LETTERS TO THE EDITOR

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Phase-coherent communications without explicit phase tracking (L)

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Phase-coherent communications typically requires a reliable phase-tracking algorithm. An initial phase estimate with training symbols allows a receiver to compensate for a motion-induced Doppler shift. Following the training period, however, explicit phase tracking can be avoided in time reversal communications that has been implemented on a block-by-block basis to accommodate time-varying channels. This is accomplished by a smaller block size and adaptive channel estimation using previously detected symbols on a symbol-by-symbol basis. The proposed time reversal approach without explicit phase tracking is demonstrated using experimental data (12–20 kHz) in shallow water. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3466860]

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I. INTRODUCTION

Reliable, high-speed, phase-coherent underwater acoustic telemetry faces two major challenges. One is delay spread due to multipath propagation resulting in a significant intersymbol interference (ISI). The other is Doppler spread due to temporal variation of the channel (e.g., surface waves) and/or relative motion between a source and receiver. Over the last two decades, much effort has been directed at developing adaptive channel equalizers which simultaneously remove ISI and accommodate channel variations.[1] A commonly used and effective algorithm is an adaptive decision-feedback equalizer (DFE) coupled with an external second-order phase-locked loop (PLL) for carrier phase tracking,[2] although in principle the adaptive equalizer is capable of tracking the phase. Often, the most distinct time-varying feature of the channel is a mean variable Doppler shift. An explicit PLL, capable of estimating and compensating for this phase offset in a rapid, stable manner, allows the adaptive equalizer to track the complex, relatively slowly varying channel responses.

Recently a time reversal approach to channel equalization has been studied as an alternative to adaptive multichannel equalizers.[3–5] Time reversal exploits spatial diversity to mitigate the ISI and provides near-optimum performance when combined with channel equalization[6] (see Fig. 1). In addition, explicit phase tracking usually is carried out after multichannel time reversal combining with a maximum likelihood (ML) decision-directed carrier phase estimate.[7] Note that the estimated phase is averaged across channels due to the time reversal combining process. A subsequent DFE then is relieved of the burden of carrier phase tracking while focusing on elimination of the residual ISI.

The time reversal approach, however, assumes that the channel is time-invariant or slowly varying. As an extension to either rapidly time-varying channels[5] or long duration data packets,[3] the time reversal approach has been implemented on a block-by-block basis along with channel updates using previously detected symbols (decision-directed mode). This letter shows that a potential benefit of this block time reversal approach is elimination of an explicit phase tracking algorithm required for phase-coherent communications except during the initial training period. This is accomplished by a combination of a smaller block size and adaptive channel estimation on a symbol-by-symbol basis. The most recent channel estimates then are applied as matched filters to the immediately following block, leaving just the incremental phase evolution. Any residual phase averaged across channels can be further compensated by the subsequent adaptive equalizer. The proposed time reversal approach without explicit phase tracking will be demonstrated using experimental data (12–20 kHz) collected in shallow water.

II. TIME REVERSAL RECEIVER: BLOCK-BASED APPROACH

Two approaches to time reversal communications with channel updates on a block-by-block basis have been developed to accommodate time-varying channels.[3,5] The ap-

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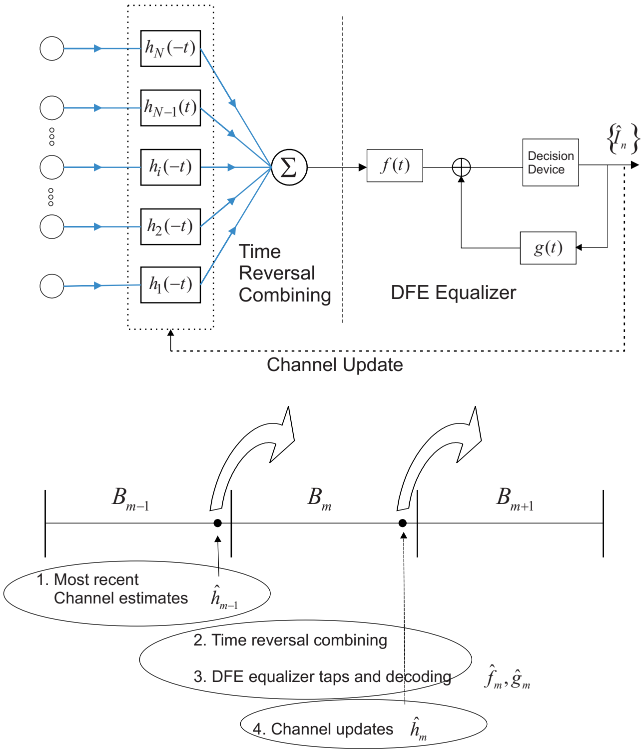

FIG. 1. (Color online) Time reversal communications on a block-by-block basis along with adaptive channel estimation on a symbol-by-symbol basis. Following the training period N_T, the most recent channel estimates from the previous block B_{m-1} in a decision-directed mode, $\hat{h}_{m-1}$, are applied as matched filters to the current block B_m, resulting in canceling the incremental phase evolution. Time reversal multichannel combining is followed by a single-channel adaptive equalizer on a symbol-by-symbol basis. The most recent equalizer taps used for decoding of the current block B_m, $\hat{f}_m$ and $\hat{g}_m$, are reused as initial equalizer taps in the following block B_{m+1}. Now update the channel $\hat{h}_m$ using detected symbols $\{\hat{I}_n\}$ in the current block B_m along with $\hat{h}_{m-1}$ as an initial condition. This approach ensures seamless processing across the blocks.

proaches are distinguished in two respects. First, Song *et al.*[5] update the channels using a least-squares (LS) algorithm so that the channel estimates are averaged over a block (see Fig. 3 of Ref. 5). On the other hand, Ref. 3 employs an adaptive least mean square (LMS) algorithm on a symbol-by-symbol basis, allowing the channels to vary slowly within a block. Note that other adaptive algorithms such as recursive least-squares (RLS) can be used, but the low-complexity LMS is chosen for faster execution of multichannel estimation while a subsequent single-channel DFE employs the RLS algorithm. Second, phase tracking is carried out separately on each channel prior to time reversal combining in Ref. 5, whereas Ref. 3 estimates the element-averaged phase after time reversal combining but prior to channel equalization (see Fig. 5 of Ref. 3). Both approaches include an adaptive DFE as a post-processor which requires initial training symbols to adjust the equalizer coefficients to their optimum values.[7] An initial phase estimate with the training symbols then allows the receiver to compensate for motion-induced Doppler shift and/or mismatch in sampling frequency.

The approach proposed in this letter is a combination of the two involving adaptive LMS channel estimation on a symbol-by-symbol basis and phase tracking on an individual channel. An interesting finding, however, is that explicit phase tracking may not be necessary after the training since each channel estimate includes the phase information which can be used for phase cancellation during the time reversal (matched-filtering) process. As illustrated in Fig. 1, the block-based time reversal approach can be summarized in steps as follows:

(1) The most recent channel estimates using an LMS algorithm from the previous block B_{m-1} in a decision-directed mode on a symbol-by-symbol basis, $\hat{h}_{m-1}$, are saved as matched filters for the current block B_m, minimizing a potential mismatch between assumed and actual channel responses.
(2) Multichannel time reversal combining produces a single channel time-series in the current block B_m. During this process, the phase can be cancelled out first at each element and then any residual phase is averaged across the channels (see Fig. 4).
(3) An adaptive DFE equalizer using an RLS algorithm on a symbol-by-symbol basis yields estimates of the current symbols $\{\hat{I}_n\}$. The averaged residual phase in Step 2 can be further compensated by the adaptive equalizer.
(4) The channel estimates $\hat{h}_m$ are updated using detected symbols $\{\hat{I}_n\}$ in the current^ block B_m along with $\hat{h}_{m-1}$ as an initial condition and saved as matched filters for the next block B_{m+1}.

Note that the most recent equalizer taps (feedforward and feedback) on a symbol-by-symbol basis from the current block B_m, $\hat{f}_m$ and $\hat{g}_m$, are reused as initial equalizer taps in the following block B_{m+1}. Thus we are updating both the equalizer taps and channel estimates on a symbol-by-symbol basis. This approach ensures seamless processing across the blocks as demonstrated with data in the next section.

III. KAM08: EXPERIMENTAL DEMONSTRATION

The proposed time reversal approach which does not require explicit phase tracking is applied to communications data collected during the KAM08 experiment carried out in shallow water from June 16 to July 2, 2008, west of Kauai, Hawaii. The schematic of the KAM08 experiment is shown in Fig. 2. Two vertical receive arrays (VRA1 and VRA2) were moored in about 106-m water at 4 km and 8 km ranges, respectively, from an 8-element source array suspended from the R/V Melville in dynamic positioning mode. The middle element at 57-m depth (Ch. No. 5) was chosen as a single transmitter during the communications experiment on June 22 (JD174) reported in this paper. The source level was 185 dB re 1 μPa at 1 m. The VRAs consisted of 16-elements spanning a 56.25-m aperture with 3.75-m element spacing, covering about half the water column. An example of the channel responses received by VRA1 at 4 km range is shown in Fig. 2, indicating a delay spread of about $T_d = 10$ ms. For a symbol rate of $R = 5$ ksymbols/s, the delay spread amounts to the ISI spanning about 50 symbols. The sound speed profiles measured within three days around JD174 are also shown in the box next to the source. Note that both the source and receivers are positioned in the dynamic region of the sound speed profile.

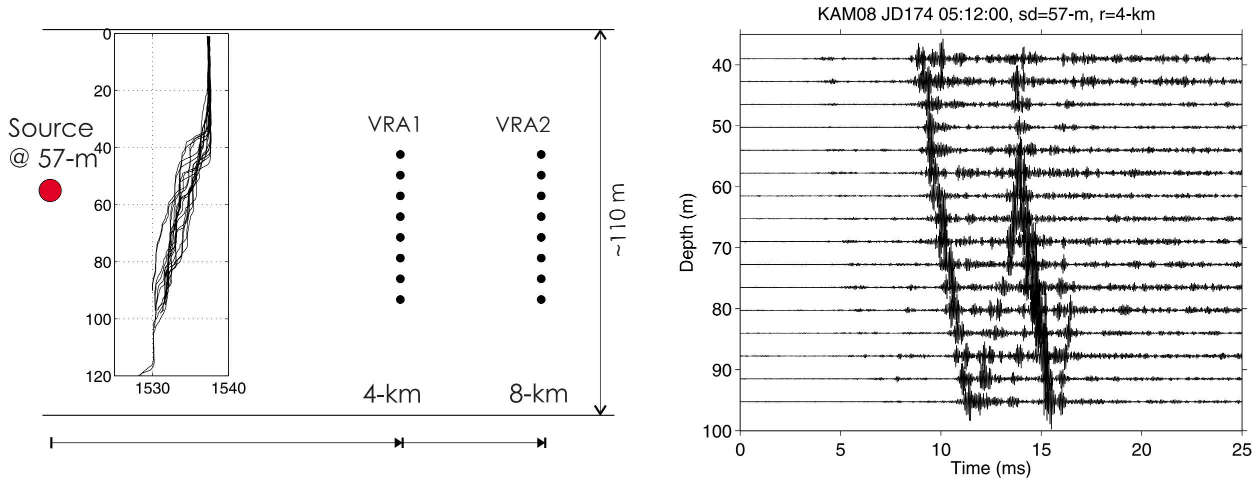

FIG. 2. (Color online) (a) Schematic of the KAM08 acoustic communications experiment. Two sets of 16-element vertical receive arrays (VRAs) were moored in about 106-m deep water at 4 km and 8 km ranges, respectively, from an 8-element source array suspended from the R/V Melville in dynamic positioning mode. The middle element at 57-m transmits the communications signal reported in this paper. (b) An example of the channel responses received by the VRA1 at 4 km range with a delay spread of about 10-ms, resulting in the intersymbol interference (ISI) spanning about 50 symbols for a symbol rate of $R=5$ ksymbols/s.

The communication signal consists of a LFM (linear frequency modulation) channel probe followed by information message signals. The duration of the data packets was 9-s utilizing a high-frequency band (12–20 kHz) with a carrier frequency of $f_c=16$ kHz. The signal shaping pulse was a square-root raised cosine filter with a roll-off factor of $\beta=0.6$. While various constellations from QPSK (quaternary-phase shift keying) up to 32-QAM (quadrature amplitude modulation) were transmitted, we present two representative examples: (a) 8-QAM at 4 km (JD174 05:12:00) and (b) QPSK at 8 km (JD174 11:12:00).

The temporal evolution of the channel responses over a 9-s period are displayed in Fig. 3 at 80-m depth. The LMS algorithm is used for channel estimation with a known sequence of symbols (training mode) and the step size is $\Delta=0.006$ and $\Delta=0.004$, respectively. During the actual decoding process, however, previously detected symbols are used for channel estimation (decision-directed mode).

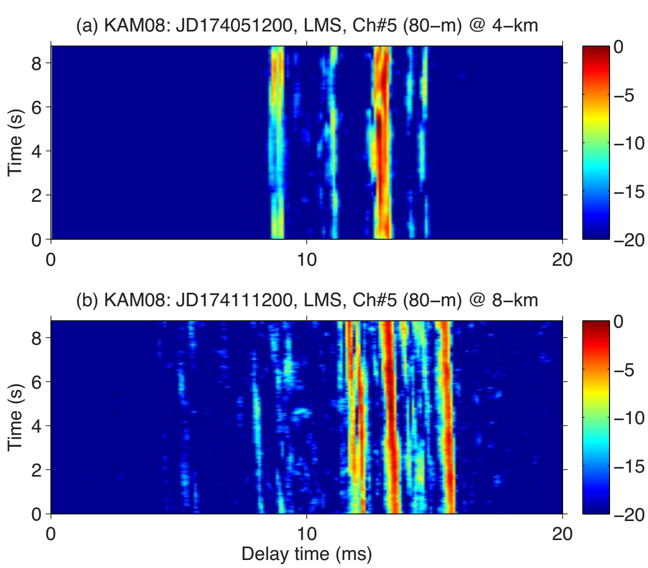

FIG. 3. (Color online) Temporal evolution of the channel response at 80-m depth with the source at 57-m depth: (a) 4-km range and (b) 8-km range. The least mean square (LMS) algorithm is used for channel estimation using the known sequence of symbols (training mode). The color scale is in dB.

To further quantify the channel variations over time, the channel correlation $C_{hh}(t)$ defined below is shown in Fig. 4 (top) for the same receiver element

$$C_{hh}(t)=\frac{\left|\int_0^{T_d}\tilde{h}^*(\tau;0)\tilde{h}(\tau;t)d\tau\right|}{\sqrt{\int_0^{T_d}|\tilde{h}(\tau;0)|^2d\tau\int_0^{T_d}|\tilde{h}(\tau;t)|^2d\tau}}, \tag{1}$$

where $\tilde{h}(\tau;t)$ is a baseband channel response at time t due to an input applied at time $t-\tau$ and $*$ denotes complex conju-

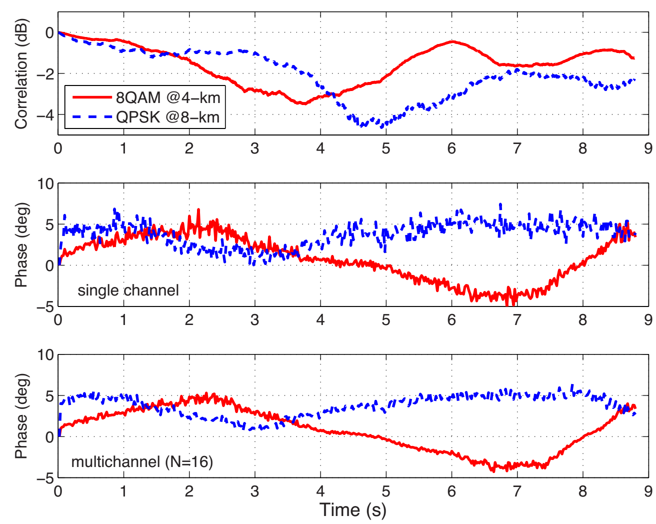

FIG. 4. (Color online) Channel correlation and differential phase defined in Eqs. (1) and (2) for the channels displayed in Fig. 3: 8QAM (solid) and QPSK (broken). The channel correlation decreases by up to 5 dB, motivating the proposed block-based time reversal approach along with channel updates. On the other hand, the differential phase variation (i.e., between blocks) is shown to be small confined to within ±5° over the entire data packet when $\Delta=20$ ms as a result of matched-filtering operation for a single channel (middle) which is smoothed out by the averaging process in multichannel time reversal combining (bottom).

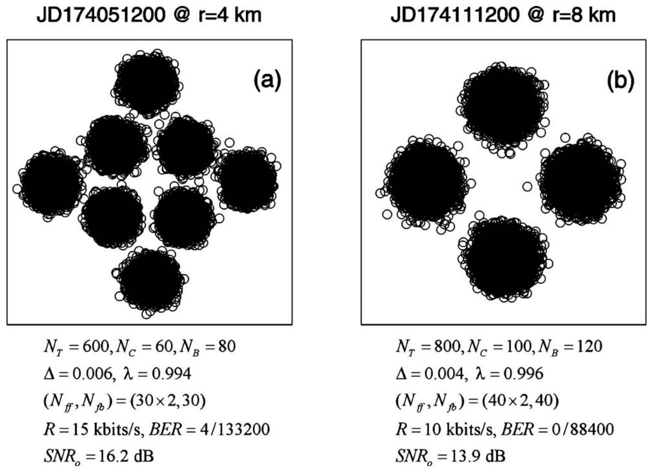

FIG. 5. Performance of time reversal communications without explicit phase tracking for a symbol rate of $R=5$ ksymbols/s: (a) 8QAM at 4-km range and (b) QPSK at 8-km range. The communication sequence is 9-s long with the signal bandwidth of 12–20 kHz. The data rate R is 15 kbits/s and 10 kbits/s, respectively. N_T, N_C, and N_B are the number of training, channel length, and block size in symbols. The initial Doppler shifts from the training symbols f_d are 0.19 Hz and 0.7 Hz. The output SNR is 16.2 dB and 13.9 dB, respectively.

gate. Thus, τ represents the delay (elapsed-time) variable and $\tilde{h}(\tau;0)$ is the reference channel estimate at $t=0$. As expected for this high frequency band (12–20 kHz), the channel variation over the 9-s period is significant by as much as 5 dB loss in correlation. Thus, either a channel probe or an initial channel estimate from the training symbols would suffer performance degradation due to mismatch between assumed and actual channel responses, motivating the implementation of the time reversal approach on a block-by-block basis along with continuous channel updates.

On the other hand, we consider a differential phase $\phi(t;\Delta)$ defined over a time window Δ after matched-filtering operation

$$\phi(t;\Delta) = \arg\int_0^{T_d} \tilde{h}^*(\tau;t)\tilde{h}(\tau;t+\Delta)d\tau. \quad (2)$$

The resulting phase variation for the same single channel is shown in Fig. 4 (middle) when $\Delta=20$ ms, being confined to within $\pm 5°$ over the entire data packet. The noisy phase variation at each element is further smoothed out by the averaging process in multichannel time reversal combining ($N=16$) as displayed in Fig. 4 (bottom) and can be compensated by the following adaptive DFE (see Fig. 1).

The performance of the block-based time reversal approach without explicit phase tracking is shown in Fig. 5 as a scatter plot using the 16-element array ($N=16$) data: (a) 8-QAM at 4 km and (b) QPSK at 8 km. The initial Doppler estimates f_d were 0.19 Hz and 0.7 Hz with training symbols N_T of 600 and 800, respectively. The block size N_B was 80 and 120 in symbols (or 16 and 24 ms in time), slightly larger than the channel estimation length N_C of 60 and 100 in symbols, although doubling the block size did not affect the performance noticeably. A fractionally spaced (two samples per symbol) DFE was employed and the number of taps for feedforward and feedback filters, (N_{ff},N_{fb}), was (60,30) and (80,40). The output SNR was 16.2 dB and 13.9 dB and the

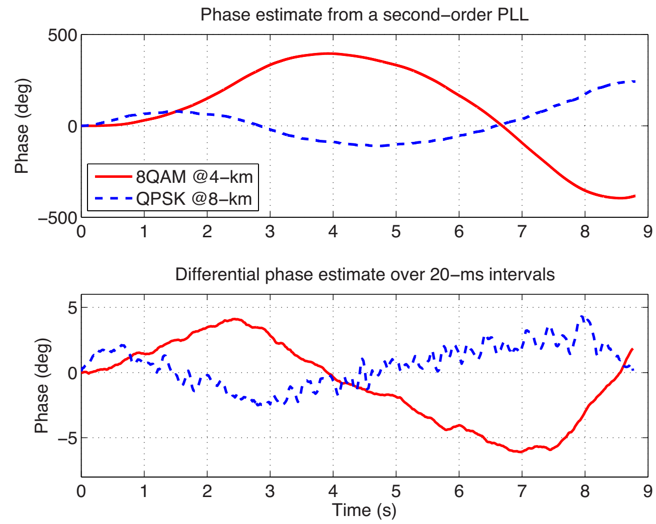

FIG. 6. (Color online) The phase estimates from a second-order PLL embedded in a multichannel DFE (top). The differential phases over 20-ms intervals (bottom) are reasonably close to the ones shown in Fig. 4 (bottom).

RLS forgetting factor was $\lambda=0.994$ and $\lambda=0.996$, respectively. The additional computational complexity for this block time reversal approach is minimal because the LMS algorithm is used for channel estimation.

For comparison purposes, we also have employed a multi-channel DFE with explicit phase tracking[2] and obtained similar performance (16 dB and 14 dB for 4 km and 8 km ranges, respectively). The phase estimates averaged across the channels resulting from a second-order PLL are shown in Fig. 6 (top). In addition, the differential phases over 20-ms intervals are displayed in Fig. 6 (bottom), being reasonably close to the ones shown in Fig. 4 (bottom). In summary, the two examples demonstrate that phase-coherent acoustic communications is possible without explicit phase tracking when the time reversal approach is implemented on a block-by-block basis along with channel estimation on a symbol-by-symbol basis.

ACKNOWLEDGMENTS

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