Time Reversal Based Channel Tracking for Underwater Acoustic Communications

Menglu Xia, Wen Xu, and Xiang Pan
Zhejiang University
Zheda Road #38, ISEE
Hangzhou, China
luluxml@gmail.com, wxu@zju.edu.cn, panxiang@zju.edu.cn

ABSTRACT
Time reversal processing (TRP) has been proved to achieve temporal compressing when the waveguide environment is invariant. Underwater acoustic communications exploit this feature as it can reduce severe inter-symbol-interferences caused by complex multi-path propagation without any prior knowledge of the underwater acoustic channel. When conducting acoustic communications in the real ocean, environmental variations occur almost all the time, and indeed become one of the main factors determining the communication performance. However, it has been shown in numerous experiments that when the TRP is applied to the channel impulse response (CIR), the resulted response is relatively slowly time-varying compared to the CIR itself. Thus in the present paper, we exploit this factor and develop a channel tracking approach based on the so-called time-reversed channel response. Experimental results demonstrate that, compared to the conventional equalization method counteracting the CIR variation, the new approach requires less frequent update of the CIR in a time-varying environment, also achieving significant computational saving in tracking the channel.

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Algorithm, Design, Experimentation

Keywords
Underwater acoustic communication, time reversal, channel equalization, state-space model, time-varying channel

1. INTRODUCTION
Underwater acoustic communication channels are characterized by large time-delay and Doppler spread [1]. Time-delay spread is caused by multi-path propagation in a waveguide environment with upper and lower boundaries, resulting in inter-symbol-interferences (ISI) for communications. Intensive efforts have been made to alleviate the effects of time-delay spreads, mostly via channel equalization and/or channel coding. Numerous algorithms have been developed, for example, the decision feedback equalization (DFE) combined with the Turbo coding [2].

In the past decade, time-reversal processing (TRP) is incorporated into coherent single-carrier and multi-carrier underwater acoustic communications [3] [4] [5] [6] to handle the time-delay spread problem. Time reversal is a signal processing method developed based on the reciprocity of sound propagation in a time-invariant environment. Specifically in the context of array receiving, when the environment is stationary and the array spans the water column enough, if the received signals at the array from initial transmission are time reversed and re-transmitted, one can obtain the original signal at the original transmitting position achieving spatial focusing and time compression. Due to time variation of the channel or limited number of propagation paths, the channel response after time-reversal does not show as an ideal impulse; instead the response still has some spread, i.e., there still exists some residual ISI in communications. Hence passive time reversal processing is often followed by a simple decision feedback equalizer to remove the residual ISI [7].

When the channel varies with time, the performance of most of the equalization algorithms explicitly or implicitly depends on how frequent and how accurate the channel impulse response (CIR) is updated. Refs. [8] and [9] use the least-squares estimate to update the replica CIR block by block, while the length of the block is fixed. Ref. [7] discusses the passive time reversal communication results when choosing different block lengths. A state space time-varying model for a channel with moving scattering clusters has been proposed, and the extended Kalman filter (EKF) is applied to estimate and track the channel CIR [10]. Since the CIR has a large time delay spread and changes with time, the required computational effort is significant.

One of the key questions is then when to update the CIR. In the case of time-reversal communications, with a rapidly time-varying channel, the time-reversed channel will spread more; it is thus necessary to update the replica CIR used to implement the passive time reversal algorithm. A receiver structure including channel estimation and time reversal multichannel combining has been developed (see, e.g., Refs. [11] and [12]), in which the channel estimation is regularly updated using the known symbols during the preamble or the previously detected symbols via various least squares algorithms. However, it has been shown in numerous
experiments that when the TRP is applied to the CIR, the resulted response is relatively slowly time-varying compared to the CIR itself. Thus we propose to track the so-called time-reversed channel (TRC), which is the channel correlation function after applying time-reversal processing. It is expected that tracking the time-reversed channel requires less computations as well as a lower update frequency.

2. TIME REVERSAL

When the sound field is time invariant and static, the reciprocity and time-reversal invariability of the wave equation’s solution lead to the time-reversal focalization of the sound field. That is to say, using an array of mono-static transducers, the first arrivals would be sent back last, while the last would be sent back first. Then this back signal would be spatially focused at the source position and temporally compressed to the original extent. Using the channel itself for inverse filtering instead of an acoustic model, TRP has the performance of signal processing based upon models, while avoiding any degradation caused by modeling mismatch, which promises robustness.

The whole process can be described as follows. A known signal $s(t)$ is transmitted from a point source in the waveguide, and received on the time-reversal array with $N$ transducers. The signal on the $i$th element can be expressed as

$$y_i(t) = s(t) \otimes h_i(t),$$

where $h_i(t)$ is the impulse response of the channel between the source and the $i$th element, and $\otimes$ denotes the convolution. Then every received signal of the $N$ transducers is time-reversed, which is $y_i(-t)$, and retransmitted. The signal $s_p(t)$ received at the original location can be written as:

$$s_p(t) = s(-t) \otimes [\sum_{i=1}^{N} h_i(t) \otimes h_i(-t)]$$

or

$$s_p(t) = s(-t) \otimes q(t).$$

The term in the brackets is the sum of each channel’s impulse response autocorrelation function, noted as $q(t)$. In an ideal waveguide environment, the $q$ function can be seen as a unit impulse function, which promises the focalization and compression. When coming into practice, the performance of TRP relies on the complexity of the channel (structure of the propagation paths), and the number and spatial distribution of the array transducers, and the shape of $q(t)$ can be spread.

The above process can be written in frequency domain as

$$S_{sp}(f) = \sum_{i=1}^{N} S^{*}(f)H_i^{*}(f)H_i(f) = S^{*}(f)H(f)H^{H}(f)Q(f)$$

(2)

where $S(f)$ is the Fourier transform of $s(t)$, $H_i(f)$ is the Fourier transform of $h_i(t)$,

$$H(f) = [H_1(f) \cdots H_N(f)]^T$$

(3)

$^{*}$ stands for conjugate, $( )^{H}$ for conjugate transpose, and $( )^T$ for transpose. $Q(f)$ is the spectrum of the $q$ function.

3. TIME-REVERSAL BASED CHANNEL TRACKING

In real underwater acoustic communication applications, the environment is always varying with time due to the platform moving or environmental fluctuation; also one can only have a receiving array of limited size. Besides, the performance of time reversal temporal compression would be degraded if the number of propagation paths is limited. Thus when designing a time reversal underwater acoustic communication system, we need to update the replica CIR and use a simple equalizer after time reverse processing to counter the channel dynamics.

As mentioned earlier, although the $q$ function may no longer be a unit impulse function, the dominant time delay spread can still be far less than the multipath arrival extension in most underwater acoustic communication channels. Besides, this $q$ function has a special structure with a narrow main lobe and lower side lobes aside. In order to determine when to update the CIR, we propose to track the $q$ function, instead of tracking the time-varying channel itself. This is a sounding approach since the equalization is done following the TRP, and yields two advantages: first, the $q$ function, which we term as the time-reversed channel response, is usually much shorter in meaningful temporal extension than the CIR itself, thus saving computations in tracking; second, it still reflects the CIR’s evolution with time, thus capable of capturing rapid channel variations.

The state space model has been used to estimate and track the rapidly varying CIR [10]. Here, we use the state space model to describe the time-reversed channel and apply the Kalman-type filter to estimate and track the time-reversed channel. The model is shown in Fig. 1 and can be described as

$$\begin{cases} q_{i+1} = A_i q_i + w_i \\ y_i = x_i q_i + v_i \end{cases}$$

(4)

where $q_i$, $x_i$, $A_i$, $w_i$, $v_i$ respectively denote the time-reversed channel response (column vector), the transmitted symbol (row vector), the transition matrix and the input noise. $v_i$ and $y_i$ are the additional noise and the received signal, respectively.

Figure 1. State space model.

Since the transition matrix depends on some unknown parameters to be estimated, EKF is applied to realize the tracking. There are three main steps. First, we rewrite the state-space model by introducing a parameter set

$$\begin{pmatrix} \theta \end{pmatrix} = \left[ a_i \ q_i \right]^T,$$

where $a_i$ is a column vector formed by stacking orderly all columns of $A_i$. Then Eq. (4) can be written as

$$\begin{cases} \theta_{i+1} = f(\theta_i) + v_i \\ y_i = [0 \ x_i] \theta_i + v_i \end{cases}$$

(5)
Second, we linearize \( f(\theta_i) \) around \( \theta_i \) and get 
\[ f(\theta_i) = F \theta_i + d_i. \]
Then Eq. (5) becomes
\[ y_i = [0 \ x_1] \theta_i + v_i. \]

Finally, we can apply the standard Kalman Filter to solve (6). Both \( a_i \) and \( F_i \) are initialized using the CIR obtained from the linear frequency modulation (LFM) channel probing signal appearing in the beginning of each communication frame. The detailed algorithm is described in [13].

4. TIME-REVERSED CHANNEL TRACKING BASED COMMUNICATION SCHEME

A communication scheme based on the time-reversed channel tracking is given in Fig. 2. The received signal on each array element, \( y_i(t), i = 1, \ldots, N \), is first processed by a Doppler compensator. Passive time reversal is implemented separately with each individually estimated channel impulse response, \( \hat{h}_i(t), i = 1, \ldots, N \), before summed up. Then the EKF is used to track the time-reversed channel, i.e., \( q \) function, as described in the last section. The estimated \( q \) function can be denoted as
\[ \hat{q}(f) = \begin{bmatrix} \hat{H}_1(f) & \cdots & \hat{H}_N(f) \end{bmatrix} \]
where \( \hat{H}_i(f) \) is the estimated replica CIR on the \( i \)th element, and \( H_i(f) \) is the real CIR on the \( i \)th element embedded in communication data frames. Note that Eq. (7) is a bit different from that defined in (2) for the purpose of better describing the spread caused by CIR variations (the \( q \) function in the last section is defined the same way, also termed as the time-reversed channel response). To compensate the non-ideality of the estimated \( q \) function, a simple DFE follows to equalize the time-reversed symbols.

Here the estimated \( q \) function, \( \hat{q}(t) \), is normalized with respect to the maximum of this function when \( \hat{h}_i(t) \) is obtained from the channel probing signal. Having done that, \( \max|\hat{q}(t)| \) is monitored. If \( \max|\hat{q}(t)| < 0.5 \), the replica CIR of each channel is updated. By using this scheme, the system can decide when to update the replica CIR and compensate the residual ISI all together.

The replica CIR \( \hat{H}_i(f) \) is first estimated using the LFM probing signal, and then when necessary, updated within one frame using the previously demodulated symbols and the estimated \( q \) function through a least squares algorithm. That is to say, the estimated \( q \) function defined in (7) is updated via the estimated CIR; however, when to update the CIR is determined from the spread of the estimated \( q \) function in (7) rather than the CIR itself.

5. EXPERIMENTAL RESULTS

5.1 Experimental setup

The experiment was conducted in Qiandao Lake near Hangzhou, China, in December, 2011. A 16-element vertical array is moored in a location with water depth of about 50 m. The space between each element is 1 m and the top element’s depth is 10 m. A projector with a depth of 10 m is carried by a slowly-moving or drifting boat, and transmits signals at different ranges, e.g., 295 m, 5 km and 7.5 km. Fig. 3 shows the sketch of the experimental setup. The carrier frequency of the transmitted signal is 8 kHz, and the bandwidth is 4 kHz. Each communication frame consists of 3 s continuous symbols.

Fig. 4 shows the sound speed profile at the receiving array location. On top, it is almost isovelocity. There is a strong thermocline below 30 m with sound speed difference of 15 m/s, which causes the top elements receiving stronger signals than those on the bottom.

5.2 Experimental data processing

During the experiment, we noticed that the multipath propagation causes severe time delay and varies with time rapidly at range 295 m, while for 5 km and 7.5 km the time delay spread is much shorter and more stable. Fig. 5 shows the CIR’s variation during 3 s at 295 m: (a) is the CIR on the top element with depth of 10 m; (b) is the CIR on the bottom element with depth of 25 m. The time delay spread is around 25 ms and on either element, there is some obvious CIR structure change during 3 s, particularly for non-direct returns.

Figure 2. Time-reversed channel tracking-based communication scheme.
Figure 3. Experimental setup.

Figure 4. The sound speed profile at the receiving array location.

Figure 5. CIR at range 295m: (a) receiving element depth 10 m; (b) receiving element depth 25 m.

Figure 6. Time-reversed CIR at range 295 m: (a) using receiving elements 1-16; (b) using receiving elements 1-8.

Figure 7. Scatter plot at range (a) 295 m and (b) 5 km.

Fig. 6 shows the time-reversed channel impulse response at 295 m: (a) using all 16 elements; (b) using top 8 elements. The time delay spread is around 2 ms, much shorter than the CIR shown in Fig. 5.
and the structure is quite stable. Only the amplitude of the main lobe changes with time.

Fig. 7 shows the scatter plots at range 295 m and 5 km, respectively. Fig. 7 (a) has a data rate of 10 kbps and a range of 295 m, while the slowly-moving platform has a speed of 1.92 m/s and the CIR is updated 4 times during 3 s. Fig. 7 (b) has a data rate of 10 kbps and a range of 5 km, while the drifting platform has a speed of 0.84 m/s and there is no updating of the CIR during 3 s.

Fig. 8 shows the image transmission results at ranges from 7.9 km to 7.3 km: (a) is the origin picture; (b) is the received picture; and (c) shows the error pixels in the highlighted area of (b). The data rate is 4 kbps and a conventional convolution code with a code rate of 1/2 is used to reduce the bit error rate to below $10^{-5}$. The boat is drifting during the communication series of about 10 minutes, and there is no updating of the CIR during every 3 s, i.e., one communication data frame length.

Figure 8. Data transmission results: (a) the origin picture; (b) the received picture; and (c) error pixels in the highlighted area of (b).

6. CONCLUSION
A new approach of channel tracking-based communication scheme is proposed: tracking $q$ function based on time reversal instead of the CIR itself. The key steps of using $q$ function in a time-varying time reversal communication is (a) decide when to update the replica CIR; (b) show what to compensate using a DFE. Performance advantages have been demonstrated in a lake experiment, where the proposed method has been successfully used for short-range and long-range underwater image transmissions.

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8. REFERENCES