Spatially focusing a radio signal and simultaneously nulling it at another location using time-reversal signal processing

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***Abstract*—Phased array antenna techniques for beamforming are thwarted in a cluttered environment. The time-reversal method utilizes the clutter (and associated multipath) to focus beyond the Rayleigh limit. This method makes use of the reciprocity of wireless propagation channels. Time-reversal can also be used to null signals, either to reduce unintentional interference or to prevent eavesdropping. We present a simple technique that nulls the transmitted signal at a specific location, while simultaneously focusing the signal at a desired location. This technique can also be used for the reverse problem of reception of a desired signal while nulling out an interfering source.**

I. Introduction

Time-reversal signal processing is a spatial focusing technique that utilizes the reciprocity of wireless channels. 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.

This 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. This is simply the auto-correlation of the channel.

The time-reversal technique has some practical benefits. It does not require knowledge of the receiver location and does not require line-of-sight. Increased multipath increases the focusing ability of the channel. In a physical context, the clutter in the environment is beneficially used 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 narrowband approximation to time-reversal, have been used to obtain focus resolution beyond the Rayleigh limit with microwaves [3].

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. In practical applications, it is desirable to focus a signal at the intended target while nulling it at unintended user locations so that co-channel interference to the unintended users can be decreased.

In this paper, we will compare techniques for nulling a signal at a one location, while focusing the signal energy at a different location.

Section II briefly describes the theory of time-reversal and its application to spatial focusing. Section III shows how time-reversal can be used for simultaneous focusing and nulling. Finally, section IV shows electromagnetic simulations demonstrating focusing and nulling in a variety of environments.

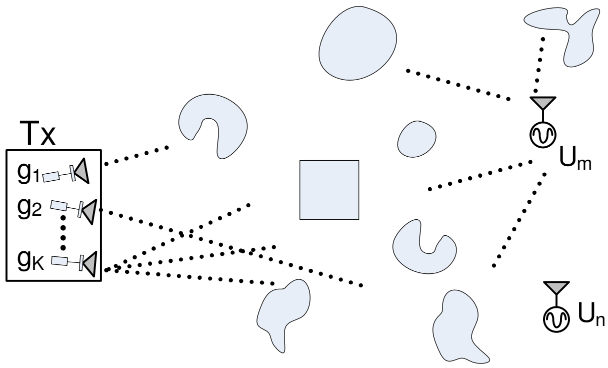

Fig. 1. Time reversal transmitter and receiver.

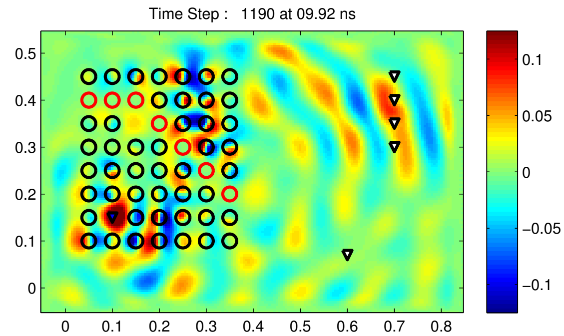

Fig. 2. 2-D EM simulation of time reversal focusing showing the E-field (normalized units of V/m) at a slice in the X-Y plane. An approximate grid of vertical rods is shown in the left half plane of the figure. The black circles are glass rods. The red circles are copper rods. The receiver is placed 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.

II. Time-Reversal Focusing

Consider the array transmitter, Tx, as shown in Figure 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

$$\mathbf{y}(t) = p(t) * \mathbf{h}_m(t). \qquad (1)$$

$\mathbf{h}_m(t)$ 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,

$$z(t) = \sum^{K} \mathbf{y}_{tr}(t) * \mathbf{h}_m(t) = \sum^{K} \mathbf{y}(-t) * \mathbf{h}_m(t). \qquad (2)$$

$z(t)$ 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 autocorrelation.

$$z(t) = \sum^{K} p(-t) * \mathbf{h}_m(-t) * \mathbf{h}_m(t). \qquad (3)$$

We denote the autocorrelation of the channel from the transmitter array elements to U_m as $R_{hm}(t)$.

$$z(t) = p(-t) * R_{hm}(t), \qquad (4)$$

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 weights, $\mathbf{g}(t) = -\mathbf{h}_m(t)$.

Figure 2 demonstrates an irregular array antenna focusing a signal using time-reversal onto a receiver hidden within an array of obstructions. A complete electromagnetic simulation of this scenario is performed using Finite-Difference Time-Domain (FDTD) [4].

A. Channel model for time-reversal simulation

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. There are several techniques for solving for EM channels, but most appropriate for this purpose is the Finite-Difference Time-Domain (FDTD) technique. FDTD is based on first principles and solves for the EM fields within a space in a time-stepped manner, by using Maxwell's equations [4]. The simulations in this paper use a 2-dimensional FDTD simulation to make computations tractable.

III. Simultaneous Focusing and Nulling using Time Reversal

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 [5].

$$\mathbf{g}'(t) = \begin{bmatrix} 1 & -1 & 1 & -1 & \cdots \end{bmatrix} \circ \mathbf{g}(t), \tag{5}$$

where $\circ$ is the operator for the Hadamard product (element-by-element).

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 [6]. 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 [6]

$$\mathbf{g}(\omega) = \frac{\gamma \int \|\mathbf{h}_m(\omega)\|^2 \, \mathrm{d}\omega \quad \mathbf{X}(\omega)}{\int \mathbf{h}_m^T(\omega)\mathbf{X}(\omega)\,\mathrm{d}\omega}, \quad \text{where,} \tag{6}$$

$$\mathbf{X}(\omega) = \left[\left(R^H(\omega)R(\omega)\right)^{-1}\mathbf{h}_n^*(\omega)\right]. \tag{7}$$

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

$$R(\omega) = \operatorname{diag}\left[h_{n,1}(\omega) \quad h_{n,2}(\omega) \quad \cdots \quad h_{n,K}(\omega)\right], \tag{8}$$

where $h_{n,k}$ is the channel between the null location, U_n, and the k^{th} antenna element of Tx. Inserting equation 8 into equations 6 and 7 simplifies the weighting filter to a satisfying result in the frequency domain.

$$\mathbf{g}(\omega) = \gamma \begin{bmatrix} \frac{h_{m,1}^*(\omega)}{\|h_{n,1}(\omega)\|^2} \\ \frac{h_{m,2}^*(\omega)}{\|h_{n,2}(\omega)\|^2} \\ \vdots \\ \frac{h_{m,K}^*(\omega)}{\|h_{n,K}(\omega)\|^2} \end{bmatrix}, \tag{9}$$

where γ is a normalization constant. For simultaneous focus 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.

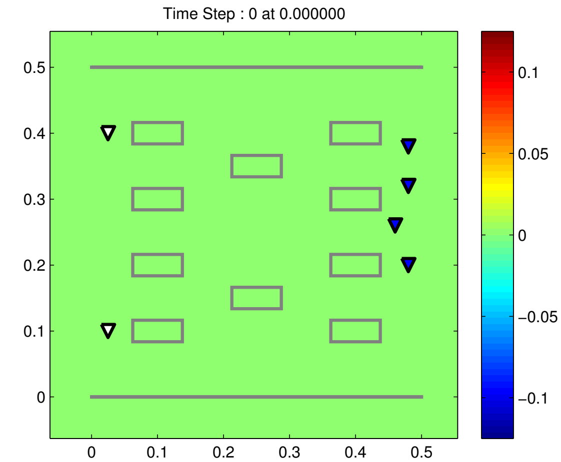

Fig. 3. Setup to demonstrate time-reversal focusing and nulling with an X-Y cross-section. The rectangular sections are metallic pipes(such as HVAC ducts) running vertically. The irregular array on the right is used for transmission. The intended focus location (the Receiver) is on the top left. The null location (the Eavesdropper) is on the bottom left. X,Y dimensions are in meters.

A. 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.

B. Comparison with heuristic nulling

Figure 3 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.

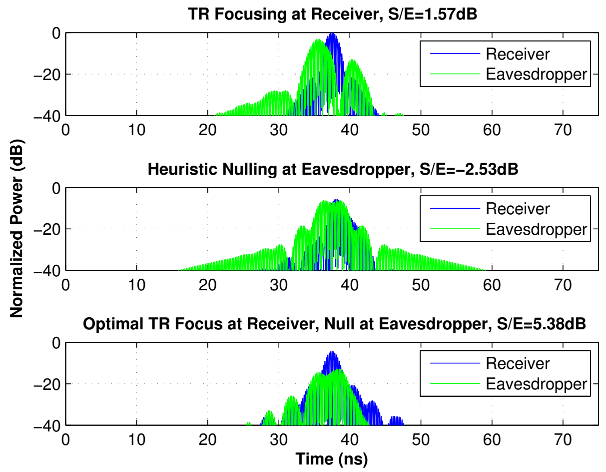

Fig. 4. Receiver vs Eavesdropper signal for time reversal focus, heuristic nulling, and optimal simultaneous focus and nulling, for the setup in Fig 3. The transmitted signal is a cosine modulated Gaussian waveform at 2.5 GHz with a bandwidth of 800 MHz.

3) Using the optimal simultaneous focus and null technique (Equation 9).

Figure 4 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 4a). In this case, the signal at the eavesdropper is also high. The ratio of the signal (at receiver) to the signal at eavesdropper, Signal-to-Eavesdropper, S/E is 1.57 dB. Fig 4b shows the effect of nulling the eavesdropper by alternating the polarity of the transmit antenna weights [5]. 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. It is very dependent on the geometry of the scenario. This is one of the pitfalls of simply nulling at the eavesdropper location. Fig 4c shows the effect of simultaneous focus and null. Here we can see that the signal at the receiver has decreased a little, and the signal at the eavesdropper has dropped even more to give an improved signal-to-eavesdropper ratio of 5.38 dB.

IV. 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

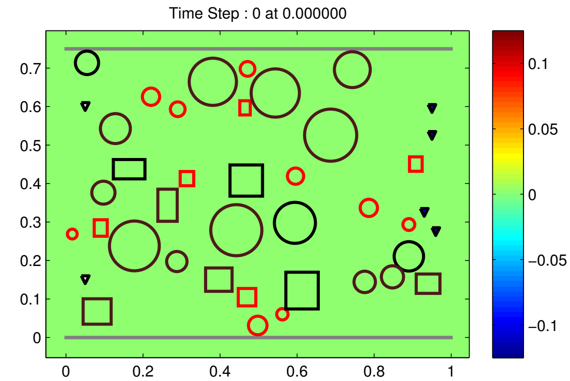

Fig. 5. Randomly created scenario for time-reversal processing. f_c = 3 GHz, BW = 500 MHz. Black objects are glass columns, Brown objects are wooden columns, Red objects are metal pipes. All axes are in meters.

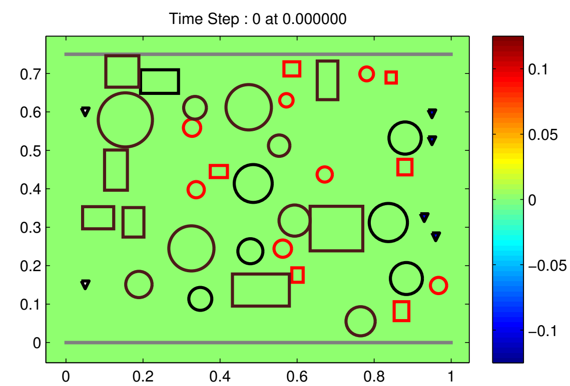

Fig. 6. Another randomly created scenario with similar parameters as in Fig 5

generator. We created 100 scenarios with fixed fill ratios of metal, glass and wood. Two of these randomly created scenarios are shown in Figures 5 and 6. 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 7. 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.

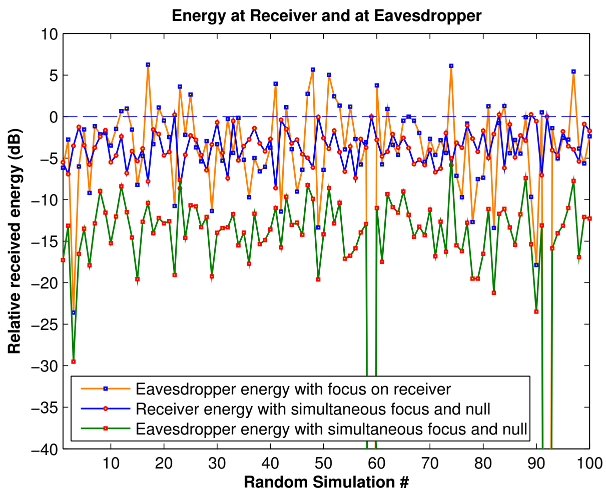

Fig. 7. Energy received relative to the receiver energy with time-reversal focusing (0 dB line) for a variety of random scenarios.

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 high. In these cases, the receiver has a location disadvantage compared to the eavesdropper. In these cases, the simultaneous focus and null technique reduces the eavesdropper energy but it also reduces the receiver energy more than in other cases.

V. Conclusion

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. Time-reversal techniques can be used to null energy at an "eavesdropper" location if the channel to the eavesdropper is known.

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.

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