

Time Reversal With MISO for Ultrawideband Communications: Experimental Results

Robert C. Qiu, Chenming (Jim) Zhou, Nan Guo, and John Q. Zhang

Abstract—Time reversal (TR) communications marks a paradigm shift in ultrawideband (UWB) communications. The system complexity can be shifted from the receiver to the transmitter, which is ideal to some applications. 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 increase in collected-energy with the number of antennas are verified. Also, the reciprocity of realistic channels, the cornerstone of TR, is demonstrated perhaps for the first time in electromagnetics.

Index Terms—Channel reciprocity, multiple input–single output (MISO), time reversal (TR), ultrawideband (UWB).

I. INTRODUCTION

ULTRAWIDEBAND (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 pioneering work on UWB has been done by Win and Scholtz [9]–[11], including the first channel measurements [10], [11], basic UWB impulse radio [12], and foundation for RAKE receiver analysis [12], [13]. One central issue facing UWB community is to effectively collect energy that is dispersed in rich multipath [9], [10], [5], [15], [16]. Time reversal (TR) appears to be a paradigm shift in exploiting the rich multipath unique to a UWB channel. As a result, the complexity of the receiver can be shifted to the transmitter, which is ideal for some applications. By using TR, extremely simple noncoherent receivers can be used for low-cost and low-power sensors. Synchronization [17], [18] is critical to TR.

The irreversibility of time is a topic generally associated with fundamental physics. The objective here is to exploit TR invariance, a fundamental symmetry that holds everywhere in fundamental particle physics to create useful systems. What one

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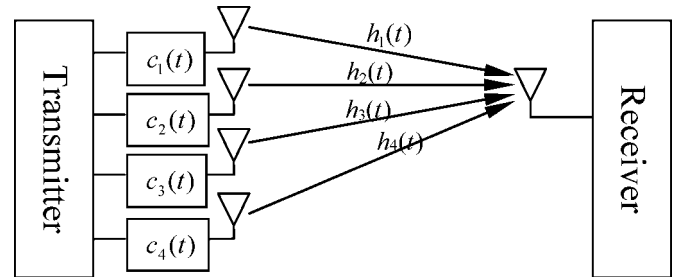


Fig. 1. Precoded MISO communication systems with $M = 4$ transmitting antennas and one receiving antenna.

wants is macroscopic TR invariance, (such as the UWB channel composed of randomly formed multipath). Happily, this symmetry does hold in both acoustic-wave and electromagnetic-wave phenomena. Many applications of the reciprocity theorem are treated in [14] and the results of reciprocity have been verified in many electromagnetic systems. It is perhaps the first time that it has been verified in this particular UWB system in rich multipath environments. If the sounding pulse is sufficiently short, the channel impulse response (CIR) is composed of a number of resolvable pulses that are formed through different paths. If propagation is reciprocal along each path, the channel represented by the CIR is also reciprocal.

II. THEORY

The antenna array configuration of a UWB MISO system with four transmitting elements and one receiving element 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 its CIR (from Rx to Tx), $h_m(t)$, between the receiving element and the m th transmitting element. Second, the transmitter records the received signal, $y_m(t) = x(t) * h_m(t)$. Third, the transmitter transmits data and uses the TR 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 $h_m(t)$. Assuming the channel reciprocity (that will be experimentally confirmed later), the received signal can be expressed as

$$y(t) = R_{xx}(t) * \left(\sum_{m=1}^M A_m R_{h_m h_m}(t) \right) + n(t) \quad (1)$$

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 auto-

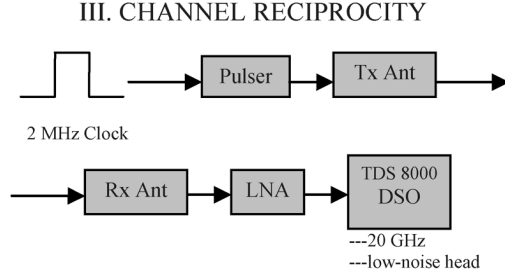


Fig. 2. Experiment setup.

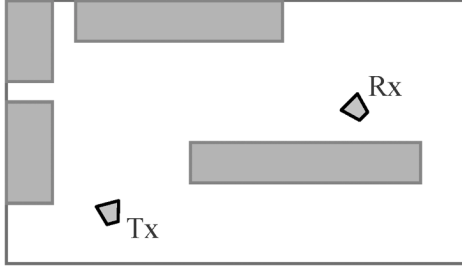


Fig. 3. Experiment layout.

correlation of $h_m(t)$. The $R_{xx}(t)$ 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 $\exp(j\alpha t^2)$; correlating 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) the $R_{h_m h_m}(t)$ 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 processing our experimental data, i.e.

$$A_m = \frac{1}{\sqrt{M} \sqrt{\|y_m(t)\|^2}}. \quad (2)$$

From (1), the equivalent channel is defined as

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

A. Compensation for Pulse Waveform Distortion

A UWB channel shares a number of similarities to an acoustic 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

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

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 unit energy. The autocorrelation of the CIR

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

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

B. Coherent Sum of Signals Transmitted From M-Antenna Elements

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 pulse of sharp peak that is located around the center of the equivalent CIR defined in (3) (see Fig. 6). If one transmitter antenna element is used [single-input–single-output (SISO)], 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 the energy of only the sharp peak is detected. When M transmitter antennas (MISO) are used, however, the peak of the equivalent CIR will increase proportionally to \sqrt{M} [1]. For example, if $M = 4$, there is a gain factor of 2, as seen in our experimental results (Fig. 6). In terms of energy, the MISO-TR achieves a gain of M over the SISO-TR. This gain is called the array gain achieved from the coherent diversity combining performed in (3). Note that the gain is available in the absence of the fading. But different from a narrowband system, here the diversity gain is negligible since the channel is almost static.

C. Channel Reciprocity

Analytical solutions for the CIRs are infeasible in realistic channels. As in acoustics [1], the dissipation of the channel will theoretically cause the reciprocal theorem in electromagnetics to break down in inhomogeneous media. What one wants is macroscopic TR invariance. In what degree can the channel be treated as reciprocal (or symmetric)? This question is basic. In this letter, some initial verification has been obtained using the time domain UWB radio pulses indoors. See Section IV.

D. Extreme Simple Receivers

Since nanosecond pulses require high sampling rates that are expensive to realize in today’s semiconductor industry, coherent receivers like RAKE and OFDM are too complicated to collect

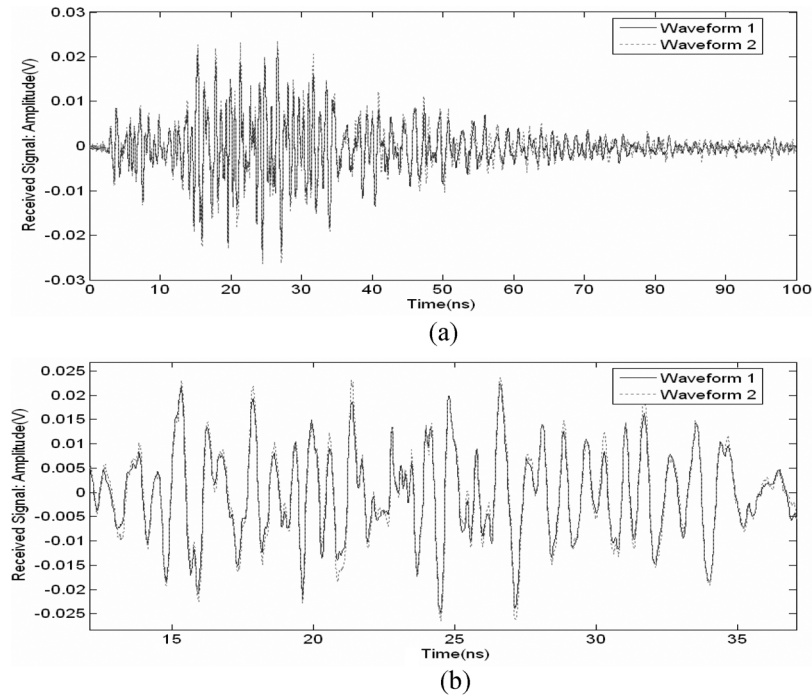


Fig. 4. Comparison of received waveforms in the reciprocal channels of Fig. 3.

energy from rich multipath in the UWB channel [10]–[13]. A transmitted reference based receiver requires a long delay line that is very difficult to implement in hardware [5]. Noncoherent energy-detection is promising for UWB sensors. Here we propose to use TR as the precoding scheme through TR signaling.

One way is to view the TR [(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 transmitter, 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.

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 [6]. These simple receivers may be of interest to indoors, urban, forest, shipboard, and oversea HF communications. HF UWB operates in the band of 30–50 MHz.

III. CHANNEL RECIPROcity

The test setup has been reported in [7] and is included here for convenience. A digital sampling oscilloscope (DSO) is used to capture short UWB pulses. The sounding pulse has a 10-dB bandwidth of 700 MHz–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 0.98. 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 to 40 ns.

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). Antennas used in the experiment are omni directional ones with linear polarization. The heights of both Tx and Rx antennas are set to 1.4 m.

All the measurements are conducted during off-peak hours (midnight). The reason of choosing off-peak hours is to isolate the problem and avoid being interrupted by human activities. This is not essential in the real-life application where a short burst of symbols are often concerned. The channel can be treated as static within such a burst. In fact, we find by measurements that within 3 min the two forward and reverse links remain unchanged. The UWB channel stability has to be considered in designing any real-time UWB TR scheme in the future, especially when there is mobility in either the transmitter or the receiver. TR signaling network protocols must be considered when there are channel variations.

A virtual antenna array is employed in the experiments. The antenna elements are sufficiently spaced such that there is no correlation between these elements. It is found that the spacing of 20 cm is sufficient. A virtual antenna array consisting of four

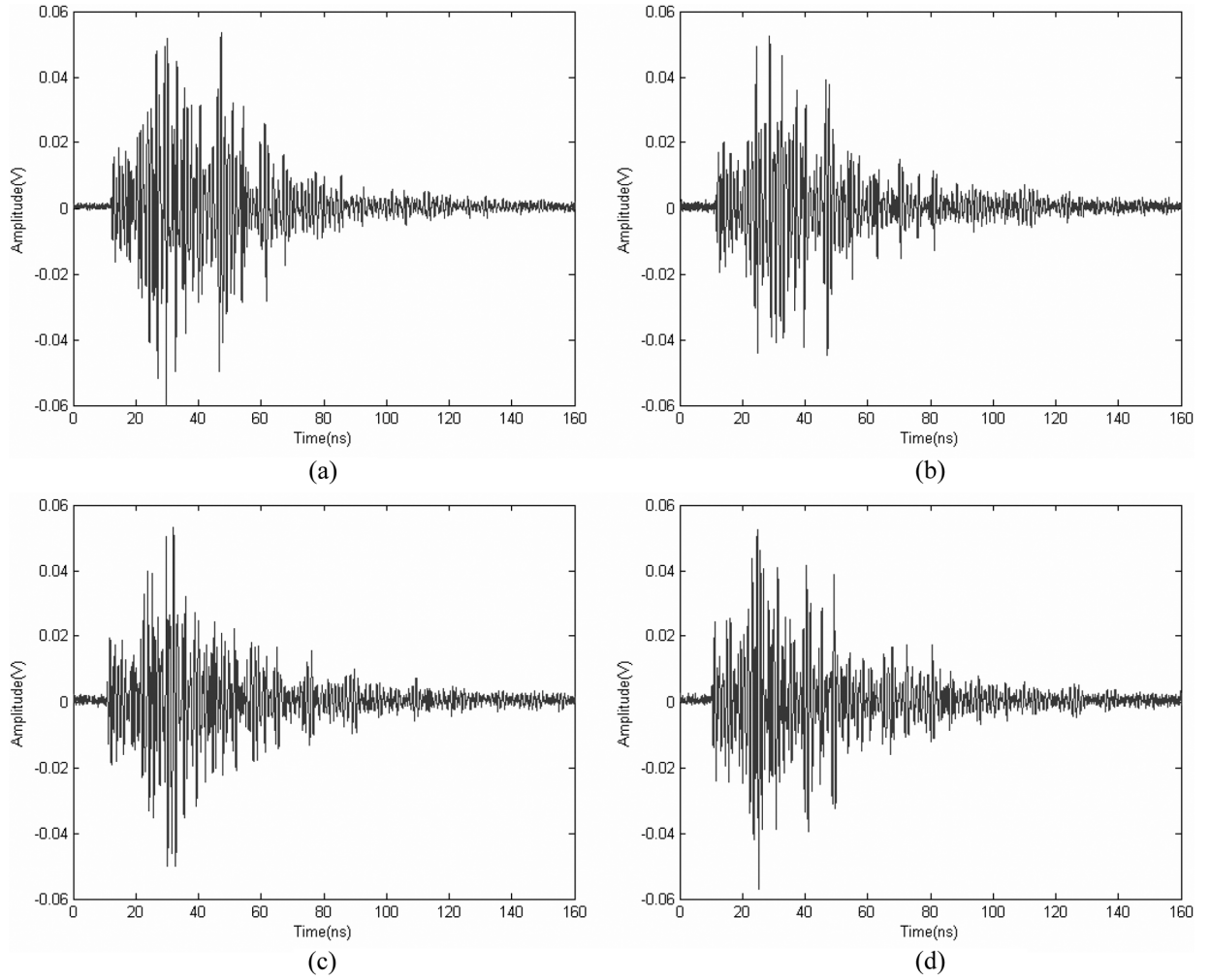


Fig. 5. Recorded waveforms for four virtual antenna elements at each transmitter location.

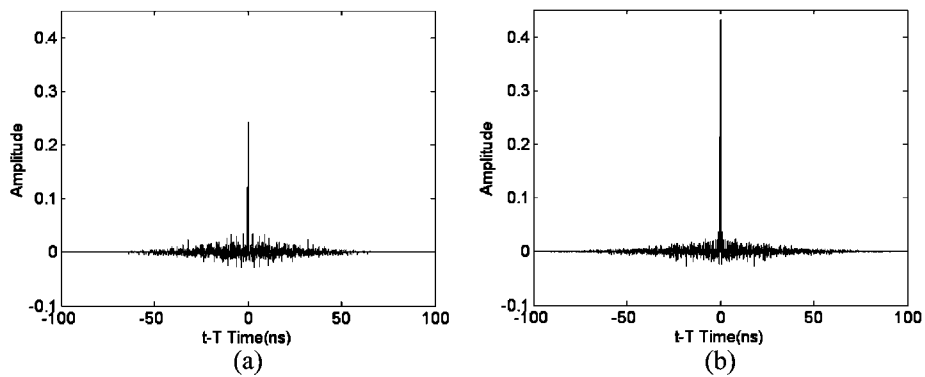


Fig. 6. A comparison of equivalent impulse responses defined in (3). (a) Equivalent impulse response of a SISO system. (b) Equivalent impulse response of the corresponding MISO system.

elements that are equally spaced along a line is used. The receiving antenna (element) is moved to different locations, and individual channels are sounded. Non-line-of sight (NLOS) is available for all the measurements.

Four waveforms recorded at each transmitter location are shown in Fig. 5. Different waveform distortions are observed for different virtual antenna elements. TR process converts

the CIR of Fig. 5(a) into an equivalent CIR of sharp peak in Fig. 6(a). This is true for a SISO system. For the MISO system [Fig. 6(b)], TR coherently combines the M equivalent SISO CIRs through (3) [2], [3], [5]. The peak of the MISO ($M = 4$) is roughly twice as that of a SISO system, as predicted in Section II-B. In Fig. 6, the CLEAN algorithm is applied to extract the CIRs from individual measurements [7].

V. CONCLUSION

UWB MISO is combined with the TR scheme. Two basic problems for the TR scheme are investigated experimentally using short UWB radio pulses (nanosecond duration). Temporal focusing and the increase in energy-collection with a number of antennas are experimentally verified. Also, the channel reciprocity is experimentally demonstrated perhaps for the first time in a UWB system. Note that the spatial part of channel is reciprocal, but the RF circuits part is not.

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