SINGLE CARRIER WITH MULTI-CHANNEL TIME-FREQUENCY DOMAIN EQUALIZATION FOR UNDERWATER ACOUSTIC COMMUNICATIONS

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ABSTRACT

Single-carrier with frequency domain equalization (SC-FDE) has been considered for bandwidth efficiency underwater acoustic (UWA) communication recently due to its reduced computational complexity and low peak-to-average power ratio. A multi-channel time-frequency domain equalization method for pseudurandom noise (PN) based SC-FDE is proposed in this paper. The proposed equalizer includes a multi-channel frequency domain equalizer followed by a low order multi-channel adaptive time domain decision feedback equalizer (DFE).

The proposed algorithm is applied to the real data receiving from a lake test conducted in November 2011. It is demonstrated that the uncoded error-free data rates of around 1500 and 3000 bps are achieved using one transmitter and six-channel receiving hydrophone array at a distance of 1.8 km. Experiment results shows that the performance can be enhanced by 4.5-5.5 dB in terms of output signal-to-noise ratio (SNR).

***Index Terms*—** Underwater acoustic communications, single carrier modulation, time-frequency domain equalization.

1. INTRODUCTION

With the development of ocean exploring and environment monitoring, high-rate underwater acoustic communication (UAC) for underwater platform has received much attention recently. Various receivers for spatial diversity and equalization have been studied over the last two decades[1].

So far, high-rate UAC methods in the literature are mainly divided into three categories. The first one is based on single carrier adaptive multi-channel time-domain decision feedback equalizer (SC-TDE) with an embedded second order digital phase locked loop (DPLL) to simultaneously track carrier phase as well as mitigate multipath channel distortions proposed by Stojanovic[2]. SC-TDE receiver is quite demanding in terms of computational complexity when the channel order is high. There are several methods for solving these problems, including time-reversal underwater acoustic communication [4], multi-beam decision feedback equalizer [6], channel estimation based equalizer [3], correlation-based DFE [5] and various low complexity adaptive algorithms. The second one is based on OFDM. One key shortcoming of OFDM based UAC is the complexity of acoustic transducers (e.g., hydrophones) when OFDM signals exhibit high peak-to-average power ratio (PAPR). High PAPR will seriously affect the efficiency of power amplifier and transducer safety. Another drawback of OFDM is the difficulty in preserving orthogonal subcarriers under relative high Doppler shifts at acoustic wavelength [7, 8, 9, 10].

Single-carrier with frequency domain equalization (SC-FDE) as the third one , through a single tap frequency equalizer, can obtain the same, or even better performance than OFDM, with close computational complexity[11, 12, 13, 15, 17]. In addition, SC-FDE signal has lower PAPR and is less sensitive to frequency offset than OFDM. Its calculation is approximately proportional to the logarithmic of the multipath extension length. PN-based single carrier has been proposed for UWA communication in our previous work [14] to obtain some advantages in synchronization, channel estimation, Doppler shift estimation and multi-user detection.

To combat the residual ISI caused by channel variations or channel estimation error in each block, we have investigated a hybrid time-frequency domain equalizer to combat the residual ISI in our previous work[16]. In this paper, a multi-channel time-frequency domain equalizer is presented to improve the system performance. Our lake experimental results confirm the effectiveness of the proposed methods.

The rest of this paper is organized as follows. The system model is introduced in Section 2. In Section 3, two receiver structures are shown, including hybrid time-frequency domain equalizer and the proposed method. Section 4 illustrates the experiment and the communication results. The information about the experiment, and examples of channel response are shown. Conclusions are given in Section 5.

2. SYSTEM MODEL

For PN-based SC-FDE system, the data are divided into serial blocks first at the transmitter, each having length $N-P$, and

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then PN code of length P is inserted into the end of each block. At the beginning of the data, additional PN code is inserted. where PN code can be viewed as a CP by the fast fourier transform (FFT) device and is always the same. If P is larger than multipath spread, inter-block interference (IBI) can be ignored.

$$\mathbf{x} = [x(0), x(1), \ldots, x(N-P-1), q(0), q(1), \ldots, q(P-1)]^T, \tag{1}$$

where $q(i)$ is PN code with length P; $(\cdot)^T$ represents matrix transpose.

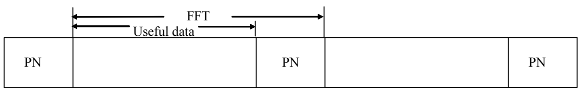

Fig. 1. PN-based SC-FDE block structure

Suppose that the equivalent symbol spaced channel impulse response (CIR) is invariant over each block duration

$$h(k) = [h(k,0), h(k,1), \ldots, h(k, L-1)]^T, \tag{2}$$

where k denotes the k-th block, L is the channel order and T represents the matrix transpose. Due to the effect of the timing offset and Doppler shift, the received signal can be expressed as

$$r_k(n) = e^{j(2\pi f_k n T_s + \phi_{k,0})} \sum_{l=0}^{L-1} h(k,l) x_k(n-l) + w(k,n), \tag{3}$$

where T_s is data symbol duration; f_k is Doppler shift in k-th block, caused by relative motion between tranceivers, A/D, D/A sampling, variant water current, etc.; $\phi_{k,0}$ is phase rotation caused by symbol timing offset in k-th block; $w(k,n)$ is additional white Gaussian noise with power σ^2. The k-th received block is expressed as

$$\mathbf{r}(k) = [r(k,0), r(k,1), \ldots, r(k, N-1)]^T. \tag{4}$$

For simplicity, without loss of generality, we eliminate the block index k. The received data block is

$$\mathbf{r} = \mathbf{Dhx} + \mathbf{w}, \tag{5}$$

where $\mathbf{w} = [w(0), w(1), \ldots, w(N-1)]^T$ is noise vector, and $\mathbf{D}$ is a diagonal rotated-phase matrix caused by Doppler shift, expressed as

$$\mathbf{D} = \mathtt{diag}\left\{ e^{j\phi_{k,0}}, e^{j(2\pi f_k 2T_s + \phi_{k,0})}, \ldots, e^{j(2\pi f_k 2(N-1)T_s + \phi_{k,0})} \right\}. \tag{6}$$

where

$$\mathbf{h} = \begin{bmatrix} h_0 & 0 & \ldots & h_{L-1} & \ldots & h_1 \\ h_1 & h_0 & \ldots & \ldots & \ldots & h_2 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ h_{L-1} \ldots & h_1 & h_0 & & 0 & 0 \\ 0 & \ldots & \ldots & \ldots & \ldots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \ldots & h_{L-1} & \ldots & h_1 & h_0 \end{bmatrix} \tag{7}$$

is an $N \times N$ circulant matrix.

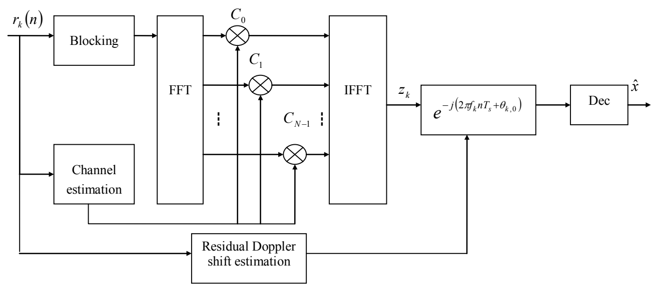

Fig. 2. Basic FDE structure for single carrier system

In the receiver, the data is converted back to frequency-domain from time-domain via FFT operation, and then frequency-domain equalization is conducted. The equalized sinal is converted back to time-domain signal.

$$\mathbf{R} = \mathbf{D}\Lambda\mathbf{X} + \mathbf{W}. \tag{8}$$

Fig. 2 illustrates the frequency domain equalizer (FDE) structure of a PN based SC-FDE system. In summary, the FDE part consists of rotated-phase compensation, channel estimation, frequency domain equalization (demapping).

3. PROPOSED ALGORITHM

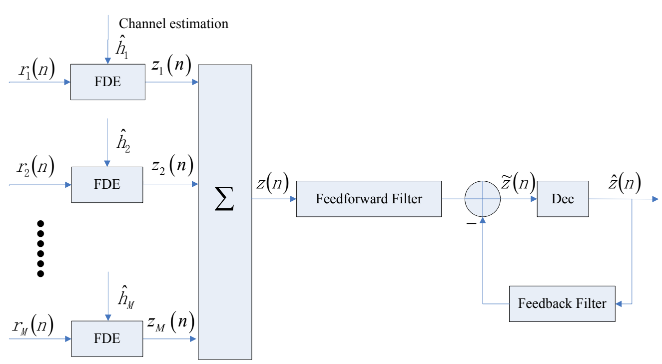

Fig. 3. Hybrid time frequency receiver

The basic FDE assumes the channel is invariant in one block. For channel variations in one block or channel estimation error, there is ISI in the output of FDE. To get spatial diversity, multi-channel frequency domain equalizers are used following a single channel DFE in order to combat the residual ISI in our previous work[16] as shown in Fig.3. The recursive least square (RLS) algorithm is used to update the tap coefficients of DFE.

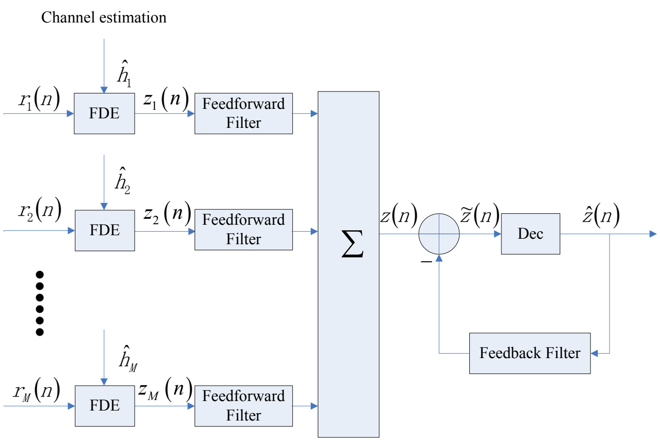

Fig. 4. Proposed receiver structure

To improve the performance of hybrid time frequency domain equalization, multi-channel time-frequency domain adaptive equalizer is proposed in order to obtain the additional spatial diversity. Not like hybrid time-frequency domain equalization, each FDE is followed by a feedfward filter as shown in Fig.4. The basic multi-channel FDE in the proposed receiver will reduce the UWA channel order, and hence the length of following feedforward and feedback filter become small. Thus, the computational complexity will be reduced, compared with the normal multi-channel time domain DFE. The detail of the multi-channel FDE part includes phase rotation compensation, least square channel estimation using PN code and MMSE equalization as shown in Fig.2. Since the phase rotation is compensated in the multi-channel FDE part, there is no DPLL in the following multi-channel time domain FDE and its details can be found in [2].

4. EXPERIMENTAL RESULTS

To verify the performance of the proposed method in real UWA channel, experiment was conducted in a practical lake environment of Shaanxi Province in November 2011. The water is with a depth of 4 m and 12 m at the transmitter and receiver sites respectively. Six hydrophones with space 0.75 m were equally located on the linear receiver array. The transmitter transducer was deployed below the surface of 1 m, and the receiver hydrophone array were deployed below the surface of 3 m. The distance between transmitter and receiver was 1.8 km. Fig.5 (a) shows the channel impulse response (CIR) in the lake experiment, which reflects the channel response varying with time, and the x axis is the expansion of channel response; y axis represents the time variation. Fig. 5 (b) shows the CIR at channel 1 in the experiment. The experiment channel has a dense multi-path feature because of several times reflection since the transmitter is close to the shore. The maximum multi-path spread is around 40 ms, and strong multi-path interference appears before the main path.

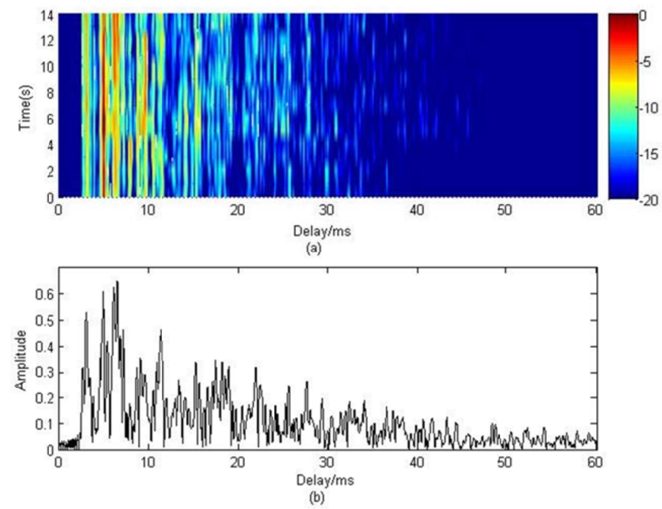

Fig. 5. Lake experiment channel structure

Table 1. Receiver Parameters

Parameters	Description	Values
f_s	Sampling frequency	36 kHz
B	Bandwidth	4 kHz
T_c	Symbol duration	0.5 ms
N	Block size	512
P	PN length	128
M	Channel numbers	6
K	Oversampping rate	2
N_p	The training symbol length	300
L_p	Length of the impulse response estimate	42
N_f	Feedforward filter order	8
N_b	Backward filter order	2
K_{f_1}	Proportional tracking constants in PLL	0.001
K_{f_2}	Intergral tracking constants in PLL	0.0001
λ	RLS forgetting factor in DFE	0.999

The receiver parameters are shown in Table 1. The PN length equals 128 with a corresponding duration of 64 ms, which is larger than the maximum multi-path spread. Each data block contains 512 symbols (FFT length is 512), including 384 useful data symbols, and 60 blocks in total. The symbol duration is 0.5 ms. The total length of the packet is about 15 s. BPSK and QPSK modulation are applied with useful data-rate around 1500 bit/s and 3000 bit/s, and the useful data are 23040 bits and 46080 bits respectively.Communications performance is quantified in terms of BER and output SNR. The output SNR is defined as [2]

$$\mathrm{SNR_o} = 10\log\frac{E\{|z(n)|^2\}}{(1/L)\sum_1^N |z(n) - \hat{z}(n)|^2} \tag{9}$$

with L is the number of data symbols.

The results are based on the receiver parameters listed in Table 1 if not otherwise mentioned. The least square channel estimation and FDE are operated individually in each block. The numbers of feedforward and feedback filter taps in time-frequency domain equalizer are 8 and 2 respectively, while the numbers of feedforward and feedback filter taps in multi-channel time-domain DFE are 40 and 40 respectively. In multi-channel time-domain equalizer, a second-order DPLL is embedded to track carrier phase. For HTDFE and the proposed method, there is no DPLL in the additional time-domain equalizer, since the phase rotation is compensated in FDE [14]. Table 2 illustrates the output SNR and BER improvements using different channel combination.

Results from Table 2 are displayed in Figs.6 and 7. The figures show the scatter plots of above schemes for SC-FDE with BPSK and QPSK modulation from top to bottom and left to right:(a) normal multi-channel frequency domain equalizer (FDE), (b) hybrid time-frequency domain equalizer (HTFDE), (c) proposed method and (d) multi-channel time-domain equalizer (MTDE). For BPSK modulation, the output SNRs are 7.89 dB, 8.73 dB, 13.38 dB, 15.47 dB and the BERs are 1.9×10^{-3}, 5.89×10^{-4}, 0 and 3.27×10^{-5} by the above methods respectively. For QPSK modulation, the output SNRs are 8.83 dB, 10.24 dB, 13.34 dB, 14.43 dB and the BERs are 8.9×10^{-3}, 1.1×10^{-3}, 0 and 3.35×10^{-5} respectively. From the results, we can find that the proposed method can improve the normal multi-channel frequency domain equalization around 4.5-5.5 dB in terms of output SNR. The output SNR of MTDE is higher, because it has a longer feedforward and feedback filter. It's computation is quite high for six-channel receiver. For different modulations, the first line shows the output SNRs and the second line shows the BERs. The MTDE is quite sensitive to the DPLL parameters. As shown in Fig.6 and 7, slight phase rotations are observed in MTDE method. The parameters of the DPLL $K_{f_1} = 0.001$ and $K_{f_2} = 0.0001$ may be not optimal for this real data.

Table 2. SNR and BER performance of different equalizers

Mod.	FDE	HTFDE	Proposed	MTDE
BPSK	7.89	8.73	13.38	15.47
	1.9×10^{-3}	5.89×10^{-4}	0	3.27×10^{-5}
QPSK	8.83	10.24	13.34	14.43
	8.9×10^{-3}	1.1×10^{-3}	0	3.35×10^{-5}

5. CONCLUSION

A novel multi-channel time-frequency domain equalization approach is proposed for PN-based SC-FDE systems over UWA channel. The advantage of the proposed algorithm is that it can remove the residual ISI and hence significantly improve the performance of multi-channel single carrier system. Moreover, the computational complexity is also greatly reduced compared with the existing multi-channel time-domain DFE methods. Lake experiment results verify the superior performance of the proposed algorithm and show it is a promising method for single carrier high-rate UWA communication. Future work will analyze its performances when the number of receiver channels is limited.

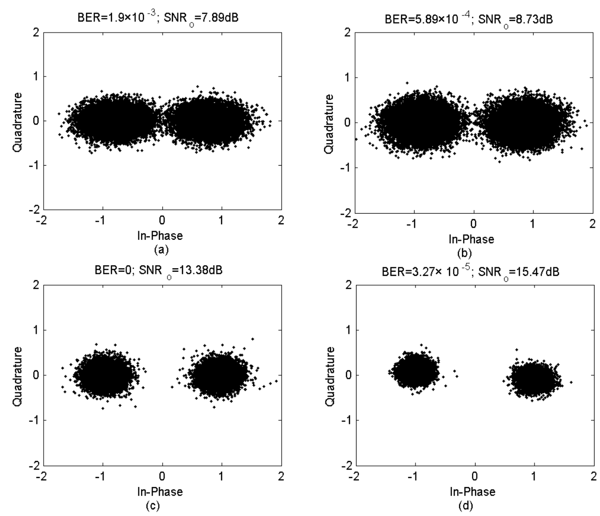

Fig. 6. Results for BPSK modulation in the lake experiment

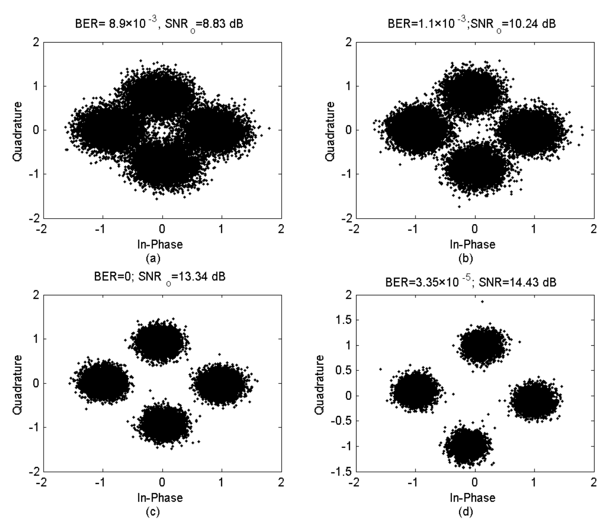

Fig. 7. Results for QPSK modulation in the lake experiment

References

[1] D. B. Kilfoyle and A. B. Baggeroer, “The state of the art in underwater acoustic telemetry,” *IEEE J. Ocean. Eng.*, vol. 25, no. 1, pp. 4-27, Jan. 2000.

[2] M. Stojanovic, J. A. Catipovic and J. G. Proakis, “Phase-coherent digital communications for underwater acoustic channels,” *IEEE J. Ocean. Eng.*, vol. 19, no. 1, pp. 100-111, Jan. 1994.

[3] M. Stojanovic, “Efficient processing of acoustic signals for high rate information transmission over sparse underwater channels,” *Elsevier Journal on Physical Communication*, pp. 146-161, Jul. 2008.

[4] G. F. Edelmann, H. C. Song, S. Kim, w. s. Hodgkiss, W. A. Kuperman and T. Akal, “Underwater acoustic communications using time reversal,” *IEEE J. Ocean. Eng.*, vol. 30, no. 4, pp. 852-864, Oct. 2005.

[5] T. C. Yang, “Correlation-based decision-eeedback equalizer for underwater acoustic communications,” *IEEE J. Ocean. Eng.*, vol. 30, no. 4, pp. 865-880, Oct. 2005.

[6] Yang T C, “A study of spatial processing gain in underwater acoustic communications,” *IEEE J. Ocean. Eng.*, vol. 32, no. 3, pp. 689-709, July 2007.

[7] B. Li, S. Zhou, M. Stojanovic, L. Freitag and P. Willett, “Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts,” *IEEE J. Ocean. Eng.*, vol. 33, no. 2, pp. 198-209, Apr. 2008.

[8] M. Stojanovic, “OFDM for underwater acoustic communications: adaptive synchronization and sparse channel estimation,” in *Proc. IEEE ICASSP* , Las Vegas, Apr. 2008.

[9] S. J. Hwang and P. Schniter, “Efficient multicarrier communication for highly spread underwater acoustic channels,” *IEEE Journal on Selected Areas in Communication*, vol. 26, no. 9, pp. 1674-1683, Dec. 2008.

[10] T. Kang and A. I. Iltis, “Iterative Carrier Frequency Offset and Channel Estimation for Underwater Acoustic OFDM Systems,” *IEEE Journal on Selected Areas in Communication*, vol. 26, no. 9, pp. 1650-1661, Dec.2008.

[11] D. Falconer, S. L. Ariyavisitakul, A. Benyamin-Seeyar and B. Eidson, “Frequency domain equalization for single-carrier broadband wireless systems,” *IEEE Communications Magazine*, vol. 40, no. 4, pp. 58-66, Apr. 2002.

[12] Z. D. Wang, X. L. Ma, and G. B. Giannakis, “OFDM or single-carrier block transmission,” *IEEE Tran. Communication*, vol. 52, no. 3, pp. 380-394, Mar. 2004.

[13] S. L. Zhou and G. B. Giannakis, “Single-carrier space-time block-coded transmissions over frequency-selective fading channels,” *IEEE Tran. Information Theory*, vol. 49, no. 1, pp. 164-179, Jan. 2003.

[14] C. He, J. Huang, Q. Zhang and X. Shen, “Single carrier frequency domain equalizer for underwater wireless Communication,” in *Proc. IEEE Mobile Computing and Communication 2009 Conf.*, KunMing, China, Jan. 2009.

[15] Y. R. Zheng, C. Xiao, T. C. Yang and W. B. Yang, “Frequency-domain channel estimation and equalization for shallow-water acoustic communications,” in *Elsevier Journal on Physical Communication*, pp. 48-63, Mar. 2008.

[16] C. B. He, J. G. Huang, Q. F. Zhang, “Hybrid Time-Frequency Domain Equalization for Single-Carrier Underwater Acoustic Communications” *WUWNet’12*, Nov.5-6, 2012, Los Angeles, California, USA.

[17] M. Xia, D. Rouseff, J. A. Ritcey, and X. Zou, Underwater Acoustic Communication in a Highly Refractive Environment Using SCCFDE. *IEEE J. Ocean. Eng.*, vol.39,no.3,pp.491-499, 2014.