SPATIAL FOCUSING AND INTERFERENCE REDUCTION USING MISO TIME REVERSAL IN AN INDOOR APPLICATION

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ABSTRACT

This paper evaluates the spatial focusing performance of the Time Reversal (TR) method in a multiple input single output (MISO) situation with experimental data. For the target user, the received signal is related to the channel link from the transmitter to the target receiver. The received power increases as we enlarge the array size, and it increases by 15.6 dB with 16 transmit antennas, compared to the single link. For the eavesdropper, the received signal is determined by both the channel link from the transmitter to the target user and the channel link from the transmitter to the eavesdropper. In terms of unbalanced branch power, the minimum average Eavesdropping Margin (EM) and Peak Eavesdropping Margin (EM\text{Peak}) are 14 dB and 13 dB from 16 transmit elements.

Index Terms— MISO, time reversal, spatial focusing

1. INTRODUCTION

Time Reversal (TR) is a pre-filtering scheme, which has the potential to achieve time compression and spatial focusing [1]-[6]. The time compression refers to the capability of reducing the effective length of the resulting impulse response (IR) in the time domain, and the spatial focusing indicates the beamforming capability by concentrating the signal on the target user. Furthermore, the application of the TR method can achieve transmit diversity and has the potential to tolerate a rather simple receiver.

The concept of TR was introduced in acoustic wave applications [1]-[3], and has recently been studied in the field of wireless communications by using electromagnetic waves [4]-[8], specifically in the multiple input single output (MISO) setting. So far, measurement investigations of MISO TR have been focused on either the time compression property [6]-[7], or the spatial focusing performance in outdoor environments [7]-[8]. In this paper, we concentrate on the spatial focusing performance of TR in a Wideband (WB) indoor environment with quasi-static channel conditions.

The prerequisite for the application of TR is that the transmitter (Tx) has the Channel State Information (CSI). This can be achieved either from the Uplink transmission where by the Tx acquires the CSI, or through a feedback loop where the receiver (Rx) estimates the CSI and feeds it back to the Tx [6], [9]. In this paper, we assume perfect channel estimation and synchronization, and we only consider a MISO Downlink situation.

In the following, bold symbols denote matrices and underlined symbols indicate vectors. \((\cdot)^*\) and \((\cdot)^H\) are the complex conjugate and the hermitian of the argument \((\cdot)\), respectively. \(E[\cdot]\) is the expected value of the argument \([\cdot]\). The superscripts ‘Target’ and ‘Eav’ are the notations of the target user and the eavesdropper, respectively.

2. MISO TIME REVERSAL

Let us assume a MISO communication system with \(M\) transmit antennas and \(I\) receive antenna. The transmitted and received data streams are denoted as \(x(t)\) and \(y(t)\), respectively. The channel IR from the \(m\)-th Tx antenna to the

![MISO Time Reversal Diagram](Fig1)

Figure 1. MISO Time Reversal Diagram.
Rx is expressed as \( h_{\text{m}} \), where \( h_{\text{m}} = h(\tau; L_{\text{TX}}, L_{\text{RX}}) \). \( \tau \) and \( r \) are the delay and space variables, respectively. \( L_{\text{TX}} \) denotes the location of the \( m \)-th Tx antenna, and \( L_{\text{RX}} \) indicates the position of the Rx. We apply the TR scheme, by adding filters at the Tx side, where the filter at the \( m \)-th Tx element is the complex-conjugate time-reversed channel IR \( C_{\text{m}} \) of the IR from the \( m \)-th Tx antenna to the target Rx (see Figure 1).

In the evaluation of the spatial focusing performance, we distinguish 2 different receivers: the target user and the eavesdropper. In the absence of noise, the received signal at the target user \( y(\tau; L_{\text{TX}}, L_{\text{RX}}) \) and the eavesdropper \( y(\tau; L_{\text{TX}}, L_{\text{RX}}) \) can be expressed as:

\[
y(\tau; L_{\text{TX}}, L_{\text{RX}}) = \alpha \sum_{m=1}^{M} \sum_{r=1}^{W} x(\tau) \odot h^{*}(\tau; L_{\text{TX}}, L_{\text{RX}}) \odot h(\tau; L_{\text{TX}}, L_{\text{RX}})
\]

where \( \tau_{\text{max}} \) denotes the maximum delay of the channel IR.

We define the ‘effective channel IR’ for both the target user \( h_{\text{eff}}^{\text{Target}}(\tau; L_{\text{TX}}, L_{\text{RX}}) \) and the eavesdroppers \( h_{\text{eff}}^{\text{Eav}}(\tau; L_{\text{TX}}, L_{\text{RX}}) \) as:

\[
h_{\text{eff}}^{\text{Target}}(\tau; L_{\text{TX}}, L_{\text{RX}}) = \alpha \sum_{m=1}^{M} R_{\text{m}}(\tau; L_{\text{TX}}, L_{\text{RX}})
\]

\[
h_{\text{eff}}^{\text{Eav}}(\tau; L_{\text{TX}}, L_{\text{RX}}) = \alpha \sum_{m=1}^{M} h^{*}(\tau; L_{\text{TX}}, L_{\text{RX}}) \odot h(\tau; L_{\text{TX}}, L_{\text{RX}})
\]

From equations (1) and (2), we can observe that the received signals at the target user and the eavesdropper are related to the auto- and cross-correlation functions of the channel IRs, respectively. Therefore, the difference of these resulting correlation functions attracts our interest in the spatial focusing performance.

In this indoor experiment, the carrier frequency was 5.8GHz (wavelength \( \lambda = 5 \text{cm} \)). The instantaneous channel IR is obtained from 16 Tx antennas with a sampling rate of 60Hz. The total period of the measurement is around 15s, i.e. 900 samples. However, we only select 70 samples that behave in a relatively stationary manner. The measurements are taken in a building with several partitions made up by 1.5m-height wooden boards (see Figure 2).
Two Access Points (APs) are arranged in a corridor at a height of 2.1m, and each AP is mounted with 8 antenna elements. 4 users sit around the table (0.8m height) and face the APs. The outside walls of the building are made of bricks, and have glass windows. The window frame is made of aluminum. Each user has 2 types of Rx antennas: laptop and body mounted antennas, and there are 4 elements of each type on each user. During the measurements, each user mimics the behavior of typing at the laptop keyboard. In this measurement, we use 1 antenna on the laptop as the target user, and 3 body mounted antennas as the eavesdroppers, namely Eav1, Eav2 and Eav3 (see Figure 3).

4. SPATIAL FOCUSING PERFORMANCE

This section evaluates the spatial focusing performance of TR in a MISO situation, in terms of the received power and the average EM. In order to evaluate the influence of the difference among channel links, we rearrange the channel links from the Tx antennas to the intended Rx in an ascending order of their mean branch power, so that adding one more Tx antenna will always lead to involving a channel link with higher average power than the links which are currently used. In addition, the normalization factor \( \alpha \) is recalculated when we add one more transmit antenna, so that the total transmit power is \( I \).

4.1. Average Signal Power

In this subsection, we look at the intended signal at both the target and the eavesdropper, by showing the average received signal power.

4.1.1. Average Received Power at \( \tau=0 \)

We first investigate the average power of the received signal

Figure 4. Average received signal power at \( \tau=0 \) with respect to the number of Tx antennas at AP1 (\( M_{\text{AP1}} \)) and AP2 (\( M_{\text{AP2}} \)), respectively.

![Graph showing average received signal power at \( \tau=0 \) for different numbers of Tx antennas at AP1 and AP2.](image)

Figure 4. Average received signal power at \( \tau=0 \) with respect to the number of Tx antennas at AP1 (\( M_{\text{AP1}} \)) and AP2 (\( M_{\text{AP2}} \)), respectively.

In order to illustrate the variation of the power for the eavesdropper, we investigate the phase difference between the current effective channel and the summation of the previous channels, and its influence on the variation of the increasing/ decreasing trend of the received signal power. We investigate specifically the phase difference (\( \theta_0 \)) between the effective channel IR after the summation of \( \ell \)-th terms and the cross-correlation of the \( \ell \)-th term at \( \tau=0 \). Each term
corresponds to the contribution from 1 Tx antenna at either AP1 and AP2.
\[ \theta_L = \mathcal{L} \left( \sum_{m=1}^{L} b^E_{m} \cdot (L^E_{m}^T \cdot h^E_{m})^H \right) - \mathcal{L} \left[ b^E_{L} \cdot (h^E_{L}^T \cdot h^E_{L})^H \right] \] (11)

We show \( \cos(E[\theta_L]) \) in Table 1. The value varies from -1 to 1, which indicates the trend of 2 vectors from completely non-coherent to coherent. For instance, \( L=7 \) for Eav1 from AP1, \( \cos(E[\theta_L])=1 \). This means the 7-th effective channel link is added coherently with the summation of the previous 6 links. Hence the received signal power increases at this point (See Figure 5, the right upper plot for Eav1). At \( L=8 \), \( \cos(E[\theta_L])=-0.8 \), which indicates the non-coherent phase between the 8-th effective channel IR and the summation of previous 7 effective channel IRs. Therefore, the received signal power does not increase, though we add one more antenna at the transmit side.

<table>
<thead>
<tr>
<th>Configuration</th>
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<tr>
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<tr>
<td>AP1 Eav1</td>
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<tr>
<td>Eav2</td>
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4.1.2. Average Peak Power over Delay Domain

We show the peak power over the delay domain for the target user and the eavesdropper in Figure 6. This value describes the maximum power the eavesdropper may intercept from the signal intended to the target over the delay domain. Therefore, this received signal power at the eavesdropper can be higher than the one observed at the same eavesdropper at \( \tau=0 \). This is the result shown in Figure 3. Let us take Eav1 as an example. In order to obtain 30dB EM, we can either select 6 antenna elements from AP1, or choose 3 elements from AP1 and 1 element from AP2. A similar procedure can also be applied for Eav2 and Eav3 to achieve high EM. Therefore, the selection of transmit antenna can help us to reduce the

4.2. Average EM

In this subsection, we compare the difference in received signal power between the target user and the eavesdropper, by investigating the average EM at \( \tau=0 \) and the Peak EM EM\(_{\text{Peak}}\) with respect to the number of Tx antenna elements at the 2 APs.

4.2.1. Average EM at \( \tau=0 \)

Figure 7 shows the average EM as the number of Tx antenna elements varies at both AP1 and AP2. Again, due to the imbalance of the branch power and the non-coherent summation of the effective channel links at \( \tau=0 \), we can not observe the 3dB increase per doubling of M as expected. In the single link situation (1 Tx antenna from either AP1 and AP2), a minimum average EM of 7dB can be achieved over the 3 eavesdroppers. When we fully use 16 Tx antennas, the minimum EM for the 3 eavesdroppers is 14dB.
interference at each specific eavesdropper. However, in order to reduce the interference over all eavesdroppers, we need to select the transmit antennas so that we have high EM at all eavesdroppers.

4.2.2. Average Peak EM (EM_{Peak})

We also investigate the EM_{Peak} in Figure 8, which indicates the lowest possible EM. The EM_{Peak} values are smaller and fluctuate less than the average EM. The EM_{Peak} increases as the number of transmit element increases. This trend is not clearly obvious for average EM. With 1 Tx element from either AP1 and AP2, the minimum EM_{Peak} is 4.5dB. With 16 Tx antennas, the minimum EM_{Peak} over the 3 eavesdroppers is 13dB.

![Figure 8. Average EM_{Peak} with respect to the number of Tx antenna at AP1 (M_{AP1}) and AP2 (M_{AP2}), respectively.](image)

8. CONCLUSIONS

This paper investigates the spatial focusing performance of MISO TR in an indoor environment with 2 distributed APs (16 Txs) and 4 Rx (1 target user and 3 eavesdroppers). The feasibility of the TR application requires the Tx knows the CSI of the intended user. With the assumption of perfect channel estimation, we calculate the received signal power at $\tau=0$ and maximum power over the delay domain.

The result shows the received signal power is mainly determined by the effective channel link. In terms of unbalanced branch power, the average EM at $\tau=0$ and EM_{Peak} are at least 7dB and 4.5dB for all the combinations of Tx antennas. In the presence of 16 Tx elements, the minimum average EM and EM_{Peak} are 14dB and 13dB, respectively.

9. REFERENCES


