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Time Reversal Signal Processing for Communication

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Ratish J. Punnoose, David T. Counsil, Derek P. Young, Neil Jacklin

Abstract

Time-reversal is a wave focusing technique that makes use of the reciprocity of wireless propagation channels. It works particularly well in a cluttered environment with associated multipath reflection. This technique uses the multipath in the environment to increase focusing ability. Time-reversal can also be used to null signals, either to reduce unintentional interference or to prevent eavesdropping. It does not require controlled geometric placement of the transmit antennas. Unlike existing techniques it can work without line-of-sight.

We have explored the performance of time-reversal focusing in a variety of simulated environments. We have also developed new algorithms to simultaneously focus at a location while nulling at an eavesdropper location. We have experimentally verified these techniques in a realistic cluttered environment.

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Nomenclature

EM Electromagnetics

RF Radio Frequency

channel The transfer function between a transmitter and receiver

PSD Power Spectral Density

kHz Kilo-Hertz

GHz Giga-Hertz

BW Frequency Bandwidth

PML Perfectly Matched Layer

VNA Vector Network Analyzer

MTS Multiport Test Set

S/E Ratio of signal at intended receiver to signal at eavesdropper

TR Time Reversal

Chapter 1. Introduction

Time-reversal signal processing is a spatial focusing technique that utilizes the reciprocity of wireless channels. The concept itself is quite simple. Visualize a signal that is sent out from a transmit location. The signal is picked up at several receive locations, some close-by and some farther away. The farther locations receive the signal after a greater delay. Imagine that they record these received signals. Now visualize this system in reverse. The previous receive locations are now transmit locations. They transmit the previously recorded signals in reverse time order. The farther locations which originally received the signal after a greater delay, now transmit the signal earlier. The closer locations transmit the signal later. This allows the signals from the farther locations to “catch-up”. At the target location (the original transmitter), all the signals converge in time (Fig 1.1). They will also focus in space, much like the signals from a phased array antenna.

Time-reversal focusing works not just in free-space but also in a complex environment with many reflectors and scatterers. A signal received in a complex environment will have undergone multiple reflections, refractions, and scattering. It consists of the sum of multiple time-delayed and attenuated versions of the original signal, i.e., the channel is time dispersive. When the received signal is time-reversed and re-transmitted, the different time-delayed components go through the same channel in reverse and converge on the original source location. This convergence occurs in both space and in time.

The spatial and temporal convergence is the basis of time-reversal focusing. In a signal processing context, the time-reversal operation is the convolution of a channel with its time-reversed version. In communications terminology, this is an ideal matched filter.

Time-reversal focusing has some practical benefits. It does not require knowledge of the receiver location and does not require line-of-sight. Increased multipath improves the focusing ability of the channel. In a physical context, the clutter in the environment is used beneficially to create a virtual antenna aperture that increases focusing ability.

This technique was first proposed for use in acoustics and has been under active exploration [1]. Classically, the focusing ability of an antenna depends on its size and is limited by the Rayleigh diffraction limit. In the last decade, experimental proof-of-concept articles in *Science* [2], and *Physics Review Letters* [3] showed that it is possible to focus beyond the diffraction limit in a spatially cluttered environment using time-reversal techniques. Similarly, phase-conjugate arrays, a narrow-band approximation to time-reversal, have been used to obtain focus resolution beyond the Rayleigh limit with microwaves [3].

Figure 1.1. Time reversal concept.

The spatial and temporal focusing due to time-reversal depends on the physical channel, i.e., there is a strong dependence on the geometry of the environment. Results reported in the existing literature are for specific geometries and experiment setups. There is not much known about the statistical performance of this technique in a variety of random physical environments. In this work, we characterize the performance of time-reversal in a variety of randomly simulated environments.

In practical applications, it is desirable to focus a signal at the intended target while nulling it at unintended user locations so that interference to the unintended users can be decreased. In this work, we present a new algorithm for nulling a signal at a one location, while focusing the signal energy at a different location, and compare it to existing techniques.

Chapter 2 briefly describes the theory of time-reversal and its application to spatial focusing. Chapter 3 shows how time-reversal can be used for simultaneous focusing and nulling. Chapter 4 describes how the performance of time-reversal for a wideband multi-antenna system can be unintuitive in certain cases. Chapter 5 provides experimental results for time-reversal focusing and nulling in a complex environment. Chapter 6 describes how time-reversal can be incorporated into a practical communication system.

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Chapter 2. Time-Reversal Focusing

Time-reversal focusing requires knowledge of the channel between the transmitter and the receiver. Due to reciprocity, the channel is the same in either direction. The channel information can be obtained by an end-point when any known signal transmission is received at that end-point. Consider the array transmitter, Tx , as shown in Figure 2.1 (note that the K array elements do not have to be in a regular geometric arrangement). In a time-reversal system, an initial probe pulse, $p(t)$, is transmitted by the intended receiver, U_m . The pulse received by Tx is

$$\mathbf{y}(t) = p(t) * \mathbf{h}_m(t), \quad (2.1)$$

where $\mathbf{h}_m(t)$ is an array of channels. $h_{m,k}(t)$, where $h_{m,k}(t)$ is the channel between the receiver, U_m , and the k^{th} element of Tx . $\mathbf{y}(t)$ is the array of received signals at the array elements.

Tx then transmits $\mathbf{y}_{tr}(t)$, the time-reversed version of $\mathbf{y}(t)$. The receiver U_m receives the signal,

$$z(t) = \sum^K \mathbf{y}_{tr}(t) * \mathbf{h}_m(t) = \sum^K \mathbf{y}(-t) * \mathbf{h}_m(t). \quad (2.2)$$

$z(t)$ is the summation of the signals transmitted by the K antenna elements convolved with the respective channels to the receiver. The transmission of $\mathbf{y}_{tr}(t)$ results in the convolution of the channel with its time-reversed version, which is the channel auto-correlation. The received signal is

$$z(t) = \sum^K p(-t) * \mathbf{h}_m(-t) * \mathbf{h}_m(t). \quad (2.3)$$

We denote the auto-correlation of the channel from the transmitter array elements to U_m as $R_{hm}(t)$. Therefore,

$$z(t) = p(-t) * R_{hm}(t), \quad (2.4)$$

Increased complexity in the environment increases the randomness of $\mathbf{h}_m(t)$, which increases the auto-correlation peak (this is indicative of sharp focus). In imaging or detection applications, Tx illuminates the region and $p(t)$ is reflected from the target. In communication applications, $p(t)$ is a known probe and the transmitter Tx uses the channel, $\mathbf{h}_m(t)$ to transmit a new information signal using the beam-forming filter, $\mathbf{g}(t) = -\mathbf{h}_m(t)$.

Figure 2.2 demonstrates an irregular array antenna focusing a signal using time-reversal onto

Figure 2.1. Time reversal transmitter and receiver.

Figure 2.2. 2-D EM simulation of time reversal focusing showing the E-field (normalized units of V/m) at a slice in the X-Y plane. An approximate grid of vertical rods is shown in the left half plane of the figure. The black circles are glass rods. The red circles are copper rods. The receiver is placed within the array, replacing rod(2,2) in the array. An irregular transmit array is in the right half plane of the figure. X and Y axes are in meters. $f_c = 3$ GHz, BW=100 MHz.

a receiver hidden within an array of obstructions. A complete electromagnetic simulation of this scenario is performed using Finite-Difference Time-Domain (FDTD) [4].

2.1 Time-reversal Simulation Technique

The spatial and temporal focusing due to time-reversal is critically dependent on the physical characteristics of the channel, such as the spatial correlation. Evaluation of these properties by simulation requires realistic channels; simple statistical channel models will not suffice. Time-reversal has been applied to geometric models of electromagnetic environments [5]. However, these channels are not complex enough to correspond to physical channels.

There are several techniques for solving for EM fields in an environment. These include geometrical and physical optics based techniques, method of moments (finite-element), and finite-difference techniques [6]. The geometrical and physical optics based techniques give good approximations for path loss but are not precise enough to provide us with frequency-specific complex channel vectors. For precise results, techniques based on first principles, such as Finite-Difference Time-Domain (FDTD) or Method of Moments, are needed. The most appropriate technique for our purpose is Finite-Difference Time-Domain (FDTD). FDTD solves for the EM fields within a space in a time-stepped manner, using Maxwell's equations [4]. The time-stepped nature of this technique directly yields EM fields as a function of time. It is fairly easy to model arbitrary objects in a space with this technique. However, the technique is computationally demanding, and the problem space that can be simulated is limited by computer memory. The simulations in this paper use a 2-dimensional FDTD simulation to make computations tractable. A perfectly matched layer (PML) is used to circumvent the discontinuities at the boundaries [7].

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Chapter 3. Simultaneous Focusing and Nulling using Time Reversal

In practical systems, it is desirable to focus a signal at the intended receiver while nulling the signal at other locations to reduce co-channel interference to unintended receivers.

The time-reversal system can be used for nulling by modifying the weighting filters of the transmit array. We will assume that the channels to both the focus location and the null location are known.

A heuristic method for nulling that has been reported in the literature is to modify the time-reversal weights, $\mathbf{g}(t)$ by inverting the polarity of the transmission from alternate antennas before transmission [8]. Note that this may not necessarily maintain focus at the desired location.

$$\mathbf{g}'(t) = [1 \quad -1 \quad 1 \quad -1 \quad \dots] \circ \mathbf{g}(t), \quad (3.1)$$

where $\circ$ is the operator for the Hadamard product (element-by-element). This is a heuristic that may work better when the antenna spacings are regular. Other work on nulling has also been described in the context of acoustics using a cross-spectral density matrix calculation [9]. However, this work is most applicable in a free space environment without obstructions.

In practical usage, it is desirable to focus on one user while nulling the signal at another. An optimal technique for this has been developed in the context of focusing a signal from an access point and reducing the interference to another access point and to a different user [10]. The solution requires minimizing the signal power to the null location(s) while transmitting non-zero power to the desired location. The weighting filter in the frequency domain is given as [10]

$$\mathbf{g}(\omega) = \frac{\gamma \int \|\mathbf{h}_m(\omega)\|^2 d\omega \quad \mathbf{X}(\omega)}{\int \mathbf{h}_m^T(\omega) \mathbf{X}(\omega) d\omega}, \quad \text{where}, \quad (3.2)$$

$$\mathbf{X}(\omega) = \left[(R^H(\omega) R(\omega))^{-1} \mathbf{h}_n^*(\omega) \right]. \quad (3.3)$$

$R(\omega)$ is a matrix of the channel between the transmitter array and all the null locations (corresponding to the antenna locations of the second access point and the second user), γ is a normalization constant.

We can simplify this for the case of a single null location at U_n . For this case, $R(\omega)$ reduces to

$$R(\omega) = \text{diag} [h_{n,1}(\omega) \quad h_{n,2}(\omega) \quad \cdots \quad h_{n,K}(\omega)], \quad (3.4)$$

where $h_{n,k}$ is the channel between the null location, U_n , and the k^{th} antenna element of Tx . Inserting equation 3.4 into equations 3.2 and 3.3 simplifies the weighting filter to a satisfying result in the frequency domain.

$$\mathbf{g}(\omega) = \gamma \begin{bmatrix} \frac{h_{m,1}^*(\omega)}{\|h_{n,1}(\omega)\|^2} \\ \frac{h_{m,2}^*(\omega)}{\|h_{n,2}(\omega)\|^2} \\ \vdots \\ \frac{h_{m,K}^*(\omega)}{\|h_{n,K}(\omega)\|^2} \end{bmatrix}, \quad (3.5)$$

where γ is a normalization constant. For simultaneous focusing and nulling, the optimal weighting vector at any frequency component is the time reversal weight $h_{m,k}^*(\omega)$ for the channel to the focus location divided by the squared magnitude of the corresponding frequency component of the channel to the null location.

3.1 Implications of the optimal technique simplified for one eavesdropper

The optimal beam-forming in this case depends on the known channel to the focus location but does not require complete knowledge of the channel to the null location. Only the power spectral density (PSD) of the channel to the null location is needed. This is a useful result, as the receivers at the null location may be part of a different communication system and may not be cooperative. But since only the PSD of the channel is important, we can use simpler channel estimation techniques.

3.2 Comparison with heuristic nulling

Figure 3.1 shows a scenario with an irregular array transmitter, a receiver (focus location), and an eavesdropper (null location). The location of the receiver and eavesdropper are approximately symmetric with respect to the metal pipe obstructions and the transmitter. A signal, $s(t)$ is transmitted using three techniques:

1. Time-reversal focusing on the receiver (ignoring the eavesdropper).
2. Heuristic nulling by attempting focusing on the eavesdropper but alternating the polarity of the transmit antenna weights.

Figure 3.1. Setup to demonstrate time-reversal focusing and nulling with an X-Y cross-section. The rectangular sections are metallic pipes(such as HVAC ducts) running vertically. The irregular array on the right is used for transmission. The intended focus location (the Receiver) is on the top left. The null location (the Eavesdropper) is on the bottom left. X,Y dimensions are in meters.

Figure 3.2. Receiver vs Eavesdropper signal for time reversal focus, heuristic nulling, and optimal simultaneous focus and nulling, for the setup in Fig 3.1. The transmitted signal is a cosine modulated Gaussian waveform at 2.5 GHz with a bandwidth of 800 MHz.

3. Using the optimal simultaneous focus and null technique (Equation 3.5).

Figure 3.2 shows the signal received by the receiver and the eavesdropper in these three cases. The best reception at the focus location is obtained when purely focusing on that location (Fig 3.2a). In this case, the signal at the eavesdropper is also large. The ratio of the signal (at receiver) to the signal at eavesdropper, Signal-to-Eavesdropper, S/E is 1.57 dB. Fig 3.2b shows the effect of nulling the eavesdropper by alternating the polarity of the transmit antenna weights [8]. This heuristic technique does not take into account the channel to the intended receiver. In this example, it decreases the signal at the receiver and does not succeed in nulling the eavesdropper. The signal-to-eavesdropper ratio dropped to -2.53 dB. The heuristic technique is very dependent on the geometry of the scenario. This is one of the pitfalls of simply nulling at the eavesdropper location. Fig 3.2c shows the effect of simultaneous focus and null. Here we can see that the signal at the receiver has decreased slightly, but the signal at the eavesdropper has dropped even more. This leads to an improved signal-to-eavesdropper ratio of 5.38 dB.

3.3 Statistical performance of the optimal simultaneous focus-null algorithm

The ability to focus or null using time-reversal is dependent on the channel characteristics. To this end, it is desirable to characterize the performance in many randomized scenarios. We created a randomized clutter generator. We created 100 scenarios with fixed fill ratios of metal, glass and wood. Two of these randomly created scenarios are shown in Figure 3.3.

Two methods are used to transmit the signal:

1. Focus solely at the receiver (focus location).
2. Simultaneously focus at the receiver and null at the eavesdropper.

Heuristic nulling at the eavesdropper has been ignored since it always performs poorly compared to the simultaneous focus and null technique. The energy received at the eavesdropper and receiver are shown in Figure 3.4(a). All measurements are shown relative to the energy at the receiver with direct time reversal focusing. Here are some observations:

1. In all cases, the simultaneous focus and null technique decreases the energy at the eavesdropper.
2. In all cases, the simultaneous focus and null technique provides slightly less energy at the receiver. This is expected since direct time-reversal focusing is optimal for delivering energy to the receiver.
3. In several cases, when focusing on the receiver, the eavesdropper energy is large (greater than that at the receiver). In these cases, the receiver has a location disadvantage compared to the eavesdropper.
4. In all cases, the simultaneous focus and null technique improves the S/E ratio (Figure 3.4(b)).

Figure 3.3. Randomly created scenarios for time-reversal processing. $f_c = 3$ GHz, BW = 500 MHz. Black objects are glass columns, Brown objects are wooden columns, Red objects are metal pipes. All axes are in meters.

(a) Energy received relative to the receiver energy with time-reversal focusing (0 dB line) for a variety of random scenarios.

(b) Improvement in Signal to Eavesdropper ratio (S/E) using simultaneous focus-null.

Figure 3.4. Statistical performance of simultaneous focus-null. Note that a line plot is used for visual effect but there is no implied relation between each simulation.

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Chapter 4. Multiple Antenna Weighting

We found that for a wideband multi-antenna time-reversal system, in rare cases, the addition of transmit antennas decreases focusing ability. This is unintuitive and is therefore important enough to deserve an explanation. Let a, b be channel vectors in the frequency domain from transmit antennas A and B to the receiver. For illustration, only the specific cases of one and two antenna transmissions are shown. In this time-reversal scenario, there is only one receive location. The following observations apply to a system with any number of transmit antennas. In the equations below, a_k^2 is the magnitude squared of a_k , i.e., $a_k^2 = |a_k|^2 = a_k a_k^*$.

The complex channel vectors in the frequency domain are matrices of dimensions N by K , where N is the number of discrete frequency points, and K is the number of antennas. The channel vectors for one and two antenna systems are given as:

	One antenna	Two antennas
$H(F)$	$\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix}$	$\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \\ \vdots & \vdots \\ a_N & b_N \end{bmatrix}$

The energy in the channels is

$$\sum_F H(F) H(F)^* \quad \left| \quad \sum_n a_n a_n^* = \sum_n a_n^2 \quad \right| \quad \left| \quad \sum_n a_n a_n^* + \sum_n b_n b_n^* = \sum_n a_n^2 + \sum_n b_n^2 \right|$$

The transmit beam-forming filter is the complex conjugate of the channel vector. After normalization, it is

$$bf(F) \quad \left| \quad \frac{\begin{bmatrix} a_1^* \\ a_2^* \\ \vdots \\ a_N^* \end{bmatrix}}{\sqrt{\sum_n a_n^2}} \quad \right| \quad \left| \quad \frac{\begin{bmatrix} a_1^* & b_1^* \\ a_2^* & b_2^* \\ \vdots & \vdots \\ a_N^* & b_N^* \end{bmatrix}}{\sqrt{\sum_n a_n^2 + \sum_n b_n^2}} \right|$$

For an impulse, wide-band signal, let us use a transmit signal which is a vector of all ones in the frequency domain. At the receiver, the transmission from each antenna goes through its unique

channel and the net signal at the receiver is summed. The signal seen by the receiver is

$$y(F) = bf(F)H(f) \quad \left| \quad \frac{\begin{bmatrix} a_1^* a_1 \\ a_2^* a_2 \\ \vdots \\ a_N^* a_N \end{bmatrix}}{\sqrt{\sum_n a_n^2}} = \frac{\begin{bmatrix} a_1^2 \\ a_2^2 \\ \vdots \\ a_N^2 \end{bmatrix}}{\sqrt{\sum_n a_n^2}} \quad \right| \quad \frac{\begin{bmatrix} a_1^* a_1 + b_1^* b_1 \\ a_2^* a_2 + b_2^* b_2 \\ \vdots \\ a_N^* a_N + b_N^* b_N \end{bmatrix}}{\sqrt{\sum_n a_n^2 + \sum_n b_n^2}} = \frac{\begin{bmatrix} a_1^2 + b_1^2 \\ a_2^2 + b_2^2 \\ \vdots \\ a_N^2 + b_N^2 \end{bmatrix}}{\sqrt{\sum_n a_n^2 + \sum_n b_n^2}} \quad (4.1)$$

The energy in the received signal per frequency bin is

$$y(F)y(F)^* \quad \left| \quad \frac{\begin{bmatrix} a_1^4 \\ a_2^4 \\ \vdots \\ a_N^4 \end{bmatrix}}{\sum_n a_n^2} \quad \right| \quad \frac{\begin{bmatrix} (a_1^2 + b_1^2)^2 \\ (a_2^2 + b_2^2)^2 \\ \vdots \\ (a_N^2 + b_N^2)^2 \end{bmatrix}}{\sum_n a_n^2 + \sum_n b_n^2} \quad (4.2)$$

The cumulative energy over frequency is

$$\sum_F y(F)y(F)^* \quad \left| \quad \frac{\sum_n a_n^4}{\sum_n a_n^2} \quad \right| \quad \frac{\sum_n a_n^4 + 2 \sum_n a_n^2 b_n^2 + \sum_n b_n^4}{\sum_n a_n^2 + \sum_n b_n^2} \quad (4.3)$$

For a single-tone channel (N=1), this reduces to

$$y(1)y(1)^* \quad \left| \quad \frac{a_1^4}{a_1^2} = a_1^2 \quad \right| \quad \frac{(a_1^2 + b_1^2)^2}{a_1^2 + b_1^2} = a_1^2 + b_1^2$$

In a narrowband, single-tone system, having a greater number of antennas in the transmit system will always perform better than having fewer number of transmit antennas for the same total transmit energy. Intuition would lead us to believe that the same principle holds in a wideband system, but this is not always the case.

Counter-intuitive operation in a wideband system: In general, for a system with N tones and K transmit antennas, the cumulative received energy is

$$\sum_F y(F) y(F)^* = \frac{\sum_n \left[\sum_k a_{(n,k)}^2 \right]^2}{\sum_n \left[\sum_k a_{(n,k)}^2 \right]}, \quad (4.4)$$

where $a_{(n,k)}$ is the component of the channel corresponding to the k^{th} transmit antenna and the n^{th} frequency tone.

Increasing the number of antennas, K , in a wide-band system usually increases time-reversal performance. However, this is not always the case because,

$$\frac{\sum_n \left[\sum_{k=1}^{K-1} a_{(n,k)}^2 \right]^2}{\sum_n \left[\sum_{k=1}^{K-1} a_{(n,k)}^2 \right]} \text{ is not always less than } \frac{\sum_n \left[\sum_{k=1}^K a_{(n,k)}^2 \right]^2}{\sum_n \left[\sum_{k=1}^K a_{(n,k)}^2 \right]} \quad (4.5)$$

The consequence is that in a given time-reversal system that is operating with some number of antennas, the addition of one more antenna can in some cases decrease performance (assuming that the total energy transmitted is kept constant).

Hypothetical wideband receiver: Here we explore, how we could create an artificial wideband time-reversal system where adding an antenna would always improve performance. Consider a hypothetical wideband receiver in which the signal in each of the frequency tones can be shifted to a single base frequency and summed. In such a system, we can sum up the rows in Equation 4.1. As before, the equations for one and two transmit antenna systems are shown as,

$$y = \sum_F y(F) \quad \left| \quad \frac{\sum_n a_n^2}{\sqrt{\sum_n a_n^2}} = \sqrt{\sum_n a_n^2} \quad \left| \quad \frac{\sum_n a_n^2 + \sum_n b_n^2}{\sqrt{\sum_n a_n^2 + \sum_n b_n^2}} = \sqrt{\sum_n a_n^2 + \sum_n b_n^2} \right.$$

The energy in the received signal will be

$$yy^* \quad \left| \quad \sum_n a_n^2 \quad \left| \quad \sum_n a_n^2 + \sum_n b_n^2 \right.$$

In such a hypothetical wideband receiver, the multi-antenna transmission will always perform better than a single-antenna transmission for the same transmit energy.

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Chapter 5. Experimental Results

Laboratory experiments were performed to evaluate time-reversal in a real physical setting. The experiments consisted of measuring real channels between transmitters and receivers. The channels were measured in a static environment (no movement in the environment during a measurement). Once this was done, the performance of the time-reversal algorithms could be evaluated on the real measured channels. This evaluation itself was done in MATLAB; actual time-reversed signals were not transmitted.

Experiments were made for different arrangements of the physical environment to study their effect on time-reversal (Figure 5.3). During each measurement an array of channel measurements from a number of transmit antennas to receive antennas were measured.

5.1 Equipment Setup

The channels between the transmit and receive antennas were measured using a network analyzer. Most network analyzers have two ports, some have four ports. A channel measurement can be obtained by measuring the complex transfer function between ports using scattering parameters (S-parameters) [11]. A network analyzer sweeps the scattering parameter measurement across frequency. For a channel measurement, it is essential that nothing is disturbed (channel is kept static) during a single measurement sweep.

With a four-port network analyzer, we can measure channels between a maximum of four antennas. For our time-reversal characterization, we wanted to use on the order of eight transmit and eight receive antennas. The equipment used for the channel measurement in our experiments was the combination of an Agilent E5071C vector network analyzer (VNA) and an Agilent E5092A multiport test set (MTS) (Figure 5.1). The E5071C is a four-port network analyzer. The multiport test set was used to increase the effective number of ports. The VNA was connected to the MTS via USB. The MTS has a bank of single-pole multi-throw RF switches. The switch configuration can be controlled by the VNA. The RF inputs and outputs of the switches can be interconnected to create arbitrary setups. The VNA does not dynamically change the switch configuration. For any switch configuration, the VNA does a 4-port measurement. Different switch configurations can be saved and loaded manually or by using remote programming. The multiport test set switch configuration is shown in Figure 5.2. The equipment was configured to measure an 8x8 array of channels (8 transmit antennas and 8 receive antennas). For some of the experiments only a subset

Figure 5.1. Network analyzer and multi-port test set for measuring an array of channels

Figure 5.2. Agilent E5092A multiport test set switch configuration

Figure 5.3. Laboratory layout for multipath tests

of this was needed. Figure 5.3 shows 6 transmit antennas and 8 receive antennas. The 8 receive antennas are placed in different arrangements (shown in light red) to examine performance.

Channel measurements were taken in the range of 5 and 6 GHz. A resolution bandwidth of 1 kHz was used to provide large dynamic range in measurement. High-quality RF cables were used to keep the phase stable during measurement. The combined setup of VNA, MTS and cables was calibrated before the measurement run.

5.2 Lab setup

The laboratory experiments were primarily conducted in an electro-magnetically shielded room with many obstructions (Figure 5.4). Care was taken to ensure that nothing was moved in the environment during a measurement sequence. Obstructions (chairs, bookcases, metallic containers, benches, lab equipment, etc.) were placed to create a multipath rich environment. Transmit antennas were mounted on tripods, but the mounting was not controlled (Figure 5.5). This was intentional since the time-reversal technique does not depend upon controlled inter-antenna spacing, or height or orientation. The network analyzer was controlled from the outside of the shielded room.

Figure 5.4. Laboratory setup for multipath tests

Figure 5.5. Transmit antennas are placed in an irregular array to demonstrate that time-reversal does not require specific spacing, height, or even orientation of transmit antennas

(a) Linear array of receive antennas in Styrofoam

(b) Receive antenna array with a grid spacing of 13.5 cm

Figure 5.6. Receive antennas located in an array

5.3 Time-reversal performance

The setup shown in Figure 5.6 was used to characterize the performance of the time-reversal algorithm in several areas.

Focusing Ability

Measurements were made using eight receive antennas (one row at a time). The row of eight antennas was moved eight times to take channel measurements along 64 grid locations. Time-reversal focusing was applied to the channels one row at a time. The focus spot was always the center of the row. Figure 5.7 shows the focusing ability in the horizontal direction (parallel to the transmit array). The difference in energy delivered to the center of the grid versus any of the side elements is approximately 8 dB. Another observation made during this measurement was that once a row of antennas was moved, it was difficult to re-place it identically since even small cable movements affected the channel. This could be alleviated partially by using foil backed Styrofoam which decreased the effect of the cables on the channel measurements.

Further measurements are shown using only linear arrays of 8 receive antennas. Figure 5.8

Figure 5.7. Signal focusing parallel to the transmit antenna plane

shows the focusing in the horizontal (parallel) and vertical (away) direction from the transmit array. The focusing ability is very similar in both directions.

Figure 5.9 shows simultaneous focus and nulling. A linear horizontal array and a linear vertical array were used to measure the channels for this purpose. Time-reversal is used to focus energy on the center and null out the closest adjacent antennas (the regions outlined in red). The figure shows that the signal is decreased an additional 3 dB at the null locations. Nulling at farther locations from the central focus point is even easier.

A smaller array (4.5 cm grid-spacing) was used and provided very similar performance as the larger array (Figure 5.10). This is because the metallic antennas in close proximity to each other provided some multipath that helps in the time-reversal focusing. At these distances, adjacent antennas are well within the near-field,

$$dist_{nearfield} = \frac{2D^2}{\lambda} \approx 80 \text{ cm}, \quad (5.1)$$

where, D is the largest dimension of the antenna and λ is the wavelength.

Using the channel data, we can also compute the performance of time-reversal if we were to vary bandwidth (Figure 5.11). The lowest performance results if we use a single-tone. This is to be expected since in a multipath rich environment, it is very possible for the specific tone to have a channel with large path loss due to a multipath null. As the bandwidth is increased, it becomes

Figure 5.8. Experimental performance of time-reversal signal focusing in X and Y directions (grid spacing of 13.5 cm). The horizontal and vertical receive array placements do not result in the same energy at the center since the placement of the antennas affects the channels. The top and bottom quadrants of the center square show the signal at the center when the receive array is in the vertical arrangement. The side quadrants show the signal at the center when the receive array is in the horizontal arrangement.

Figure 5.9. Experimental performance of simultaneous focus and null in X and Y directions (grid spacing of 13.5 cm). Nulling is performed on the regions outlined in red.

Figure 5.10. Experimental performance of time-reversal signal focusing in X and Y directions with close spacing of receive antenna array (grid spacing of 4.5 cm).

Figure 5.11. Experimental performance of time-reversal signal focusing vs bandwidth.

less likely that the entire bandwidth of the signal can encounter a multipath null.

The channel data can also be used to compute the performance with respect to the number of transmit antennas (Figure 5.12). As seen in simulations, experimental results show that increasing the number of antennas increases time-reversal performance. Though this is usually the case, it is possible that for some specific channels, this may not be the case as explained in Chapter 4.

Comparison with free space

The time-reversal technique works in the presence of multipath as seen in the previous experiments. To contrast its performance in a multipath environment with its performance in a free space environment, experiments were also conducted in an anechoic chamber without the obstructions (Figure 5.13). Some sources of reflections such as tripods and cables could not be avoided as we were attempting to place the transmit antennas in similar positions as in the shielded room. Horizontal (across) and vertical (away) measurements were made with the 8 receive antenna array. We can compare the performance in the anechoic chamber (Figure 5.14) with the performance in the multipath environment (Figure 5.10). It can be seen that in the anechoic chamber about 5 dB of focusing selectivity is obtained as opposed to the 8 dB in the multipath environment. Also, note that the anechoic chamber is not completely free of multipath since the multipath caused by the receive antenna array is still present. Another thing to note is that even though the distance

Figure 5.12. Experimental performance of time-reversal signal focusing with varying number of antennas

Figure 5.13. Experiment setup in an anechoic chamber

Figure 5.14. Experimental performance of time-reversal signal focusing in an anechoic chamber (grid spacing of 4.5 cm)

between the transmit array and receive array is about the same in both experiments, the absolute energy received in the multipath environment is approximately 25 dB higher than in the anechoic chamber.

5.4 Sensitivity to changes in the environment

Time-reversal focusing depends critically on the channel signature of the environment. A change in the channel signature will affect the focusing of a signal at a receiver. Time-reversal techniques can thus be used to detect changes in the physical environment [12]. To evaluate the change, the foreground bookshelf in Figure 5.4 was moved towards the transmit array in increments of 10 cm. The change is quite detectable as seen in Figure 5.15. The focusing ability decreases.

A small black metallic container (seen in the foreground in Figure 5.4) was placed on the lab bench and moved in increments of 10 cm. This change was less detectable (Figure 5.15). However, it is to be noted that a change in the channel is observed. Time-reversal is for focusing energy and de-focus may not be the best metric to detect change in the environment. An algorithm targeted for channel change detection may be able to work better for this purpose.

(a) De-focus due to movement of a shelf. The shelf was moved distances of 0,10,20,30 cm from its base position, towards the transmit array. The plot shows de-focus as the shelf is moved away from the base-position of 0 towards 30 cm and as the shelf is moved from the base-position of 30 cm towards 0.

(b) De-focus due to movement of a small container. The container was moved in increments of 10 cm

Figure 5.15. Detection of change in the environment using time-reversal de-focus

Chapter 6. Practical considerations for Time-Reversal

Time-reversal can be implemented in communication systems in a fairly straight-forward manner. A primary benefit is the ability to focus a signal without line of sight and without knowledge of the receiver location. This chapter address two aspects of implementation. Section 6.1 describes the embedment of time-reversal into a full-duplex communication system with resiliency against jamming. Section 6.2 describes the radio hardware needed for implementation of time reversal.

6.1 Communication System Embedment with Jamming Resilience

Time reversal can be used to focus energy on a target. This technique can also be used by potential jammers to focus a jamming signal on communication nodes. To prevent this, it is essential to deny the jammers, the knowledge of the channel from their locations to the communication nodes.

When communication commences between two nodes employing time-reversal, the channel to the intended target is not known. A probe signal is used to compute the channel. In an adversarial environment, it also necessary to authenticate the probe signal, since a forged probe signal can yield incorrect time-reversal weights. Digital signatures can be used for this purpose.

Figure 6.1 shows a communication sequence. To obtain the channel, a probe signal (known signal) has to be sent in one direction. In this figure, *node A* sends a probe message. The probe message is not directed at any particular target and is therefore “blind”. The probe message also has to contain information authenticating the sender. Without this, the probe message cannot be trusted by the recipient. When the probe message is received by *node B*, it can compute the channel and thus the time-reversal weights to be used. *Node B* can now send messages to *node A* by convolving the reply message with the time-reversal filter. A similar message sequence in the reverse direction will allow *node A* to send directed messages to *node B*.

This simple embedment has the following disadvantages:

1. full-duplex time-reversal transmission requires probe messages in both directions.
2. the probe messages provide enough information to allow an adversary to focus a jamming signal (via time-reversal) on either node.

The scheme shown in Figure 6.2 remedies these deficiencies. In this alternative scheme, a

Create a query
Add digital signature

Figure 6.1. Authenticated half-duplex time-reversal

randomly created time-reversal filter is used for the initial probe message. The filter weights are also inserted into the probe message which is then digitally signed and encrypted by *node A*. The message is then convolved with the randomly created time-reversal filter and transmitted. Due to the use of the random weights, whose values are encrypted, only valid nodes (nodes that can decrypt the values) can compute the actual time-reversal weights. *Node B* can authenticate this message as being genuine due to the digital signature. It can also decrypt the message. From the message, it retrieves the random time-reversal filter used by *node A* for transmission. Given that, it can compute the channel to *node A* and the time-reversal filter that will focus a signal on *node A*. An adversarial node will not be able to decrypt the message to read the random weights and it will not be able to compute the real time-reversal weights either.

Any message that *node B* sends to *node A* should likewise include the time-reversal weights and the message should be encrypted and signed. When *node A* receives such a message, it will also be able to calculate the channel and the time-reversal filter weights. The channel between *node A* and *node B* is the same in either direction and so are the weights of the time-reversal filter. Technically, *node A* does not need to compute the time-reversal filter weights, since it is already included in the message from *node B*. However, it is best that *node A* recomputes this as the channel may have changed slightly in the intervening time due to changes in the environment.

The disadvantage of the improved scheme in Figure 6.2 is that the time-reversal weights have to be embedded in the communication messages. This requires a greater integration between the data link layer and the physical layer of the communication system than is common.

The schemes shown above make it difficult for a jammer to focus on a communication node but do not make it impossible. It may still be possible for a sophisticated jammer to determine the

Figure 6.2. Authenticated full-duplex time-reversal with jammer resiliency

channel using other techniques with greater complexity.

6.2 Hardware Implementation

The time-reversal technique can be implemented purely by digital signal-processing. It does not need any special hardware beyond that which would be present in modern design multi-antenna radios (Figure 6.3). Such a multi-antenna radio would have banks of I/Q modulators (inphase-quadrature) driven by the same oscillator at the carrier frequency. In relation to modern radio designs, the computational requirements for time-reversal are fairly low. The most dominant computation in the time-reversal technique, is the channel calculation, which is computationally modest.

Figure 6.3. Hardware block-diagram of a radio with time-reversal capability

Chapter 7. Summary

Time reversal signal processing can be used to focus energy at a target location. It does not require line-of-sight and does not require knowledge of the target location. It also does not require careful arrangement of the transmit antennas. Time-reversal techniques can also be used to null energy at an “eavesdropper” location if the channel to the eavesdropper is known. This can also be done in a cooperative system to decrease interference to a neighboring node.

We have presented the optimal scheme to simultaneously focus energy on a receiver while nulling at one eavesdropper. The optimal scheme is very simple in that only the PSD of the eavesdropper channel is needed. This makes it possible to use simplified scalar channel estimates to perform simultaneous focusing and nulling. Random simulation of several scenarios showed that the simultaneous focus/null technique works well for decreasing the eavesdropper power in most scenarios.

Our experimental results have confirmed the results obtained through simulation. We have observed focusing selectivity of approximately 8 dB within a distance of 13 cm. A Rough comparison shows that time-reversal in a multipath environment performs much better than in a free-space environment. Time-reversal is critically dependent on the multipath environment. It can therefore be used to detect changes in the multipath environment.

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