal, then

$$\sum_{p=0}^{P-1} B_p^{(l)} = 0 \quad (10)$$

Let $\dfrac{\partial J_{HD}^{(l)}}{\partial B_p^{(l)}} = 0$ and combine Eq. (10), we obtain

$$B_p^{(l)} = -\frac{r_{S_p,\hat{S}_p^{(l-1)}}}{M_{\hat{S}_p^{(l-1)}}}[H_p C_p^{(l)} - \gamma^{(l)}] \quad (11)$$

where $p = 0, 1, \cdots, P-1$, and

$$\gamma^{(l)} = \sum_{p=0}^{P-1} H_p C_p^{(l)} \quad (12)$$

Let $\frac{\partial J_{HD}^{(l)}}{\partial C_p^{(l)}} = 0$, then

$$C_p^{(l)} = \frac{H_p^*}{M_W + M_{S_p}\left(1 - \frac{|r_{S_p,\hat{S}_p^{(l-1)}}|^2}{M_{\hat{S}_p^{(l-1)}} M_{S_p}}\right)|H_p|^2};$$

$$p = 0, 1, \cdots, P-1 \tag{13}$$

Theoretically speaking, the more iterative operations are operated, the better performance we can obtain. A simulation result is presented in Figure 2 to verify this conclusion. It shows the average BER of an uncoded transmission as a function of the average Signal-to-Noise Ratio (SNR) at the receiver input at iterations 1 ~ 7. Besides, it is simulated over a Rayleigh fading channel in MATLAB, and the time synchronization and frequency synchronization are supposed to be perfect. The detailed system parameters used in the simulation are indicated in Table I.

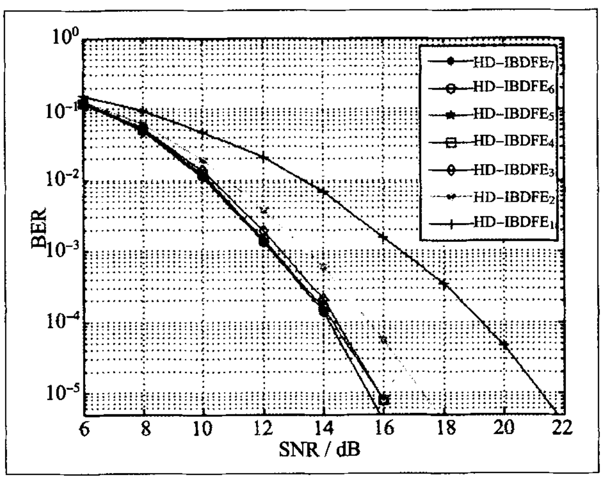


Fig.2 *Average BER vs. average SNR of HD-IBDFE*

Table I *System simulation parameters*

FFT length	256
Guard interval type	CP
Guard interval length	64
Channel length	256
Channel type	Rayleigh fading channel
Multipaths number	18
Frequency offset	0
Signal modulation type	QPSK

From Figure 2, we note that when the number of iteration is equal to or greater than 4, the BER performance lines are very close. But the more iterations were operated, the higher degree of computational complexity the system will need.

III. SIMULATION AND EXPERIMENT RESULTS

3.1 Simulation results

For an HD-IBDFE, Figure 3 shows the average BER of an uncoded transmission as a function of the average SNR at the receiver input at iterations 2 ~ 4. For comparison, the performance of H-DFE is shown, as well as ZF, MMSE and MFB. And System simulation parameters are the same as Table I.

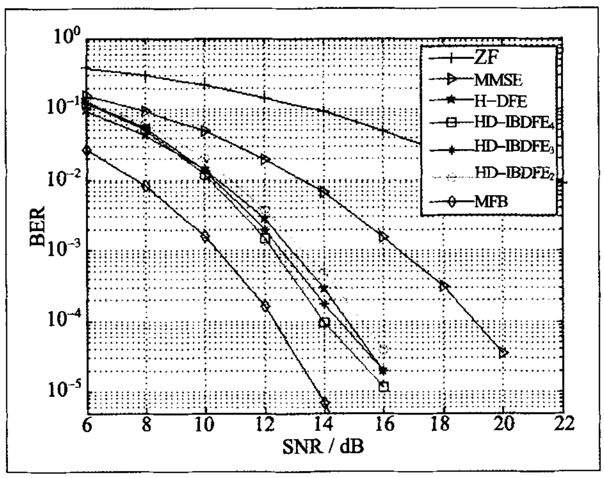


Fig.3 *Average BER vs. average SNR of various equalization schemes*

As can be seen from Figure 3, HD-IBDFE exhibits a significant improvement of performance. When the number of iteration is 4, it is easily found that HD-IBDFE outperforms ZF, MMSE and H-DFE by about 11 dB, 5 dB and 0.7 dB respectively at BER = 10^{-4}. As for MFB, the HD-IBDFE still has a degradation of 1.6 dB.

3.2 Experimental pool experiments

The experiment is done at the experimental pool in Xiamen University. System specification for the experiment is shown in Table II. Figure 4 is the original image, and Figure 5 exhibits the location of transmitter and receiver transducers. Both of them are kept still during the whole experiment. The distance between the transmitter and the receiver is 10 m. Table III shows the BER results of the experiment, and each scheme is tested six times. Figure 6 shows the received images after equalization, according to the 6th data in Table III. Here, the iteration number of HD-IBDFE is 2-4. For distinctiveness, they are denoted as IB-2, IB-3 and IB-4 respectively.

Table II *System specification*

FFT length	512
IFFTlength	512
Guard interval	42.666 7 ms
Symbol duration	170.666 7 ms
Effective bandwidth	6 kHz
Effective speed	6 kbit/s
Pilot type	Block-type
Multipaths number	18
Signal modulation type	QPSK

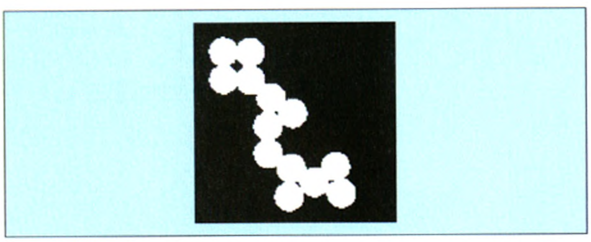


Fig.4 *Original image*

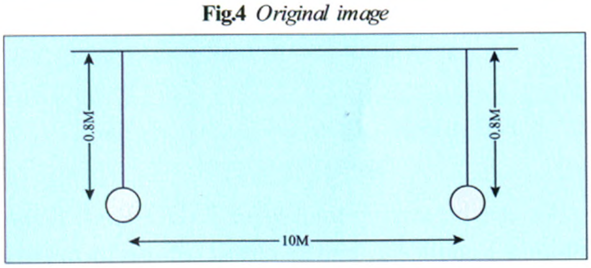
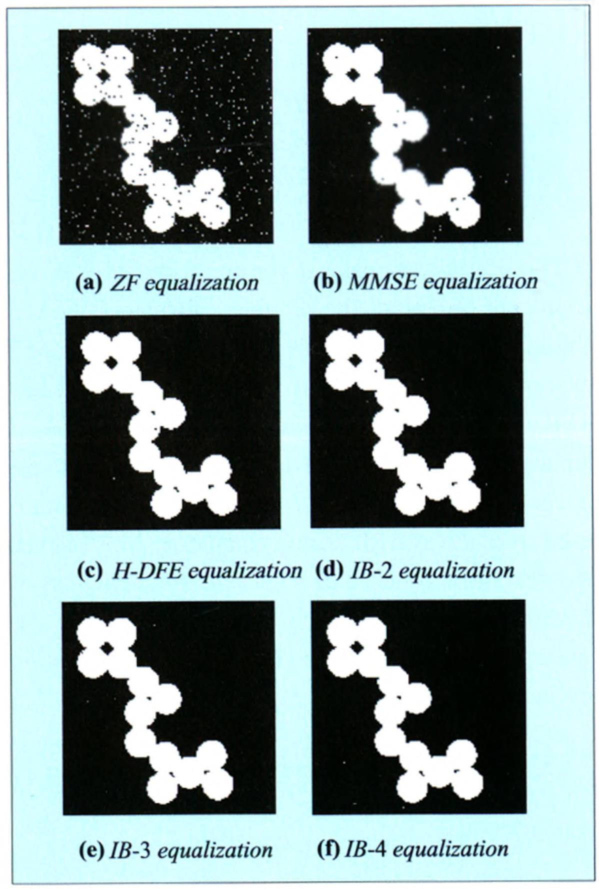


Fig.5 *Location of transmitter and receiver*

Table III *Experiment pool test results*

No.	ZF	MMSE	H-DFE	IB-2	IB-3	IB-4
1	0.055 07	0.001 10	0.000 11	0.000 28	0.000 15	0.000 18
2	0.047 91	0.005 23	0.000 28	0.000 35	0.000 21	0.000 12
3	0.052 32	0.003 85	0.000 19	0.000 27	0.000 16	0.000 13
4	0.046 81	0.005 51	0.000 30	0.000 36	0.000 24	0.000 15
5	0.053 97	0.002 75	0.000 22	0.000 20	0.000 26	0.000 09
6	0.049 56	0.004 41	0.000 33	0.000 38	0.000 23	0.000 17
Ave	0.050 94	0.003 81	0.000 24	0.000 31	0.000 21	0.000 14



(a) *ZF equalization* (b) *MMSE equalization*

(c) *H-DFE equalization* (d) *IB-2 equalization*

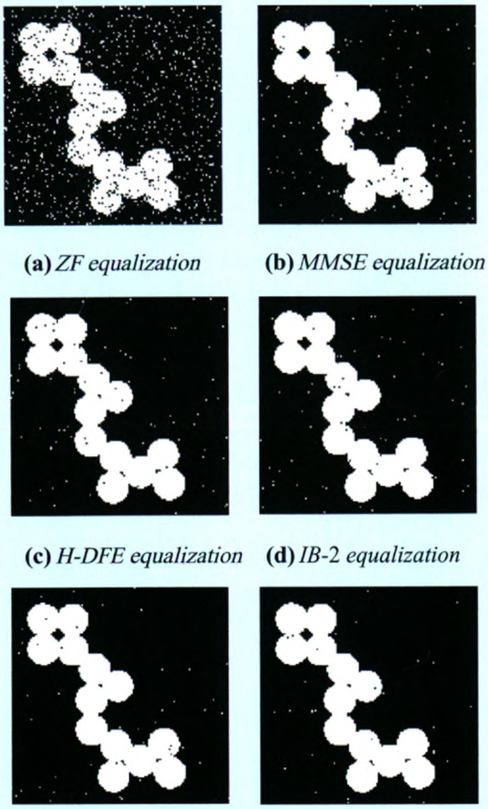
(e) *IB-3 equalization* (f) *IB-4 equalization*

Fig.6 *Received images after ZF, MMSE, H-DFE equalization and HD-IBDFE equalization at the receiver input at iterations 2 ~4 respectively*

3.3 Shallow water experiments

The experiment is also operated in the shallow water near Xiamen University. System specification for the experiment is the same as Table II. The distance between transmitter and receiver is 840 m. And the transmitter and receiver are put about 4 meters under water.

Table IV gives the BER results of the experiment. Each kind of frequency domain equalization method is tested six times. Figure 7 shows the received images after equalization, according to the 6th data in Table IV. And the iteration number of HD-IBDFE is set to be 2 ~4. For distinctiveness, they are also denoted as IB-2, IB-3 and IB-4 respectively.



(a) *ZF equalization* (b) *MMSE equalization*
(c) *H-DFE equalization* (d) *IB-2 equalization*
(e) *IB-3 equalization* (f) *IB-4 equalization*

Fig.7 *Received images after ZF, MMSE, H-DFE equalization and HD-IBDFE equalization at the receiver input at iterations* 2 ~ 4 *respectively*

According to the results of Table III, Figure 6, Table IV and Figure 7, we know that H-DFE and HD-IBDFE significantly outperforms linear equalization in the underwater acoustic channels. Next, the computational complexity of H-DFE and HD-IBDFE in the equalizer design will be discussed.

Table IV *Shallow water experiment results*

No	ZF	MMSE	H-DFE	IB-2	IB-3	IB-4
1	0.133 57	0.019 65	0.009 54	0.009 65	0.004 82	0.004 78
2	0.100 80	0.014 38	0.009 01	0.009 54	0.005 13	0.005 00
3	0.127 95	0.016 97	0.008 90	0.009 30	0.004 65	0.004 35
4	0.122 42	0.013 88	0.009 25	0.009 01	0.004 50	0.004 62
5	0.112 78	0.018 72	0.009 16	0.009 25	0.004 92	0.004 88
6	0.116 64	0.015 95	0.009 55	0.009 63	0.005 11	0.004 93
Ave	0.119 03	0.016 59	0.009 24	0.009 40	0.004 86	0.004 76

IV. COMPUTATIONAL COMPLEXITY OF H-DFE AND IBDFE

Based on Ref. [19], the number of H-DFE and HD-IBDFE's Complex Multiplications (CMUL) in the equalizer design are $O[(2L)^2+2P+P\log_2^P]$ and $(3N_I+1)P$ respectively. Here, L is the CP extension; P denotes FFT size, and N_I is the number of iterations. In our experiment, the size of the FFT is set to $P=512$, while the CP extension is set to $L=128$. So the CMUL of H-DFE, HD-IBDFE at the receiver input at iterations 2-4 needed for filter design are 71 168, 3 584, 5 120 and 6 656 respectively. We can easily find that the degree of computational complexity of HD-IBDFE is much lower than that of H-DFE. What's more, the equalization effects of HD-IBDFE on the receiver input at iterations 2 ~ 4 are very close. For the best equalization effect, the iteration number is chosen to be 4. And we believe that the cost of computational complexity is valuable.

V. CONCLUSIONS

In this paper, we studied the IBDFE. Simulation and experiment results showed that IBDFE has a better performance than H-DFE in underwater acoustic single carrier system. What's more, when compared with existing H-DFE, due to the fact that both the filter design and signal processing are fully operated in the FD, the computational complexity is greatly reduced. 中国通信

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