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Experiential assessment of iteratively residual interference elimination in the passive phase conjugation for acoustic underwater communications

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ABSTRACT

Underwater acoustic communications have found a growing interest because of its variety usages both in military and commercial applications. But, for ocean environment, the channel has an extended time varying multipath due to acoustic propagation. These phenomena cause pulse spreading and time varying inter-symbol interference (ISI). To overcome the interference caused by this harsh environment, equalizers with Passive Phase Conjugation (PPC) have been widely used in coherent communications. In this paper, we have proposed a combined scheme of PPC followed by an iteratively ISI cancelation algorithm to remove the residual ISI remained at the output of the PPC processor. By using a coarse estimation of the channel along with the ISI alleviated PPC output symbols; we can eliminate residual ISI from the received data signal. We have conducted extensive simulations and some experimental tests at the coastal environment of the Persian Gulf to investigate the performance of the proposed scheme. The advantages of the proposed combined scheme are using the channel probe signal for both frame synchronization and coarse estimation of the channel impulse response to using it in the iteratively ISI cancellation and the PPC processing block. The results showed the effectiveness of the combined method.

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1. Introduction

In the last three decades, acoustic communications have found a growing interest in underwater research, target detection, underwater imaging, mine exploration and underwater communications. But underwater environment has turned to a complicated waveguide because of the rapid changes of the environment, reflections and the rapid phase changes which cause rapid channel changes (Edelmann, et al., 2002). Therefore, coherent communications has been suffered by multipath, especially in very shallow water environment (Edelmann, et al., 2005; Proakis, 1995; Yang, 2003). Decision Feedback Equalizers (DFE) plus carrier phase tracking are widely used to remove the interference caused by this multipath (Vilaipornsawai, et al., 2010; Yang, 2004; Zhang and Dong, 2011a, 2011b). However, their complexity is noticeable and their performance is suboptimal (Proakis, 1995). Refocusing the propagated signal is an approach to remove this interference (Rouseff, et al., 2001, 2004; Flynn, et al., 2004; Song et al., 2005; Stojanovic, 2005; Edelmann, et al., 2005; Zhang et al., 2012; Zhang and Dong, 2012).

Time reversal communications are based on the reciprocity property of linear wave equation, which says when a probe signal is transmitted from a point source at a distance in the ocean, and then received by an array of receivers in different paths, if the received signals are time reversed and retransmitted into the ocean, the ocean combines the individual paths to produce a signal close to the transmitted probe signal at the source location (Yang, 2003). To realize this procedure in the underwater acoustic communications, passive time reversal has been considered in the literature. Where, an array of receivers is considered to process the received signal. Therefore, there would be a one way link to send data as required in the one way communication systems (Yang, 2004). In passive time reversal communication a probe signal is sent ahead of the data signal to sound the channel. Also, the received probe signal is used to process the received data signal. In fact a cross correlator realizes the time reversal operation. It is expected that if enough paths are captured, the signal energy is converged sufficiently and the interference is reduced (Song et al., 2006a, 2006b).

The simplicity of PPC causes some deficiency in its performance. Using an array of receivers which captures enough paths is an efficient approach to improve the output performance, but, it is

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not enough to overcome the interference in a harsh environment and we have always some residual ISI (Song et al., 2006a, 2006b; Song and Dotan, 2006; Song, et al., 2007). Therefore, in the last years the idea of using other equalization approaches, especially decision feedback equalizer has been discussed to overcome this residual ISI (Peng and Dong, 2013; Lianyou, et al., 2013; Zhang, et al., 2012; Zhang and Dong, 2011a, 2011b, 2012). Gomes et al. (2006, 2008) have considered joint multichannel equalization and adaptive spatial combining for PPC communications.

There are some other combinations of PPC with coding schemes and multichannel processing in the literature (Peng and Dong, 2013; Ijaz, et al., 2012; Lianyou, et al., 2013; Zhang and Dong, 2012). In (Peng and Dong, 2013), an iterative channel equalization and decoding technique has been introduced to improve the performance of PPC based underwater acoustic communication. The PPC processor can realize pulse compression reducing the computational burden of the turbo equalizer. The authors in (Lianyou, et al., 2013) have been proposed a receiver structure which exploits spatial diversity by combining the adaptive multichannel processing and PPC to improve the performance of passive time reversal communications. The bidirectional decision feedback equalizer has been replaced the classical DFE to eliminate intersymbol interference.

Briefly speaking, whereas the input SNR increases, the output SNR of PPC will be finally saturated and there is always some residual ISI. To overcome this residual ISI or at least delay this phenomenon, decision feedback equalizer and multichannel processing combined with the PPC concept have been utilized. However, the time reversal channel impulse response is not causal and this can affect the equalizer performance dramatically.

In this paper, we propose a simple recursive interference cancellation after the PPC processor. In fact, with this idea we can alleviate the residual ISI after the PPC processing. We call our proposed method Interference Elimination PPC (IE-PPC). In this method, the interference is directly removed from the data signal instead of using adaptive equalization. To do that, we need the estimated channel which can be obtained by the probe signaling approach. Because the PPC output equivalent channel impulse response is not causal, we will need the future symbols beside the previous symbols. Therefore, an initial decision is done on the PPC output and this initial decision symbols can be used to remove the interference caused by the next symbols. This procedure is used iteratively to overcome the PPC output residual interference.

The rest of this paper is organized as follows. Section 2 represents the basic equations of time reversal communication and reviews some of the important notes regarding the concept of this technique. Section 3 discusses the proposed combined scheme. Simulation studies, comparisons, and experimental results are presented in Section 4 to validate the theoretical issues. Finally, Section 5 concludes our paper.

2. A review on passive phase conjugation

In passive phase conjugation communication, a probe pulse, which is usually a Linear Frequency Modulated (LFM) chirp signal as we used in our experimental tests, is sent ahead of the data signal. The received replica of the LFM chirp signal is then cross correlated with the data signal and the output is the result for time reversal processing. In fact, this cross-correlation is equivalent to convolving the received signal with the time-reversed version of the channel impulse response. Note that the received probe signal cross correlation with the replica version of the actual LFM chirp signal produces approximately an estimation of the channel impulse response. In an array of receivers, the resulted outputs are time aligned and summed over the array. In an ideal condition the resulted signal should be free of interference and it is ready to be demodulated (Yang, 2003).

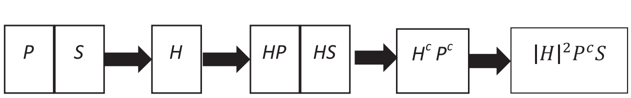

Fig. 1. Passive phase conjugation in frequency domain.

Fig. 1 shows a simple view of PPC process in the frequency domain for a single channel mode. In this figure, S is the transmitted signal, P is the probe signal and Hshows the channel impulse response all in the frequency domain. The transmitted signals S and Ptravels through the channel H, and they observed on the right hand station as $H \times S$and $H \times P$, respectively. The received probe signal, $H \times P$ is then phase conjugated to be multiplied by the received data signal $H \times S$ in the frequency domain. To do that, the receiver side cross-correlates in the time domain or multiply $H \times S$and $H \times P$in the frequency domain to produce$|H|^2 \times P \times S$. The different elements of the receiver array focused terms are typically aligned along their main peak, prior to averaging. As a result, they share a common main peak, but have side-lobes at different locations. Upon averaging, all elements contribute the same main peak, and by knowing the probe signal P, the transmitted data can be demodulated properly.

In view of the time domain, PPC 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 j th receiver, where $h_j(t)$ is the j th channel impulse response and $*$ denotes the convolution operation. To obtain a coarse estimation of the j th channel impulse response, time reversing $p(t)$ and convolving with $p_{r_j}(t)$, the j th channel impulse response is approximately obtained as follows

$$h_j(t) \approx p_{r_j}(t)*p(-t) \tag{1}$$

Where $*$ denotes the convolution operator.

Note that the probe signal $p(t)$ is completely known both at the transmitter and the receiver. Furthermore, the probe signal autocorrelation is nearly equal to the Dirac delta function as it is occurred for the considered LFM chirp signals in our experimental results.

Now, after guard duration, the data signal $s(t)$ is transmitted into the ocean from the source. The transmitted signal is convolved with the j th channel impulse response $h_j(t)$, thus, $v_j(t)$, the received signal at the j th element in a N-element array receiver, can be written as

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

Where $*$ denotes the convolution operator.

Using time reversal matched filter and summing over the array we obtain

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

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

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

is the auto-correlation function of the channel impulse response, which behaves like a sinc function which has some side-lobes in practical situations (Rouseff et al. 2001). Therefore, $s(t)$ can be approximately detected. Because of the serious residual ISI, the performance of the PPC can be improved by combining the simple PPC idea and other signal processing methods.

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