Long-range time reversal communication in deep water: Experimental results

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Abstract: In December 2011 a long-range acoustic communication experiment was conducted in deep water, west of Izu-Ogasawara Islands, Japan. The experiment involved a stationary source (450–550 Hz) and an 18-element vertical array (102-m aperture), both deployed at around the sound channel axis. Initial analysis of data demonstrates that a data rate of 400 bits/s can be achieved over ~600-km range in deep water using 16 quadrature amplitude modulation and passive time reversal equalization.

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1. Introduction

Over the last decade time reversal communication has been studied extensively in underwater acoustic channels as an alternative to conventional adaptive multichannel equalizers.1–3 A key aspect of time reversal is its ability to turn complex multipath propagation inherent in the oceanic waveguide into a benefit. Specifically, time reversal exploits spatial diversity to achieve temporal and spatial focusing that allows for mitigating 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. The effectiveness of the time reversal approach has been demonstrated using experimental data (1–20 kHz) collected from various shallow water environments.2–6

While research activities in underwater acoustic communication7 predominantly have been in shallow water, a few notable exceptions are reported in early 1990s. In 1991, Stojanovic et al.8 conducted a phase-coherent communication experiment in deep water off the California coast using a 1 kHz carrier and achieved 1000 bits/s using two hydrophones at ~200 km range. Two other experiments conducted in the Mediterranean Sea9,10 obtained signaling rates of 200 and 400 bits/s at 50-km range using a 1.7 kHz carrier and several hydrophones. Separately, analysis of archival data collected during tomography experiments indicated that phase-coherent communication is feasible at a basin-scale range (e.g., ~3250 km).11 By treating the tomography signal

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(m-sequence) as a binary-phase shift-keying (BPSK) communication signal, an information rate of 37.5 bits/s was achieved at a 75-Hz carrier frequency using a 20-element vertical array and time reversal equalization.

Recently long-range acoustic communication in deep water has attracted attention in conjunction with the development of long-cruising autonomous underwater vehicles.12 Time reversal communication has been applied successfully to experimental data collected at various ranges (10–1000 km) in deep water using BPSK modulation and achieved a data rate of up to 100 bits/s utilizing a 100-Hz bandwidth (450–550 Hz).12–14

In an effort to further increase the spectral efficiency with a higher data rate, a long-range acoustic experiment was conducted in deep water, west of Izu-Ogasawara Islands, Japan, during December of 2011 (see Fig. 1). The experiment involved a stationary source and a vertical receive array (VRA), both deployed at around the sound channel axis (≈1000 m) and separated by ≈600 km range. This letter reports that a data rate of 400 bits/s (i.e., a spectral efficiency of 4 bits/s Hz) can be achieved using a high-order constellation such as 16-QAM (quadrature amplitude modulation) and passive time reversal combined with a decision-feedback equalizer (DFE).

2. Communication experiment

The long-range acoustic communication experiment (KY11-11) was carried out in December 2011, west of Izu-Ogasawara Islands, south of Japan, as illustrated in Fig. 1. The data discussed in this letter were collected on December 5 and 6, 2011. An 18-element VRA (denoted by B) was deployed around the sound channel axis extending from 937 to 1039 m (102-m aperture) with 6-m element spacing, corresponding to two wavelengths (2) at the carrier frequency of 500 Hz. The VRA was moored for stable operation. The third element from the top did not work properly and will be excluded from data analysis in this letter. The source (denoted by A) also was moored at ≈1184 m depth, a little deeper than the sound channel axis (≈1000 m). The source level was estimated ≈196 dB re 1 μPa and the distance between the source and receiver was about ≈600 km. The sound speed profile measured at points A and B is displayed in Fig. 1(c) where a noticeable difference appears above the sound channel axis. There were no significant bathymetric features in the deep water bathymetry (≈4000 m) along the acoustic path.

Three data packets with different modulations were transmitted in a round-robin fashion repeatedly for about 5 h with a total of 67 packets over the two days.

Fig. 1. (Color online) (a) Schematic of the communication experiment conducted in deep water, south of Japan. The detailed map including bathymetry is shown in (b). Note that the source and 18-element vertical receive array (VRA) were moored at points A and B, respectively, and the distance between them was ≈600 km. (c) Sound speed profiles measured at points A and B. The source (o) was at ≈1184 m depth while the 102-m aperture VRA extended from ≈937 to ≈1039 m depth.
The order of the data packets was \{BPSK, QPSK, 16-QAM\}. Each data packet was 50-s long including a 5-s, 450–550 Hz linear frequency modulation chirp as a channel probe, followed by a 30-s long communication sequence at the carrier frequency of 500 Hz utilizing a 100-Hz bandwidth (450–550 Hz). The symbol rate was \( R = 1/T = 100 \) symbols/s with a total of \( N = 3000 \) symbols. The signal shaping pulse was a square-root raised cosine filter with a roll-off factor of \( \beta = 0.5 \) although the effective bandwidth of the transducer was limited to 450–550 Hz. The channel probe is useful for synchronization and channel estimation. Examples of channel impulse responses (CIRs) measured one day apart are displayed in Fig. 2 which are quite similar to that observed at basin scale (see Fig. 2 in Ref. 11) except that the delay spread is about one half (\( \sim 3 \) s). The early arriving wavefronts are visible but weak while a majority of the energy is concentrated on the later arrivals associated with lower-order modes propagating near the sound-channel axis. The later arrivals with significant energy (\( \sim 0.5 \) s) will be utilized for acoustic communication as opposed to the early identifiable rays used typically for acoustic tomography data analysis.

3. Performance analysis

To decode the communication data packets, we apply time reversal equalization that involves multichannel time reversal combining followed by a single channel DFE with a second order phase-locked loop (PLL).\(^\text{11}\) Due to the relatively short data packet (50 s), the channel remains time invariant and frequent channel updates are not necessary. Thus the estimated channels from the channel probe signal are applied as spatio-temporal matched filters for time reversal combining. Still, the first \( N_T = 200 \) symbols are used for training purposes to adjust the equalizer coefficients to their optimum values. The recursive least squares algorithm is employed for the adaptive DFE with a forgetting factor of 0.997. A fractionally spaced equalizer (i.e., two samples per symbol) is employed for feedforward filter taps, and the number of feedforward and feedback filter taps is 40 and 20, respectively. Note that 20 symbols correspond to 0.2 s which is much shorter than the delay spread (2–3 s) shown in Fig. 2. Then the total number of parameters for the adaptive DFE is 60 (\( = 40 + 20 \)). The proportional and integral phase tracking constants for the PLL are chosen as \( P_1 = 5 \times 10^{-5} \) and
The performance metrics are the input SNR to the equalizer after time reversal combining and the output SNR after equalization which is the inverse of the mean-square-error of the soft output.

The resulting performance of time reversal communication is summarized in Fig. 3(a) in terms of output SNR for a total of 67 data packets transmitted over a 5-h period, with three different modulations: BPSK (○), QPSK (□), and 16-QAM (▲). The input SNR (+) evaluated after time reversal combining is superimposed for comparison purposes. Note that the output SNR, ranging between 14 dB and 22 dB, closely follows the characteristics of the input SNR (~5 dB below) regardless of modulation, indicating that the output SNR is a reasonable metric. An example of a 16-QAM data packet (57th, solid triangle) is shown in Fig. 3(b) as a scatter plot with an output SNR of 20 dB and no errors. For the symbol rate of $R = 100$ symbols/s, the data rate amounts to 400 bits/s achieving a spectral efficiency of 4 bits/s Hz. Although not shown here, another 5-h data transmission the following day exhibited similar performance.

![Fig. 3. (Color online) (a) Performance of time reversal communication over a total of 67 data packets with three different modulations alternating: BPSK (○), QPSK (□), and 16-QAM (▲). The input SNR (+) evaluated after time reversal combining is superimposed for comparison purposes. (b) Performance of a 16-QAM data packet (57th, solid triangle) as a scatter plot. The output SNR is 20 dB and the data rate is 400 bits/s for the symbol rate of 100 symbols/s.](image)

$P_2 = 5 \times 10^{-6}$, respectively. The performance metrics are the input SNR to the equalizer after time reversal combining and the output SNR after equalization which is the inverse of the mean-square-error of the soft output.

Fig. 4. (Color online) (a) Impact of spatial diversity on the performance of 16-QAM communication sequence shown in Fig. 3(b). The elements are combined sequentially either from the bottom (■) or from the top (▲) of the array, and the corresponding input SNRs are superimposed. (b) The normalized $q$-functions are displayed for $M = 1, 5, 17$. 

![Fig. 4. (Color online) (a) Impact of spatial diversity on the performance of 16-QAM communication sequence shown in Fig. 3(b). The elements are combined sequentially either from the bottom (■) or from the top (▲) of the array, and the corresponding input SNRs are superimposed. (b) The normalized $q$-functions are displayed for $M = 1, 5, 17$.](image)
The impact of spatial diversity ($M$) on the communication performance is illustrated in Fig. 4(a) for the 16-QAM data packet shown in Fig. 3(b). The elements are combined sequentially either from the bottom (●) or from the top (●) with the corresponding input SNRs. The number of feedforward and feedback taps remains the same for the analysis. Both directions show a similar behavior in performance which initially improves rapidly with the first few elements and then gradually increases with an increase in the number of array elements. Similar to Fig. 3(a), the output SNR follows closely the input SNR. Taking advantage of spatial diversity requires an appropriate element spacing to ensure the CIRs are sufficiently different from one another and characterized by a $q$-function representing the summation of the autocorrelation of each CIR. The VRA element spacing is 6 m which corresponds to $2\pi$ at 500 Hz. The normalized $q$-functions are displayed in Fig. 4 for $M = 1, 5, \text{and } 17$ where the sidelobe levels decrease as $M$ increases, indicating that there is sufficient element spacing. As a separate confirmation, we did not find any noticeable difference between the case of selecting every other element ($M = 9$) and using just the first nine elements with half the aperture.

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**References and links**