Time Reversal with MISO for Ultra-Wideband Communications: Experimental Results (*invited paper*)

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***Abstract* — Time reversal (TR) communications marks a paradigm shift in UWB communications. The system complexity can be shifted from the receiver to the transmitter, which is ideal to UWB sensors. UWB Multiple Input Single Output (MISO) is enabled by the use of the TR scheme. Two basic problems are investigated experimentally using short UWB radio pulses (nanosecond duration). Temporal focusing and SNR increase with the number of antennas are verified. Also, reciprocity of realistic channels, the foundation of TR, is demonstrated for the first time in electromagnetics.**

***Index Terms* — TR, MISO, UWB, channel reciprocity.**

I. INTRODUCTION

UWB has found a new application for lower-data-rate moderate-range wireless communications, illustrated by IEEE 802.15.4a with joint communication and ranging capabilities unique to UWB. The application of UWB to low-cost, low-power sensors is promising. The centimeter accuracy in ranging and communications provides unique solutions to applications, including logistics, security applications, medical applications, control of home appliances, search-and-rescue, family communications and supervision of children, and military applications.

The central issue facing UWB community is the complexity of the receivers [5]. Time reversal (TR) seems be a paradigm shift in UWB communications. The complexity of the receivers can be shifted to the transmitter, which is idea for the sensors. By using TR, extremely simple non-coherent receivers can be used to enable low-cost and low-power sensors.

The irreversibility of time is a topic generally associated with fundamental physics. The object is to exploit time reversal invariance, a fundamental symmetry that holds everywhere in fundamental particle physics to create useful systems. What one wants is macroscopic time-reversal invariance. Happily this symmetry does hold in both acoustic-wave and electromagnetic-wave phenomena.

II. THEORY

The configuration of an UWB MISO system with 4 transmitting antennas and one receiving antenna is illustrated in Fig. 1.

The antenna array can be viewed as a time-reversal mirror (TRM) that records a waveform $f(t)$, time reverses it, and then retransmits $f(-t)$. There are three steps in TR communications. First a signal, $x(t)$, is transmitted at the receiver side to sound the channel with the channel impulse response (CIR) (from Rx to Tx), $h_m(t)$, at the *m*-th transmitter antenna. Second, the

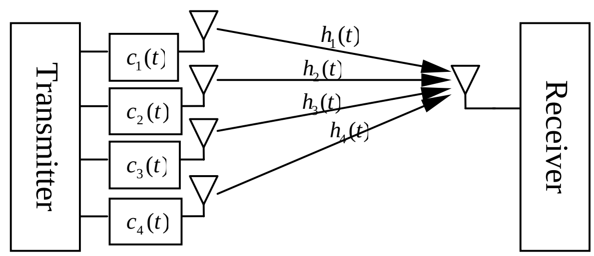


Fig. 1. Precoded MISO communication systems with M=4 transmitting antennas and one receiving antenna.

transmitter records the received signal, $y_m(t) = x(t) * h_m(t)$. Third, the transmitter transmits data and uses the time reversed signal as the precoding filters, i.e., $c_m(t) = A_m y_m^*(-t)$. The channel reciprocity implies that the CIRs (from Tx to Rx) are identical to the CIRs (from Rx to Tx) and both are represented by $h_m(t)$. This reciprocity is the foundation of TR (to be experimentally verified later). Assuming the channel reciprocity, the received signal can be expressed as

$$\begin{aligned} y(t) &= \sum_{m=1}^{M} x(t) * c_m(t) * h_m(t) + n(t) \\ &= R_{xx}(t) * \left(\sum_{m=1}^{M} A_m R_{h_m h_m}(t) \right) + n(t) \end{aligned} \tag{1}$$

where *n(t)* is the noise at the receiver, * denotes the convolution operation and $R_{h_m h_m}(t) = h_m^*(-t) * h_m(t)$ is the autocorrelation of $h_m(t)$. $R_{xx}(t)$ denotes the autocorrelation of $x(t)$. If $x(t)$ is properly chosen, a low-amplitude, long-power lasting signal can be compressed to form a high-power pulse [8]. A typical example is the "chirped" signal $\exp(j\alpha t^2)$: correlation it with itself generates a Dirac pulse since $\exp(j\alpha t^2) * \exp(j\alpha t^2) = \delta(t)$. If a chirp signal is used, according to (1) $R_{h_m h_m}(t)$ will dominate the performance. Different sets of scaling factors A_m could be chosen to describe different power allocation situations [4]. Equal power allocation scheme is employed in our experiments, i.e.,

$$A_m = \frac{1}{\sqrt{M}\sqrt{\|h_m(t)\|^2}} \tag{2}$$

The equivalent channel is

$$h_{eq}(t) = \sum_{m=1}^{M} A_m R_{h_m h_m}(t) \tag{3}$$

A. Compensation for Pulse Waveform Distortion

A UWB channel shares many similarities to an acoustical channel. A wave originating from a point scatterer and propagating in an inhomogeneous medium is not only delayed. The spatial and temporal shape of the wave is also distorted through refraction, diffraction and multiple scattering. For a pulse signal, all the individual received waveforms need to be taken into account for optimal reception [1-3]. A generalized multipath channel model [2,3,5] is proposed for each $h_m(t)$. To simplify the notation let us drop the index m for the transmitter antennas. It follows that

$$h(t) = \sum_{l=1}^{L} a_l h_l(t) * \delta(t-\tau_l) \tag{4}$$

where L generalized paths are associated with amplitude a_l, delay τ_l, and per-path impulse response $h_l(t)$. The $h_l(\tau)$ represents an arbitrary function of the normalized energy. The autocorrelation of the CIR

$$\begin{aligned} R_{hh}(t) = \sum_{l=0}^{L-1} a_l^2 \left\{\left[h_l(t) * h_l(-t)\right]\right\} + \\ \sum_{\substack{i=0 \\ i\neq k}}^{L-1} \sum_{k=0}^{L-1} a_i a_k \left\{\left[h_i(t) * h_k(-t)\right]\right\} * \delta[t-(\tau_k-\tau_i)] \end{aligned} \tag{5}$$

At $t=0$, $R_{hh}(0) = \sum_{l=0}^{L-1} a_l^2$ which is the total energy of the CIR. At this point, all the energies of L paths add coherently (focused around $t=0$). However this is not true for $t \neq 0$, as the terms in the second part of Eq. (5) will add destructively and form noise-like spikes.

B. Coherent Sum of Signals Transmitted from M Antenna Elements

The autocorrelation of an arbitrary function is symmetric and reaches its maximum (equal to the energy of this function) at the center of its time axis. Thus at $t=0$, $R_{h_m h_m}(t)$ is always positive and reaches its maximum. According to (3), all contributions from M antenna elements add constructively around $t=0$, whereas at earlier or later times uncorrelated contributions tend to interference destructively. The recreation of a sharp peak (around $t=0$) after TR on an M-element array can be viewed as an interference suppression process between the M outputs of M matched filters. Even if $h_m(t)$ are completely random and apparently uncorrelated signals, each term in this sum adds constructively. This may be the most important property of MISO-TR. One application of the resultant compressed sharp pulse is to eliminate ISI.

After TR, the uncorrelated signals are compressed into a very high peak pulse around the center of the receiver output (see e.g. Fig.6). If one transmitter antenna is used, the peak accounts for around 50% of the total energy of the CIR for a typical indoor channel. In other words, only 3 dB will be lost if only the high peak is used for detection. When M transmitter antennas (MISO) are used, the SNR will increase proportionally to $\sqrt{M}$ [1]. For example, if M=4, the SNR increase by a factor of 2, as seen in our experimental results (Fig.6).

C. Channel Reciprocity

The channel reciprocity or symmetry is the foundation of TR, as seen from the above derivation. Analytical solutions for the CIRs are infeasible in realistic cannels. As in acoustics [1], in electromagnetics the dissipation of the channel will theoretically make the reciprocal theorem break down in inhomogeneous media. What one wants is macroscopic time-reversal invariance. In what degree can the channel be treated as reciprocal (or symmetric)? This question is very basic. Unfortunately to our best knowledge no prior work regarding this topic has been published in electromagnetics. In this paper, some initial verification has been obtained using the time domain UWB radio pulses indoors.

D. Extreme Simple Receivers

Due to short UWB pulses that requires extremely high sampling rate, coherent receivers like RAKE and OFDM are too complicated for some applications. A transmitted reference based receiver requires a long delay line that is very difficult to implement in hardware. Non-coherent receivers like energy detection and leading edge detection are very promising for UWB sensors. Here we propose to use TR as the precoding scheme combined with simple non-coherent receivers. Intuitively these types of new systems will behave very close to the coherent schemes. The theoretical and simulation work to support this claim will be reported elsewhere due to the limitation of space.

One way is to view the TR (Eq. (3)) as a “spatial spreading” system, similar to the spread spectrum. One pulse is spatially spread to a large number of pulses (e.g., 80-200 pulses). This is called spatial spreading with the

PN code $h_m(-t)$. This spatial spread signals are transmitted at Tx (precoding). After TR process at the receiver, the channel decodes or despreads the transmitted signal with the code $h_m(t)$. The random channel information unique to the pair of transmit and receive antennas (e.g., Fig. 4) has been used to decode the transmitted information. This feature introduces LPI/LPD, as demonstrated in [6,7]. The low complexity of TR is due to the fact that it uses the channel itself as the matched filter. Each distorted pulse serves like a “chip” in a spread spectrum.

More interesting is the fact that sampling the CIR and using reduced-bit A/D conversion can be as good as full-rate and normal-resolution (8 bits) A/D approach [8]. Low rate (say, the Nyquist rate) sampling with one-bit A/D conversion greatly simplifies the transmitter complexity of realizing TR, which is the primary concern in TR implementation. Some implementation schemes have been reported by us recently [7].

These simple receivers may be of interest to indoors, urban, forest, shipboard, and oversea HF communications. HF UWB uses surface wave propagation and operates in the band of 30-50 MHz. Digital implementation of pulse waveform for HF is quite feasible using today’s technology.

III. CHANNEL RECIPROCITY

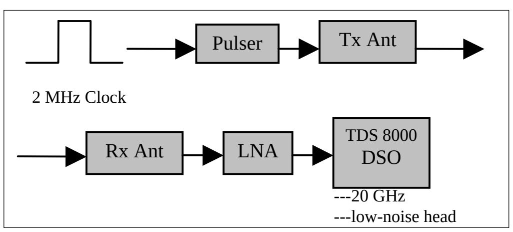


Fig. 2 Experiment setup

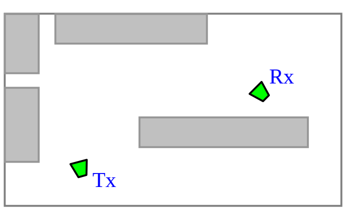
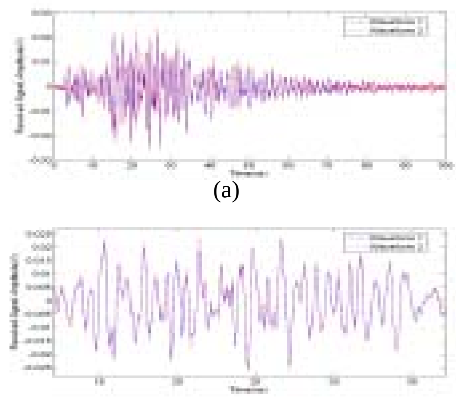


Fig. 3 Experimental layout

The test setup was reported in [7]. A DSO is used to capture short UWB pulses. The sounding pulse has a 10 dB bandwidth of 700MHz-1.6 GHz. Directional horn antennas are used. Amazingly two received waveforms in the reciprocal channels of Fig. 3 almost coincide with each other, as shown in Fig. 4. The correlation between these two waveforms is as high as about 0.96. This plot demonstrates channel reciprocity. In Fig. 4 (a) waveform 1 (dash curve) and waveform 2 (solid curve) are measured under the same conditions, except that the transmitter (excluding antenna) and the receiver (excluding antenna) are switched. Fig. 4 (b) shows a closer look of Fig. 4 (a) with the arrival time from 10 ns to 40 ns.



(a)

(b)

Fig. 4 Comparison of Received Waveforms in the Reciprocal Channels of Fig. 3

IV. MISO UWB TIME REVERSAL

A set of measurements has been conducted in a lab/office area of TTU. That is a typical indoor area with wooden and metallic furniture (chairs, desks, bookshelves and cabinets). All the measurements were conducted during off-peak hours (midnight) to ensure channel stationary. .Antennas used in the experiment are omni directional ones with linear polarization. The height of both Tx and Rx antennas was set to 1.4 m.

A virtual antenna array was employed in the experiments. Note that the virtual antenna array has no mutual coupling, regardless of element spacing. To emulate a real antenna array with negligible mutual coupling effect, in the measurements the distance between any two adjacent antenna elements was set to 20 cm, which is far enough to ignore the mutual coupling effect. A Tx antenna array of four elements equally spaced along a line was used to emulate a (4,1) SIMO system. The antenna (element) was moved to different locations, and individual channel was sounded and measured sequentially. No Line of Sight (LOS) was available for all the measurements.

Four receiving waveforms at each location are shown in Fig. 5. Different waveform distortions are observed for different locations. As shown in Fig. 6, time reversal coherently combines these different waveforms (through Eq. (3)) without complicated channel estimation [2,3,5].

In Fig. 6 the CLEAN algorithm was applied to extract the CIR from individual measurements [7].

V. CONCLUSION

UWB Multiple Input Single Output (MISO) is enabled by the use of the TR scheme. Two basic problems are investigated experimentally using short UWB radio pulses (nanosecond duration). Temporal focusing and SNR increase with a number of antennas are verified. Also the channel reciprocity, the foundation of TR, is also demonstrated for the first time in electromagnetics.

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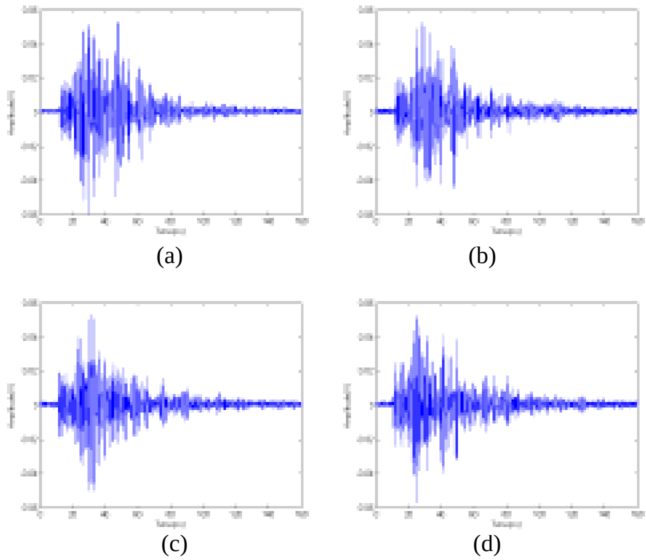

Fig. 5 Received Waveform for each virtual antenna.

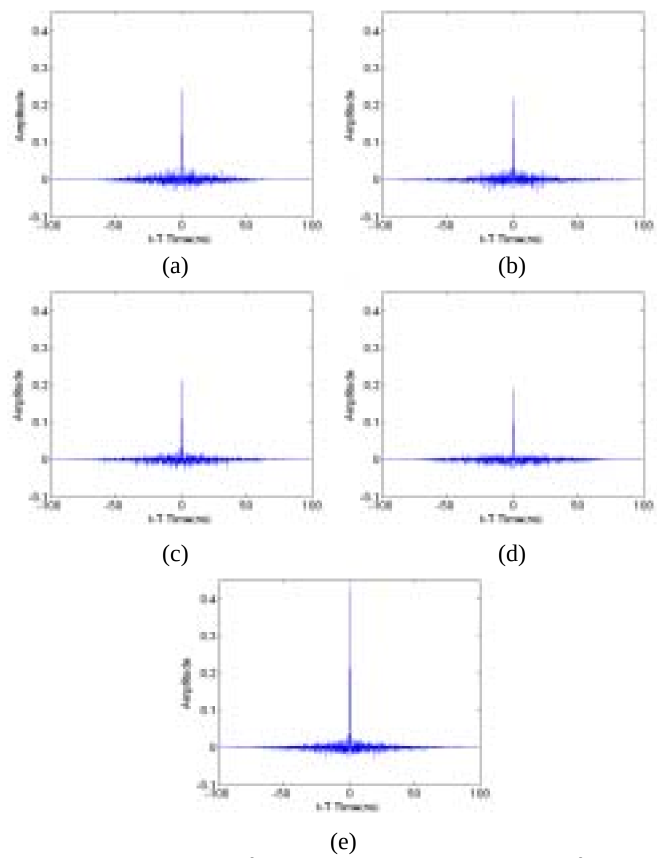

Fig. 6. A comparison of equivalent impulse responses defined in Eq. (3). (a), (b), (c) and (d) are equivalent impulse responses of a SISO system for different channels; (e) is the equivalent impulse response of the corresponding MISO system.