Study of Single-Carrier Coherent High-Speed Underwater Acoustic Communication

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***Abstract*—Sparse channel estimation algorithms and frequency-time domain combined equalization technique used in single-carrier coherent high-speed underwater acoustic (UWA) communication are researched. First the UWA channels are estimated by a modified MP algorithm called DAMP. Then, frequency domain time reversal (FDTR) processing (in fact same to the frequency domain zero-forcing equalization, FDEQ) is used to combine the multiple channels at low computation complexity compared with time domain equal. At the same time, equalization in frequency domain is done. Then the multi-channel combined signal is processed by the decision-feedback equalization (DFE) algorithm. At Jan and Mar, 2013, sea tests at Xiamen Harbor, China were done. According to the results, the bit error rates of FDTR-DFE are about 10^{-3} in SISO system. In SIMO system, the bit error rates are less than 0.05% (three channels, except one test).**

Keywords—sparse channel estimation; time reversal; decision-feedback; underwater acoustic communication;

I. INTRODUCTION

The two major obstacles for high-speed communication in the UWA channel, which is varying with time and space, are the excessive multipath delay spread and the time-varying Doppler shift. In order to improve the performance of high-speed UWA communication in a medium or long range, researches are mostly focused on robust channel estimation algorithms at low SNR and equalization technique at low computation complexity. Equalization in frequency domain has been utilized instead of time domain equal to reduce the computation complexity and improve the performance of equalization[1]. Taking advantage of the property of adaptive matching in TR processing, multi-channel signals will be combined more efficiently. And it has been demonstrated in [2]-[5] that TR processing can be used in UWA communications to fight against frequency selective fading. T. C. Yang has adopted the combination of passive phase conjugate and adaptive DFE with phase-locked loop to make the coefficients of equalizers fixed, which improves the robustness of the system[6]. H. C. Song and his team have made research in MIMO and done sea tests to prove that MIMO in UWA communications is a promising way to achieve high performance[7]. An algorithm at low computation complexity to combine FDTR and DFE is proposed and has been applied to sea tests at Xiamen Harbor. The bit error rates of single channel are less than 0.5% and those of multi-channel processing are less than 0.2% while the source-receiver range is 10km.

II. FREQUENCY DOMAIN TIME REVERSAL COMBINED WITH DFE IN TIME DOMAIN

TR processing is a low computation complexity method to combine multi-channel signals. And like RAKE processing, the TR processing can strengthen the main path.

Regardless of noise, the source in frequency domain is $S(w)$. Providing that the frequency-domain impulse response of channel is $H(w)$, the received data in frequency domain can be expressed as

$$Y(\omega) = S(\omega)H(\omega) \tag{1}$$

After FDTR processing based on channel estimation, the received data can be expressed as

$$Y_{tr}(\omega) = S(\omega)\hat{H}^*(\omega)H(\omega) \approx S^*(\omega)\,|\,H(\omega)\,|^2 \tag{2}$$

In SIMO TR system, the signal can be expressed as

$$Y_{tr}(\omega) = S(\omega)\sum_{i=0}^{M-1} H_i(\omega)\hat{H}_i^*(\omega) \tag{3}$$

In theory [6], if we neglect errors of channel estimation, the multi-channel receiver can make the sound field of TR tend to be a constant in communication band.

And the frequency domain zero-forcing equalization (FDEQ) is

$$Y_i^{'}(\omega) = \frac{X(\omega)\hat{H}_i^*(\omega)}{|\,\hat{H}_i^*(\omega)|^2} = \frac{S(\omega)\hat{H}_i^*(\omega)H_i(\omega)+N(\omega)}{|\,\hat{H}_i^*(\omega)|^2} \tag{4}$$

So we first use a FDEQ (including FDTR processing) to every channel. Then the multi-channel signals are added up directly in frequency domain. Then the combined signal is

Supported by the Fundamental Research Funds for the Central University (No.2013121023) and the Natural Science Foundation of Fujian Province of China (No.2013J01253).

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transformed to time domain and processed by a DFE equalizer in order to eliminate residual ISI and track the changing UWA channels, which is shown in Fig.1.

From (2) and (4), we can see that the procedure of FDTR is similar to FDEQ. TR processing can decrease the influence of ISI, but can't remove it at all. A method with higher performance based on channel estimation is proposed to combine FDTR processing and equalization in time domain.

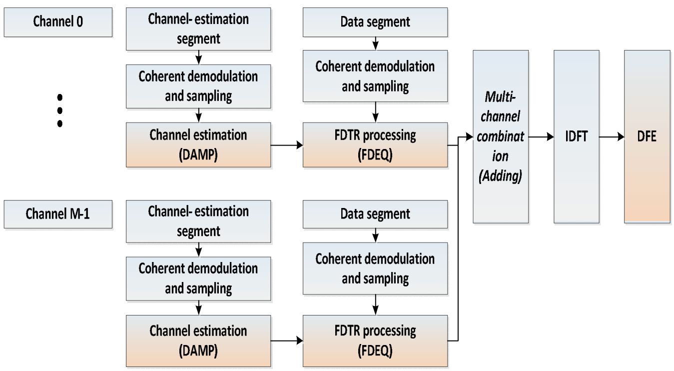

Fig.1.The proposed FDTR-DFE structure

III. THE SEA TESTS

A. Marine environment

On January 21st and March 22nd, 2013, we made sea tests in Xiamen Harbor. The source-receiver range is 10km. The position of transducers at transmitter and receiver are depicted in Fig.2. And sea conditions are listed in TABLE Ⅰ.

TABLE Ⅰ. SEA TEST CONDITIONS

Parameters	January	March
Range	10km	10km
Temperature(℃)	15℃	18℃
Sea/transducer Depth(transmitter)	20/9m	18/(3-10)m
Sea/receiver Depth (receiver)	16/9m	17/(3-10)m

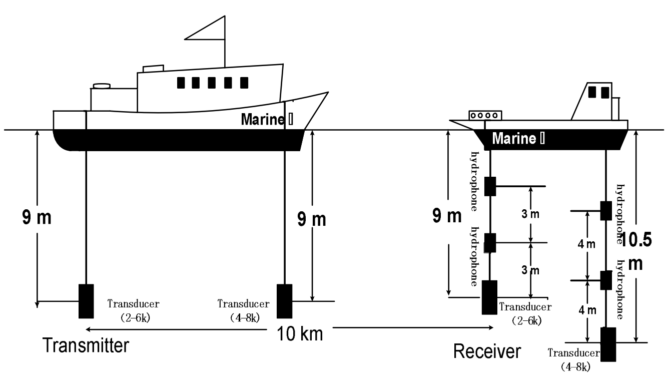

Fig.2.The depth of transducers and receivers (Jan)

B. Sea tests results

The signals are QPSK modulated and the parameters are listed in TABLE Ⅱ.

In sea tests, LS and DAMP channel estimation algorithms and three different equalizers are compared including the proposed FDTR-DFE equalizer. The mean square error and the constellations of one frame from single channel (MAR) are shown in Fig.3 and Fig.4, respectively. In Fig.3 (a) (b) and Fig.4 (a) (b) (c), LS algorithm is adopted. In others, DAMP algorithm is used. Obviously, the proposed DAMP algorithm has better performance than the LS equal. And comparing Fig.4 (d) (e) (f), the separation of the constellations of (d) (e) is not clear. But by using the proposed FDTR-DFE, the separation of the constellations of Fig.4 (f) is very clear, which can testify the performance of the proposed algorithm.

TABLE Ⅱ. THE PARAMETERS OF THE SYSTEM

Sampling rate	60kbps	Synchronous signals	Chirp(4-8kHz)
Frequency of carriers	6kHz	Length of training sequence	512bit
Data rate	4kbps	The type of training sequence	Gold sequence
Modulation	QPSK	Channel estimation algorithm	DAMP/LS

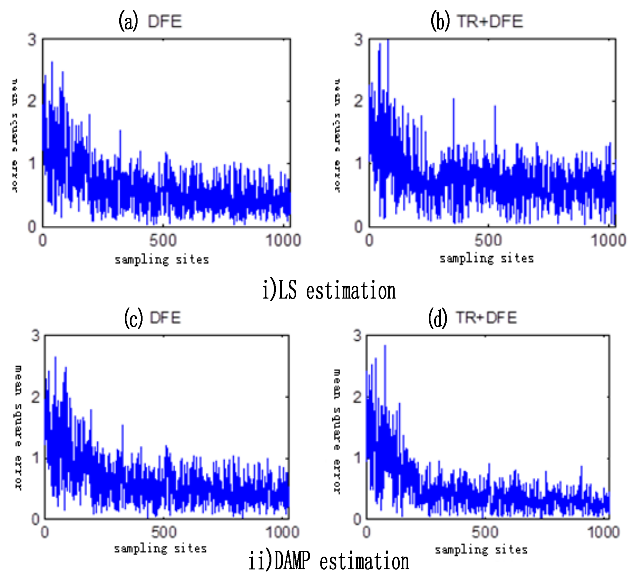

Fig.3.The mean square error

(a) (c) DFE in time domain.　(b) (d) FDTR-DFE.

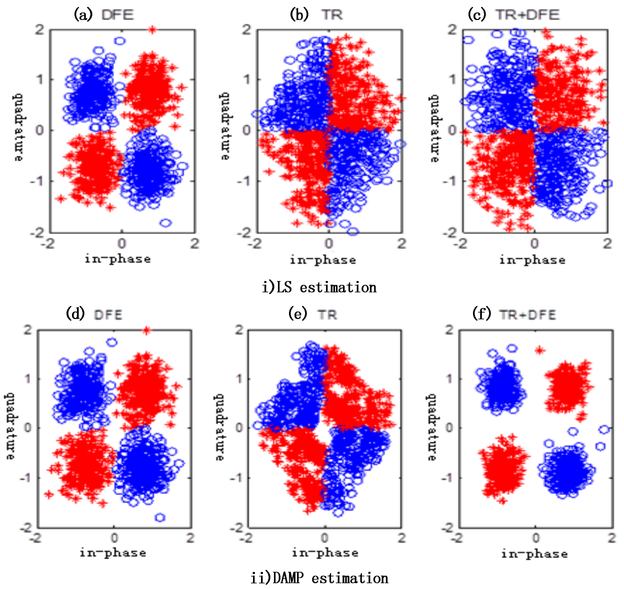

Fig.4.The constellations

(a) (d) DFE in time domain. (b) (e) FDTR(in fact FDEQ). (c) (f) FDTR-DFE

The bit error rates of one channel processing by using different channel estimation algorithms and equalizers are listed in TABLE Ⅲ. The performance of FDTR-DFE is the worst compared with the other two equalizers with LS channel estimation. The reason is that the performance of FDTR-DFE is sensitive to the accuracy of channel estimation and the processing with inaccurate channel estimation brings about noise instead of high performance. The bit error rate of the proposed FDTR-DFE employing DAMP estimation algorithm is 0.45% and much less than that of LS estimation, which testifies the performance of the proposed DAMP algorithm.

TABLE Ⅲ. RESULTS WITH ONE CHANNEL (The bit error rate %)

	DFE in time domain	**FDTR**	**FDTR-DFE**
LS estimation	9.35	8.59	21.67
DAMP estimation	9.35	7.75	0.45

The detail sea tests (Jan) results are listed in TABLE Ⅳ. From index 1-4, the SISO results are shown. From index 5-15, the SIMO results are shown. And the results of sea tests (Mar) can draw the same conclusions, which are listed in TABLE Ⅴ. From index 1-3, the SISO results are shown. The others are the results of SIMO.

From the results shown in index 5-15 of TABLE Ⅳ, the bit error rates are less than 0.2% when two channels are used and less than 0.05% when three channels are used. From the results listed in index 4-7 of TABLE Ⅴ, the bit error rates are less than 0.3% when two channels are used and less than 0.04% when three channels are used. The multi-channel processing has better performance than single channel and when the number of channels is more than three the bit error rates decline sharply.

TABLE Ⅳ. DETAIL SEA TESTS RESULTS (JAN) (The bit error rate%)

Index	Receive channel				Data rate:5kbps, DAMP estimation		
	Channel 1	Channel 2	Channel 3	Channel 4	Time-domain DFE	FDTR	FDTR combining time-domain DFE
1	1				0.13	9.61	0.27
2	2				0.16	9.77	0.24
3	3				0.07	9.55	0.29
4	4				1.60	7.79	0.02
5	1	2			0.05	9.38	0.18
6	1	3			0.07	9.47	0.20
7	2	3			0.05	9.74	0.18
8	2	4			1.84	9.45	0.13
9	1	4			1.49	9.44	0.74
10	3	4			1.88	9.20	0.44
11	1	2	3		0.07	9.72	0.20
12	1	2	4		0.40	8.91	0.05
13	1	3	4		0.34	8.79	0.05
14	2	3	4		1.43	8.89	0.05
15	1	2	3	4	0.34	8.41	0.05

TABLE Ⅴ. DETAIL SEA TESTS RESULTS (MAR) (The bit error rate%)

index	Receive channel			Data rate:5kbps, DAMP estimation		
	Channel 1	Channel 2	Channel 3	Time-domain DFE	FDTR	FDTR combining time-domain equalization
1	1			7.91	7.68	0.23
2	2			9.35	7.75	0.45
3	3			1.07	7.52	0.11
4	1	2		1.97	7.68	0.09
5	1	3		6.30	7.45	0.29
6	2	3		6.56	7.45	0.31
7	1	2	3	3.09	7.40	0.04

The mean square error and the constellations of index 13 in TABLE Ⅳ are shown in Fig.5 and Fig.6, respectively. Comparing the mean square error results adopting DAMP estimation algorithm in Fig.3 and Fig.5, the convergence rate employing the proposed multi-channel FDTR-DFE algorithm is faster than employing multi-channel DFE in time domain. In Fig.6, only by using the proposed FDTR-DFE algorithm, the separation of the constellations is clear. Sea tests results confirm that the multi-channel FDTR-DFE has stronger robustness than multi-channel DFE does. And the bit error rates of multi-channel FDTR-DFE decrease from 10^{-3} to 10^{-4} compared with the single channel equal.

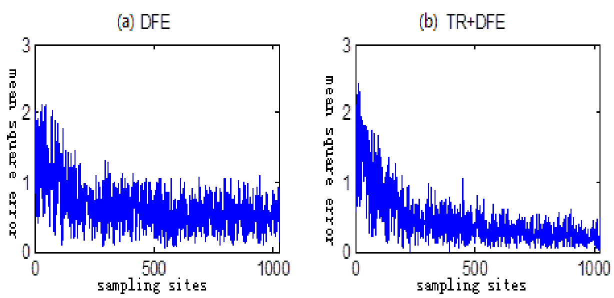

Fig.5.The mean square error

(a) DFE in time domain. (b) FDTR-DFE.

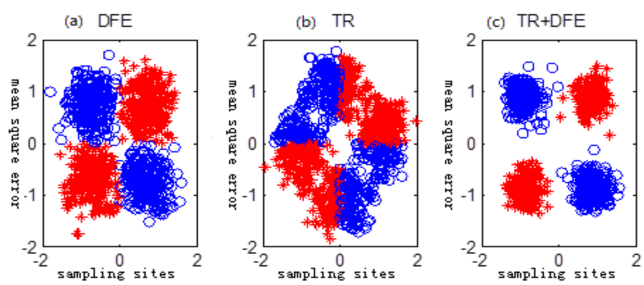

Fig.6.The constellations

(a) DFE in time domain. (b) FDEQ (FDTR). (c) FDTR-DFE.

IV. CONCLUSION

Frequency-time domain combined equalization and FDTR-DFE algorithms for single-carrier coherent high-speed UWA communications are researched. The proposed scheme of FDTR-DFE has been used to process data at sea tests conducted at Xiamen Harbor in Xiamen, China. Taking the results of January and March into consideration, the accuracy of channel estimation has more effect on FDTR-DFE than FDTR and equalization in time domain. In SISO system, the bit error rates of FDTR-DFE are less than 0.5% and the performance of FDTR-DFE is similar to time domain equal while equalization in time domain has good performance. The performance of multi-channel FDTR-DFE is better than that of single channel processing, which is affected by every channel. In SIMO system, the bit error rates of multi-channel FDTR-DFE decline sharply compared with those of single channel. Especially on condition that the number of processing channel is more than three, the bit error rates reduce to 10^{-4}. FDTR-DFE has stronger robustness and the bit error rates decline one to two orders of magnitude compared with those of FDTR and equalization in time domain.

ACKNOWLEDGMENT

This work was supported by the Fundamental Research Funds for the Central University (No.2013121023) and the Natural Science Foundation of Fujian Province of China (No.2013J01253).

REFERENCES

[1] Zheng Y. R, Chengshan Xiao, Yang T. C, Wen-Bin Yang. Frequency-Domain Channel Estimation and Equalization for Single Carrier Underwater Acoustic Communications [J]. OCEANS 2007.

[2] H. C. Song, W. S. Hodgkiss, W. A. Kuperman, M. Stevenson, and T. Akal. Improvement of Time-Reversal Communications Using Adaptive Channel Equalizers [J]. IEEE Journal of Oceanic Engineering, Vol.31, pp. 487-496, 2006.

[3] Yu Zhu, Khaled Ben Letaief. Single-Carrier Frequency-Domain Equalization with Decision-Feedback Processing for Time-Reversal Space-Time Block-Coded Systems [J]. IEEE Transactions of Communications, Vol.53, pp. 1127-1131, 2005.

[4] Myoung-Seok Kim, Misun Yoon, Chungyang Lee. Performance Analysis of a Frequency-Domain Equal-Gain-Combining Time-Reversal Scheme for Distributed Antenna Systems [J]. IEEE Communication Letters, Vol 16, pp. 1454-1457, 2012.

[5] SONG H C, HODGKISS W S, KUPERMAN W A. Experimental demonstration of adaptive reverberation nulling using time reversal [J]. The Journal of the Acoustical Society of America, 2005, 118(3):1381-1387.

[6] Yang T C. Correlation-based decision-feedback equalizer for underwater acoustic communications [J]. Oceanic Engineering, IEEE Journal of. 2005, 30(4): 865-880.

[7] Song H C, Roux P, Hodgkiss W S, et al. Multiple-input-multiple-output coherent time reversal communications in a shallow-water acoustic channel [J]. Oceanic Engineering, IEEE Journal of. 2006, 31(1): 170-178.