An overview of time-reversal acoustic communications

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AN OVERVIEW OF TIME-REVERSAL ACOUSTIC COMMUNICATIONS

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This paper will present an overview of the application of the time-reversal process to acoustic communications. Coherent underwater acoustic communication systems must mitigate the inter-symbol interference caused by the time-varying, dispersive, shallow-water ocean environment. Time reversal, or phase conjugation, focuses energy back to its origin despite the complexity of the propagation channel. The spatial and temporal focal properties of time-reversal reduces dispersion and channel fading in addition to increasing the SNR at the receiver. These properties make time reversal a stand-alone technique or an attractive component of a coherent communication system.

1 Introduction

Reliable high speed communication in the ocean is a challenging problem. Modern coherent underwater communications must deal with the inter-symbol interference caused by time-varying multipath environments. The ocean is a bandwidth limited channel where signals are susceptible to fading, noise, and attenuation. In order to achieve low bit error rates most system employ a combination of adaptive equalization, spatially diverse receivers, and error correction encoding. Another way to overcome these challenges is by utilizing the principle of time reversal.

Time reversal, or phase conjugation in the frequency domain, is a process where a source at one location transmits sound which is received at another location, time reversed, and retransmitted. The retransmitted sound then focuses back at the original source location, where the reception is relatively free of multipath contamination. The first time-reversal ocean experiment occurred over 40 years ago when Parvulescu and Clay used a single element receiver/transmitter pair [22, 23]. Recently the idea once again appeared in the acoustic literature in an ultrasonic laboratory setting [19, 17]. Instead of retransmitting with a single receiver/transmitter, an array or time-reversal mirror (TRM) was used to focus sound.

In 1996 Kuperman et al. demonstrated that the time-reversal process could be used to focus sound at sea despite the inherent variability [12]. Working jointly with what is now called the North Atlantic Treaty Organization Undersea Research Centre (NURC), they were able to focus sound more than 18 miles away. And even more remarkably, they did this without needing laborious measurements of the water column and sediment.

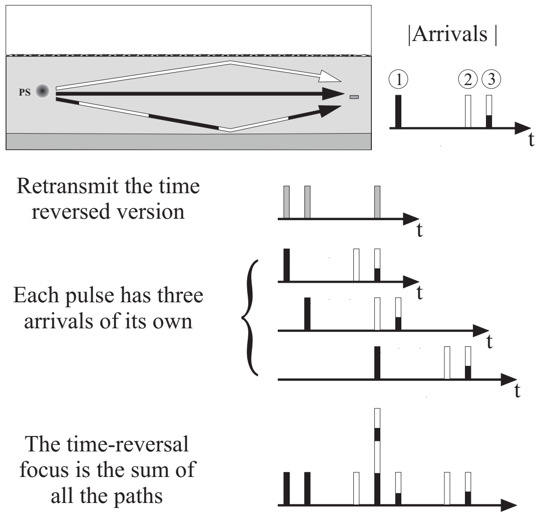

Figure 1. From the point of view of Parvulescu and Clay [22, 23] a probe source (PS) ping is received by a single element some distance away. It receives three equal amplitude arrivals representing direct, bottom, and surface reflected paths. The recording is time reversed and retransmitted. Each of the three pulses produces three reciprocal echoes of their own. Since waves are linear each path adds at the PS position.

2 Time Reversal

Time reversal is made possible by the reciprocity of wave propagation in the ocean. Thus if a receiver and transmitter were swapped the same measurements would be recorded.

Parvulescu and Clay performed a series experiments on the reproducibility of signals measured in the ocean [22, 23]. They recorded, reversed and played back the channel response measured at a distant source/receive element while listening at the original source location as shown in Fig.1. They envisioned a receiver measuring three distinct ray paths from a probe source (PS). The magnitude of the direct, surface, and bottom bounce arrivals are pictured as equal amplitude impulses in the upper right corner. The channel response is time-reversed and retransmitted. By reciprocity, each of those three impulses produces three paths of their own such that nine total paths will arrive back at the PS. The time-reversal focus is the sum of all of these paths with three of the paths adding coherently at the PS. From this point of view, extended multipath produces a focus with higher peak-to-sidelobe ratio. Although some temporal recombining was measured in their experiment, effective time-reversal focusing requires multiple elements. By adding more elements, the total number of paths are increased thus aiding the focus.

Fink et al. carried out a series of experiments with a large aperture TRM at ultrasonic frequencies [19, 17, 18, 16]. One of these experiments investigated the improved spatial resolution of the time-reversal process by adding steel rods between a TRM and the PS. Compared with the free space resolution, the effective aperture of the TRM was enlarged by the multiple scattering of the rods [30]. They also investigated a waveguide which is analogous to the ocean [29]. Blomgren et al. carried out analysis of the increased effective aperture denoted ”super resolution” in mathematical literature [2].

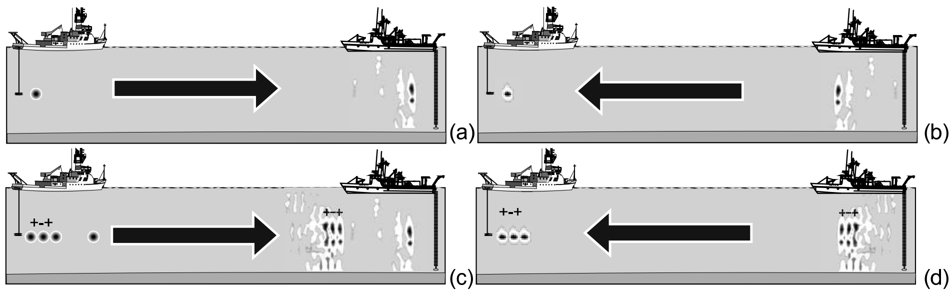

Figure 2. The basic experimental setup for an at sea time-reversal communications experiment is shown. (a) A PS emits a ping which is capture by an array of source/receiver elements. (b) This array retransmits the time-reversed version of the captured ping. The ping focuses back to the original PS location. (c) A passive time-reversal system transmits the PS followed by a standard communication sequence. The transmission is matched filtered and combined in computation. (d) Using the channel response in (b) as a communications symbol, that symbol is phase encoded and combined into a communications sequence. Though there is substantial overlap at the TRM the sequence focuses back at the receiver.

The application of a water column spanning array to focusing sound in the ocean waveguide was first proposed theoretically in the early 1990s by Jackson et al. $[10, 11, 4, 3]$. Simulations showed the potential use of an array of acoustic source/receive elements to focus energy without knowledge of the ocean. In the late 1990s, ocean acoustic time reversal was implemented by Kuperman et al. $[12, 13, 14]$. The initial experimental work took place at 450 Hz where a focus at up to 30 km in range and over time periods of days was measured. The stability of the time-reversal focus was noted and a method to change the focal range by shifting frequency was demonstrated $[9, 32]$.

3 Time Reversal Communications

Since the idea of applying the time-reversal process to underwater communication was first put forward $[28]$ time-reversal communications has become an active area of research. This section will begin with an example of an active time-reversal communications scheme. It will then discuss advances made in passive time-reversal communication systems. Lastly, adaptive time-reversal communications will be discussed.

3.1 Active Time-reversal Communications

Figure 2 shows a diagram of a typical at sea time-reversal communications experiment. A PS is shown in (a) initializing the TRM. The channel response is captured and time reversed. If retransmitted the signal would focus back at the PS location as shown in (b). Two bits of information are carried by transmitting either the time-reversed signal or its negative in (d). Although there will be substantial overlap at the TRM, the individual foci compress both spatially and temporally at the PS. More advanced time-reversal transmissions can be made with any typical encoding scheme. In essence, the time-reversed channel response becomes a type of array shading not dissimilar to Eigenvector beamforming $[15]$.

An active time-reversal communications system was first suggested for underwater communications $[12]$ and some calculations for a 3500 Hz pulse with a kilohertz bandwidth were carried out which demonstrated the temporal multipath recombination and sidelobe suppression needed for underwater communications [13]. The experimental application of a time-reversal communication system are discussed in [1, 8, 6, 5, 7]. At sea-experiments demonstrated successful shallow-water coherent communications over 10 km, with a carrier frequency of 3500 Hz, a bandwidth of 500 Hz, and a bit rate of 1000 Hz.

Currently 3500 Hz systems have been able to reliably transmit simultaneously 8 QAM transmissions to multiple listeners [33]. The focal properties of the time-reversal process were able to suppress cross-talk even though the receivers were at the same range and only separated by depth.

3.2 *Passive Time-reversal Communications*

Rouseff et al. suggested a passive phase conjugation communication system [25, 27, 20]. In this literature, time reversal is referred to as active phase conjugation. Instead of using a TRM to actively transmit a time-reversal communications sequence to the PS the array passively correlates each channel with a measured PS signal as shown in Fig. 2 (c). In essence, the system transmits a communications sequence as would be done in typical single source communications. However, before the communications sequence is sent to a receive array, a channel probe is sent first. The channel response is windowed, matched filtered with each channel and the results then combined across channels. This process naturally time aligns the channels before summing thus increasing the signal-to-noise ratio. Recently scaling rules for how passive phase conjugation performs as a function of bandwidth, number of array elements, the spacing of the array elements, and the quality of the estimated impulse response have been developed [24]. The temporal resolution of passive phase conjugation was explored with both simulation and data [36]. Coherent shallow water communication over 10 km, with a bandwidth of 500 Hz, at a center frequency of 3550 Hz was shown.

3.3 *Adaptive Time-reversal Communications*

Most successful coherent communication systems utilize some form of adaptive channel equalization. Although time-reversal communications is a stand alone method, it can benefit from post-processing at the receiver. Since the time-reversal process degrades as the ocean changes an adaptive receiver could increase the time intervals between PS update. Additionally, some residual inter-symbol interference remains in the transmissions which could be mitigated by an equalizer. A time-reversal transmission is ideally suited for post processing due to the fact that the temporal focus of the time-reversal process increases the signal-to-noise ratio as well as reduces spatial fading and multipath. Since the burden of spatial diversity is shifted to the transmitter, only a single element receiver is required. Such systems have been tested with success showing marked improvement in bit error rates [7, 35, 34].

Similarly passive phase conjugation communications can benefit from adaptive processing. Adaptive systems can be used to update or even estimate the channel response. Data directed equalizers have been shown to update the matched filters that are used on subsequent data symbols. Such data directed channel responses can provide better results that the measured channel response [21]. The effect of different modulations schemes, bandwidths, and number of array elements were explored using transmissions simulated from data directed estimates of the time-varying channel response [26].

4 Conclusion

A time-reversal communication system takes advantage of its ability to focus sound without *a priori* information of the ocean. Time reversal recombines multipath propagation thus reducing both channel fading and inter-symbol interference as well as increasing the signal-to-noise ratio. Additionally the time-reversal focus yields two beneficial side effects: It reduces cross-talk and benefits only the desired listener. Since a time-reversal signal is dispersed except at the focal spot, it reduces cross-talk between multiple listeners. Additionally only the privileged listener at the focal region would receive the signal-to-noise gain and reduction of multipath. The ability to communicate simultaneously with multiple listeners without crosstalk increases the effective Shannon channel capacity of the channel [15].

A time-reversal system is a stand alone system that requires no computationally intensive algorithms. However an active time-reversal system is well-suited for post-processing using adaptive algorithms. Such algorithms could extend the period before needing to update the PS and help reduce residual inter-symbol interference. Passive systems also benefit by using adaptive algorithms to estimate and update the channel response.

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