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Time-Reversal for UWB Communication Systems

ABSTRACT

UWB radio is a revolutionary, power-limited technology for its unprecedented system bandwidth and the potential of low-cost and low-power. The most pressing challenge is, however, how to reduce the transceiver complexity of coherent reception caused by the high sampling rate and stringent timing requirements. The proposed system paradigm uses time-reversal with noncoherent detection as an alternative to coherent reception. It exploits the hostile, rich-multipath channel as part of the receiver chain. This new method also integrates time-reversal with MIMO, the most promising approach to use spectrum and transmission power. As a result, time-reversal trades the huge bandwidth of UWB radio and the high power efficiency of MIMO for the noncoherent detection of extremely low cost. This proposed new system paradigm is to take advantages of the impulse nature of UWB signals, a new dimension of a communication channel, through time-reversed MIMO. The new dimension of impulsive time-reversal adds more degrees of freedom in exploiting the spatiotemporal dimensions. In this project we investigate open problems in the framework of UWB. Our focus is to exploit rich multipath by using time reversal, to simplify the system structure. Experiments and analysis are performed. This final report serves as two purposes: (1) it proposes a big master plan of research for the next two years; (2) it summarizes the results obtained in the last year by the support of the project. The significance of the finished work is clearer in the framework of a three-year plan.

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2. N. Guo and R.C.Qiu, "Improved Autocorrelation Demodulation Receivers Based on Multiple-Symbol Detection for UWB Communications", IEEE Trans. Wireless Communications, To appear.

3. R. C. Qiu, J. Q. Zhang, N. Guo, "Detection of physics-based ultra-wideband signals using generalized RAKE and multi-user detection (MUD)," IEEE J. Select. Areas Commun., Vol. 24, No. 4, pp. 724-730, April 2006.

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2. J.Q.Zhang and R. C. Qiu, "Detection of Physics-based Ultra-wideband Signals Using Generalized RAKE in Presence of Inter-Symbol Interference," IEEE 38th Southeastern Symposium on System Theory, Cookeville, TN, USA, 2006.
3. C.Zhou and R. C. Qiu, "Spatial Focusing of Time-Reversed UWB Electromagnetic Waves in a Hallway Environment," IEEE 38th Southeastern Symposium on System Theory, Cookeville, TN, USA, 2006.
4. R.C.Qiu, C.Zhou, N.Guo, J.Q.Zhang, "Time Reversal with MISO for Ultra-Wideband Communications: Experimental Results," Invited Paper, IEEE Radio and Wireless Symposium, San Diego, CA, 2006.
5. N.Guo, R.C.Qiu, B.M.Sadler, "An Ultra-Wideband Autocorrelation Demodulation Scheme with Low-Complexity Time Reversal Enhancement," IEEE MILCOM'05, Atlantic City, NJ, Oct. 17-20.

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2. N. Guo and R. C. Qiu, “Decision-Feedback Aided Autocorrelation Demodulation Receivers for UWB Communications,” IEEE Trans. Vehicular Technology, in the 2nd revision.
3. C. M. Zhou and R. C. Qiu, “ Pulse Distortion Caused by Cylinder Diffraction and Its Impact on UWB Communications,” IEEE Trans. Veh. Tech., Resubmitted after revision, March 2006.

Conference

1. N. Guo and R. C. Qiu, "UWB MISO Time Reversal With Energy Detector Receiver Over ISI Channels," submitted to Intelnational Conference on Ultra-wideband (ICUWB) 2006.
2. C. Zhou, N. Guo, R. C. Qiu, "Experimental Results on Multiple-Input Single-Output (MISO) Time Reversal for UWB Systems in an Office Environment," IEEE Miltary Communications (MILCOM) 2006, submitted.
3. C. M. Zhou and R. C. Qiu, “Pulse Distortion Caused by Cylinder Diffraction and Its Impact on UWB Communications,” IEEE Int’l Conf. Ultra-Wideband (ICUWB),Submitted for publication, March, 2006.

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Robert Qiu	0.20	No
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Time Reversal for Ultra-Wideband (UWB) Wireless Communications

Final Technical Report[1], Principal Investigator: Robert C. Qiu[2]

SUMMARY

UWB radio is a revolutionary, power-limited technology for its unprecedented system bandwidth and the potential of low-cost and low-power. The most pressing challenge is, however, how to reduce the transceiver complexity of coherent reception caused by the high sampling rate and stringent timing requirements. The proposed system paradigm uses time-reversal with noncoherent detection as an alternative to coherent reception. It exploits the hostile, rich-multipath channel as part of the receiver chain. This new method also integrates time-reversal with MIMO, the most promising approach to use spectrum and transmission power. As a result, time-reversal trades the huge bandwidth of UWB radio and the high power efficiency of MIMO for the noncoherent detection of extremely low cost. This proposed new system paradigm is to take advantages of the impulse nature of UWB signals, a new dimension of a communication channel, through time-reversed MIMO. The new dimension of impulsive time-reversal adds more degrees of freedom in exploiting the spatiotemporal dimensions. In this project we investigate open problems in the framework of UWB. Our focus is to exploit rich multipath by using time reversal, to simplify the system structure. Experiments and analysis are performed. This final report serves as two purposes: (1) it proposes a big master plan of research for the next two years; (2) it summarizes the results obtained in the last year by the support of the project. The significance of the finished work is clearer in the framework of a three-year plan.

[1]The work reported here is in part funded by the Army Research Laboratory through the Army Research Office under a Short Term Innovative Research (STIR) grant (W911NF-05-1-0468).

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Tables of Contents

Illustrations

1 Introduction

1.1 Problems and Challenges

Ultra-wideband (UWB) transmission has recently received significant attention in both academia and industry for applications in wireless communications [1-11]. UWB has many benefits, including high data rate, availability of low-cost transceivers, low transmit power, and low interference. It operates with emission levels that are commensurate with common digital devices such as laptops, palm pilots and pocket calculators. The approval of UWB technology, made by the Federal Communications Commission (FCC) of the United States in 2002, reserves the unlicensed frequency band between 3.1 to 10.6 GHz (7.5 GHz) for indoor UWB wireless communication systems. Industrial standards, such as IEEE 802.15.3a (high data rate up to 480 Mbps) and IEEE 802.15.4a (very low data rate from several Kbps to 1 Mbps), have been introduced based on UWB technology. The low emission and impulsive nature of UWB radio leads to enhanced security in communication. Good through-wall penetration capability makes UWB systems suitable for hostile indoor environments. Finally, 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.

A UWB signal uses broad bandwidth relative to its center frequency. A narrowband, carrier-based signal consists of sinusoids. By its nature, a short UWB pulse signal is impulsive and transient. Transient-electromagnetic characteristics of such a pulse must be taken into account, when a pulse travels in its journey from the source of the pulse generator to the detector. A pulse of short duration, say 0.2 ns, is the building block for a UWB system. The limit of a UWB signal is the Dirac pulse of zero duration, but of infinite bandwidth, while that of a narrowband signal is the monochromatic sinusoid of zero bandwidth, but of infinite duration. The two limits represent the extremities of a communication signal. Intuitively, a UWB signal represents a paradigm shift [9], as illustrated in the following. (1) The transient, impulsive UWB signal requires transient electromagnetics in its interaction with antennas and objects encountered in its multipath propagation. In addition to their attenuations and delays caused by multipathing, the pulse shapes vary from one path to another at the receiver. This pulse shape distortion [9,137-150] is caused by the frequency-dependent spatial filters, including antennas and the channel. First suggested by the PI one decade ago, the model of frequency-dependency was adopted in IEEE 802.15.4a [152]. Pulse shapes are also different for different angles of antenna radiation or reception. Frequency mismatch in RF circuitry is inevitable for such a bandwidth and leads to internal reflections that distort pulse shapes. (2) Extreme high temporal resolution changes the fast-varying, narrowband fading channel into an impulsive one composed of a large number of short, stable, resolvable, distorted pulses. For example, with a resolution of 0.167 ns, as many as 30 significant paths are observed indoors [9]. (3) The assigned UWB spectrum allows time-division duplexing, while the spectrum bands of most narrowband systems are only permitted to use frequency-division duplexing (FDD)[115].

The most pressing and challenging problem, caused by the unprecedented bandwidth, may be the increased transceiver complexity [6-11]. The impulsive UWB pulses require extremely high sampling rates as well as accurate timing synchronization. As a result, such coherent transceivers as RAKE and Orthogonal Frequency Division Multiplexing (OFDM), used in IEEE 802.15.3a, are too complicated for current application. Capture of energy from such a large number of weak paths is challenging to RAKE based solutions. Processing many wideband carriers in OFDM is complex, as well. For these reasons, a transmitted reference based transceiver has been proposed [12-22,142], but requires a long delay line that is very difficult to be implemented in hardware. Although a solution is found to avoid this delay line [23-24], what role this new structure will play in impulse radio is unclear. As a result, UWB community is forced to use noncoherent receivers like energy detection [25-35] in IEEE 802.15.4a for sensors and RFID applications. This type of receiver can be implemented, using such cheap analog components as schottky, tunnel and germanimum diodes, for its detector.

The momentum of UWB technology is mainly thwarted by the practical aspects. Our vision is that impulse radio is a next-generation technology of great potential. The low-complexity, energy-detecting receiver provides the first commercially feasible solution to a broad class of low-data-rate applications such as IEEE 802.15.4a. The challenge of high-data-rate solutions facing OFDM and RAKE, however, remains unresolved. Is it possible to follow the path of IEEE 802.15.4a to use low-cost receivers for high data rates? The transceiver complexity and thus its cost are, after all, the dominant factors that limit these high-data-rate commercial applications. The current solutions in the literature cannot provide a satisfying answer to this need. At the writing of this report, the IEEE 802.15.3a working group was disbanded [135], leaving RAKE and OFDM based technologies to compete in the marketplace. The PI attended these decision-making standards meetings three years ago, and the insight gained from these technology conflicts can be useful in developing the next generation UWB systems. The main driver for this disbanding has been the different views of how to reduce the transceiver complexity. One wonders whether there is a better alternative to the two unsatisfying system paradigms.

1.2 Time-Reversal—A Review

Time-reversal [36-66] is closely related to retrodirective array in microwave [67-82] and phase-conjugation in optics [154-156]. The birth of time reversal is related to the works of Parvulescu & Clay (1965) [157,37,38], Fink (1989) [42-46], Dowling & Jackson (1991) [47-49] and Kuperman (1998) [50-55]. The original motivation of time-reversal is to use the ocean as correlator in saving calculation of correlation, limited by the computing capabilities of 1960s. Time-reversal mirror is a generalization of an optical phase-conjugated mirror in the sense that the time-reversal mirror applies to pulsed broadband signals [44], rather than to monochromatic ones. Fink is initially motivated [42-44] to use time-reversal to compensate for pulse shape distortion [41].

Another use of time-reversal is related with compensation for distortions, caused by multipath and unknown antenna array deformation, which limit the capacity of underwater communications [47-66]. Furthermore, time-reversal can confine acoustic energy to a narrow beam that will track the intended receiver [47], called spatial focusing. In 1990s shallow-water acoustic communications systems are forced to rely on noncoherent processing techniques because of complexity in the acoustic environment [48]. This is true for the state-of-the-art of UWB communications today. *Time-reversal* was explored [49] to be an *alternative to* *coherent underwater communications.* The first experimental demonstration of time-reversal was done by Kuperman et al in 1998 [50]. Time-reversal is regarded as an environmentally self-adaptive process in complicated ocean environments. The primary result is that the time-reversal mirror focus is robust. Rather simple signal processing is used. *A new method of using time-reversal for coherent communication was experimentally demonstrated* [56]. The true power in the technique comes from using spatial diversity provided by the array. The received signals are then coherently summed across the array. The first known application of *non-coherent time-reversal* [57], which developed a signaling scheme for communications purposes, was experimentally demonstrated [61,62], using a *non-coherent envelope detector* at the expense of increased complexity in the transmitter. The two paper series are the major milestones as far as we are concerned in this proposal.

Multiple-input multiple-output (MIMO) has been used by UWB community without using time-reversal [122-127], including the PI's work [122]. There is no clear winner among the proposed schemes. The use of time-reversal in UWB wireless communications is relatively new [83-107]. The combination of time-reversal with UWB-MIMO does not appear in the literature, although combining time-reversal with UWB-MISO has been proposed [86,89,94,96,104,107], including the PI's work [104,107]. Pre-coding using time-division duplexing and pre-RAKE [128-131] are related to time-reversal. Time-reversal does not use the capacity-achieving power allocation [132]. Time-reversal is experimentally demonstrated for electromagnetics [83,84]. The first use of time-reversal for UWB communications is done at Stanford [85,86,89-94]. The first paper is probably [86] where the used data are measured by Intel using the vector network analyzer (VNA). Similar VNA-based measurements are done for microwave and electromagnetics at CMU [84,97-99]. Related work of using phase-conjugation is done in microwave [87,88]. The use of spatial focusing to reduce co-channel interference is done using narrowband [95] and UWB measurements [96].

The time-reversal research conducted at TTU in the frame work of UWB radio roughly followed two phases: pulse distortion compensation and spatio-temporal focusing. In the first phase [9,11,139,141], we were motivated to compensate for pulse shape distortion [137-141,144-147]. The second phase started in the summer of 2004 [100-107]. Our goal was to understand the combination of time-reversal with transmitted-reference UWB system, called the TR-TR scheme [100,103,106]. This new scheme increases the data rate by an oder of magnitude [100]. It was found that time-reversal could greatly simplify the receiver structures [9]. It was also demonstrated that the mono-bit A/D was feasible for time-reversal implementation [103,106].

2 Project Overview

One goal of the proposed research is to investigate non-coherent time-reversal as an alternative to coherent communications. If the project succeeds, the proposed system structure can potentially be a new system paradigm for the next generation UWB technology. The proposed research will take advantage of the unique characteristics of impulse radio, through a new paradigm of using time-reversal combined with MIMO. In this paradigm, only a noncoherent energy detector[3] is required in the receiver that will be cost-effective. The use of a noncoherent receiver as an alternative to coherent communications through time-reversal is inspired by the success of this scheme in underwater acoustics [49,61,62]. The principle of time-reversal is as follows: the receiver, first, sounds the channel by transmitting a Dirac pulse; second, at the transmitter, the received short pulse signals are recorded, time-reversed, and re-transmitted into the channel; third, the re-transmitted signal propagates back through the same channel (assuming channel reciprocity), retrace their former paths, and eventually refocus its power in space and time on its source (the receiver). There are four reasons for us to propose the use of time-reversal. (1) In a UWB channel of rich scattering, this space-time compression—unique to broadband time-reversal, can be strong, and, at the focal point, the effective channel obtained after time-reversal is hardened. Spatio-temporal focusing simplifies the receiver by enabling the possible use of noncoherent energy-detection as an alternative to coherent-reception. (2) A time-reversal mirror can be used to focus a random sequence of bits, simultaneously, to different users that are close, e.g., only 20 cm apart indoors. This is ideal for space division multiple access (SDMA). (3) Time-reversal is well known in acoustics, and has led to remarkable applications in underwater communications and ultra-sound. The extension of time-reversal to wireless communications has yet to be precisely investigated, although some work [83-107] in this direction has just appeared in the context of UWB radio (since 2004), including the PI's work [100-107]. The time-reversed multiple input single output (MISO) has, indeed, been studied, but its non-trivial extension to the framework of the time-reversed MIMO is not yet attacked. (4) A systematic extension of time-reversal, by analogy with the rich results in the narrowband MIMO, to impulsive UWB-MIMO is potentially more prolific than some isolated results in the current literature. The impulse nature does add difficulty to theoretical understanding, but simplifies the hardware implementation, as a huge payoff.

In narrowband systems, MIMO recently emerged as the most promising way of using spectrum [108-122], including the PI's work [121,122,100-107]. Its efficiency derives from exploiting multipath through space-time processing. This spirit is identical to that of UWB time-reversal. It is, thus, natural to extend the impulsive time-reversal to be combined with MIMO. This combination is proposed to exploit rich multipath and the time-division duplexing spectrum that is required for the use of channel reciprocity—the basis of time-reversal. If a single-input single-output (SISO) array receives L equal-energy pulses, the MIMO array can coherently capture roughly LMN equal-energy pulses. The coherence is like a symphony conducted by the orchestra—the time-reversed impulse MIMO; every pulse has its freedom in traveling any parts of the system, but, as a whole, they form a beautiful music: it is the chords (coherent summing) generated by these tiny pulses that make the music beautiful.

Let us explain this picture using an example. For a single impulse ($L = 1$), due to the geometric configuration of the MIMO array, distances between the antenna elements of the transceiver are slightly different (MN pairs of combinations); these traveled distances display themselves in the form of the different time arrivals of this impulse at the receiver, and eventually lead to MN temporally-resolvable impulses in the channel impulse response

[3]Transmitted Reference based auto-correlation receiver can be used [103,106], due to its capability to filter interference or noise in the template. This receiver is more complex than energy detection.

(CIR); we cannot tell if the MN impulses are caused by multipathing or by the particular geometric configuration of the MIMO array. It is the infinite temporal-resolution capability of such an impulse that makes all the difference to resolve these (MN) impulses in the CIR. For a pulse of T_p (say 0.1 ns), the minimum difference in such two distances required to resolve two pulse arrivals in the received CIR, is only cT_p(3 cm), where c is the light speed (30 cm/ns). It is practically easy for the MIMO array to satisfy this requirement. Next, after time-reversal, the effective CIR is formed and equal to the auto-correlation of the CIR (composed of MN impulses or pulses). If the pulses in the CIR are temporally resolvable, the auto-correlation of the CIR is equal to the sum of the auto-correlations of pulse responses. Since the auto-correlation of any pulse response is always symmetric and the peak of the auto-correlation in the center of the time axis is the energy of the pulse, these MN pulses are coherently summed in the center of the time axis; as a result, the captured total energy is increased by a factor of MN. Finally, if L paths are present instead, this factor is LMN. There is no difference between the orthogonality (of the received pulse signals) improved by the geometric configuration of the array and the orthogonality improved by multipathing. As a result, an increase in the number of the transceiver antennas transforms into a linear increase in the number of the orthogonal pulses and thus the total captured energy. In narrowband MIMO, this time-domain coherent summing is, however, impossible, since all of the MN pulses are not resolvable in time (by narrowband frequency-flat fading assumption). Rather the gain of the narrowband MIMO comes from increased degrees of freedom for a monochromatic sinusoid.

Let us compare UWB-MIMO with narrowband MIMO in the following three aspects. (1) The physical mechanism of UWB-MIMO is fundamentally different from that of narrowband MIMO, although the essence of the two systems is the same—to exploit the time-space dimensions. The former employs the impulse nature of short pulse UWB signals, a long train of Dirac-like pulses; the latter is another extreme, however—it uses the monochromatic sinusoid waves. (2) Impulse MIMO uses the spectrum at a stretch. The narrowband MIMO decomposes the bandwidth of the otherwise frequency selective channel into a number of orthogonal, frequency-flat MIMO channels; as a result, MIMO-OFDM is an ideal system paradigm, because OFDM further divides its bandwidth into a large number of sub-bands where each small sub-band can be represented by a simple carrier (tone). (3) MIMO-OFDM takes channel fading as given, and exploits decorrelation offered by narrowband frequency-flat fading to make the transmitted signals more orthogonal, for higher capacity; its world picture is mathematical because the ideal, narrowband, frequency-flat fading model is a mathematical abstraction. The impulse MIMO, however, resolves a few resolvable, time-variant, fading paths (fingers) into a huge number (tens or even hundreds) of resolvable, time-invariant, distorted, transient (short, impulsive) pulses; the impulse MIMO deals with real, physical signals composed of the tiny pulses caused by multipathing and additional path-lengths created by the MIMO array—physically understanding time-domain transient propagation directly results in a better understanding of communications, since each pulse arrival corresponds to a physical path (or ray) in time-space.

The proposed research is restricted to the following three broad tasks.

- We propose to investigate the new time-reversed impulse MIMO paradigm by a practical example; using cost-effective, noncoherent detectors in the receivers, the system performance in the level of coherent reception will be explored.

- In the theoretical aspects, we propose to take advantage of spatio-temporal focusing, a new physical phenomenon governed by transient electromagnetics, which is unique to time-reversed impulse systems. We are particularly interested in extending the current work to the framework of MIMO to improve the spatio-temporal focusing. A systematic extension of UWB-MIMO, in parallel with the narrowband MIMO, will be carried out in the context of time-reversal.

- For both theoretical and practical aspects, an experimental testbed for time-reversed UWB-MIMO (or impulse MIMO) is proposed. There is no such testbed available worldwide. We can, fortunately, leverage the current in-house development for a general-purpose UWB transceiver testbed, funded by other sources. The only additional development work required to implement the proposed scheme is to implement the time-reversal part, and integrate it into the in-house testbed, which will be ready by the fall of 2006.

3 RESEARCH METHODOLOGY

3.1 The Fundamental Physical Mechanism of Time-Reversed UWB-MIMO

The fundamental idea comes from the impulsive nature of the UWB communication. For an impulsive point source, located at r' for time t' in a homogenous medium, the scalar Green function, for an observation point, located at r for time t, satisfies [136]

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) g(r, r'; t, t') = -\delta(r - r')\delta(t - t') \tag{1}$$

where c is the speed of light. The impulse response of the channel is that a linear time-invariant (LTI) system is a function of the scalar Green function, depending on the antenna configurations. The Green function is given by

$$g(r, r'; t, t') = \delta\left[(t - t') - |r - r'|/c\right]/4\pi\,|r - r'|\,. \tag{2}$$

It is obvious, from (2), that switching the locations of source and observation does not affect the Green function. This implies the spatial reciprocity of the channel. Mathematically, spatial reciprocity is satisfied as long as the spatial part of the wave operator is self-adjoint. Eq. (2) represents an outgoing propagation wave. However, exchanging the time instants of source and observation points will lead to an interesting result,

$$g(r', r; t', t) = \delta\left[(t - t') + |r - r'|/c\right]/4\pi\,|r - r'| \tag{3}$$

Eq. (3) represents an inward propagation wave carrying the same energy as the outgoing wave in (2). This exercise suggests that if the time-reversed version of the received fields is sent again at the received point, the energy will retrace the same path back to the original source point. If all the fields are captured, time-reversed , and sent again at these observation points,

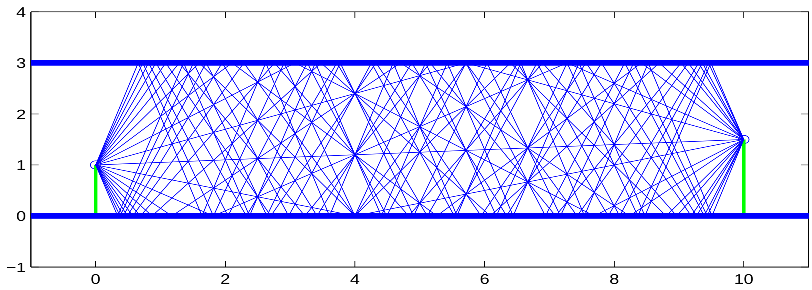


Figure 1: Time-reversal in a hallway. X and Y coordinates are in meters.

then these fields will travel backward along their forward paths and converge to the original point source, r', at the same time, t', leading to $\delta(r-r')\delta(t-t')$ in Eq (1). This property is called *spatio-temporal focusing*, *unique to the impulse nature of UWB communications.* as illustrated in Figure 1.

For a monochromatic sinusoidal signal, time-reversal is equivalent to complex phase conjugation of the amplitude. In Figure 1, if one transmits a monochromatic sinusoidal wave, there is no reason for these multipath waves to refocus on a point. The spatial refocusing process works only with broadband pulses, with a large number of eigenmodes in the bandwidth of the transmitted pulse. Here, the averaging process that gives a good estimate of the spatial correlation function is not obtained by summing over different realizations of the waveguide, but a sum over "pseudo-realizations" which correspond to the different modes in the same waveguide [158-162]. The signal-to-noise level should increase as the square-root of the number of modes in the width of the transmitted pulse. For a large bandwidth like UWB, if one has statistical decorrelation of the wave fields for different frequencies, the time-reversed field is self-averaging.

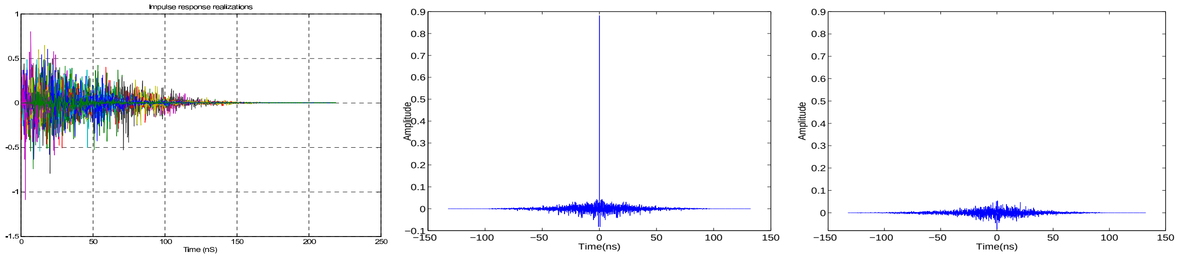
For a waveguide as illustrated in Figure 1, the exact expression for the CIR, transient Green function, can be obtained in a closed form [158-162]. This physics-based analytical model is useful in modeling rich multipath via a mode representation. Each mode is orthogonal to each other and can be treated separately. For example, the first primary mode is treated in [159]. When sensors are placed in such an environment, e.g., tunnel, mine, street canyon, etc., this model combined with information theory may provide insight by answering the fundamental limits given the transmitted energies of sensors.

3.2 Time-Reversed UWB-MISO—Spatio-Temporal Focusing

With an array of M elements, the time-reversed signal, recreated at the source, writes as a sum:

$$h_{MISO}(t) = \sum_{m=1}^{M} h_m(t) * h_m(-t) \tag{4}$$

Even if $h_m(t)$ are completely random and apparently uncorrelated signals, each term in this sum reaches its maximum at time $t = 0$, whereas, at earlier or later times, uncorrelated contributions *tend to destroy one another.* Thus the recreation of a sharp peak, after time-reversal in an array of M elements, can be viewed as an *interference process,* between M



(a) IEEE 802.15.3a channel model (b) The target user (c) The observation point

Figure 2: Experimental demonstration of spatio-temporal focusing by the effective CIR.

outputs of M matched filters.

For brevity, the index of antennas is dropped in Eq. (5) and Eq. (6). The CIR, $h_m(t)$, can be expressed as

$$h(\tau) = \sum_{l=0}^{L-1} A_l h_l(\tau) * \delta(\tau - \tau_l) \tag{5}$$

where per-path impulse response $h_l(\tau)$ is a function of finite energy and finite duration. The $h_l(\tau) = \delta(\tau), \forall l$ is assumed in a conventional Turin model in a narrowband system. Originally suggested by the PI, this model is accepted in IEEE 802.15.4a [152]. After time-reversal, the effective response of each antenna is the auto-correlation of its own CIR ($h_m(t)$), defined as

$$R_{hh}(\tau) = \sum_{l=0}^{L-1} a_l^2 \left[h_l(\tau) * h_l(-\tau)\right] + \sum_{i=0, i\neq k}^{L-1} \sum_{k=0}^{L-1} a_i a_k \left[h_i(\tau) * h_k(-\tau)\right] * \delta\left[\tau - (\tau_k - \tau_i)\right] \tag{6}$$

where $h_l(\tau) * h_l(-\tau)$ are symmetric with maxima at $\tau = 0$. Per-path pulse waveform distortion, described by $h_l(\tau)$, is thus automatically corrected by the operation of this convolution, as a result of matched filtering. When a MISO is used, according to (4), the responses of each antenna will add coherently at $t = 0$, while, at other times, these responses will add incoherently and tend towards zero on the average (see Fig. 2 (b)). This mechanism reduces the delay spread of the effective CIR. A symbol is often represented as N_s short pulses [1,2,9]. It follows, from (4), that the symbol energy captured in the effective CIR by M antennas is, roughly, $LMN_s \times E_p$, where E_p is the pulse energy. Recent experiments done in the PI's lab confirmed this relationship [104,107]. Channel reciprocity implied by Eq. (2), the basis of time-reversal, was experimentally confirmed in the PI's lab [104,107]. The normalized correlation, similarity, between the CIRs of the forward and reverse links is as high as 0.98, higher than the value of 0.96 reported in ultrasound by Fink and collaborators.

Let us consider a MISO case. We denote $h_m(\mathbf{r}_0, \mathbf{r}_2, t)$ the CIR from the m-th element of the array, located at $\mathbf{r}_0$, to an observation point, located at $\mathbf{r}_2$ apart from the intended receiver location $\mathbf{r}_1$. Similarly we define $h_m(\mathbf{r}_0, \mathbf{r}_1, t)$. The signal recreated at $\mathbf{r}_2$ can be written:

$$h_{MISO}(\mathbf{r}_1, \mathbf{r}_2, t) = \sum_{j=1}^{N} h_m(\mathbf{r}_0, \mathbf{r}_1, -t) * h_m(\mathbf{r}_0, \mathbf{r}_2, t) \tag{7}$$

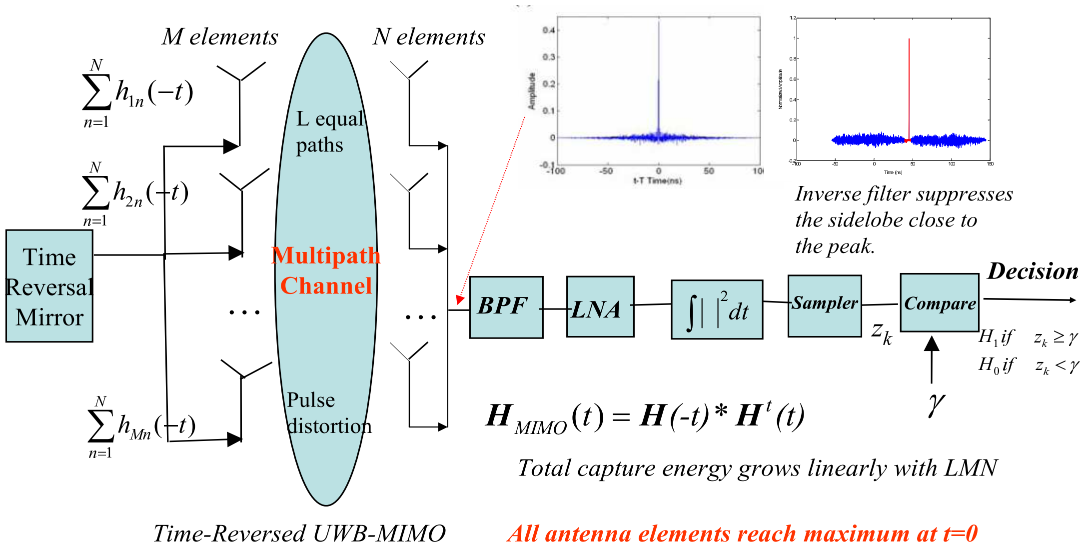


Figure 3: Time-Reversed UWB-MIMO uses the noncoherent energy-detecting receiver.

The expression of (7) can be used as a way to define the directivity pattern of the time-reversed waves around the intended receiver. Eq. (7) reduces to (4) if the observation point overlaps the target user location, $\mathbf{r}_1 = \mathbf{r}_2$: the cross-correlations in (7) reduces to the auto-correlations. This is not the case when the observation point is located at a distance, d, away from the intended user. For example, in Figure 2, the effective CIR defined in Eq. (7) is calculated at two different locations: (b) at the intended user, $\mathbf{r}_1$; (c) an observation point, $\mathbf{r}_2$, located $d = 20$ cm from the intended user, $\mathbf{r}_1$. It is experimentally observed at TTU (Fig. 2) that, at time $t = 0$, the peak at the intended user is much stronger than that of the observation point. The $h_m(\mathbf{r}, \mathbf{r}', t)$ behaves as natural, spatio-temporal, orthogonal codes, varying from location to location. Ideal spatio-temporal focusing makes the right side of Eq. (7) approach $\delta(\mathbf{r}_1 - \mathbf{r}_2)\delta(t)$. Only access to the transceiver locations information, as done in using time-reversal [103,106], can decode the key to a particular channel encrypted by the short random-like pulses (Fig. 2(a)).

3.3 Time-Reversed UWB-MIMO–Theory

Insight gained in Eq. (7) and Figure 2 suggests a novel scheme of UWB-MIMO, shown in Figure 3. Let us denote $h_{mn}(t)$ the CIR from the n-th element at the receiver to the m-th element at the transmitter. Using $\sum_{n=1}^{N} h_{mn}(-t)$ as the pre-filter for the m-th transmit antenna, a sum of all the signals captured by the n receive antennas yields the effective CIR for time-reversed MIMO, given by

$$h_{MIMO}(t) = \underbrace{\sum_{n=1}^{N}\left[\sum_{m=1}^{M} h_{mn}(-t) * h_{mn}(t)\right]}_{Signal\ (Sharp\ Peak)} + \underbrace{\sum_{m=1}^{M}\left\{\left[\sum_{n=1,k\neq n}^{N} h_{mn}(-t)\right] * \left[\sum_{k=1,k\neq n}^{N} h_{mk}(t)\right]\right\}}_{Inter-Symbol-Interference\ (ISI)} \tag{8}$$

(Note that each $h_{mn}(t)$ contains L impulses of pulse waveform distortion defined in (5)). It follows from (8) that the effective channel is given in matrix form

$$\mathbf{y}(t) = \left[\mathbf{H}(-t) * \mathbf{H}^t(t)\right]_{M\times M} * \mathbf{x}(t) \tag{9}$$

where superscript "t" represents the transpose of a matrix, and the channel matrix $\mathbf{H}(t)$ contains elements of $h_{mn}(t)$, m=*1,2, . . . ,* M and n=*1,2,..,* N; the notation of "*" represents element-by-element convolution, following matrix's rule; the transmitted signals are collected in a vector, $\mathbf{x}(t) = [x_1(t), x_2(t), ..., x_M(t)]^t$, and the received signals are collected in a vector, $\mathbf{y}(t) = [y_1(t), y_2(t), ..., y_N(t)]^t$. For brevity we define $\mathbf{H}_{MIMO}(t) = \mathbf{H}(-t) * \mathbf{H}^t(t)$. Eq. (8) is equivalent to the sum of all the elements of the effective time-reversal (channel) matrix $\mathbf{H}(-t) * \mathbf{H}^t(t)$. This is the case: if one defines the received signal as $r(t) = \sum_{n=1}^{N} y_n(t)$, it follows, from Eq. (9) considering a special case of $x_m(t) = s(t)$, that $r(t) = s(t) * h_{MIMO}(t)$, where $s(t)$ is the transmitted signal. The $\mathbf{H}(-t) * \mathbf{H}^t(t)$ hints us the familiar form in the capacity formula of narrowband MIMO [115]. Spatial reciprocity of a channel implies that $\mathbf{H}^t(t)$ corresponds to the channel matrix from transmitter antennas to receiver antennas. For frequency-flat, narrowband signal, all the convolutions in (8) and (9) reduce to the simple products. The rank of the channel matrix in (9) determines the number of parallel channels, the number of spatial degrees of freedom, as in narrowband MIMO.

The MIMO array of M x N can be viewed as N such MISO arrays of M x 1. The diagonal elements of $\mathbf{H}_{MIMO}(t)$ involve only the auto-correlations of $h_{mn}(t)$, while the non-diagonal ones consist of the cross-correlations of $h_{mn}(t)$. The signal part of Eq. (8) is given by $trace(\mathbf{H}_{MIMO}(t))$, where the trace of an matrix is the sum of all its diagonal elements. Since these auto-correlations all reach maximum at $t = 0$ and the maximum of individual auto-correlation is its energy of the impulse, they are summed up coherently, in Eq. (8), at this time to form a sharp peak, but at other times they are summed up incoherently. As a result, the amplitude (height) of such a peak is given by the total energy of the channel, $E_{total} = trace(\mathbf{H}_{MIMO}(t)|t = 0)$. The energy captured by the MIMO array is thus roughly N times that of MISO of Mx1. Spatial focusing results in the spatial decorrelation of the received signals at the N receive antennas: the elements of $\mathbf{y}(t)$ are more uncorrelated. The total energy capture by the MIMO array was shown experimentally to grow linearly with MN in the PI's Lab, as predicted by the theory above. Therefore, the total energy for an impulse radio is, roughly, $LMN \times N_s \times E_p$. The goal of this theoretical exploration is to find the fundamental limits of using spatio-temporal focusing. The ideal situation is $h_{MIMO}(t) = \delta(t)$. There is no ISI in this case. Using MIMO can suppress more ISI than using only MISO and make $h_{MIMO}(t)$ resemble $\delta(t)$ more. Due to spatial focusing, each MISO focuses on one receive antenna. If this spatial focusing is ideal—the cross-correlation at any two locations, defined in Eq. (7), is a spatial Dirac function—then $\mathbf{H}_{MIMO}(t)$ will be diagonal, since all these non-diagonal elements vanish. This is approximately the case when the receive antennas are located sufficiently far apart. One issue is to understand the impact of the spacings of the transceiver antennas on the $\mathbf{H}_{MIMO}(t)$. If high capacity is desired, by diagonalizing $\mathbf{H}_{MIMO}(t)$, parallel channels can be formed using impulse MIMO, as in narrowband MIMO. In this case the elements of $\mathbf{x}(t)$ are used to represent parallel streams of bits. This scheme uses MIMO for capacity, unlike the scheme defined in Eq. (8)

that uses MIMO mainly for diversity. Exact capacity analysis for impulse MIMO is still an open issue.

Another open issue is to suppress the ISI. In (9), the channel matrix, $\mathbf{H}(-t)$, is used as pre-filter before retransmission. The approach of using $\mathbf{H}(-t)$ as pre-filter is, indeed, simple, but not optimal, e.g., in an absorbing medium. A new broadband inverse technique, the spatio-temporal inverse filter, is proposed for imaging [153]. The inverse filter will make $h_{MIMO}(t)$ resemble $\delta(t)$ more. The spirit of this approach is similar to that of narrowband MIMO, but more general. There are five steps. (1) The Fourier transform of $\mathbf{H}(t)$ leads to the monochromatic channel matrix $\mathbf{H}(\omega)$. (2) The inversion of the matrix $\mathbf{H}(\omega)$ is carried out using the singular-value decomposition (SVD), giving the noise filtered inverse matrix, $\mathbf{H}^{-1}(\omega)$; Regulation is achieved by keeping only significant singular values, defining the rank of channel matrix and degrees of freedom. (3) The inversion is carried out at each frequency. (4) The inverse Fourier transform of matrix $\mathbf{H}^{-1}(\omega)$ yields $\mathbf{H}^{-1}(t)$ that is used to obtain transmission pulse signals. (5) The resultant receive matrix is $\mathbf{y}(t) = [\mathbf{H}^{-1}(-t) * \mathbf{H}^{t}(t)]_{M\times N} * \mathbf{x}(t)$. Note that the linearity and the spatial reciprocity of the channel are always valid, irrespective of information losses or not. As long as there is no information loss, the time-reversal invariance of the wave equation holds, and time-reverse corresponds to the spatio-temporal matched filter, the approach mentioned above.

The preliminary result, shown in Figure 3, demonstrates the capability of the inverse filter to suppress the sidelobe close to the peak. Note a SISO channel is used for inverse filter, while an MISO is used for time-reversal in Fig. 3. The MIMO case proposed here is expected to be better than conventional time-reversal. Since a short time window is employed in the energy-detecting receiver, shown in Figure 3, the reduced sidelobe will transform into the increased SNR in the detection. Indeed, the weakness of the inverse filter is to amplify the noise power. However, one only collects the energy in the short neighborhood of the peak, so this weakness is almost irrelevant to the proposed receiver structure. For the SISO example, the inverse filter can be nicely explained as two filters: time-reversal filter and power inverse filter. If $H(\omega)$ is used as the channel frequency response, the above inverse filter for MIMO reduces to a simple inverse filter, $1/H(\omega)$, or $H^{*}(\omega)/\left|H(\omega)\right|^{2}$. In time domain, it is $h(-t) * h_0(t)$, where $h_0(t)$ is the inverse Fourier transform of $1/\left|H(\omega)\right|^{2}$. The received signal after using the inverse filter as a prefilter at the transmitter is $[h(-t) * h(t)] * h_0(t)$. The first part is the time-reversal response. The second part is to inverse the power such that the overall response of the effective channel looks like a Dirac pulse, $\delta(t)$. Thus, the inverse filter successfully inverses the spectrum of the channel to compensate for the information loss due to propagation, but keeps the nice property of time-reversal. Other alternatives to the inverse filter can be explored. Three parts of research are proposed.

- Investigate spatial focusing mechanisms.
- Establish the mathematical models about the channel capacity of using UWB-MIMO.
- Develop capacity-achieving system schemes.

The exact analogy between the narrowband MIMO and UWB-MIMO is unclear and deserves further exploration. Designing a capacity achieving system scheme is challenging, with the constraint of low signal processing. Low duty cycles of these pulses are one of primary advantage of UWB radios. Recall that the time-reversal UWB MIMO is effectively a bank of $LMN \times N_s$ matched filters in a symbol time interval. For example, this filter bank leads to a gain of $100 \times 20 \times 5 \times 4 = 40,000$ or 46 dB over a scheme of one pulse per symbol in one path using SISO. This high gain can afford extreme low duty cycles of low power pulses, which lead to low cost.

Due to the coherent summing, both transmit and receive antennas contribute to the total captured energy. This is not true, however, for systems without using time-reversal. In [124], it is found that doubling the number of transmit antennas, M, does not change the SNR, while doubling the number of transmit antennas, N, does. The received signal amplitudes after the N matched filters add coherently whereas the corresponding noise components add incoherently. Doubling N yields a 3 dB gain in SNR. But with the diversity order of UWB channels being inherently very large, increasing diversity through adding more transmit antennas is only marginal. In the time-reversal scheme, the final summing up at the receiver can be effectively viewed as after the MN matched filters. Doubling M also causes the same performance as doubling N.

3.4 Time-Reversal UWB-MIMO—Practice

3.4.1 Time-Reversal with Noncoherent Detection as an Alternative to Coherent Reception

Time-reversed signals combined with the channel form the whole spatio-temporally matched filter. For detection and decision, the conventional system principle applies, following the block of the matched filter achieved by time-reversal. For example, in Figure 3, after band-pass filter (BPF) and low-noise-amplifier (LNA) the noncoherent energy-detector can be used, followed by a threshold for decision. Although noncoherent, energy-detecting receiver is used, it is expected that the time-reversed system achieves the performance close to coherent processing.

The approach in Figure 3 provides an original and relatively simple algorithm to overcome the inter-symbol interference (ISI) problem. The solution is not based on sophisticated processing algorithms, but equivalent to matched field processing with the filter matched to the impulse response of the UWB channel. The low computational load required in this technique is because it uses the channel itself as the matched filter for the radio propagation between the source and receiver. By using rather simple signal processing at the transmitter (suitable for real-time implementation), the multipath structure at the receiver end is virtually absent, allowing a reduced-complexity receiver structure. This technique uses time-reversal arrays to generate a spatio-temporal focus of electromagnetic energy at the receiver location, eliminating (or greatly reducing) distortion introduced by channel propagation. Array processing is no longer required, because the time-reversal array's footprint is well defined at the receiver location due to spatial focusing. Time-reversal array adds benefits of longer range, due to energy focusing, and covert coding, due to the inherent scrambling induced by the environment at points other than the intended receiver. In order to achieve high-speed data transmission, the use of bandwidth-efficient phase-coherent communications was also suggested in underwater acoustics [61,62]. Other approaches should be explored under these variable conditions, such as increased symbol information through amplitude modulation.

Simplifying receivers is paramount. The three parts of research are proposed.

- Systematically compare the performance of the time-reversed systems with the coherent systems such as RAKE and OFDM.
- Robustness of time-reversal in UWB environments.
- Extend the system framework, using time-reversal, with a partially coherent, transmitted reference receiver, called TR/TR, in the context of MIMO.

The motivation of the first part is apparent. Although the new system framework is justified in a heuristic way, rigorous analysis and simulations are still required to quantify the performance gaps. The robustness of time-reversal is a central part of this proposal. Channel estimation error is critical to final performance. The reciprocity needs to be investigated in a variety of environments. The effect of RF circuitry on the reciprocity needs to be quantified, since it affects the peak of temporal-spatial focusing. Finally, the synchronization to the main received peak can be achieved using energy-detection, as also realized in [96]; Due to temporal focusing, the fraction of the signal energy used for synchronization is higher than that in the case of traditional systems without time-reversal. We will explore how time-reversal will mitigate the need for synchronization, a major challenge in UWB community.

The third part is mainly motivated by the weak anti-jamming capability of energy-detecting receivers. The problem lies in its non-linearity. The linear TR based auto-correlation receiver is proven to be efficient in anti-jamming, but still keeps a reasonable receiver complexity. TR is also accepted as part of IEEE 802.15.4a. The TR/TR scheme was the first system structure studied in the PI's lab [100,103,106]. It was found [100] that the TR/TR scheme can achieve the highest data rate of up to 200 Mbps, compared with that of 20 Mbps obtained using the conventional TR system. The energy-detecting receiver is proposed to be the primary structure, due to its simplicity in implementation. The long delay line required in the TR is a show-stopper. But another version of TR without a delay line greatly simplifies the receiver complexity [23,24]. We will mainly attack the problem from this angle.

3.4.2 Channel Sounding Measurements

Channel sounding is always a basic ingredient in MIMO research. The spirit of our proposal is to exploit the spatio-temporal dimensions. The foundation lies in solid, realistic channel models. One strength of this proposal is the in-house capability to sound the UWB channel in the time domain and the frequency domain. The received pulse train is captured by a Digital Sampling Oscilloscope (DSO). Alternatively, a Vector Network Analyzer (VNA) can be used to measure the frequency response of the channel. The former has the advantage of measuring the real-time channel impulse response, but it is mainly limited by the pulse generator. The latter has the flexibility of varying the spectrum bandwidth, and thus is very useful in our research in time-reversal. But this approach generates a much larger dataset, requiring a longer time to collect the data. When channel variability is a concern, the time domain approach is better than the frequency response approach. The third alternative is to use a physics-based multipath model. This approach provides analytically tractable expressions, for some simplified channels (to gain insight). A ray tracing model is simple, and physically clear, as illustrated in Figure 1. It is scalable to all bandwidths, since a ray represents a Dirac impulse, traveling through a specific path. Actual impulse response is, thus, obtained. Green's functions (or impulse responses) are required in our proposed research. Many classical problems [138-140,145,146] have been solved by the PI, for this purpose.

3.5 Spatial Focusing for Multiple Users

Consider a total of K users. Each user has M transmit antennas and only one receive antenna. There are P users simultaneously operating $M \times 1$ MISO systems, each one targeting a different user. For a SISO link with time reversal, it follows for the target user that $s(t) * [h_{ij}(-t)^* * h_{ij}(t)]$, where $h_{ij}(t)$ is the CIR between i-th transmit antenna and j-th receive antenna, and $s(t)$ is the transmitted symbol. For the off-target user, the received signal has the incoherent form $s(t) * [h_{ij}(-t)^* * h_{ik}(t)]$, where $h_{ik}(t)$ denotes the CIR from the i-th transmit point to the k-th off-target point. Note that the cross-correlation of the two CIRs,rather than the coherent auto-correlation of the CIR for the target user, is involved. For the j-th user, $j = 1, 2, .., K$, the received signal becomes

$$y_j(t) = \underbrace{s_j(t) * \left[\sum_{i=1}^{M} h_{ij}(-t)^* * h_{ij}(t)\right]}_{Signal(j)=s_j(t)*h_j^{eq}(t)} + \underbrace{\sum_{i=1}^{M} \sum_{k=1;k\neq j}^{K} s_j(t) * [h_{ij}(-t)^* * h_{ik}(t)]}_{Interference(j)} + \underbrace{n_j(t)}_{Noise(j)} \tag{10}$$

Link capacity and performance are expressed as a function of signal-to-interference-plus-noise ratio (SINR) defined at the same time lag that reaches the peak of the Signal(j)

$$SINR_j = \frac{|Signal(j)_{peak}|^2}{|Interference(j)_{peak} + Noise(j)_{peak}|^2} \tag{11}$$

In (10), the received signal are not only coherently added up in the time domain but also in the spatial domain (multiple antennas). Spatial focusing/selectivity and temporal compression are achieved *at the same time* by time-reversal. The rich scattering environment, which makes the propagation channel of each link independent and unique, can provide the natural, quasi-orthogonal codes, $h_{ij}(t)$ and $h_{ik}(t)$ [95,96]. These codes are useful in further separating the signals intended for different users, thus minimizing the cross-correlation term in (10) [103,106]. Consequentially, the data throughput can be further improved by taking advantage of the spatial diversity focusing properties of the time-reversal array, using MISO [95,96] and MIMO discussed above.

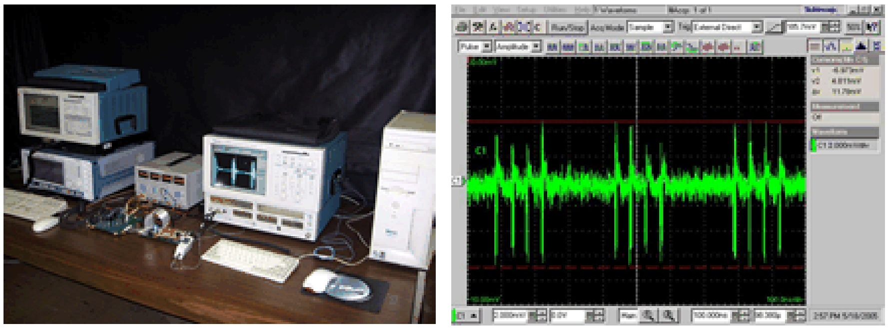
In the cases presented in underwater acoustics [61,62], *the time-reversal array was able to focus simultaneously different messages at different receiver locations.* The message signal designed for a given receiver only focused at the intended receiver location. Furthermore, this seems a good technique for secure communications, because the different message signals will overlap both in time and frequency at other unintended locations, making it difficult to recover any of the transmitted messages [103,106]. Due to the spatial diversity focusing properties of the time-reversal array, the time-reversal array may have an important role in a local area network. Each array is able to simultaneously transmit different messages that will focus at the destination receiver node. One unique feature of the proposed paradigm is that the distortions caused by array deformation and circuitry are automatically corrected through time-reversal, the property of auto-correlation (see (4) and (8)). The antenna elements can be randomly distributed in a network. Since the receiver is environment-adaptively matched to the short pulses (say 0.2 ns), the system is very robust and easy to maintain. This is true in underwater acoustics communications. The focusing does not change for half an hour. In indoor UWB systems, the reciprocity of the two links is extremely steady. The channel CIRs of two links are almost identical after 3 minutes, as observed in the PI's lab.

Three parts of research are proposed.

- Time-reversed signaling protocols must be carefully investigated to take the advantage of the full benefits of simultaneous spatio-temporal focusing in mainly physical and MAC layers.
- Experimentally support the time-reversal UWB-MIMO theory for multiple users.
- Investigate the properties of spatial focusing to communicate with many users.
- Cooperative time reversal for sensor networking.

There is an analogy between the number of achievable focal spots and the number of eigen-channels in a narrow MIMO system. Time-reversal is good for one-to-one communications. As pointed out by Fink [94], the question is how to apply it and communicate with many users simultaneously. The central theme of the three parts is to deal with multiple users, exploiting this new phenomenon. It is possible to conduct the coherent summing of tens of thousands of short pulses, without sophisticated signal processing. True, there are a lot of open issues. For example, how do dynamic users work with multiple antennas? How about distributed antennas? How to select K users out of N_u users, in a cell that have the most "orthogonal" channels, at any given time instant? The probability of low interference improves, as the number of users increase. How to exploit this? How to exploit polarization to benefit from improved orthogonality?

A special interest lies in applying virtual MISO arrays for sensor networking. For a single user MISO, it is experimentally confirmed [104,107] that SINR grows linearly with M, the number of transmit antennas (or sensors in a virtual MSO array). In other words, $SINR \propto M$. We argue that this conclusion is true for multiuser cases, according to (10), due to spatial focusing. If this is true (being confirmed experimentally in TTU), the normalized aggregate data rate is given by $log(1 + SINR) \propto log(M)$ when M is large. It is assumed that M sensors with almost equal energy are cooperative in forming a virtual MISO array to serve an arbitrary sensor. As a result, it follows that the aggregate data rate is in the order of $log(M)/M$, $\Theta(log(M)/M)$, bits/Hz per node. Our simple empirical argument agrees with the recent result that is derived from a view of information theory [163]. This rate is, in fact, shown to be optimal[163], and can be achieved by time reversal. Cooperative time-reversal is promising, but the timing synchronization between different users that employ different clocks is challenging due to the short pulse property. For the multiple antennas that use the same clock, only symbol-level timing synchronization is required, by using a technique [164] that is originally suggested by Fink [44].



(a) (b)

Figure 4: A UWB transceiver testbed under development at TTU.

3.6 Time-Reversal UWB-MIMO Testbed

Each antenna element of the array has its own electronics: detection amplifier, A/D converter, digital memory, and a programmable generator capable of synthesizing the temporally inverted signal stored in the memory. The electronics are not perfect and introduce phase shifts, which depends on temperature [94]. Synchronization and local oscillator stability are essential. Since different cables are used for the two links, this is not something that is automatically corrected for with time-reversal. Also, the dynamic range of the receivers is not considered. The three parts of research are proposed.

- Develop a testbed for time-reversal using UWB-MIMO, leveraging the on-going, in-house UWB testbed.
- Investigate the practical need for the sampling rate of the A/D converter.
- Investigate the robustness of the system, taking into account channel estimation error.

The primary task is to integrate the time-reversal operation into the in-house testbed. The first part is impossible without the on-going, in-house effort jointly supported by different synergic sources, including the Army of Research Office (ARO), Army Research Laboratory (ARL), Nissan, NSF, and the State of Tennessee. Started 18 months ago, the on-going effort is to build a general-purpose testbed for UWB communications and ranging. The system will support on-off keying (OOK), pulse amplitude modulation (PAM) and pulse position modulation (PPM). The noncoherent, energy-detecting receiver is used, as adopted in IEEE 802.15.4a mentioned above. This is one important reason why noncoherent reception is focused on in the proposed research above. The testbed development is expected to finish before the summer of 2006. Currently, there are eight persons directly working on this testbed, among them are the PI, one R&D engineer with doctoral degree (N. Guo), two Ph.D. students (J. Q. Zhang, C. Zhou), and four MS students (M. Calderon, P. Agarwal, S. Artham, P. Gudipati). The first three are female MS students. In addition, it is expected that supported by the REU program from NSF, two undergraduates will also join the team in the summer like last year.

The second and third parts deal with implementation of time-reversal operation. High speed A/D sampling is always an issue for UWB radio. Funded by ARO/ARL, we were motivated to study this critical issue 12 months ago, through a promising approach of using mono-bit A/D. One approach was demonstrated by simulation [103,106]. This approach will be implemented in the proposed testbed. Based on the previous research, channel estimation error is an open issue. Research work, funded by ARO/ARL, will continue to explore this issue. Implementation issues will be studied in the context of the proposed testbed.

4 MAIN RESEARCH RESULTS

Key papers that are in part funded by the current grant are cited in the tile of each section for convenience. All these papers have acknowledged the sponsor with the grant number.

4.1 Reduced-Complexity UWB Time Reversal [103,106,141]

One unique characteristic that differentiates a UWB system from a “narrow” band system is the UWB propagation channel. The UWB channel impulse response (CIR) contains a large number of resolvable components coming through different paths, especially in indoor environments. Can we take the advantage of multipath scattering to simplify receiver and improve performance? The answer is yes. However, making good use of these signal components is not straight-forward.

Time reversal is a signal focusing technique that indeed takes advantage of rich scattering environments to achieve signal focusing both temporally and spatially. Generally speaking, the temporal focusing feature can soften the impact of ISI, while the spatial focusing feature can not only enable “spatial-division” multiple access, but also provide a certain level of security for a system with symbol duration much less than the multipath channel excess delay spread (an intercept receiver would see highly overlapped signal that is hard to be demodulated). Time reversal is very promising for low-cost wireless applications since it shifts part of receiver complexity burden to the transmitter side. In addition, a sharpened signal would enable narrow-window integration that reduces noise accumulation without remarkably affecting signal energy collection, which is greatly in favor of some low-complexity suboptimal receivers, such as the autocorrelation demodulation (ACD, called differential TR sometimes) and energy detector receivers.

However, exploring time reversal in UWB area is a new research topic and implementing UWB time reversal is extremely challenging. The major difficulty is posed by a high-bandwidth pre-filter at the transmitter. We have proposed a simplified pre-filter implemented by a low-complexity digital FIR filter (or a last-in first-out memory) followed by an interpolator. The FIR filter utilizes near-Nyquist sampling rate, mono-bit coefficient resolution, and a relatively shorter filter length. With such simplified configuration, it is found that the resulted signal is still focusing. Performance is evaluated based on experimental data, considering practical signal waveforms, propagation channels and radio-frequency (RF) front-ends. Numerical results suggest that the proposed simplified time reversal technique does work and performance gain over ordinary schemes can be achieved. In particular, the performance can be further improved if an antenna array is employed at the transmitter to form a multiple input single output (MISO) time reversal configuration.

4.2 UWB Time Reversal Enabled New Functions and Performance Evaluation [103,106]

Time reversal provides spatial-temporal focusing, and the property of focusing can not only enhance system performance but also enable some interesting features. Examples of these features include spatial-division multiple access and location-based security enhancement (multipath encryption). The spatial-division multiple access is directly enabled by time reversal's spatial focusing. The location-based security, a by-product of time reversal, can reduce signal leakage of the intended user. Interestingly, higher data rate transmission can be more secure since an interceptor at other location can only observe a highly overlapped signal that is extremely difficult to be demodulated. We have demonstrated these based on measured data. Thanks to multipath scattering mechanism, multi-user access and location-based security enhancement can be effectively provided in the time reversal system without consuming additional radio resource. Also, these add-on functions are easy-to-use since they do not need any spreading code and/or encryption code.

A transmitter-side antenna array is especially meaningful for time reversal. While providing "array gain", the antenna array makes the received signal more focusing, which in turn leads to significant performance gain. Another benefit of using the array is increase of robustness. Radio link reliability is a killing issue for any wireless applications. With sounding signal emitted from an omni-directional transmit antenna placed at a fixed location, the received signal energy can vary dramatically as the receiver moves around. In other words, a robust link between a pair of transmit and receive antennas is not guaranteed. However, the link reliability can be greatly improved by using MISO. In our office environment, for an ACD receiver at a bit rate 33.3 bps (implying some ISI suffering), the use of MISO time reversal results in more than 6 dB gain at BER=0.001 over any single input single output (SISO) time reversal schemes. It can be concluded that the benefit of using MISO time reversal is tow-fold: (1) performance improvement over the SISO scheme because of enhanced focusing and magnified main lobe, and (2) increase of link robustness due to spatial diversity among antenna elements. Therefore, MISO is strongly recommended for time reversal systems.

4.3 Suboptimal UWB Receivers [165]

In contrast to the "optimal" schemes based on either the RAKE or OFDM, suboptimal alternatives target at low-cost wireless applications, such as sensor networks. These suboptimal solutions include transmitted reference (TR), autocorrelation demodulation (ACD, called differential TR sometimes) and energy detection using a square law detector.

To improve ACD's performance, a multiple-symbol-based ACD receiver has been investigated. Compared to the ordinary ACD scheme that uses symbol-by-symbol decision, the proposed structure uses block-based multiple-symbol joint decision. Performance of the new scheme is evaluated analytically for arbitrary block sizes employing Gaussian approximation approach. The accuracy of the method is verified by computer simulation. Furthermore, a simplified multiple-symbol-based ACD using decision feedback has been studied. The evaluation shows that the proposed schemes offer several dB improvement in performances with only a moderate increase in complexity. In addition, performance of an OOK-energy detection scheme has been analyzed using approximate approach, considering ISI and nearly optimal threshold.

In parallel with examining these suboptimal receivers, a baseline UWB radio testbed is under development. To research new concepts unique to UWB, theoretical and simulation approaches are not sufficient. It is desired to use experimental ways to test schemes and algorithms, verify theoretical and simulation results, and remove some uncertainties caused by channels, hardware and software. A testbed would be very convenient to evaluate the pros and cons of some specific system aspects, such as modulation schemes, receiver structures, and the analog-to-digital (A/D) converter, etc. In particular, the experimental approach is usually the only effective means to find the actual impacts of radio frequency (RF) circuits, including antennas. Essential tasks of the testbed project includes: (1) theoretical investigation of the receiver performance; (2) system design; (3) board level design; (4) implementation; and (5) test and validation.

4.4 Experimental Study of Channel Reciprocity for UWB Signal [104,107,164]

It is known that time reversal technique uses the channel impulse response (CIR) as the precoding to achieve the excellent temporally-spatial focusing. This is based on the assumption that the channel is reciprocal. In other words, channel reciprocity is the foundation of the time reversal technique and thus deserves further investigation.

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. We answer such a basic question by some initial verification using the time domain UWB radio pulses in an indoor environment

In our measurements, a Communications Signal Analyzer 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. No line of sight (LOS) is available. The result shows that two received waveforms (downlink waveform and uplink waveform) coincide with each other very well. The correlation between these two waveforms is as high as about 0.98.

4.5 UWB Channel Measurement and Physics-Based Modeling [140,166,16

One of the notable characteristics of UWB signal is its multipath resolvability, inherently determined by its huge bandwidth (corresponding to short pulse in time domain). Time reversal technique takes advantage of multiple scattering and thus its efficiency is closely related with the channel conditions. Channel impulse response (CIR) is thus one of the key information for the study of time reversal. However, the public CIR data base like IEEE 802.15. 3a (4a) does not include location information, which is needed if we consider antenna array. It is thus very important for us to develop CIR database that includes location information.

We have completed a series of measurements to obtain the CIRs in different locations. CLEAN algorithm is used to extract the CIR from the individual measurements. These measurement results will serve as raw database for future time reversal study.

Pulse distortion caused by cylinders is studied via a physics-based approach. This model is useful to study time-reversal in this non-line-of-sight (NLOS) environment. Time reversal serves as an approach to adaptively correct for pulse distortion on a pulse-by-pulse basis [141,166,167].

4.6 Spatial Focusing and Temporal Focusing Analysis [105,140]

We study the spatial focusing, as well as temporal focusing of time reversal technique in different environments.

1) UWB MISO Time Reversal in an office environment

We experimentally investigate the scheme of time reversal combined with multiple-input single output (MISO) antennas over ultra-wideband (UWB) channels. In particular, temporal and spatial focusing as well as array gain is studied based on a (4×1) MISO scheme in an office environment. The results confirm that the energy of UWB signals in a MISO scheme is more spatial-temporally focused than in a single-input single-output (SISO) scheme. As a result, a strong peak is formed in the equivalent channel impulse response. The magnitude of this peak grows linearly with the square root of the number of elements at the transmitter. All the measurements and data processing are completed in the time domain.

We also study how the number of antennas in a MISO array affects the spatial focusing and temporal focusing. It is interesting to find that the time reversal alone will not increase the RMS delay spread, it is the use of multiple antennas that reduces RMS delay spread. The reason why time reversal alone does not reduce the RMS delay spread is that the length of the equivalent CIR is almost doubled, after an autocorrelation operation. The additional length of the channel contributes to the calculation of the delay spread.

The concept of impulse-MISO is introduced, considering the wideband characteristic of the UWB signals. It is known that a short UWB pulse signal, by its nature, is impulsive and transient. The limit of a UWB signal is the Dirac pulse of zero duration, but of infinite bandwidth. Therefore, it is suggested to study the limit of MISO in the context of time reversal , which is called impulse-MISO. In impulse-MISO scenario, all the analysis will be based on CIR. Impulse-MISO gives the bound (limit) of the UWB signal and of theoretical significance.

2) Physics-Based Simulation Model (Hallway environment)

By taking advantage of our strength on electromagnetics, we also explore some simple models that are mathematically tractable to study the spatial focusing of the time reversal technique. Physics-based model gives insight into the problem and is more convenient for some canonical models. As the first example, a hallway environment is selected due to the fact that only reflection propagation mechanism is involved and hence easy to obtain closed form channel model. Using a hallway as an example, the spatial focusing has been demonstrated. The impulse response of the hall way is conveniently obtained through time-domain ray tracing. Although similar work has been done in acoustics, in electromagnetics this demonstration appears be done for the first time. Our approach of using time domain ray tracing is also novel for time reversal in electromagnetics. The simulation model can be conveniently applied to study the impact of the building size on time reversal . Moreover, although it is built based on hallway environment, this propagation model has a lot of other applications. e.g., this model is well suited to be used to model UWB signal propagating in an urban canyon and a tunnel.

The analytical results obtained here give some insight that is beyond the experiment approach.

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