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

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ABSTRACT:
Underwater acoustic communication is suffered from the channel effects 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 Industrials' pool are 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 adaptive DFE. The experimental results showed that the third approach outperforms the others while a simpler receiver is obtained.
KEYWORDS: underwater communications, experimental test, passive phase conjugation, adaptive equalizers, decision feedback equalizer.

1. 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 Error Rates (BER). So, some equalization processing is needed to overcome the channel effects and detect the original signal without any errors [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 focusing the transmitted signal energy [4]. Time Reversal (TR) and sending back to the transmitter refocuses the signal energy at the source location and thus, the original signal will be obtained [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 at a location. The replicas of the transmitted pulse are received by an array of source/receivers (SRA), time reversed and retransmitted into the ocean. Based on the reciprocity property of the sound wave, the paths refocus at the source location 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, 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 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-lobes. 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 conduct 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 is obtained; 2) in some cases of the investigated underwater channel, the multichannel PPC approach has a good performance for underwater data communications, 3) the PPC method is 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 approach. 4) Using the coarse channel estimation provided by the probe signal has less destroying effect on the PPC performance.

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. In section III, the decision feedback equalizer and the combination of DFE and PPC is briefly presented and in section IV the software defined structure of the transceiver has been described. In section V, experimental results conducted in Sa-Shiraz Electronic Industrial's pool have been reported. Finally, section V concludes the paper.

2. PASSIVE PHASE CONJUGATION THEORY

Passive Phase Conjugation process begins with sending channel probe signal, $p(t)$, into the ocean waveguide. Assuming noiseless environment the replica, $p_{r_j}(t) = p(t) * h_j(t)$ is received at the jth receiver, where $h_j(t)$ is the jth 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 jth array element as

$$v_j(t) = s(t) * h_j(t) \tag{1}$$

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

$$h_j(t) \approx p_{r_j}(t) * p(-t) \tag{2}$$

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

$$y(t) = \sum_{j=1}^{N} y_j(t) * h_j(-t) =$$

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

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

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

is the auto-correlation function of the channel impulse response, which is expected to be a 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 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 delta function. Therefore, $s(t)$ can be easily detected. Figure 1 shows PPC process in frequency domain. As shown in Figure 1, $|H|^2 P^* S$ is received at the receiver and it is clear that, ignoring noise, the signal S is easily detectable. In this figure, P^* denotes the complex conjugate of P.
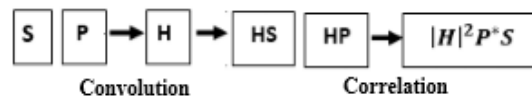

Fig. 1. Passive Phase Conjugation in frequency domain

3. JOINT PASSIVE PHASE CONJUGATION AND DFE EQUALIZATION

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. Figure 2 shows DFE uses RLS algorithm to estimate the tap coefficients.

In order to combine the multiple received signals a pre-processing stage is needed. That means a PLL is needed to estimate channel phase. But, here, the point is that the pre-processing stage is omitted and PLL has not been used. Therefore summing received signals over the array is not useful for DFE alone. Figure 3 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 capturing 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.
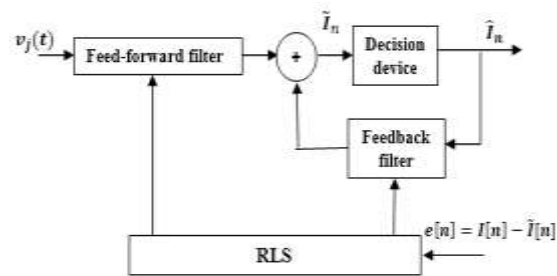

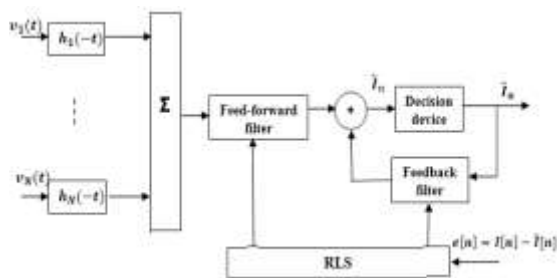Fig. 2. Decision Feedback Equalization with RLS algorithm to estimate the filter coefficients

Fig. 3. The combination of DFE and PPC

4. 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 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 $\cos(2\pi fc/fs)$ or $\sin(2\pi fc/fs)$ 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 Figure 4. 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.

Figure 5 shows an example of transmitted signal. In this figure three blocks of transmitted signal are shown.
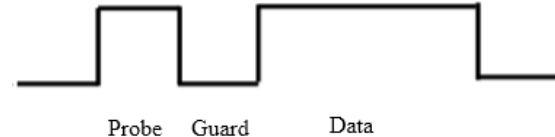

Fig. 4. General form of the transmitted frames

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 the order of 64 is used to filtering the received signal. In Figure 6, you can see the depicted frequency response of the considered band pass filter. Moreover, figure 7 shows the filtered signal 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 delta function, the received probe signal is filtered by LFM chirp matched filter to obtain the begging 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.
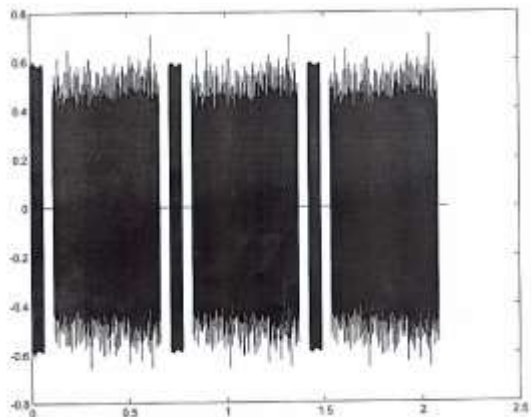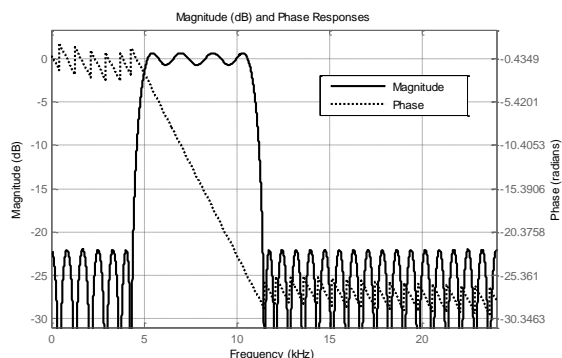

Fig. 5. An example of transmitted signal

Fig. 6. Frequency response of the band-pass filter used in the receiver

5. EXPERIMENTAL RESULTS AND COMPARISONS

In this section, experimental measurements have been discussed. Three sets of data packets are collected at Sa-Shiraz pool. This pool has 3 meters depth, 3 meters width and 4 meters length. The transmitter is fixed at the middle of the pool and the receiver array with 6 elements is putted in different places in the pool. The distance between the elements is about 30 centimeters.

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.

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.
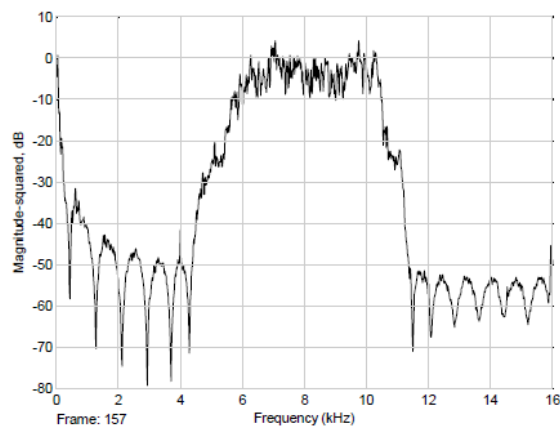

Fig. 7. The band-pass filter output in the receiver side

5.1. Data Set A

Figure 8 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.

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 Figure 9. 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.
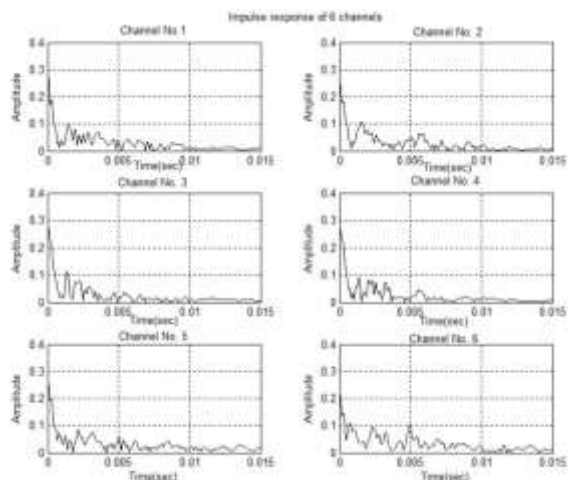

Fig. 8. The impulse response of 6 used channels in data set A

5.2. 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. Figure 10 shows the four typical channels estimated by the probe signal in this scenario.

Assuming this window length, more secondary taps are considered in channel responses. Figure 11 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 places we put the receiver array. Not 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 Figure 11, by using 13 channels the error would be lower than 10^{-2}.
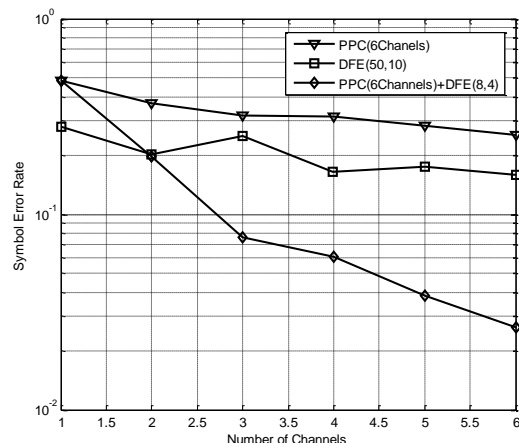

Fig. 9. The symbol error rate versus number of channels for data set A. PPC and DFE and PPC-DFE are compared here.
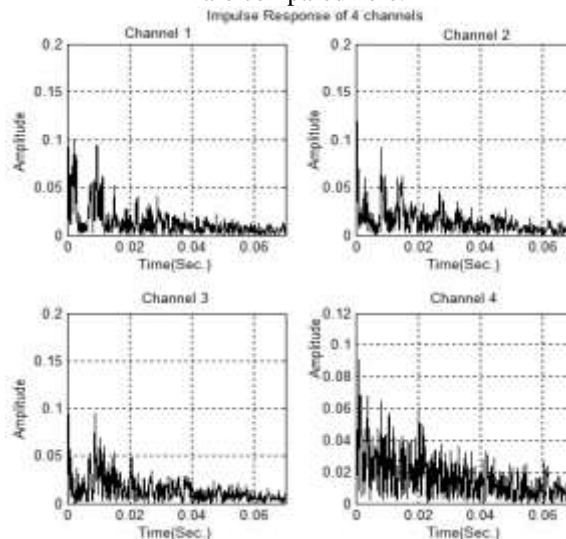

Fig. 10. The impulse response of 4 channels for data set B

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. In the simulations, we consider data set B. To determine the suitable window length, in Figure 12, the symbol error rate versus the window length for PPC processing is shown for 4 selected channels among 16 channels. It is seen in Figure 12, when the window length is too small or too large, the error will be increased. At the range of 40-80 ms, the symbol error rate tends to its lowest value. So, window length 40-80 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.
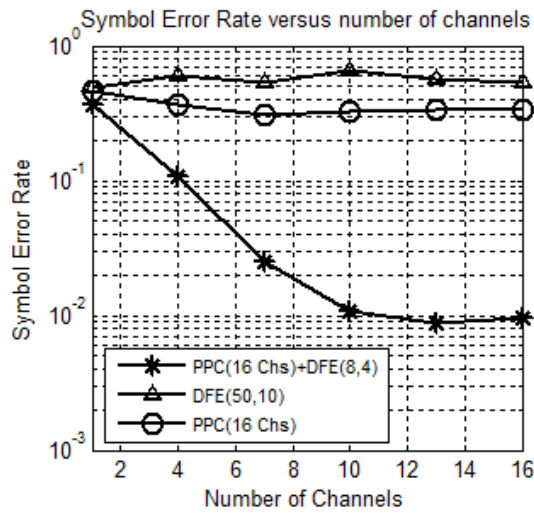
Fig. 11. The symbol error rate versus number of channels for data set B. PPC, DFE and PPC-DFE are compared here.
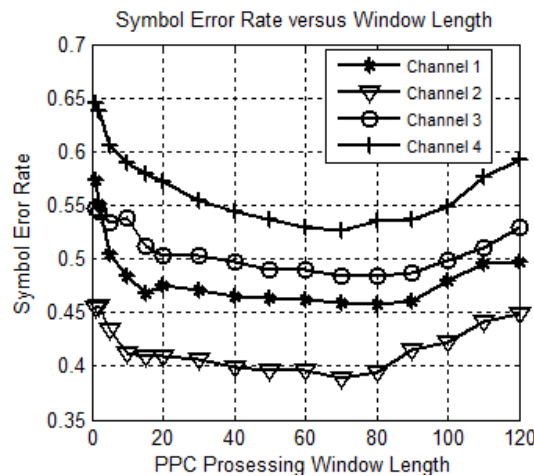

Fig. 12. The symbol error rate versus the window length in PPC processing for four selected channels

5.3. Data Set C

In this experiment, we consider the array of 16 elements in a different location. The symbol error rate is shown in Figure 13. For data set C, PPC shows pretty good performance. But, DFE is still not capable of equalizing. The least error can be achieved by DFE alone, is 0.12 for the 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 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.
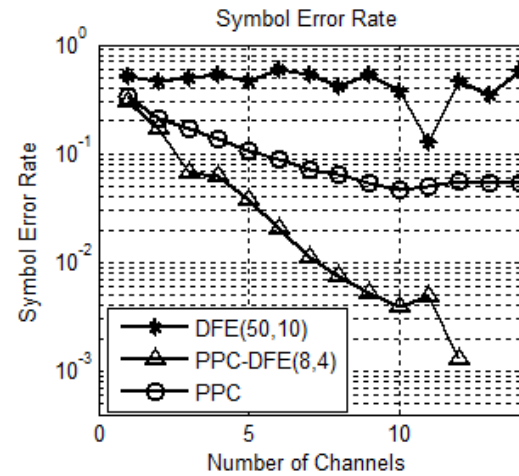

Fig. 13. The symbol error rate versus number of channels for data set C. PPC and DFE and PPC-DFE are compared here.

6. 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 equalizing 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.

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