

Performance Study on Time Reversed Impulse MIMO for UWB Communications Based on Measured Spatial UWB Channels

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Abstract—UWB technology is generally limited to short range applications, due to the strong power limitations imposed by Federal Communications Commission (FCC). In this paper we propose to use MIMO combined with Time Reversal (TR) technology to increase its transmission distance. The performance of such a UWB-MIMO-TR system is analyzed, considering a simple one correlator receiver. Performance comparisons are made among the scenarios of SISO-TR, MISO-TR, and MIMO-TR. The results show that a UWB-MIMO-TR system can achieve a huge power gain, depending on the antenna numbers employed at both the transmitter and the receiver, but still keeps low complexity at the receiver. The performance analysis is based on realistic channels measured in an office environment.

I. INTRODUCTION

Time Reversal (TR) is a technology originated from underwater acoustic and ultrasound communications [1] and has recently been extended to wireless applications [2]- [6]. Given specific time and location, TR precoding has been mathematically proved to be the optimum in the sense that it maximizes the amplitude of the field at that time and location [7]. It is then called spatio-temporal matched filter [8] because it is analogous to a matched filter both in time and space. It is also called transmit matched filter since the matched filter is placed at the transmitter side.

Considering the severe power constraints imposed on the system, the main focus of Ultra-wide Band (UWB) study has been restricted to short range applications such as communications between PCs, PDAs, cordless phones, smart appliances, and entertainment systems anywhere in and around the home. In this paper, we propose to use multiple antennas combined with TR technology (TR-MIMO) to increase the transmission distance of pulse-based UWB systems. It should be noted that MIMO technology could either be employed to increase the data rate by decomposing the channel into a series of parallel sub-channels or to increase the signal to noise ratio (SNR),

by beamforming. This paper will mainly focus on the latter application.

TR-MIMO [9] implements MIMO directly in the time domain, and hence is believed to be much simpler, compared to those algorithms implemented in the frequency domain. However, most research on UWB-MIMO is carried out in the frequency domain, and very few results on time domain UWB MIMO have been reported so far. The paper [10] studies time domain MIMO and proposes to use Maximum Ratio Combining (MRC) to accomplish the temporal alignment of received pulses, which unfortunately also causes a high complexity at the receiver. By the use of TR precoding, however, pulses are automatically aligned, and thus the receiver complexity is greatly reduced. Moreover, it is shown in [11] that TR precoding can achieve the same error performance as the MRC combining scheme.

Due to the spatial-temporally focusing of the TR technology, the energy of the received signal tends to form as a short peak. We propose to use a simple coherent receiver with one correlator to capture the main lobe energy, and treat the rest of the received signal as interference. By doing this, the receiver complexity is greatly reduced since there are no channel estimation and equalization at the receiver side. However, as we will show in this paper, the performance of such a simple receiver can still achieve the AWGN bound under ideal conditions that all the multipath components are resolvable and there is no ISI in the system, given the same transmitted power. It is shown that a gain of $10\log_{10}(MN)$ dB can be achieved by using an MIMO with M antennas at the transmitter and N antennas at the receiver.

In practice, when the pulse is short and the data rate is low, the above conditions tend to be satisfied. However, for the case of high data rate and practical pulse width, the conditions may not hold. The performance of such a practical system is investigated by Monte Carlo simulations. Considering that there is no available channel data involving multiple antennas, we carry out a series of spatial channel measurements in an office environment.

The structure of this paper is as follows: In Section II, we give the system description and the analytical performance analysis. A brief description of the experimental setup and the environment is given in Section III. Some numerical results and analysis based on measurement channels are given in Section IV. Finally, we present the conclusions of the paper in Section V.

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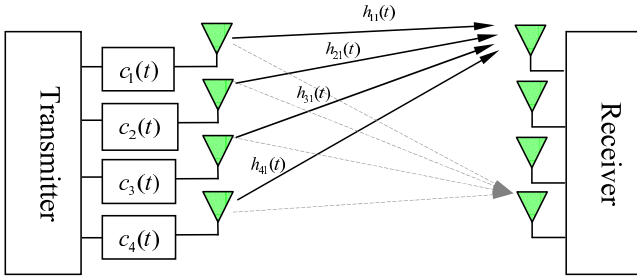


Fig. 1. Time reversal precoded MIMO communication system with $M=4$ and $N=4$.

II. PERFORMANCE ANALYSIS

A. MIMO-TR Precoding

An MIMO-TR (4×4) system configuration is illustrated in Fig. 1. Let $h_{mn}(t)$ denote the channel impulse response (CIR) between the m -th antenna at the transmitter and the n -th antenna at the receiver, and $c_m(t)$ be the corresponding prefilter code employed in the m -th antenna branch at the transmitter. In a general $M \times N$ MIMO-TR system, the code $c_m(t)$ can be written as

$$c_m(t) = A_m \sum_{n=1}^N h_{mn}(T-t) \quad (1)$$

where T is the length of the filter required to implement time reversal operation [12], and A_m is the power scaling factor to normalize the total transmission power from different antenna branches. It should be noted that different power allocation schemes can be implemented by choosing different A_m value [13]. In this paper, for simplicity, values of A_m are set to be equal for all the antenna elements, i.e.,

$$A_m = A = \frac{1}{\sqrt{\sum_{m=1}^M \sum_{n=1}^N G_{mn}}} \quad (2)$$

where $G_{mn} = \int_{-\infty}^{+\infty} |h_{mn}(t)|^2 dt$ is the channel gain of CIR $h_{mn}(t)$.

The precode $c_m(t)$ for the m -th antenna branch can be readily obtained by channel sounding, assuming channel is reciprocal and is static over one symbol duration. These two assumptions have been verified for UWB system by measurements in [6]. The process of MIMO-TR channel sounding includes two steps: Firstly, all N antennas at the receiver send a sounding pulse $w(t)$ to the transmitter simultaneously; Secondly, the received signal at each transmitter antenna branch is recorded, digitized and time reversed. The time reversed version of the signal in each antenna element will be used as the precode for that antenna branch.

B. System Description

Consider a single user transmission. Transmitted signals before precoding can be expressed as

$$s(t) = \sum_{i=-\infty}^{+\infty} s_i(t) = \sum_{i=-\infty}^{+\infty} \sqrt{E_b} b_i p(t - iT_b) \quad (3)$$

where E_b is the transmitted bit energy, $b_i \in \{\pm 1\}$ is the i -th information bit. Without loss of generality, binary antipodal modulation has been considered in this paper. $p(t)$ is the UWB pulse with a width of T_p . The energy of $p(t)$ is normalized to unity, i.e., $E_p = \int_{-\infty}^{+\infty} p^2(t) dt = 1$. T_b is the bit interval. Generally, we have $T_b \gg T_p$, in order to avoid the possible Inter Symbol Interference (ISI) caused by multipath channel. In this paper, we will show that, by using a MIMO-TR technology, T_b and T_p could be chosen to be in the same level, without significant performance degradation.

For the sake of simplicity, we assume there is no per-pulse distortion [15] caused by channel. In this case, the received signals are just a series of replicas of the transmitted signals, with different attenuations and time delays. The CIR then can be modeled as

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

where L is the number of multipath components and α_l and τ_l are its individual amplitudes and delays.

C. Performance Analysis

Before we consider MIMO-TR, let us start with a simpler scenario of SISO-TR. If there is no time reversal and a single antenna is employed at both the transmitter and the receiver, the received signal can be expressed as

$$r_i(t) = \sum_{l=1}^L \alpha_l s_i(t - \tau_l) + n(t) \quad (5)$$

where $n(t)$ is Additive White Gaussian Noise (AWGN) with a two-sided power spectral density of $N_0/2$.

The optimum receiver for the above signal would be a matched filter matched to the signal part of $r_i(t)$. Such a receiver would achieve the performance bound, namely matched filter bound, described as

$$P_e = Q\left(\sqrt{\frac{2GE_b}{N_0}}\right) \quad (6)$$

where G is the channel gain defined in the previous section. It should be noted that the notation E_b here represents the transmitted bit energy, instead of the bit energy at the receiver side, which is noted with \tilde{E}_b .

In reality, it is believed that the performance bound in (6), requires very complex receiver and thus is hard to achieve, due to the complicated UWB multipath channel. In this section, we will show that, by using TR precoding at the transmitter, the AWGN performance bound can be achieved with a simple one correlator receiver, under some conditions.

Consider a non-realistic case where we use such a short pulse that the propagation delay difference between any adjacent multipath components is always bigger than pulse duration T_p . As suggested in the title of this paper, we are interested in an impulse UWB case. An ideal UWB pulse will be a Delta function, an impulse with infinite short width in the time domain, or equivalently infinite bandwidth in the frequency domain. Mathematically, for an arbitrary $l \in [1, L]$,

we have $|\tau_{l+1} - \tau_l| > T_p$. This assumption implies that there is no inter pulse overlap after the pulse passes through the multipath channel, which corresponds to the ideal case that all the paths are resolvable. Also we assume that T_b is large enough so that there is no Inter-Symbol-Interference (ISI).

For SISO-TR, the received signal can be expressed as

$$\begin{aligned} r_i^{SISO}(t) &= s_i(t) * c(t) * h(t) + n(t) \\ &= s_i(t) * \left\{ \frac{1}{\sqrt{G}} h(T-t) * h(t) \right\} + n(t) \quad (7) \\ &= s_i(t) * h_{eq}^{SISO}(t) + n(t) \end{aligned}$$

where $c(t) = h(T-t)/\sqrt{G}$ is the prefilter code, and $h_{eq}^{SISO}(t) = h(T-t) * h(t)/\sqrt{G}$ is the equivalent CIR for the SISO-TR scenario. It is apparent that $h_{eq}^{SISO}(t)$ is an autocorrelation with peak occurring at $t = T$. The magnitude of the peak is equal to \sqrt{G} , i.e., $h_{eq}^{SISO}(t = T) = \int_{-\infty}^{+\infty} |h(t)|^2 dt / \sqrt{G} = \sqrt{G}$.

Due to its autocorrelation nature, most of the energy is focused in the central (main) peak of the CIR $h_{eq}^{SISO}(t)$. Since we assume there are no Inter Pulse Interference (IPI), ISI and pulse distortion, we can use a filter matched to the main component of the received signal. The following is to prove that even using such a simple receiver (with one correlator), we can achieve the same performance as the matched filter bound.

1) *Performance analysis based on transmit bit energy E_b* : For SISO-TR, the main component of the receiving signal can be expressed as

$$r_i^{main}(t) = \sqrt{G} \sqrt{E_b} b(i) p(t - iT_b - T) \quad (8)$$

we then use a filter matched to $p(t)$,¹ to pick up the energy lying in the above main component of the received signal. The performance can be characterized using the following analytical formula,

$$P_e^{SISO} = Q \left(\sqrt{\frac{2GE_b}{N_0}} \right) \quad (9)$$

where $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy$ is the Q-function.

Comparing (9) and (6), it is evident that a TR system with one correlator receiver can achieve the same performance as a system without TR but with ideal matched filter. Same conclusion has been obtained by other researchers [16] [11], through different approaches, in a Pre-rake system. In the following, we will extend this result to a scenario of TR with multiple antennas.

For MIMO-TR, signal captured by the n -th receive antenna can be expressed as

$$r_i^n(t) = s_i(t) * \sum_{m=1}^M \{c_m(t) * h_{mn}(t)\} + n(t) \quad (10)$$

The beauty of TR is that all the signal peaks are automatically aligned at $t = T$, which is independent of the antenna location, channel, and antenna type [12]. In this case, all the

¹In reality, considering antenna effect in the system, $\tilde{p}(t)$ instead of $p(t)$ should be used. $\tilde{p}(t) = p(t) * h_a^{tx} * h_a^{rx}$, where h_a^{tx} and h_a^{rx} represent the impulse response of transmit antenna, receive antenna, respectively.

signals captured by different antennas at the receiver can be combined directly, without additional pulse alignment process. The received signal $r_i(t)$ after combining can be expressed as

$$\begin{aligned} r_i(t) &= s_i(t) * \sum_{n=1}^N \sum_{m=1}^M \{c_m(t) * h_{mn}(t)\} + n(t) \\ &= s_i(t) * A \sum_{n=1}^N \sum_{m=1}^M \left\{ \left[\sum_{k=1}^N h_{mk}(T-t) \right] * h_{mn}(t) \right\} \\ &\quad + n(t) \end{aligned} \quad (11)$$

The equivalent impulse response for MIMO-TR scenario is then expressed as

$$\begin{aligned} h_{eq}^{MIMO}(t) &= A \sum_{n=1}^N \sum_{m=1}^M \left\{ \left[\sum_{k=1}^N h_{mk}(T-t) \right] * h_{mn}(t) \right\} \\ &= A \sum_{n=1}^N \sum_{m=1}^M \underbrace{\left\{ \sum_{k=1, k \neq n}^N h_{mk}(T-t) * h_{mn}(t) \right\}}_{\text{Interference}} \\ &\quad + A \underbrace{\sum_{m=1}^M \sum_{n=1}^N \{R_{mn}(t) * \delta(t-T)\}}_{\text{Signal}} \end{aligned} \quad (12)$$

where $R_{mn}(t) = h_{mn}(-t) * h_{mn}(t)$ is the autocorrelation of $h_{mn}(t)$. It can be seen from (12) that the equivalent CIR $h_{eq}^{MIMO}(t)$, mathematically, has MN^2 terms, consisting of MN autocorrelations and $MN(N-1)$ cross correlations. The peak of the autocorrelation terms will coherently add up, at the time instant of $t = T$, while the cross correlation term will add up noncoherently.

For $t = T$, the magnitude of the peak of the CIR h_{eq}^{MIMO} can be approximated as

$$h_{eq}^{MIMO}(T) \approx A \sum_{m=1}^M \sum_{n=1}^N G_{mn} = \sqrt{\sum_{m=1}^M \sum_{n=1}^N G_{mn}} \quad (13)$$

Here “ \approx ” is used because the contributions from the cross correlation terms in the main peak have been ignored.

Signal in the main component is then written as

$$r_i^{main}(t) \approx \sqrt{\sum_{m=1}^M \sum_{n=1}^N G_{mn}} \sqrt{E_b} b(i) p(t - iT_b - T) \quad (14)$$

Again, we use a filter whose impulse response is set to be $p(-t)$ to pick up the energy lying in the above main component, and ignore the other sidelobe energy. The error probability of such a system can be expressed using Q-function as

$$P_e^{MIMO} = Q \left(\sqrt{2 \sum_{m=1}^M \sum_{n=1}^N G_{mn} E_b / N_0} \right) \quad (15)$$

Let \bar{G} denote the average channel gain of the whole $M \times N$ channels, i.e., $\bar{G} = \frac{1}{MN} \sum_{m=1}^M \sum_{n=1}^N G_{mn}$, we have

$$P_e^{MIMO} = Q \left(\sqrt{2MN\bar{G}E_b / N_0} \right) \quad (16)$$

$$\begin{aligned}
\kappa_{MIMO} &\approx \frac{(\sum_{m=1}^M \sum_{n=1}^N G_{mn} + \sum_{n=1}^N \sum_{m=1}^M \sum_{k=1, k \neq n}^N I_{mn, mk})^2}{2 \sum_{n=1}^N \sum_{m=1}^M \sum_{k=1, k \neq n}^N \nu_{mn, mk} + \sum_{m=1}^M \sum_{n=1}^N \nu_{mn} + (\sum_{m=1}^M \sum_{n=1}^N G_{mn} + \sum_{n=1}^N \sum_{m=1}^M \sum_{k=1, k \neq n}^N I_{mn, mk})^2} \\
&= \frac{[\bar{G} + (N-1)\bar{I}]^2}{\frac{2N-1}{MN}\bar{\nu} + [\bar{G} + (N-1)\bar{I}]^2}
\end{aligned} \tag{17}$$

According to Eq. (16), it is straightforward that the performance of MIMO-TR will depend on the following parameters: the antenna number M , N and the multipath condition (channel gain \bar{G}).

When $M = 1, N = 1$, the Eq. (16) reduces to (9) for SISO-TR scenario. Moreover, comparing (9) with (16) we can find that a power gain of MN can be achieved by employing M antennas at the transmitter and N antennas at the receiver, respectively. This fact suggests that TR combined with MIMO can be used to extend the system transmission distance.

2) *Performance analysis based on receiving bit energy \tilde{E}_b* : The above analysis is based on the bit energy E_b at the transmitter side. Considering a lot of researchers analyze the performance based on \tilde{E}_b , bit energy measured at the receiver side, we also derive the performance formula for \tilde{E}_b . It should be noted that one correlator receiver proposed in this paper is not optimum. Instead, the optimum receiver should be a matched filter matched to the whole receiving waveform. The performance bound for such a receiver would be the matched filter bound, expressed as $P_e = Q(\sqrt{\frac{2\tilde{E}_b}{N_0}})$.

We introduce a new metric, peak energy ratio κ , defined by $\kappa = \frac{E_{peak}}{E_b}$, denoting the ratio of the main lobe energy to the whole receiving bit energy. The performance of one correlator receiver then can be expressed with κ as $P_e = Q(\sqrt{\frac{2\tilde{E}_b\kappa}{N_0}})$.

Let $\nu_{mn, ij}$ represent the sidelobe power of the equivalent impulse response $h_{mn, ij}(t)$. We define $\nu_{mn, ij} = \int_{-\infty}^{+\infty} |h_{mn}(-t) * h_{ij}(t)|^2 dt - I_{mn, ij}^2$ for unintended CIRs ($m \neq i$ or $n \neq j$), and $\nu_{mn, ij} = \nu_{mn} = G_{R_{mn}} - G_{mn}^2$ for intended CIRs ($m = i$ and $n = j$). Here $I_{mn, ij} = |h_{mn}(-t) * h_{ij}(t)|_{t=0} = \int_{-\infty}^{+\infty} |h_{mn}(t) \times h_{ij}(t)| dt$, and $G_{R_{mn}} = \int_{-\infty}^{+\infty} |R_{mn}(t)|^2 dt$ is the channel gain of the equivalent CIR $R_{mn}(t)$.

For MIMO-TR, the peak energy ratio κ_{MIMO} can be expressed as Eq. 17.

In Eq. 17, the bar notation $(\bar{\cdot})$ represents an averaging operation, i.e., $\bar{G} = \frac{1}{MN} \sum_{n=1}^N \sum_{m=1}^M G_{mn}$, $\bar{I} = \frac{1}{MN(N-1)} \sum_{n=1}^N \sum_{m=1}^M \sum_{k=1, k \neq n}^N I_{mn, mk}$, and $\bar{\nu} = \frac{1}{MN(2N-1)} \{2 \sum_{n=1}^N \sum_{m=1}^M \sum_{k=1, k \neq n}^N \nu_{mn, mk} + \sum_{m=1}^M \sum_{n=1}^N \nu_{mn}\}$.

In reality, if the antenna elements are placed far enough so that there is no correlation among the CIRs, the value of $I_{mn, ij}$ is very small and could be ignored. Then we have

$$\kappa_{MIMO} \approx \frac{\bar{G}^2}{\frac{2N-1}{MN}\bar{\nu} + \bar{G}^2} \tag{18}$$

For large N , Eq. (18) can be approximated by

$$\kappa_{MIMO} \approx \frac{\bar{G}^2}{\frac{2}{M}\bar{\nu} + \bar{G}^2} \tag{19}$$

For MISO-TR

$$\kappa_{MISO} \approx \frac{(A \sum_{m=1}^M G_m)^2}{A^2 \sum_{m=1}^M \nu_m + (A \sum_{m=1}^M G_m)^2} = \frac{\bar{G}^2}{\frac{1}{M}\bar{\nu} + \bar{G}^2} \tag{20}$$

For SISO-TR

$$\kappa_{SISO} = \frac{G^2}{\nu + G^2} \tag{21}$$

As a sanity check, when $N = 1$, (18) reduces to MISO case (20), and for $M = 1$ and $N = 1$, (18) reduces to SISO case (21).

It is evident from (19) and (20) that the performance of both MIMO and MISO depends on the number of transmit antenna M . If we increase M , we actually improve the focusing and then get better performance. Overall, in terms of κ , MISO outperforms MIMO, especially when N is large, the κ improvement caused by increase of M for an MISO is much faster than that of an MIMO. This has been verified by our measurement, as will be illustrated by Table I in the following section.

III. UWB SPATIAL CHANNEL MEASUREMENT

Considering that there is no available channel model with multiple antennas available so far, we conduct a series of measurements in an office environment. A virtual antenna array is employed in the experiments. The elements of the array are spaced far enough such that there is no coupling between them. Line of Sight (LOS) is not available for all the measurements. The environment for the experiment is a typical office area with abundance of wooden and metallic furniture (chairs, desks, bookshelves and cabinets). A detailed experiment setup and environment description can be found in [12].

A (4×4) virtual MIMO array, corresponding to 16 SISO channels and 4 (4×1) MISO channels, were measured in our experiment campaign. A typical received waveform and its corresponding CIR are shown in Fig. 2. The CLEAN algorithm [14] is employed to extract CIR from the received waveform.

Based on the measured CIRs, comparisons of κ among different scenarios are given in Table I. In Table I, $T_m R_n$ denotes the channel between the m -th transmit antenna and the n -th receive antenna. The parameters ν and G^2 are directly measured from the equivalent CIRs of different channels. For SISO-TR, the parameter κ is calculated using (21), while for MISO-TR and MIMO-TR, we have two approaches to calculate the value of κ . The approximated values are calculated

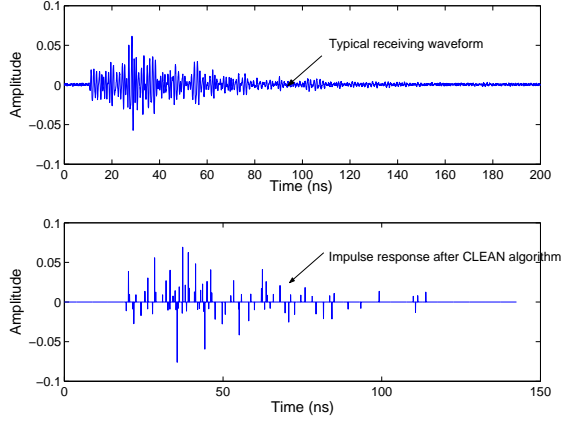


Fig. 2. Channel impulse response extracted with CLEAN Algorithm

TABLE I
A COMPARISON OF κ FOR DIFFERENT SCENARIOS

	Channel	ν	G^2	κ
SISO-TR	T ₁ R ₁	0.0459	0.0483	0.5124
	T ₁ R ₂	0.0414	0.0454	0.5230
	T ₁ R ₃	0.0485	0.0467	0.4906
	T ₁ R ₄	0.0572	0.0581	0.5040
	T ₂ R ₁	0.0516	0.0512	0.4979
	T ₂ R ₂	0.0446	0.0413	0.4810
	T ₂ R ₃	0.0457	0.0455	0.4991
	T ₂ R ₄	0.0556	0.0477	0.4615
	T ₃ R ₁	0.0562	0.0543	0.4915
	T ₃ R ₂	0.0363	0.0355	0.4944
	T ₃ R ₃	0.0346	0.0367	0.5148
	T ₃ R ₄	0.0454	0.0451	0.4983
	T ₄ R ₁	0.0502	0.0485	0.4916
	T ₄ R ₂	0.0462	0.0445	0.4906
	T ₄ R ₃	0.0595	0.0573	0.4907
	T ₄ R ₄	0.0366	0.0369	0.5020
Average	0.0472	0.0464	0.4965	
MISO-TR	T ₁₂₃₄ R ₁	0.0577	0.2022	Appro: 0.8044 Exper: 0.7781
	T ₁₂₃₄ R ₂	0.0493	0.1663	Appro: 0.7900 Exper: 0.7714
	T ₁₂₃₄ R ₃	0.0520	0.1851	Appro: 0.7992 Exper: 0.7807
	T ₁₂₃₄ R ₄	0.0605	0.1865	Appro: 0.7955 Exper: 0.7552
	Average	0.0549	0.1850	Appro: 0.7977 Exper: 0.7713
MIMO-TR	T ₁₂₃₄ R ₁₂₃₄	0.6401	0.6781	Appro: 0.5680 Exper: 0.5144

using (19) and (20), while the experimental values are exact values calculated directly based on their equivalent CIRs. It can be seen that approximated values and experimental values are very close, implying our approximations are valid.

IV. NUMERICAL RESULT

In our simulation, the second order derivative of Gaussian pulse has been used as the transmitted pulse $p(t)$, which is mathematically defined as:

$$p(t) = \left[1 - 4\pi \left(\frac{t - t_c}{w} \right)^2 \right] e^{-2\pi \left(\frac{t - t_c}{w} \right)^2} \quad (22)$$

where w is the parameter controlling the width of the pulse (and therefore the frequency bandwidth of the transmit signal),

and t_c is the parameter to shift the pulse to the middle of the window. In the following simulation, we let $w = 1$ ns and $t_c = 0.5$ ns. To avoid the presence of severe ISI in the system, we add a inter-pulse guard time T_g . Therefore, we have $T_b = w + T_g$. Moreover, T_g can be used to adjust the transmission data rate. Unless stated otherwise, we let $T_g = w$, corresponding to a data rate of 500 Mb/s.

Throughout of the paper, we assume perfect synchronization and the transmitter has the full knowledge of the channel information. Under these assumptions, we conduct Monte Carlo simulations to investigate the performance of one correlator receiver and compare them under different scenarios: SISO, MISO, and MIMO.

To make the comparison fair, performance of SISO and MISO scenarios have been averaged over all the corresponding specific channels that form the MIMO channel, i.e., $P_{ave}^{SISO} = \frac{1}{16} \sum_{i=1}^{16} P_i^{SISO}$, and $P_{ave}^{MISO} = \frac{1}{4} \sum_{i=1}^4 P_i^{MISO}$.

First let us consider a system without ISI and IPI. The performance of one correlator receiver can be characterized with Q-function as $P_e = Q(\sqrt{\frac{2\bar{E}_b\kappa}{N_0}})$. Fig. 3 shows a comparison of BER performance among SISO, MISO, and MIMO scenarios, based on receiver SNR \bar{E}_b/N_0 . The values of κ are obtained from Table I. From Fig. 3 we can see that, given the same SNR at the receiver side, MISO has the best performance. This is due to the best temporal focusing provided by MISO-TR. A comparison of BER performance with ISI and IPI is shown in Fig. 4. The performance bound for AWGN channel is also plotted as a reference.

It should be noted that an MIMO-TR channel gets extra receiving power by employing multiple antennas at the receiver. Therefore, we also compare the system performances under the same total (transmit) power constraint. Fig. 5 shows the BER performance for SISO, MISO (4×1), and MIMO (4×4) scenarios, based on transmitter bit energy, with different transmission data rates. Both IPI and ISI have been considered. As we can see from Fig. 5, MIMO-TR outperforms MISO-TR and then MISO-TR outperforms SISO-TR. Tests were conducted for data rates of 500 Mb/s and 225 Mb/s. As expected, A increase in the data rate leads to a degradation performance. For a data rate of 250 Mb/s, about 13 dB power gain is achieved by employing a 4×4 MIMO array. The power gain with ISI and IPI is slightly higher than the theoretical power gain $10\log_{10}(MN)$, derived in Section II, without ISI and IPI.

V. CONCLUSION

We evaluate the performance of UWB-MIMO-TR system, considering a simple one-correlator receiver. Performance comparisons among different scenarios, namely, SISO-TR, MISO-TR, and MIMO-TR are provided, based on both the transmitted bit energy and the received bit energy. The results show that a power gain of MN could be achieved with a system of MIMO-TR. The gain becomes even larger, if both ISI and IPI are considered, due to the MIMO-TR has better temporal focusing.

It should be noted that MIMO-TR is, indeed, simple, but not the optimal way. The philosophy behind time reversal is so

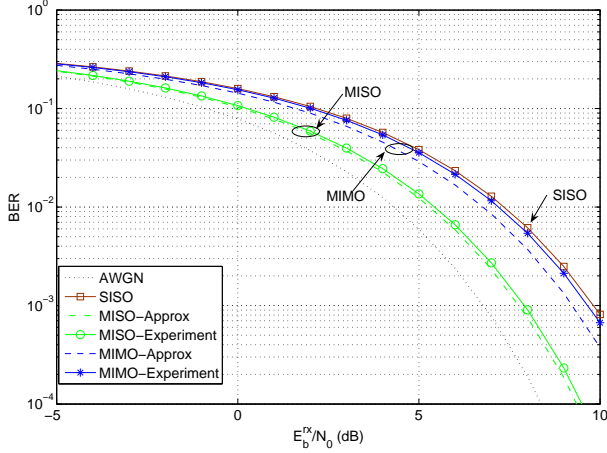


Fig. 3. BER performance based on the bit energy at the receiver side, assuming there are no ISI and IPI.

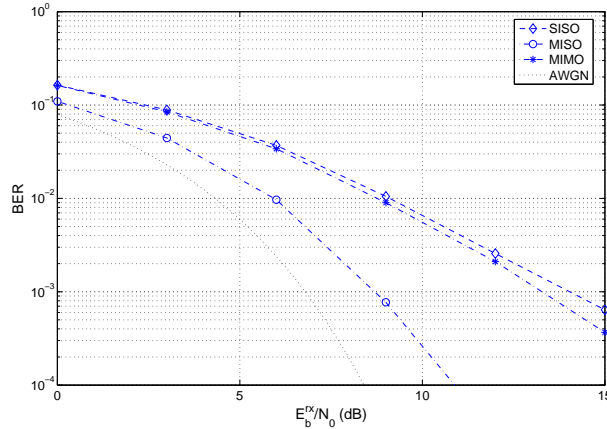


Fig. 4. BER performance in terms of received bit energy. Both IPI and ISI have been considered.

called transmit centric processing, i.e., processing the signal at the transmitter side before transmission to combat the deteriorating effects of the channel. Transmit centric processing greatly simplifies the receiver, and is desirable in the case where one base station (BS) serves many mobile stations (MS).

A single user scenario has been considered in this paper. Considering TR with multiple antennas further increases spatial focusing, thus reducing the multi-user interference, MIMO-TR should have even better performance when a multi-user (MU-MIMO-TR) scenario is studied.

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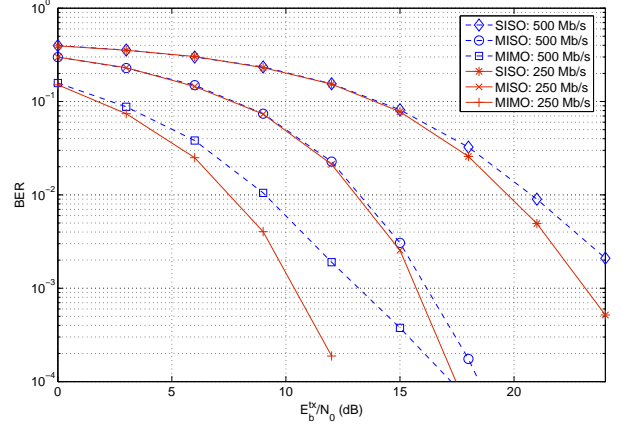


Fig. 5. BER performance in terms of transmitted bit energy. Both ISI and IPI have been considered.

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