Bidirectional equalization for underwater acoustic communication

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Abstract: The bidirectional decision feedback equalizer (BiDFE) that combines the outputs of a conventional decision feedback equalizer (DFE) and backward DFE can improve the performance of the conventional DFE by up to 1–2 dB based on simulations. In this letter, the BiDFE concept is extended to multichannel time reversal communications involving a DFE as a post-processor. Experimental data collected in shallow water (10–20 kHz) show that the performance can be enhanced by 0.4–1.8 dB in terms of output signal-to-noise ratio. In particular, a larger improvement (e.g., 1.8 dB) is achieved for time-varying channels where the channel diversity in opposite directions is more profound.

1. Introduction

Over the last decade, time reversal communications has been studied extensively in underwater acoustic channels as an alternative to conventional adaptive multichannel decision feedback equalizers (DFE). Time reversal exploits spatial diversity to mitigate intersymbol interference (ISI) and provides near-optimal performance in terms of output signal-to-noise ratio (SNR) when combined with channel equalization by removing the residual ISI. Consequently, multichannel time reversal (TR) combining followed by a single channel DFE is employed routinely in time reversal communications and further extended to time-varying channels using a block-based approach.

The non-linear DFE involving a feedback filter usually outperforms the linear equalizer (LE) in terms of reducing noise enhancement when the effect of decision errors on performance is neglected, especially for channels with spectral nulls. However, the DFE suffers from error propagation caused by the feedback of incorrect decisions. In addition, the DFE based on the minimum mean-square-error (MMSE) criterion is suboptimal from a probability of error viewpoint, whereas an optimal approach is the maximum-likelihood sequence estimation (MLSE). The drawback of the MLSE is prohibitively expensive to implement in most channels of practical interest.

In an effort to mitigate error propagation and improve the performance of a conventional DFE, a bidirectional decision feedback equalizer (BiDFE) was introduced in wireless channels for packet based communication systems as shown in Fig. 1. The BiDFE consists of two parallel DFE structures, one to equalize the received signal in a causal fashion and the other to equalize the time-reversed version of the received signal in a non-causal fashion. For example, a minimum-phase channel becomes a maximum-phase channel, and vice versa. The approach thus exploits the difference in error propagation (a form of “diversity”) between the forward DFE and backward DFE since the error burst proceeds in opposite directions with a low correlation for the errors. Initially, a selective time reversal DFE was proposed where one chooses between the outputs of forward and backward DFEs based on the global mean-square-error (MSE) performance. Meanwhile, Nelson et al. proposed a BAD (bidirectional arbitrated DFE) algorithm where the decision is performed on a symbol-by-symbol basis according to a local maximum a posteriori (MAP) criterion.
Simulations showed that the BAD algorithm can improve the performance of the conventional DFE by 1–2 dB for typical channels at modest bit error rates (BER), closing the gap between optimal MLSE and suboptimal DFE.

Separately, Balakrishnan and Johnson\textsuperscript{12} proposed combining the two data streams rather than selecting either one, and showed about 1 dB improvement based on simulations for symmetric and non-symmetric channels. In this letter, the concept of BiDFE combining the soft outputs of forward and backward DFEs is extended to multichannel time reversal communications for underwater acoustic channels which are highly frequency-selective (due to multipath) and time-varying. The performance enhancement will be investigated using experimental data (10–20 kHz) collected in shallow water for both time-invariant and time-varying channels.

2. Bidirectional equalization

The block diagram of the proposed bidirectional receiver structure in conjunction with time reversal communications is displayed in Fig. 2 performing two equalizations: (1) a normal time reversal equalization (upper) and (2) a backward time reversal equalization (lower). The upper block illustrates a conventional operation of time reversal communication involving multichannel TR combining followed by a single channel DFE where $a_f[n]$ and $b_f[n]$ are feedforward and feedback filters, respectively. TR combining requires knowledge of the channel, which is provided by either a channel probe in the

![Fig. 1. Bidirectional equalization.](image)

![Fig. 2. (Color online) Block diagram for BiDFE time reversal (TR) communications. The upper block illustrates a normal mode operation of time reversal equalization involving multichannel TR combining and a subsequent single channel DFE where $a_f[n]$ and $b_f[n]$ are feedforward and feedback filters, respectively. On the other hand, the lower block operates on the time-reversed version of the received signal. Note that the double lines prior to TR combining indicate multichannel data. The BiDFE communication combines the soft output of the forward equalization $d_{fn}$ and backward equalization $d_{mn}$ to enhance the performance.](image)
preamble or training symbols for time-invariant channels. The training symbols also are used for adjusting the equalizer coefficients to their optimum values in adaptive algorithms such as the least mean square (LMS) or recursive least squares (RLS). For time-varying environments, channels are updated using previously detected symbols (decision-directed mode) so that time reversal communication can be implemented on a block-by-block basis.\textsuperscript{9} On the other hand, the lower block processes a time-reversed version of the received multichannel signal where \(a[n]\) and \(b[n]\) are the corresponding feedforward and feedback filters, respectively. Additional training symbols at the end of a data packet (see Fig. 1) are required for both channel estimation and optimization of the backward equalizer coefficients.

### 2.1 Time-invariant channel

Assume that the channel is time-invariant and causal with a finite span, i.e., finite impulse response (FIR), \(h[n]\). The received signal at the \(i\)th received element can be expressed as

\[
r_i[n] = \sum_{k=0}^{L-1} h_i[k] d[n - k] + w_i[n], \quad n = 1, \ldots, N + L - 1,
\]

where \(L\) is the number of channel taps, \(d[n]\) represents the transmitted symbols with a total of \(N\) symbols, and \(w_i[n]\) is the additive white noise sequence. The time-reversed version of the received signal in the lower block can then be expressed as

\[
\tilde{r}_i[n] \equiv r_i[N + L - n] = \sum_{k=0}^{L-1} \tilde{h}_i[k] d[n - k] + \tilde{w}_i[n],
\]

where \(\tilde{h}[k] = h[L - 1 - k], \quad k = 0, \ldots, L - 1\) and \(\tilde{d}[n] = d[N - n + 1], \quad n = 1, \ldots, N\). This is equivalent to transmitting the time-reversed source sequence \(\tilde{d}[n]\) through a channel \(h_i[n]\) which is the time-reversed version of the channel \(h[n]\) with a delay of \((L - 1)\).

With a detection delay of \((L - 1)\) in the absence of noise \(w_i[n]\), the signal after the TR multichannel combining \(x[n]\) can be simplified to

\[
x[n] = \sum_{k=-(L-1)}^{L-1} q[k] d[n - k], \quad n = 1, \ldots, N + L - 1,
\]

where \(q[k] = \sum_{i=1}^{M} h_i[k] * h_i[-k]\) with \(M\) being the number of receiver elements and \(*\) denoting convolution. The \(q\)-function representing the summation of the autocorrelation of each channel impulse response corresponds to an effective overall channel response in time reversal communications.\textsuperscript{15} The subsequent DFE operates on the signal \(x[n]\) to further remove any residual ISI. Since the \(q\)-function is symmetric, the counterpart in the lower time-reversed block is also expressed similarly as

\[
\tilde{x}[n] \equiv x[N + L - n] = \sum_{k=-(L-1)}^{L-1} q[k] \tilde{d}[n - k].
\]

### 2.2 Diversity combining

The idea of bidirectional DFE is based on the fact that the performance of a normal mode DFE and a backward DFE is different under a finite length constraint on the number of DFE filter taps. Ariyavisitakul\textsuperscript{9} proposed the use of either a normal mode DFE or a backward DFE depending on the MSE performance of the two DFE structures, referred to as the selective time-reversal approach. The author further demonstrated that the MSE of the two DFEs are the same if the length constraint on the
DFE is relaxed. Recently, Nelson et al.\textsuperscript{11} and Balakrishnan\textsuperscript{10} independently proposed a truly bidirectional DFE architecture (BiDFE) where the output of the two streams are combined to improve the performance exploiting the time reversal diversity. The diversity is due to a combination of the non-linear structure of the DFE and anti-causal processing of the received signal.\textsuperscript{12}

As shown in Fig. 2, the soft outputs of the forward and backward DFEs are denoted by $\tilde{d}_f[n]$ and $\tilde{d}_r[n]$, respectively. The diversity combining depicted in Fig. 2 can be shown as a weighted linear combination of the two sequences

$$\tilde{d}[n] = x\tilde{d}_f[n] + (1-x)\tilde{d}_r[N-n+1], \quad n = 1,...,N,$$

where $x$ is the weighting factor, $0 \leq x \leq 1$. For the BAD algorithm\textsuperscript{11} that employs a reconstruction-based arbitration technique on a symbol-by-symbol basis, $x$ is either 1 or 0 for each symbol. While this technique is shown effective, it requires complete knowledge of the channel and is difficult to analyze. In contrast, Ref.\textsuperscript{10} optimizes the weighting factor based on minimizing the MSE, $E\left\{ |\tilde{d}[n] - d[n]|^2 \right\}$. When the MSE for the two data streams are equal (e.g., on a symmetric channel), an equal-gain combining (i.e., $x = 1/2$) is optimal.\textsuperscript{13} We will adopt the equal-gain combining strategy for time reversal communications presented in Sec. 3 given the symmetry of the $q$-function.

The performance evaluation of a DFE is complicated by occasional incorrect decisions made by the detector, which then propagate down the feedback section.\textsuperscript{7} Under the decision-free assumption with an infinite length DFE, the performance bound of the BiDFE over the conventional DFE can be derived.\textsuperscript{14} For a finite length DFE and assuming time-invariant channels known to the receiver, it is shown mostly by simulations with binary phase-shift keying (BPSK) modulation that the performance of BAD and BiDFE can be 1–2 dB better than that of the conventional DFE for symmetric and asymmetrical channels.\textsuperscript{10,11}

### 3. Performance improvement

In this section, we evaluate the performance of bidirectional time reversal communications as proposed in Fig. 2, utilizing two experimental data sets collected in shallow water environments: (1) FAF06 (11–19 kHz)\textsuperscript{1} and (2) KAM08 (12–20 kHz).\textsuperscript{6} The reason for choosing these data sets is the following. First, data from both experiments have been analyzed previously using a conventional one-way (forward) time reversal approach and reported in the literature, providing a good candidate for comparison by processing backward and subsequent bidirectional combining. Second, the channel in (1) is relatively time-invariant whereas the channel in (2) is rapidly time-varying during the data packet duration. Third, both provide a rich breadth of data with an assortment of modulation schemes from BPSK to 32-QAM (quadrature amplitude modulation) while utilizing a similar frequency band typical for acoustic telemetry. In addition, both experiments use a common 16-element vertical receive array (VRA) whose aperture is a 56.25-m with 3.75-m element spacing. More details about the experiments can be found in Refs. 1 and 6. The LMS algorithm is employed for adaptive channel estimation while the RLS algorithm is used for the adaptive DFE. The performance metric will be the output SNR which is the inverse of the MSE.

#### 3.1 FAF06

The FAF06 experiment was carried out in a down-slope propagation environment in the Mediterranean Sea off the west coast of Italy.\textsuperscript{1} The VRA was deployed in 92 m water at 2.2-km range from a source positioned at a shallower depth. The stability of the environment coupled with a relatively short duration data packet (3 s) resulted in almost time-invariant channels. It was found that the performance of backward equalization was similar to that of the conventional forward equalization, justifying an
equal-gain combining strategy as discussed in Sec. 2.2. Combining the soft outputs of the two equalizations improved the conventional approach by 0.4–0.8 dB in terms of output SNR for various constellations up to 32-QAM. Note that the enhancement comes at the expense of doubling the training symbols and computational complexity which is modest for time reversal communications.

3.2 KAM08

The KAM08 experiment was conducted in a dynamic shallow water environment west of Kauai, Hawaii. Two VRAs were moored in about 106 m water at 4-km and 8-km ranges from a source in the middle of the water column. Due to the rapid channel variations over the duration of data packets (9 s), the block-based time reversal approach was applied to minimize the mismatch between the estimated and actual channel responses. For each data set, various block-based approaches were tested along with a conventional multichannel equalizer as described in Ref. 6. As observed with the FAF06 data, the forward and backward equalizations provided similar performance. A notable difference, however, was that bidirectional equalization improved the performance of either one alone by up to 1–1.8 dB depending on the data and the approach.

One representative example of bidirectional equalization with time reversal communications at 8-km range is shown in Fig. 3 as a scatter plot for 8-QAM modulation: (a) conventional time reversal approach and (b) bidirectional combining. With a symbol rate of $R = 1/T = 5$ ksymbol/s, the data rate is 15 kbits/s. Although not shown, about 20-ms delay spread of the channel amounts to the ISI spanning about $L = 100$ symbols. Fractionally spaced equalizers ($T/2$) are used for feedforward filter taps $a[n]$, and the number of feedforward and feedback filter taps in both directions are 100 and 50, respectively. The output SNR is 12.4 dB and 13.9 dB with the corresponding symbol error rate of 1.5% and 0.5%, respectively.

4. Conclusions

The larger improvement in KAM08 (1–1.8 dB) as compared to FAF06 (0.4–0.8 dB) indicates that bidirectional equalization is more beneficial when applied in time-varying channels where the channel diversity in opposite directions is more profound. A potential benefit of the bidirectional approach is that even if corruption of the data does not allow for processing the entire data packet, the rest of the data still can be recoverable by the backward equalization process.

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References and links


