On the Practical Aspects of Joint Passive Phase Conjugation and Equalization Underwater Communication Systems

Samaneh Moezzi and Azizollah Jamshidi
School of Electrical and Computer Engineering
Shiraz University, Shiraz, Iran, Tel-Fax: +98-71-32351010
Corresponding author: Azizollah Jamshidi

***Abstract*- Underwater acoustic communication systems suffer from the channel impairments which results in time spreading of the transmitted signal. In underwater environment, multiple replicas of the transmitted signal are received at the receiver through different paths, which causes significant Inter-Symbol Interference (ISI). Decision Feedback Equalizers (DFE) was utilized to overcome this type of interference in digital communications so many years ago. However, because of the complexity of adaptive equalizers, Passive Phase Conjugation (PPC) was widely exploited in underwater communications in the recent years. Because of the poor performance of the PPC method, adaptive equalizers are jointed to improve the PPC performance. In this paper, experimental results conducted in Shiraz Electronic Industry's pool have been reported. Three different approaches are compared in terms of Symbol Error Rate (SER) versus the number of used channels at the pool: 1) the PPC method; 2) DFE equalizer for only a single channel; 3) the PPC method combined with the adaptive DFE. The experimental results showed that the third approach outperforms the others while a simpler receiver can be obtained.**

***Key words*-** underwater communications, experimental test, passive phase conjugation, adaptive equalizers, decision feedback equalizer.

I. INTRODUCTION

The underwater acoustic channel is known by significant time varying multipath. In underwater environment, especially shallow water, multiple replicas of the transmitted signal are received at different times due to reflections between sea bottom and surface [1]. This multipath causes ISI which might cause bit errors. So, some equalization process is needed to overcome the channel effects and detect the original signal [2]. Therefore, channel equalizers particularly Decision Feedback Equalizers (DFE), jointly with a Phase-Locked Loop (PLL) have been widely utilized to remove the interference [1]. However, high performance of these methods requires high computational complexity. Moreover, as shown in [3] such equalizers provide suboptimal performance. Energy focusing techniques are implemented to use the ocean in order to focus the transmitted signal energy [4]. In time reversal (TR), a short pulse transmitted by a source through a dispersive medium is received by an array, and

Manuscript Received 05-Aug.-2013 and revised 14-Oct.-2013,
Accepted on 21- Nov.-2013
ISSN 2322-3936

then time reversed, energy normalized, and retransmitted (mathematically or physically) through the same channel. If the scattering channel is reciprocal and rich in multipath, the retransmitted signal refocuses on the original source [3, 4]. The spatial and temporal focusing properties of TR are exploited in underwater communications to detect the transmitted signal [5]-[8]. The procedure is accomplished by sending a probe pulse from a source. The replicas of the transmitted pulse are received by an array of source/receivers, time reversed and retransmitted into the ocean. Based on the reciprocity property of the sound wave, the paths refocus at the source and the original signal can be obtained. In underwater communications, Passive Time Reversal (PTR) is used instead of aforementioned active time reversal, where the array is considered only at the receiver side. This procedure is called Passive Phase Conjugation (PPC) in the literature. PPC uses a probe signal transmitted prior to the data signal to estimate the channel impulse responses [9]-[16]. At first, the probe signal is transmitted, after guard duration, and waiting for the multipath to be cleared; the data signal is then transmitted into the ocean. The time-reversed (phase conjugated) copy of the probe signal will be convolved with the received probe and data signals at each receiver separately. This is equivalent to cross-correlate the received probe and data signals with the replica of the probe signal. Because the probe signal is designed so that its cross-correlation is a Dirac delta function, therefore, first part of the received signal which is based on the transmitted probe signal can give a coarse estimation of the channel impulse responses. On the other hand, based on the theory of signal propagation, one expects that the summation of the auto-correlation of the impulse responses, or Green's function, be a Dirac delta function [3]-[5]. But in real world it is not and the result has many side-lobes. Using an array of receivers, the auto-correlation summed over the array has less side-lobe. Therefore, less interference is affected the data signal. Because of the remaining side-lobes and poor performance of PPC, there is always some residual ISI may cause bit errors [9]. For this reason, DFE is combined with PPC to remove this residual ISI [10]-[16]. By doing this, a better performance and simpler receiver structure than a usual DFE can be obtained. Since the DFE jointed to PPC is much popular than DFE alone.

Some of the previous works have focused on the theoretical investigation of PPC and its combination with DFE equalizers [5, 6, 8, 11]. In some research, only the experimental results of the PPC or DFE alone have been explored [17]-[19]. In this paper, we have conducted a comprehensive experimental test to investigate and compare the performance of the ISI mitigating schemes in 1) the PPC method; 2) DFE equalizer for only a single channel; 3) the PPC method combined with multichannel or single channel adaptive DFE equalizer. The experimental results showed that 1) the third approach outperforms the others while a simpler receiver with a few taps in DFE equalizer can be obtained; 2) in some cases of the investigated channels, the multichannel PPC approach has a good performance for underwater data communications, 3) the PPC and PPC-DFE methods are sensitive to the data processing window, i.e., the number of samples participates in the PPC processing procedure.

The results showed that there is an optimum window length to achieve a better performance in the PPC-DEF approach. 4) Using the coarse channel estimation provided by the probe signal will not degrade the PPC performance considerably.

The remaining of the paper is organized as follows. We begin in section II by reviewing the background theory of PPC process briefly. This section explains how we use PPC to remove ISI from the data signal. Then, the decision feedback equalizer and the combination of DFE and PPC is briefly presented in this section, and in section III the software defined structure of the transceiver has been described. In section IV, experimental results conducted in Sa-Shiraz Electronic Industry's pool have been reported. Finally, section V concludes the paper.

II. JOINT PASSIVE PHASE CONJUGATION AND DFE EQUALIZATION

In this section, first, we will deal with the Passive Phase Conjugation concept and then we will describe the PPC-DFE equalization technique.

Passive Phase Conjugation process begins with sending channel probe signal, $p(t)$, into the ocean waveguide. Assuming noiseless environment the replica, with N elements at the receiver, $p_{r_j}(t) = p(t) * h_j(t)$ (*j=1, 2, …, N*) is received at the j th element, where $h_j(t)$ is the j th channel impulse response and * denotes the convolution operation. After guard duration, the data signal $s(t)$ is then transmitted. By neglecting the noise term in the receiver, $v_j(t)$ is received at the j th array element as [4]

$$v_j(t) = s(t) * h_j(t), \quad j = 1,2,...,N \tag{1}$$

Time reversing $p(t)$ and convolving with $p_{r_j}(t)$, j th channel impulse response is approximately obtained as follows [4]

$$h_j(t) = p_{r_j}(t) * p(-t), \quad j = 1,2,...,N \tag{2}$$

Note that the probe signal autocorrelation is nearly equal to the Dirac delta function [20]. Using time reversal matched filter and summing over the array we obtain [3]-[5]

$$y(t) = \sum_{j=1}^{N} v_j(t) * h_j(-t) = \\ s(t) * \sum_{j=1}^{N} \left(h_j(t) * h_j(-t) \right) = s(t) * q(t) \tag{3}$$

Where j is the sample index, N shows the number of channels and

$$q(t) = \sum_{j=1}^{N} \left(h_j(t) * h_j(-t) \right) \tag{4}$$

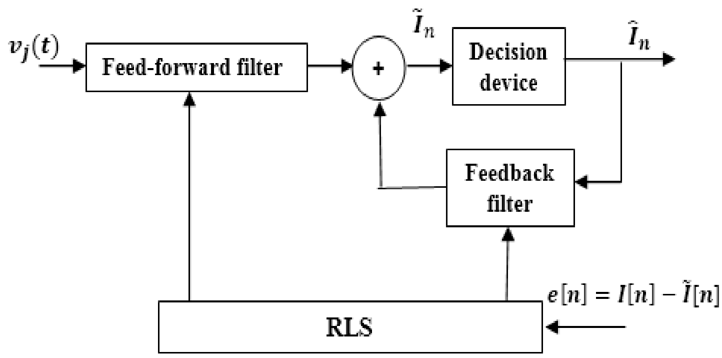

Fig. 1. Decision Feedback Equalization with RLS algorithm to estimate the filter coefficients

is the auto-correlation function of the channel impulse response, which is expected to be a Dirac delta function where number of arrays approaches to infinity [5, 6]. In practical situations, it behaves like a sinc function which has some side-lobes. As shown in [3], increasing the number of array elements (using a large aperture) the side-lobes are decreased and better Dirac delta function approximation can be achieved.

Referring to equation (3), the probe signal $p(t)$ is a known signal and $q(t)$ is approximately a Dirac delta function. Therefore, $s(t)$ can be easily detected.

Decision Feedback Equalizer uses Minimum Mean Square Error (MMSE) criterion to estimate coefficient taps in order to overcome the channel effects. The MMSE solution is obtained by minimizing the Mean Square Error (MSE) between estimated and true symbols, i.e. $J = E\{|I_k - \hat{I}_k|^2\}$. Where $E\{.\}$ denotes the expected value, I_k and $\hat{I}_k$ denote estimated and true symbols, respectively.

Fig. 1 shows a DFE equalizer uses RLS algorithm to estimate the tap coefficients. Note that $\tilde{I}_k$ is the sufficient statistic for deciding the true transmitted symbol I_k.

Fig. 2 shows the jointed DFE and PPC, where we can use the advantage of applying an array of receivers. Because of using a large aperture, it is expected to capture the more signal energy at the receiver.

In the practical results, we will see that using the DFE after the PPC processor is much simpler than the DFE alone. In fact, it needs less number of tap coefficients in the feed-forward and the feedback filters.

III. Software Defined Radio Structure of the Transmitter and the Receiver

The tremendous need and demand for wireless communication in underwater environment has led to the evolution of Software defined Radio (SDR). SDR techniques have been envisioned as a

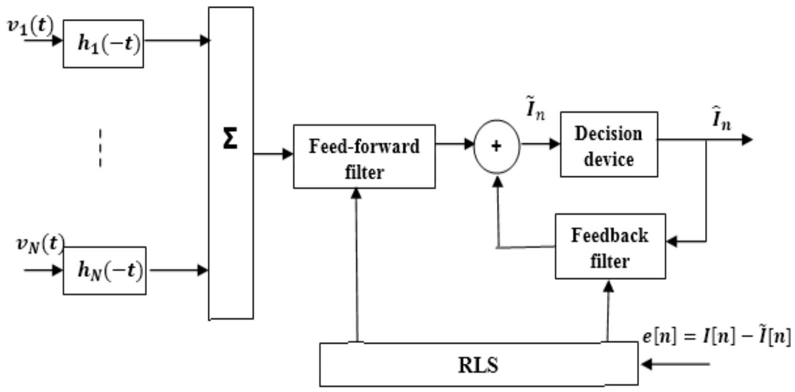

Fig. 2. The combination of DFE and PPC

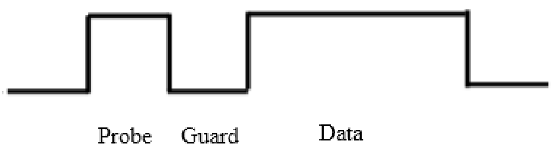

Fig. 3. General form of the transmitted frames

powerful tool for designing cognitive, intelligently adaptive links in underwater acoustic communication using the usual hardware such as DSP processors, FPGA and even a usual PC and lap top with usual sound cards. In this section, we briefly describe the transmitter and receiver structures. This transceiver has been implemented digitally in Matlab Simulink software. Note that some of the processing units such as the PPC processor and the final DFE-PPC combined scheme have been done off-line by gathering the required data using the SDR transceiver structure.

In the transmitter side, Quadrature Phase Shift Keying (QPSK) modulated signals are considered in all of the experiments. Also, sampling frequency and the carrier frequency are set to $f_s = 32KHz$ and $f_c = 8KHz$, respectively. Note that the selection of the mentioned sampling rate can reduce the complexity of the software implementation of the proposed transceiver in its modulation and demodulation blocks. In fact, multiplying by cos(2πfc/fs) or sin(2πfc/fs) in the base band modulator or demodulator is interestingly reduced to multiplying only by 0 and ±1.

The general shape of the transmitted frames is shown in Fig. 3. The probe signal is a 64 ms, 5.5–10.5 kHz linear frequency modulation (LFM) chirp signal consisted of 2048 samples. Before sending the data signal, guard duration with the length of 50 ms is sent, waiting for multipath to be cleared. The data signal duration is 546 ms including 2500 random QPSK symbols shaped with root raised cosine (RRC) filter for each sample. In fact, each QPSK sample is shaped with a 7 samples RRC filter.

Fig. 4 shows an example of transmitted signal. In this figure three blocks of transmitted signal are shown.

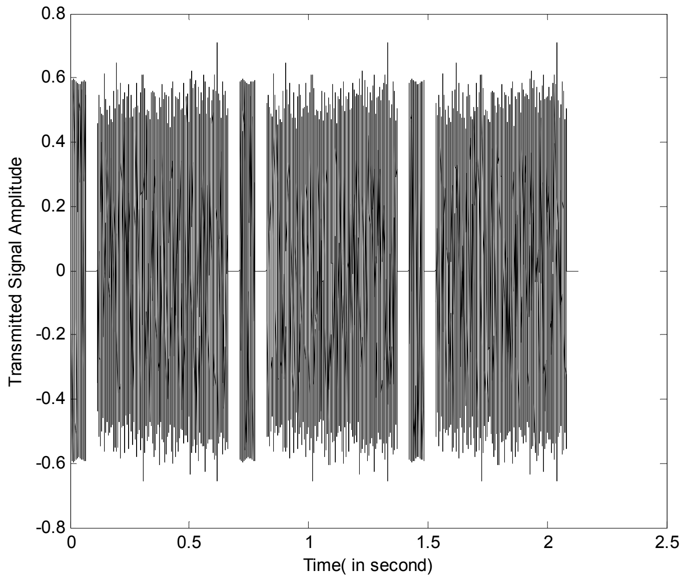

Fig. 4. An example of the transmitted signal

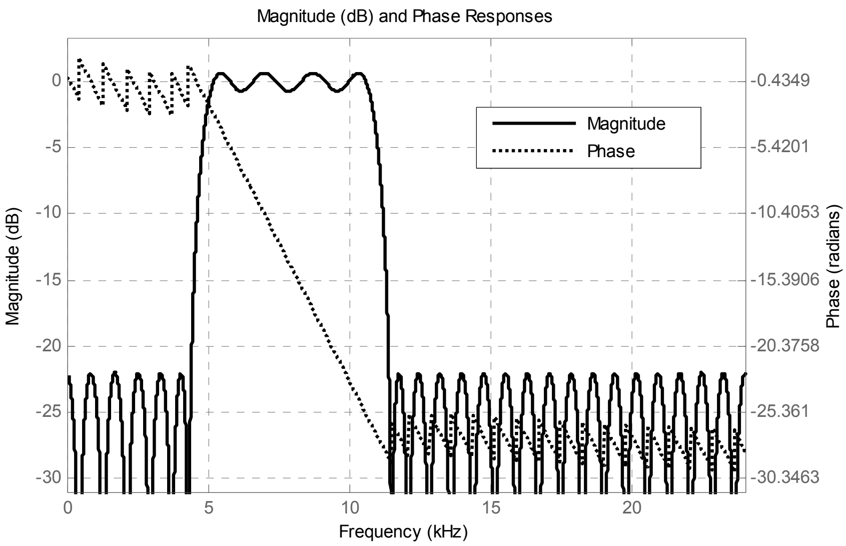

Fig. 5. Frequency response of the band-pass filter used in the receiver

Unfortunately, the used sound cards of the lap tops cannot sample at the desired 32 kHz rate. Therefore, both in the transmitter side and the receiver side we change digitally the rate of sampling to 48 kHz suitable for the sound cards. To do that, in the transmitter side we digitally up-sample the prepared signal before D/A operation and in the receiver side, we digitally down-sample the received signals to the desired sampling rate 32 kHz after A/D procedure. A band pass filter with order 64 is used to filter the received signal. In Fig. 5, you can see the depicted frequency response of the considered band pass filter. Moreover, Fig. 6 shows the filtered signal at the receiver side.

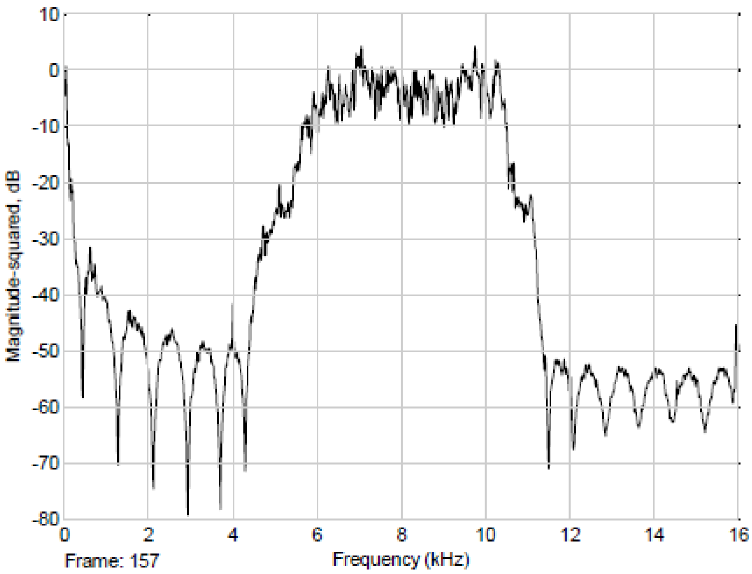

Fig. 6. Band-pass filter output at the receiver side

After demodulation and filtering the signal by RRC matched filter the raw data signal is achieved and equalization operation or PPC processing should be applied on the gathered data. Synchronization and identifying the beginning of a data frame is done by using the probe signal. Since the auto-correlation of an LFM chirp function is a nearly Dirac delta function, the received probe signal is filtered by LFM chirp matched filter to obtain the beginning of a frame. Besides the synchronization, the probe signal can be used to phase conjugating process in the PPC method. Surprisingly, using the probe signal, we can obtain a coarse estimation of the channel impulse response as we mentioned in equation (2). This coarse estimation has been used in the PPC processor. The probe signal window length implemented here is 15 ms and 6 channels are used. 2500 QPSK symbols are received and 200 symbols are used as training sequence in the DFE equalizer.

IV. EXPERIMENTAL RESULTS AND COMPARISONS

In this section, experimental measurements have been discussed. Three sets of data packets were collected at Sa-Shiraz pool. This pool has 3 meters depth, 3 meters width and 4 meters length. The transmitter was fixed at the middle of the pool and the receiver array with 6 elements was putted in different places in the pool. The distance between the elements is about 30 centimeters. In the 6 elements case, we considered a horizontal array setup with 30 centimeters distance between two adjacent elements. For the 16 elements case, we configured a 4×4 square array placed near the wall of the pool such that the square array center was coincided on the center of the wall.

Three data sets have been collected in the pool and both equalization and PPC processes and the combination of them have been applied offline. The results in terms of the symbol error rate versus the number of channels are represented in this paper.

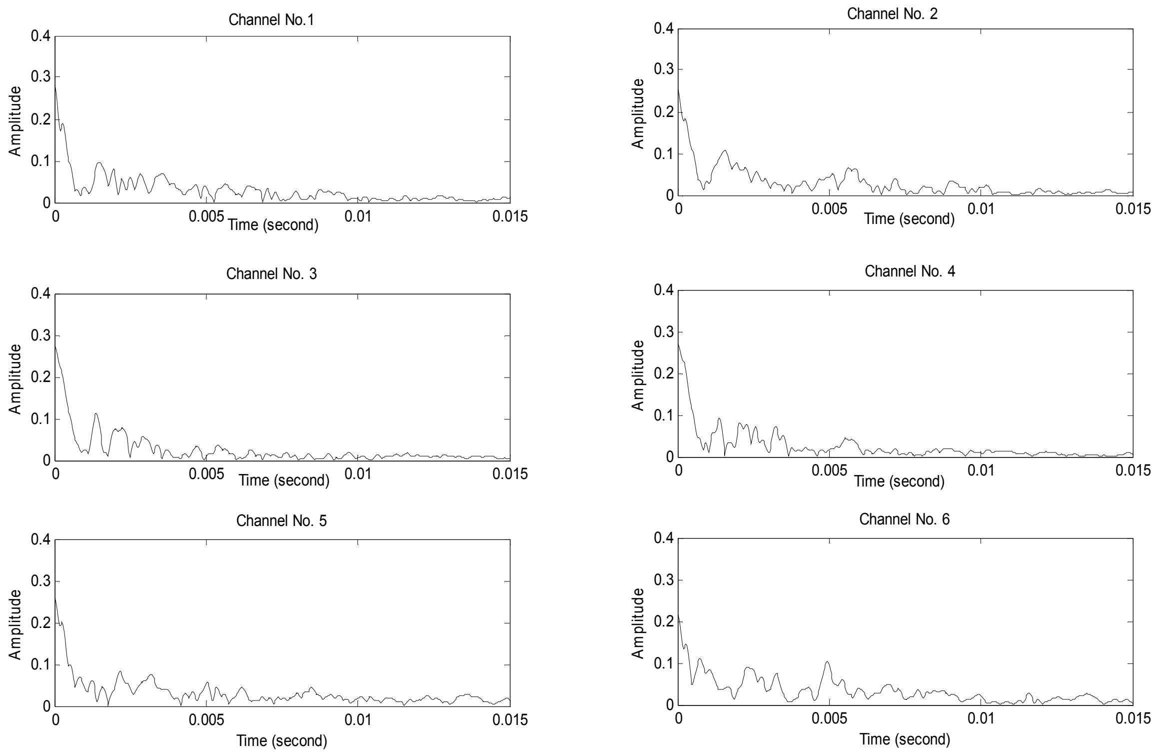

Fig. 7. The impulse response of 6 used channels in data set A

In practice, the received probe signal must be captured in a time window and correlating with the transmitted probe-signal can give a coarse estimation of the channel impulse response. Note that the probe signal is known at the receiver side. Therefore, the output signal to noise ratio (SNR) and the detection rate of passive time reversal will strongly depend on the duration of the window. In fact, a short time window fails to include all multi-paths and therefore result in an imperfect focusing. At the other hand, a too long time window will introduce additional noise in the passive time reversal system. In this paper, we consider a raw estimation of the optimum window length.

As we mentioned before at section IV, the probe signal window length implemented here is 15 ms. In the next subsections, we investigate the practical results of the gathered data.

A. Data Set A

Fig. 7 shows the impulse response of the channels for data set A. Since we placed the transducer in different positions, different impulse responses are achieved and because of the small dimension pool and very shallow water, numerous multipath can be observed in the measured channel responses. For example, channel 6 shows one of the worst multipath affected situations and channel 4 has little value for the secondary tap than the others. So less interference is affected the data signal in this channel.

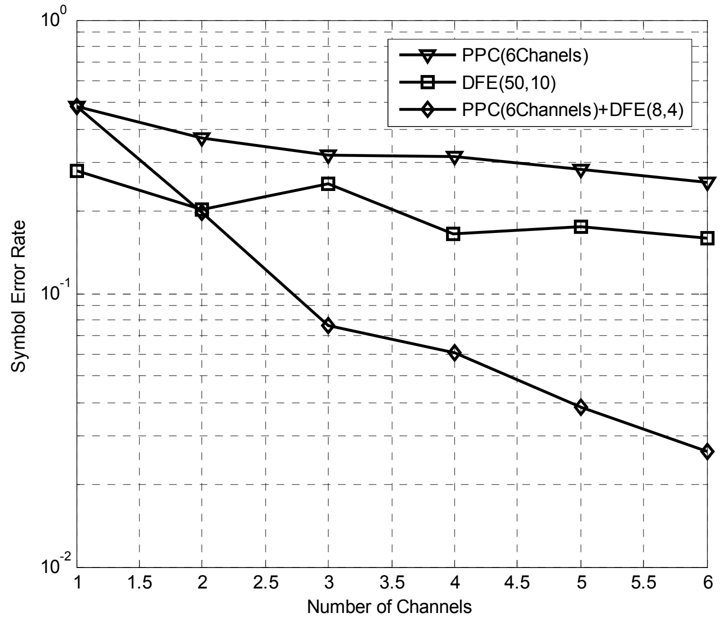

Fig. 8. The symbol error rate versus the number of channels for data set A. PPC, DFE, and PPC-DFE have been compared here.

For signal processing three equalization approaches are utilized: 1) PPC alone, 2) DFE alone for a single channel with 50 and 10 feed-forward and feedback tap coefficients, respectively, and 3) jointed PPC and DFE with 8 feed-forward and 4 feedback tap coefficients. The symbol error rate is shown in Fig. 8. It is clear that DFE alone is incapable of equalizing and achieves high symbol error rate is this scenario. By using only PPC processing, increasing the number of channels results in the decreased symbol error rate, but it is not better than DFE alone for the combination of 6 channels. It is clear that PPC has very poor performance here. By combining DFE and PPC, the symbol error rate is reduced and it will be less than 0.0261 by using the 6 channels. Note that a simpler DFE is needed by the combination of PPC and DFE, so a lower number of training symbols is required. For example, in the PPC-DFE processing case, we used 50 training symbols instead of 200 in the DFE alone equalizing case. Note that in all of the DFE equalizers we have used RLS training algorithm with forgetting factor .995.

A. Data Set B

The worse condition is considered here and the window length has been increased to 50ms. In this experiment, we consider an array with 16 elements in a 4×4 square configuration with 30 centimeters displacement between every two elements. Fig. 9 shows the four typical channels estimated by the probe signal in this scenario. Assuming the mentioned window length, more secondary taps are considered in channel responses. Fig. 10 shows the symbol error rate versus the number of channels for data set B. Here, PPC outperforms DFE, because PPC is extremely sensitive to array shape or the

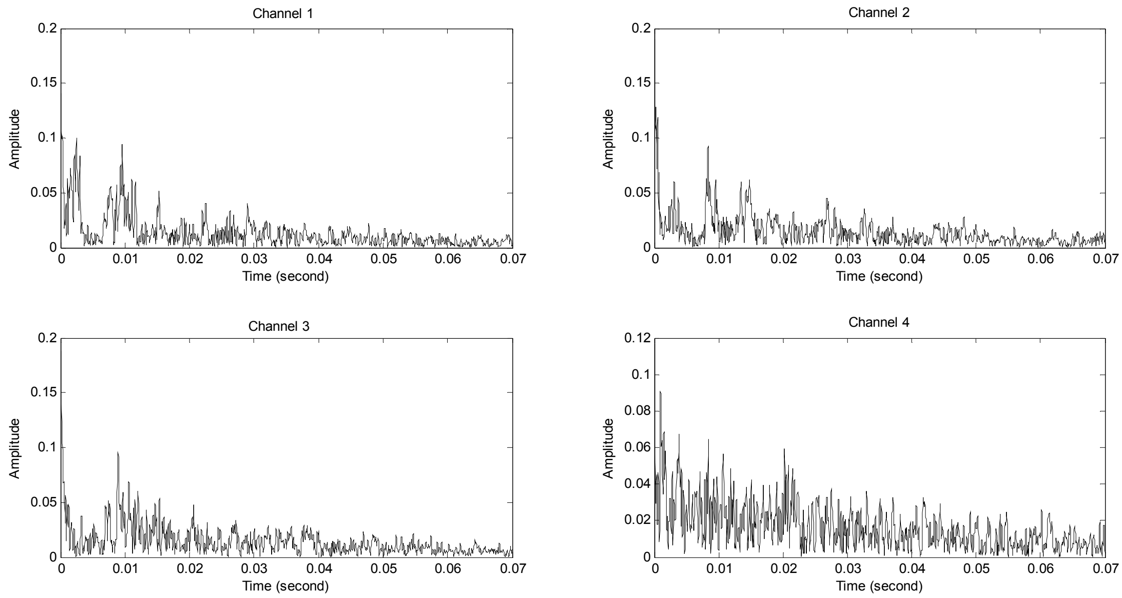

Fig. 9. The impulse response of 4 channels for data set B

places we put the receiver array. Note that PPC still has bad performance and the symbol error rate obtained by this processing method is not lower than 0.3. The jointed PPC-DFE outperforms the other two methods for any number of channels. As we see from Fig. 10, by using 13 channels the error would be lower than 10^{-2}.

Previously, stated that the probe processing window problem calls for an optimization [21]. In this paper, we consider real data from SA-Shiraz trial to obtain the optimum window length in the experimental results with 6 and 16 channels. In the simulations, we consider data set A (with 6 channels) and data set B (with 16 channels). To determine the suitable window length, in Fig. 1, the symbol error rate versus the window length for PPC-DFE processing is shown for Data set A and B. It is seen in Fig. 11, when the window length is too small or too large, the error will be increased. At the range of 20-70 ms, the symbol error rate tends to its lowest value. So, window length 20-70 ms is nearly optimum in our experiments. Since the guard duration in our experiments is set to 50 ms, the window length cannot be chosen more than that.

A. Data Set C

In this experiment, we consider the array of 16 elements in a different location. The symbol error rate is shown in Fig. 12. For data set C, PPC shows pretty good performance. But, DFE is still not capable of equalizing. Lower error can be achieved by DFE alone, which is 0.12 for 11 channels, while, PPC shows less error for any number of channels. Using more than 6 channels, the symbol error rate would be less than 10^{-1} for PPC process and using DFE after PPC by using more than 12 channels the error rate decreases to 10^{-3}. Note that because of considering 2500 data symbols in each frame, and

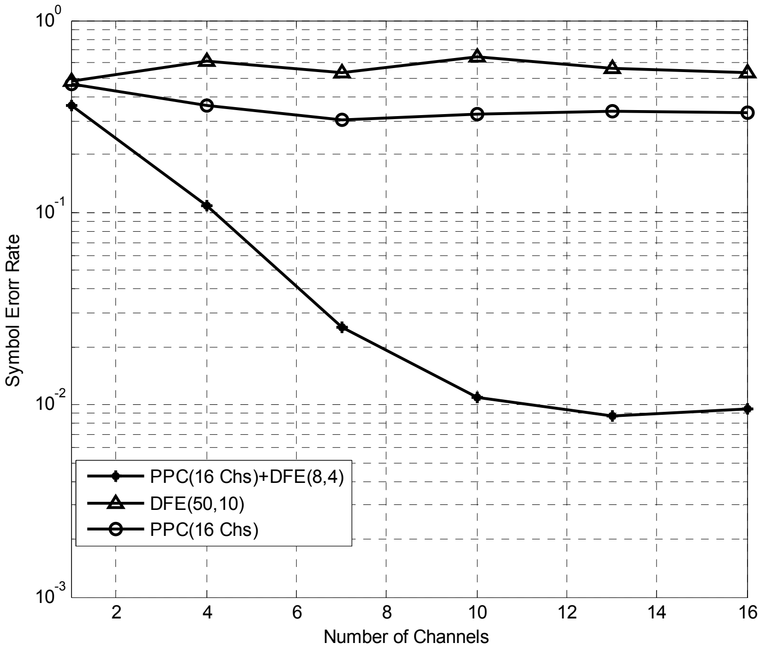

Fig. 10. Symbol error rate versus number of channels for data set B

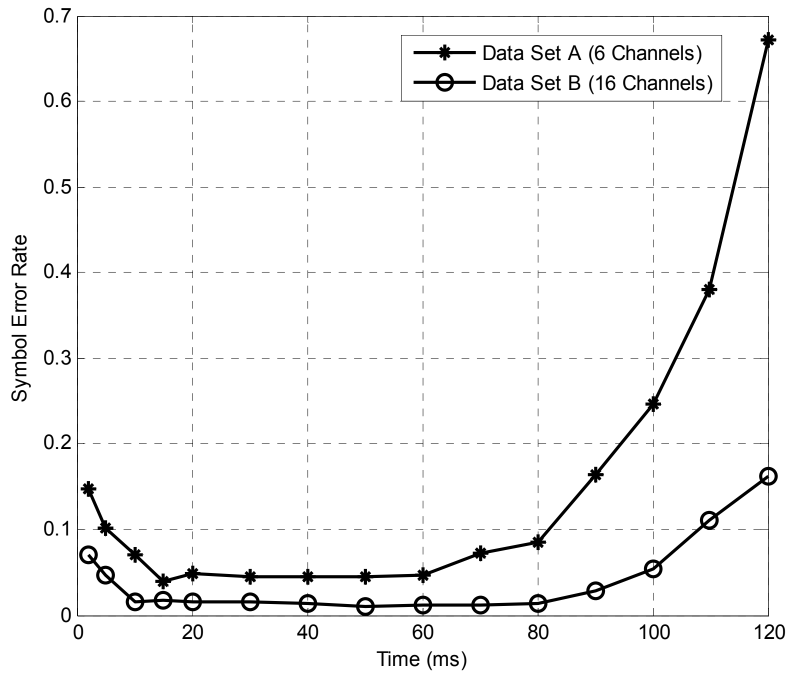

Fig. 11. Symbol error rate versus the window length in PPC-DFE processing for Data set A and B

processing of only one frame to evaluating the symbol error rate, the symbol error rate for more than 12 channels combining will be zero in the third experiment. In fact, no errors have been occurred in the received frames. It is reasonable to say that the symbol error rate is lower than 4×10^{-4}.

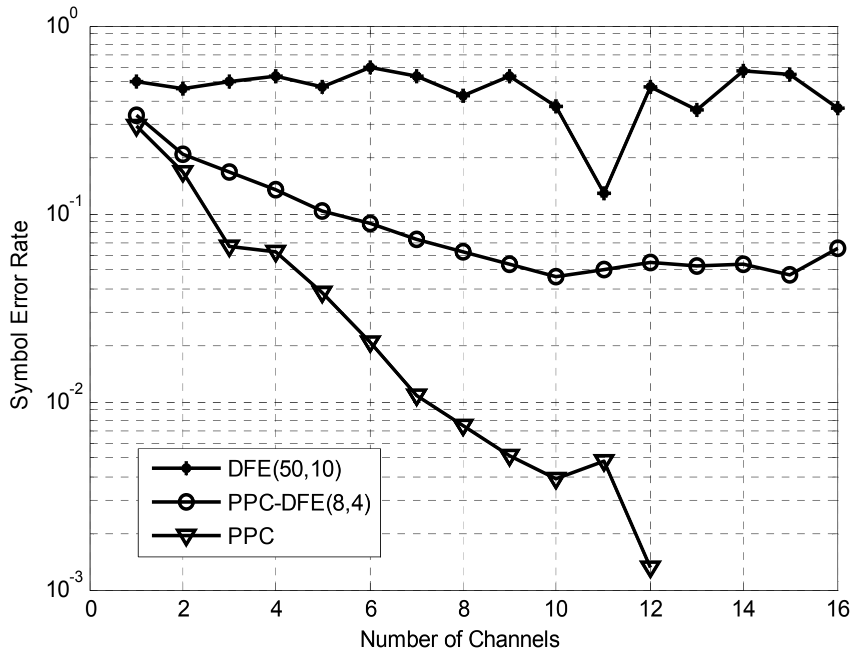

Fig. 12. The symbol error rate versus number of channels for data set C.
PPC and DFE and PPC-DFE are compared here.

V. CONCLUSION

Passive phase conjugation is a simple approach to remove interference from the signal in the ISI channels. Here PPC, DFE and PPC-DFE are used to equalize for three data sets collected in Sa-Shiraz pool.

In all of them the combination of DFE and PPC outperforms using them alone. By using PPC process before DFE a simpler equalizer is achieved. In the experimental results, it was shown that a DFE with 50 and 10 tap coefficients was incapable of equalization and noticeable error happened in data signal. While using PPC at first, a DFE with 8 and 4 tap coefficients was enough to reduce symbol error rate significantly. The other important point is the window length which should be chosen carefully. Too small or too large window length can cause errors. PPC is the most sensitive approach to array shape, inasmuch as in three data sets very different results are achieved for PPC performance. In some situations it could perform better than DFE and in some situations it has the poorest performance.

ACKNOWLEDGMENT

The authors like to acknowledge Shiraz Electronic Industry (Sa-Shiraz) for supporting the experimental tests at the Sa-Shiraz acoustic communication test pool.

REFERENCES

[1] 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.

[2] M. A. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," J. Mar. Technol. Soc., vol. 42, no. 1, pp: 103–116, 2008.

[3] D. Rouseff, J. A. Flynn, J. A. Ritcey, W. L. J. Fox, "Acoustic Communication Using Time-Reversal Signal Processing: Spatial and Frequency Diversity", AIP conference, 2004.

[4] Zhang, Guosong; Dong, Hefeng. "Joint passive-phase conjugation with adaptive multichannel combining for coherent underwater acoustic communications", Applied Acoustics, Vol. 73, Issue 4, pp: 433-439, 2012.

[5] G. Edelmann, T. Akal, W. Hodgkiss, S. Kim, W. Kuperman, H. Song, and T. Akal, "An initial demonstration of underwater acoustic communication using time reversal mirror," IEEE J. Ocean. Eng. 27, pp: 602–609, 2002.

[6] T. Yang, "Temporal resolutions of time-reversed and passive-phase conjugation for underwater acoustic communications," IEEE J. Ocean. Eng. 28, pp: 229–245, 2003.

[7] Zhang, G., J.M. Hovem, H. Dong, and L. Liu, Coherent underwater communication using passive time reversal over multipath channels, Applied Acoustics, Vol. 72, No. 7, pp: 412-419, 2011.

[8] M. Stojanovic. "Retro focusing techniques for high rate acoustic communications", Journal of the Acoustical Society of America, Vol. 117, No. 3, pp: 1173–1185, March 2005.

[9] G. F. Edelmann, H. C. Song, S. Kim, W. S. Hodgkiss, W. A. Kuperman, T. Akal, 'Underwater Acoustic Communications Using Time Reversal', IEEE J. Ocean. Eng., Vol. 30, NO. 4, pp: 852-864, OCT. 2005.

[10] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, M. Stevenson and T. Akal. "Improvement of time-reversal communications using adaptive channel equalizers", IEEE J. Ocean, Eng., Vol. 31, No. 2, pp: 487–496, April 2006.

[11] J. Gomes, A. Silva, S. Jesus, "Joint passive time reversal and multichannel equalization for underwater communications", OCEANS'06 - Boston, USA, Sept. 2006

[12] H. C. Song, A. Dotan, "Comments on "Retro focusing techniques for high rate acoustic communication"[J. Acoust. Soc. Am., 117, 1173 –1185] (L)," Journal of the Acoustical Society of America, Vol. 123 , No. 3, pp:2136-2138, 2008.

[13] Song, Hee C., W. S. Hodgkiss, W. A. Kuperman, W. J. Higley, K. Raghukumar, T. Akal, and M. Stevenson. "Spatial diversity in passive time reversal communications", Journal of the Acoustical Society of America, Vol. 120, no. 4 (2006) pp: 2067-2076.

[14] H. C. Song, W. S. Hodgkiss, S. Kim, "Performance prediction of passive time reversal communications", Journal of the Acoustical Society of America, Vol. 122, No. 5, November 2007.

[15] J. Gomes, A. silva, S. Jesus, "Adaptive spatial-combining for passive time-reversed communications", Journal of the Acoustical Society of America, Vol. 124, No. 2, pp: 1038–1053, May 2008.

[16] U. Vilaipornsawai, A. J. Silva, S. M. Jesus, "Combined adaptive time reversal and DFE technique for time-varying underwater communications", ECUA Istanbul Conference, 2010.

[17] G. Zhang, H. Dong, "Experimental research on adaptive multichannel equalization for underwater communications", In Instrumentation and Measurement Technology Conference (I2MTC), IEEE, (pp. 1-5), May 2011.

[18] G. Zhang, H. Dong, "Spatial diversity in multichannel processing for underwater acoustic communications", Ocean Engineering, Vol. 38, pp: 1611–1623, 2011.

[19] G. Zhang, J. M. Hovem and H. Dong, "Experimental Assessment of Different Receiver Structures for Underwater Acoustic Communications over Multipath Channels", Sensors Journal, Vol. 12, pp: 2118-2135, 2012.

[20] Song H.C., Hodgkiss W.S., "Efficient use of bandwidth for underwater acoustic communication", Journal of the Acoustical Society of America, Vol. 134, No. 2, pp: 905-908, Aug. 2013.