# Application of Turbo Equalization in PPC Underwater Acoustic Communication

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***Abstract*—In this paper, an iterative channel equalization and decoding technique are introduced to improve the performance of passive phase conjugation (PPC) based underwater acoustic communication system. The PPC processor can realize pulse compression reducing the computational burden of equalizer. The turbo equalizer is applied to existing PPC underwater communication structure (PPC-TEQ). Moreover, an adaptive combiner based on MMSE criteria (Adap-PPC-TEQ) is introduced to further improve the system performance. Further more, the adaptive combiner can form a new multi-channel equalizer structure with fewer sub-channels (Adap-PPC-Multi-TEQ) which provides a trade-off between performance and complexity. The turbo equalizer is implemented in a direct adaptive manner to track slow envelop variation while a digital phase lock loop (DPLL) is used for tracking fast phase variation. These three different receiver structures are demonstrated by field experiment conducted at Trondheim Fjord, Norway. An error free coded data transmission at 4 kb/s for a range of 7.4 km is achieved.**

## I. INTRODUCTION

Coherent underwater acoustic communications are challenged by harsh channel conditions such as long reverberation time which would cause severe inter symbol interference (ISI), limited available signal band due to frequency dependent transmission loss, and time variable channel state. To cope with these challenges, a variety of techniques have been proposed by underwater acoustic communication community. A digital phase lock loop (DPLL) coupled with decision feedback equalizer (DFE) was proposed in [1], and that work was extended in [2] to use multi-channel DFE (McDFE) and spatial combiner [3] for the purpose of utilizing spatial diversity. An alternative way to combat ISI is to use time reversal (TR) or passive-phase conjugation (PPC) [4]-[7]. The benefit of PPC or TR technique is its relatively low computational complexity compared with McDFE [4]. The PPC technique can realize pulse compression reducing delay spread but it can not eliminate ISI [5]. Therefore, an adaptive DFE was usually combined with PPC to improve system performance [4], [5].

Recently, the turbo equalization technique (TEQ) [9],[8] which has been shown to be able to significantly improve system performance is widely used into underwater acoustic communications [10]-[12]. In TEQ receiver, the soft information is exchanged between equalizer and channel decoder. Due to its prohibitive high computational complexity, the optimal TEQ structure composed of a MAP detector and a MAP decoder, can not be used in underwater acoustic communication scenarios. The practical TEQ structure is based on the principle of soft interference cancellation (SIC) where the soft symbol estimation is fed back to equalizer. In [12], two different popular turbo receiver structures, channel estimate (CE)- based TEQ and direct-adaptive TEQ were analyzed and compared. In [10], the multi-channel TEQ based on direct-adaptive technique was studied.

In this paper, we investigate the receiver structure which combines PPC processing and TEQ (PPC-TEQ) for the purpose of reducing the computational complexity of multi-channel TEQ. To deal with the possible mismatch in PPC processing due to channel estimation error, we, inspired by [3], propose to use an adaptive spatial combiner instead of the conventional direct sum spatial combiner in PPC processing. We denote this receiver structure as Adap-PPC-TEQ. As in [3], the adaptive spatial combiner could generate $P$ channels for multi-channel equalizer which provides the trade-off between system complexity and performance. We derive the linear TEQ structure when such adaptive spatial combiner is incorporated into the system. And we regard this receiver structure as Adap-PPC-Multi-TEQ. The performance of these three receiver structures are assessed and demonstrated by field experiment data.

The rest of paper is organized as follows. Section II describes transmitter. Section III presents the receiver structures we analyze and introduce in the paper. Section IV introduces the experiment setup and presents the results and discussions. Section V provides some conclusions.

## II. TRANSMITTER

The information bits, $\{b_k\}$ are coded by rate $1/2$ convolution code, generating channel coded bits $\{c_k\}$. The bit sequence $\{c_k\}$ then is interleaved by a random interleaver, obtaining bit sequence $\{s_k\}$. The bit sequence $\{s_k\}$ is mapped into QPSK symbols $\{x_k\}$. The symbol sequence $\{x_k\}$ is prefixed by training symbols which are QPSK modulated m-sequence. The signal is transmitted in frame form. Each frame signal is pre-ambled and post-ambled by LFM signal spanning from 11-13 kHz with a duration 0.1 s. The preamble and post-amble signals are separated from main signal by zero padding. The order of transmitted signal is presented in Fig. 1.

| | | | | | |
|---|---|---|---|---|---|
| LFM | zero padding | training symbol | data infomation | zero padding | LFM |

Fig. 1. Structure of the transmitted signal

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## III. RECEIVER

The baseband of received signal on the $jth$ hydrophone at time $n$ is denoted as

$$r_j[n] = \sum_m x[m]h_j[n-m] + w_j[n] \tag{1}$$

where $h[n]$ represents discrete channel impulse response, and $r[n]$ and $w[n]$ are the received signal and the additive noise in baseband respectively.

### A. PPC Receiver

PPC pre-processing is actually a bank of matched filter which matches with the channel impulse response. Convolving (1) with $h^*[-n]$ and summing over $K$ receivers, we have [6]

$$y[n] = x[n] + \sum_{m=1}^{L} q[m]x[n-m] + \sum_{m=1}^{L} q^*[m]x[n+m] + N_0 \tag{2}$$

where $q[n]$ is normalized summed auto-correlation function of channel impulse defined as Q function in [7], and $N_0 = \sum_{j=1}^{K}\sum_{l=0}^{L} h_j^*[l]w_j[n-l]$ is noise and $y[n]$ is defined as $y[n] = \sum_{j=1}^{K}\sum_{m=0}^{L} h_j^*[m]x[n-m]$. The PPC processing can realize pulse compression but it can not eliminate ISI. To further remove ISI, we propose to use adaptive turbo equalizer.

### B. Adaptive Turbo Equalizer

Based on (2), the relationship between the transmitted symbols and the received signals after PPC processing is represented by

$$\mathbf{y}_n = \mathbf{Q}_n\mathbf{x}_n + \mathbf{N}_n \tag{3}$$

where
$\mathbf{y}_n = [y[n-N_p], \cdots, y[n+N_f]]^T$,

$$\mathbf{Q}_n = \begin{bmatrix} q[L] & \cdots & q^*[L] & 0 & 0 \\ 0 & \ddots & \cdots & \ddots & 0 \\ 0 & 0 & q[L] & \cdots & q^*[L] \end{bmatrix},$$

$\mathbf{x}_n = [x[n-N_p-L], \cdots, x[n+N_f+L]]^T$, and $\mathbf{N}_n = [N_0[n-N_p], \cdots, N_0[n+N_f]]^T$. We also denote $\mathbf{Q}_n = [\mathbf{q}_{n,1}, \cdots, \mathbf{q}_{n,M}]$. In linear turbo equalizer [9], the prior probabilities on symbols $x_n$ feedback from soft-input-soft-output decoder are used for soft interference cancellation (SIC) and estimated symbol from equalizer is

$$\hat{x}_n = \mathbf{w}_n^H(\mathbf{y}_n - \mathbf{Q}_n\bar{\mathbf{x}}_n + \bar{x}_n\mathbf{q}_n). \tag{4}$$

The equalizer weights $\mathbf{w}_n$ can be determined according to MMSE criteria as in [9], if the channel state information (CSI) is available. And such TEQ structure is regarded as channel estimation based TEQ (CE-TEQ). The CE based TEQ would require to track CSI explicitly which could increase the computational burden. Here, we use the direct-adaptive TEQ (DA-TEQ) structure proposed by [8], which tracks the CSI variation implicitly. For DA-TEQ, the symbol estimation is expressed as (5), and the equalizer coefficients $\mathbf{a}$ and $\mathbf{b}$ are updated by adaptive algorithm.

$$\hat{x}_n = \mathbf{a}^H\mathbf{y}_n - \mathbf{b}^H\begin{bmatrix}\bar{\mathbf{x}}_{n-1} \\ \bar{\mathbf{x}}_{n+1}\end{bmatrix}. \tag{5}$$

Based on the Gaussian assumption, the external LLR of equalizer is computed as

$$LLR_{ext}(s_{n,j}) = \frac{\sum_{x_m\in\mathcal{S}_1} exp(-\frac{(\hat{x}_m - ga_m)^2}{\hat{\sigma}^2})\prod_{i\neq j}P(s_{n,i})}{\sum_{x_m\in\mathcal{S}_0} exp(-\frac{(\hat{x}_m - ga_m)^2}{\hat{\sigma}^2})\prod_{i\neq j}P(s_{n,i})}, \tag{6}$$

where $\mathcal{S}_1$ and $\mathcal{S}_0$ are the sets which are composed of constellation points whose $qth$ bits are 1 and 0 respectively. $a$ is the hard decision of $\hat{x}_n$. $g$ and $\hat{\sigma}^2$ are estimated by [9]

$$g = \frac{1}{B}\sum_{i=1}^{B}\frac{\hat{x}_i}{a_i}, \tag{7}$$

$$\hat{\sigma}^2 = \frac{1}{B}\sum_{i=1}^{B}(\hat{x}_i - ga_i)^2 \tag{8}$$

To deal with the possible Doppler shift, the digital phase lock loop (DPLL) [1] is inserted at each branch of the receiver. The receiver structure for PPC-Turbo equalizer is presented in Fig. 2.

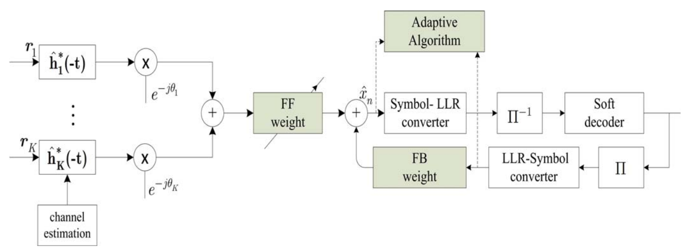


Fig. 2. Structure of PPC-TEQ

### C. PPC-TEQ with Spatial combiner

PPC processing requires CSI which is in practical obtained by channel estimation. But estimation error would cause mismatch of match filter thereby degrading system performance. Inspired by [3], we insert an adaptive combiner between PPC processing block and the equalizer. The coefficients of the combiner can be adjusted according to certain criteria to improve system performance. Moreover, we can select the number of branches of multi-channel equalizer freely, obtaining the trade-off between the computational complexity and the system performance. In this subsection, we derive the structure of adaptive linear turbo equalizer when this combiner is used. As in [9], the feedback external LLR is still used for SIC. Thus after SIC, we obtain

$$\mathbf{y}_j^s = \mathbf{y}_j^c - \mathbf{Q}_j\tilde{\mathbf{x}}_n = \mathbf{y}_j e^{-j\theta_j} - \mathbf{Q}_j\tilde{\mathbf{x}}_n, \tag{9}$$

where $\tilde{\mathbf{x}}_n = [\bar{\mathbf{x}}_{n-1}^T, 0, \bar{\mathbf{x}}_{n+1}^T]^T$ and $\mathbf{Q}_j$ is defined as auto-correlation function of channel impulse response of $jth$ channel. For brevity, we also define $\mathbf{Y}^c = [\mathbf{y}_1^c, \cdots, \mathbf{y}_K^c]$. After the received signals go through the combiner and the linear equalizer, we have

$$\hat{x}_n = \begin{bmatrix}\mathbf{a}_1^H\ \mathbf{a}_2^H\ \cdots\ \mathbf{a}_P^H\end{bmatrix}\begin{bmatrix}\mathbf{Y}^s conj(\mathbf{c}_1) \\ \mathbf{Y}^s conj(\mathbf{c}_2) \\ \vdots \\ \mathbf{Y}^s conj(\mathbf{c}_P)\end{bmatrix} \tag{10}$$

where $\mathbf{a}_i$ represents the weight of the $ith$ branch of the equalizer $\mathbf{Y}^s = [\mathbf{y}_1^s, \cdots, \mathbf{y}_K^s]$, and $\mathbf{C} = [\mathbf{c}_1, \cdots, \mathbf{c}_P]$ is the combiner matrix. Substituting (9) into (10) and after some calculation, we obtain,

$$\begin{aligned}\hat{x}_n &= \mathbf{A}\left(\mathbf{V} - \begin{bmatrix}[\mathbf{Q}_1\tilde{\mathbf{x}}_n \cdots \mathbf{Q}_K\tilde{\mathbf{x}}_n]\, conj(\mathbf{c}_1)\\ [\mathbf{Q}_1\tilde{\mathbf{x}}_n \cdots \mathbf{Q}_K\tilde{\mathbf{x}}_n]\, conj(\mathbf{c}_2)\\ \vdots \\ [\mathbf{Q}_1\tilde{\mathbf{x}}_n \cdots \mathbf{Q}_K\tilde{\mathbf{x}}_n]\, conj(\mathbf{c}_P)\end{bmatrix}\right)\\ &= \mathbf{AV} - \mathbf{A}\mathrm{VEC}\left([\mathbf{Q}_1\tilde{\mathbf{x}}_n \cdots \mathbf{Q}_K\tilde{\mathbf{x}}_n]\, conj(\mathbf{C})\right) \qquad (11)\\ &= \mathbf{AV} - \mathbf{A}(\mathbf{C}^H \otimes \mathbf{I})\begin{bmatrix}\mathbf{Q}_1\\ \vdots\\ \mathbf{Q}_K\end{bmatrix}\tilde{\mathbf{x}}_n\\ &= \mathbf{AV} - \mathbf{f}^H\tilde{\mathbf{x}}_n\end{aligned}$$

where $\mathbf{A} = \left[\mathbf{a}_1^H\, \mathbf{a}_2^H\, \cdots\, \mathbf{a}_P^H\right]$, $\otimes$ represents Kronecker product and $\mathbf{V} = \mathrm{VEC}(\mathbf{Y}^c conj(\mathbf{C}))$. (11) means that the structure of adaptive linear turbo equalizer with spatial combiner is similar to the receiver structure in [3]. The structure for adaptive PPC-turbo equalizer with spatial combiner is shown in Fig. 3. We denote the receiver structure without adaptive spatial combiner as PPC-Turbo, receiver structure with $P = 1$ as Adap-PPC-TEQ and receiver structure with $P > 1$ as Adap-PPC-Multi-TEQ in this paper. As shown in [3], the coefficients for spatial combiner and TEQ are updated in a coupled way and there is no unique set of coefficients that leads to optimal solution. We initialize the update process in the same manner as [3]. In the beginning, the coefficients for the spatial combiner are set to 1 and the equalizer coefficients begin to update with an initial value of 0. After certain steps of adaptation, the spatial combiner begins its update.

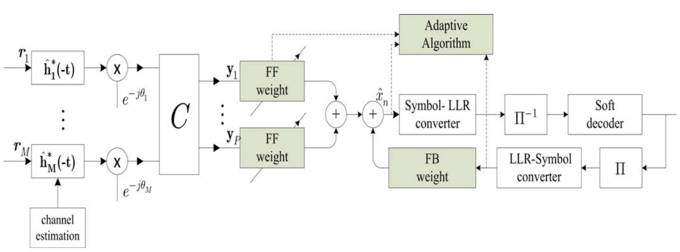


Fig. 3. Structure of Adap-PPC-Multi-TEQ

## IV. Experiment Setup

The performance of these receiver structures is evaluated by field experiment data. The field experiment is conducted at Trondheim Fjord, Norway during June 4-June 5, 2012. For channel coding, a convolution code with generator polynomial $(23, 35)_8$ and a random interleaver with size of 15000 are used. The source transducer is deployed from NTNU's research vessel R/V Gunnerus with a depth of 15 m. The vessel starts its dynamic position system. The receiving system is composed of a vertical hydrophone array which contains 8 elements apart by 1 m. The receiving array is close to shore deployed with a maximum water depth of 10 m. The transmission distance between the source and the receiving array is around 7.4 km. The carrier frequency is 12 kHz and QPSK modulation is used. The data packet consists of 512 training symbol and 7500 data symbol. The data rate varies from 1 ks/s–2 ks/s. The data packet is repeated 8 times during transmission. Each repetition is denoted as "epoch 1 8". A raised cosine with roll-off factor 1 is used in the transmitter. Besides, a LFM signal with a frequency span from 11 kHz–13 kHz and time duration of 0.1 s is used as preamble for time synchronization. And a guard time of 0.2 s is inserted between the preamble and data packet.

## V. Results

The channel estimation result with QPSK symbols is illustrated in Fig. 4. The least square (LS) method is utilized for channel estimation and the symbol rate is 2000 sym/s. As illustrated, the channel delay spread is more than 10 symbol time and it varies over time.

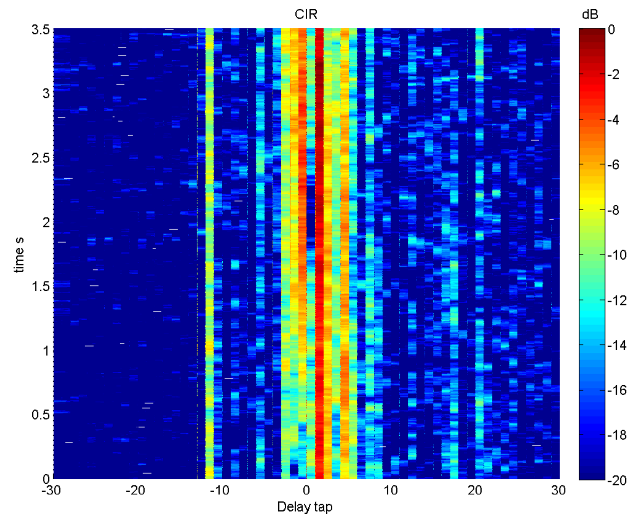


Fig. 4. Time delay presentation of channel impulse response

When we evaluate the performance of the proposed receiver structures, the CSI needed for PPC processing is obtained by using training symbols and LS channel estimator. And we use signals from 4 hydrophones which is apart by 2 m and spans from sea surface to bottom. The channel impulse response length is chosen to 13 symbol duration. The length of forward filter $N_{ff}$ is 13, and the length of feedback filter $N_{fb}$ is 25. The recursive least square (RLS) algorithm is used for updating the coefficients of the equalizer and the spatial combiner. The forget factor for RLS algorithm $\lambda$ is set to 0.998 and initial value $\delta$ is set to 0.1. The phase tracking constants in DPLL are set as $K_{f1} = 8e-2$ and $K_{f2} = 8e-3$. The performance of these three receiver structures in terms of bit error rate (BER) and output SNR during Epoch 7 are listed in Table I and Table II. In comparison, the number of forward filter of multi-channel TEQ (McTEQ) P is selected to be 2. As presented, all of these three structures could successfully recover information after one iteration and Adap-PPC-Multi-TEQ can achieve the best performance.

TABLE I. The BER for different receiver structures

| Receiver Structures | No Iter | Iter. 1 | Iter. 2 |
|---|---|---|---|
| PPC-TEQ | 0.0049 | 0 | 0 |
| Adap-PPC-TEQ | 0.0027 | 0 | 0 |
| Adap-PPC-Multi-TEQ | 0 | 0 | 0 |

TABLE II. THE OUTPUT SNR FOR DIFFERENT RECEIVER STRUCTURES

| Receiver Structures | No Iter | Iter. 1 | Iter. 2 |
|---|---|---|---|
| PPC-TEQ | 3.6658 dB | 6.5510 dB | 7.1172 dB |
| Adap-PPC-TEQ | 4.0104 dB | 7.1141 dB | 7.4818 dB |
| Adap-PPC-Multi-TEQ | 5.6665 dB | 8.8541 dB | 8.8550 dB |

To further illustrate the performance of the proposed receiver structures, Fig. 5 presents the output signal to noise ratio of these three receiver structures after 2 iterations over 8 epochs. The output SNRs of PPC-TEQ and Adap-PPC-Multi-TEQ are less than 2 dB during Epoch 4 and Epoch 5. And PPC-TEQ and Adap-PPC-TEQ fail to recover information during Epoch 4 and Epoch 5. But Adap-PPC-Multi-TEQ still could achieve reasonable performance.

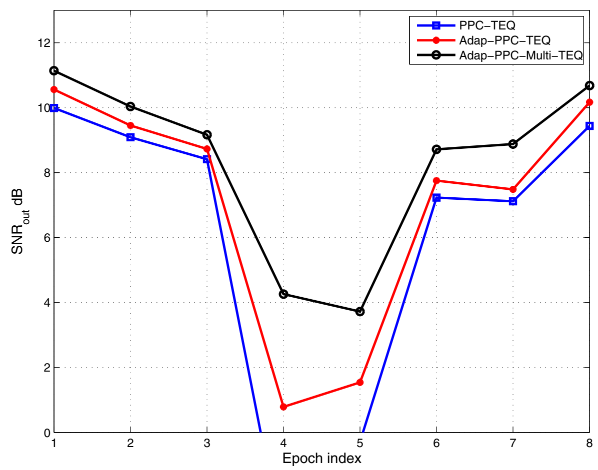


Fig. 5. The Output SNR of different receiver structures

Next, We examine the impact of number of forward filter P in McTEQ structure on system performance. We show the output signal to noise ratio as function of the number of forward filter P for all epochs in Fig. 6. We observe quite large performance improvement when P is larger than 1. But such performance gain is limited when $P > 2$.

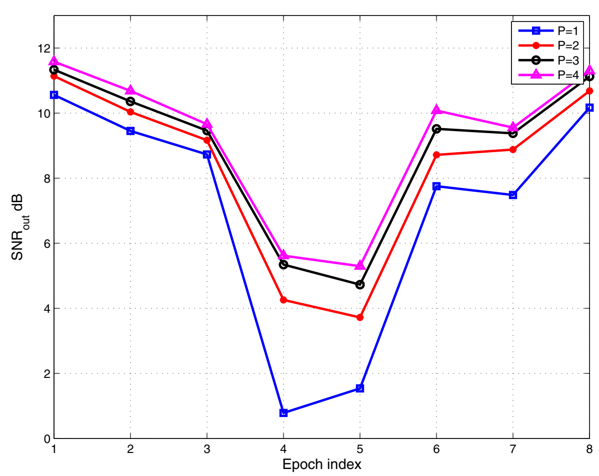


Fig. 6. The Output SNR of different value of P

## VI. Conclusion

In this paper, we study the combination of passive phase conjugation and linear turbo equalizer for underwater acoustic communication. We also propose to incorporate the spatial combiner into linear turbo equalizer. We compare three different receiver structures: PPC-TEQ, Adap-PPC-TEQ and Adap-PPC-Multi-TEQ by using field experiment data. The Adap-PPC-Multi-TEQ achieves best performance among these three structures, since it exploits much more spatial gain than another two structures. We also study the effect of selection of the number of forward filter in McTEQ. The system performance improves as the number of forward filter increases, and such improvement becomes less when the number of forward filter increases to certain number.


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