Implementation of UWB MIMO Time-reversal Radio Testbed

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Abstract—This paper presents system implementation and validation of a real-time experimental ultra-wideband (UWB) multiple-input multiple-output (MIMO) radio testbed built in Tennessee Technological University. The incorporation of UWB technology with MIMO is promising in both communication and sensing applications. With the testbed, UWB MIMO algorithms are able to be experimentally explored by transmitting data through 500-MHz-bandwidth channels supporting simultaneously two transmit and eight receive antennas. Using a $2 \times 2$ MIMO time reversal (TiR) configuration as an example, 6-dB gain over a single-input single-output (SISO) configuration is experimentally achieved, agreeing with theoretical estimation. In particular, signal to inter-symbol interference (ISI) ratio (SIR), a performance metric common to many real world applications, is experimentally evaluated with BPSK modulation. The obtained SIR results suggest that the UWB MIMO-TiR is promising for high data rate transmission in harsh RF environments.

Index Terms—Ultra-wideband, MIMO, testbed, time reversal

I. INTRODUCTION

Ultra-wideband (UWB) multiple-input multiple-output (MIMO) technology has been proved to be promising in high data rate communication and sensing applications [1] [2] [3]. Combing UWB transmission with MIMO could overcome the power limit of UWB system and further increase data rate and system robustness as well as precision of localization. One central issue facing UWB community is to effectively collect energy that is dispersed among rich multipath components [4], while a MIMO configuration makes this issue even more complicated. Time reversal (TiR) signal processing as an example [4] [5] is explored to validate the UWB MIMO testbed. The TiR spacial-temporal focusing properties has been studied in the UWB context [4] [6] [7]. In [4], UWB multiple-input single-output (MISO) scheme enabled by TiR is experimentally studied. In [1] and [5], the UWB MIMO-TiR system for spatial multiplexing is systematically studied based on analytical antenna model. In [8], UWB MIMO channel capacity, space-time coding (STC), beamforming as well as an offline testbed are discussed.

Although UWB MIMO-TiR is not adopted by any standard, it is expected to find applications in radio frequency (RF) harsh environments. The lack of real-time experimental support in UWB MIMO research motivated our experimental research. In our preliminary work we consider a $2 \times 2$ MIMO configuration.

II. BASICS OF MIMO-TiR

Here we consider a pulse-based UWB system, where the radiated energy is distributed among different spatial locations and spread in time over a large number of pulses at any observation locations (due to multipath). This phenomenon usually causes problems and the situation can be even worser for a wideband MIMO system. UWB TiR is a technique that handles severe multipath propagation [4] [5].

![MIMO-TiR system with M transmit antennas and N receive antennas.](image)

Illustrated in Fig. 1 is a MIMO-TiR ($M \times N$) system configuration. It is assumed there are $M$ transmit antennas and $N$ receive antennas in the system. The channel impulse response (CIR) matrix $H(t)$ in time domain is defined by

$$H(t) = \begin{bmatrix} h_{11}(t) & \cdots & h_{1N}(t) \\ \vdots & \ddots & \vdots \\ h_{M1}(t) & \cdots & h_{MN}(t) \end{bmatrix}_{(M \times N)}$$

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where \( h_{mn}(t) \) denotes the CIR between the m-th transmit antenna and the n-th receive antenna.

Let \( s(t) = [s_1(t), \ldots, s_N(t)] \) and \( r(t) = [r_1(t), \ldots, r_N(t)] \) be the transmitting and receiving signals. We have \( r(t) = s(t) \ast C(t) \ast H(t) \), where \( C(t) \) is a precoding matrix, \( \ast \) stands for convolution and matrix convolution is calculated in a term-by-term manner. Define the equivalent waveform precoding (or prefiltering) matrix as \( H_{eq}(t) = C(t) \ast H(t) \), then we have \( r(t) = s(t) \ast H_{eq}(t) \). By applying TiR processing, the precoding matrix would simply be \( C_{TiR}(t) = H^\top(t) \) or

\[
C_{TiR}(t) = \begin{bmatrix}
h_{11}(-t) & \cdots & h_{1M}(-t) \\
\vdots & \ddots & \vdots \\
h_{1N}(-t) & \cdots & h_{NM}(-t)
\end{bmatrix}_{(N \times M)} \tag{2}
\]

where superscript \(^\top\) in the notation denotes transpose operation. In practice, \( C_{TiR}(t) \) can be readily obtained by channel sounding and no extra computation is needed. The equivalent waveform precoding matrix for TiR is given by

\[
H_{eq}(t) = C_{TiR}(t) \ast H(t) = \left[ \sum_{i=1}^{M} R_{i1}(t) \cdots \sum_{i=1}^{M} h_{i1}(-t) \ast h_{iN}(t) \right]_{(M \times N)} \tag{3}
\]

where \( R_{mn}(t) \)'s along the diagonal are the autocorrelations of \( h_{mn}(t) \)'s, while the other terms are cross-correlations. The received signal at the n-th receive antenna can be expressed in the following equation

\[
r_n(t) = s_n(t) \ast \sum_{i=1}^{M} R_{in}(t) + O_n(t), \quad n = 1, 2, \ldots, N. \tag{4}
\]

where \( O_n(t) = \sum_{j=1, j \neq n}^{N} s_j(t) \ast \left( \sum_{i=1}^{M} h_{ij}(-t) \ast h_{in}(t) \right) \) are the cross-correlation terms. When these cross-correlation terms are such small that they can be ignored, \( H_{eq}(t) \) reduces to a diagonal matrix and we say that good temporal-spatial focusing is achieved.

One of the MIMO schemes is to send the same data stream via all transmit antennas and combine the received signals from all receive antennas. This scheme leads to a combined received signal \( r_{comb}(t) \) expressed below

\[
r_{comb}(t) = s(t) \ast \sum_{i=1}^{N} \left( \sum_{j=1}^{M} h_{ji}(-t) \ast \sum_{m=1}^{N} h_{jm}(-t) \right) \tag{5}
\]

and the transmit precoding waveform at the m-th antenna is

\[
c_m(t) = A_m s(t) \sum_{n=1}^{N} h_{mn}(-t) \tag{6}
\]

where \( A_m \) is the power scaling factor for antenna m.

It can be seen from (5) that the received combined signal consists of total \( MN \) autocorrelation terms and many cross-correlation terms. The autocorrelation terms are coherently added up, while the cross-correlation terms adds up non-coherently. As a result, the desired autocorrelation terms form a strong peak that dominates the received signal.

III. UWB MIMO TESTBED AND EXPERIMENTAL SETUP

A. UWB MIMO Transmitter

The architecture of the UWB MIMO transmitter with two antennas is illustrated in Fig. 2. It mainly consists of three parts: one Xilinx Virtex-5 FPGA platform, two identical digital-to-analog (D/A) converters, and RF front-end. The FPGA is the center part for signal processing and control in the transmitter. The two digital in-phase and quadrature-phase (I&Q) waveforms generated by the FPGA are clocked into the D/A converters at 500 mega-samples per second (Msps) sampling rate and reach 1 giga-samples per second (Gsps) after interleaving.

All algorithms and signal processing tasks are implemented in the FPGA, and module-based coding style is adopted to expedite the overall development. The transmitter baseband subsystem includes a baseline transmitter module and two digital arbitrary waveform generator modules. The baseline transmitter performs regular transmitter baseband functions such as data interface, modulation, spreading and scrambling. The digital arbitrary waveform generators implemented in the FPGA can generate virtually any type of transmitted waveforms, which greatly leverages the system capability. The quantization resolution is 8 bits; the sampling rate is 1 Gsps; dual I&Q channels are supported; the length of each I or Q waveform is 160 ns (160 samples) and it can be easily reconfigured. The output data rate is 1 GBytes/s for each I or Q, and the total data throughput is 4 GBytes/s.

During FPGA implementation process, a great effort has been made to meet the timing closure requirements of speed-critical implementations.

B. UWB MIMO Receiver

The UWB MIMO receiver architecture is given in Fig. 3. There are totally eight analog-to-digital (A/D) converters each with 3 Gsps sampling and 8-bits resolution. There are multiple Xilinx FPGAs formed an array for digital processing and a bunch of 1 GByte double data rate 2 (DDR2) memory banks for data storage and buffering. All these devices are integrated in a National Instrument (NI) PXI express (PXIe) chassis. All the sampled data from A/D converters will be gathered in one FPGA either to be processed in real-time or to be stored in DDR2 memories and then be transferred to host computer via PXIe bus for offline processing. To maintain the coherency of
the MIMO receiver, it is essential that all modules receive the same sampling clock, and an external trigger signal is necessary to have all A/D converters sampling and outputting data at the same time.

![UWB MIMO receiver block diagram](image)

Fig. 3. Block diagram of the UWB MIMO receiver.

In receiver FPGAs design, the processing clock rate is 375 MHz in DDR mode. Four A/D converters are working at full sampling speed of 3 Gsps simultaneously, and the total sampling data rate reaches 12 GBytes/s, which is an extremely aggressive data rate for a real-time system.

C. UWB MIMO RF Front-ends

The RF front-ends are based on off-the-shelf components and all the components are easily replaced and reconfigured. In our design, we consider a frequency range from 3.5 GHz to 4.5 GHz due to less users operating in this band. The antennas being used in the transmitter are omni-directional print antennas which operate from 3 GHz to 10 GHz with about 4 dBi gain. The two receive antennas being used are UWB omni-directional chip antennas which operate from 3.1 GHz to 5 GHz with about 2 dBi gain.

Each channel of the transmit RF front-end consists of a quadrature modulator, an RF power amplifier with maximum 35 dB gain and 30 dBm output power, and a single oscillator for both channels. Both clock frequency and phase synchronization between the two RF transmitter branches is the key issue for over the air coherency. The quadrature modulator is used for direct up-conversion from baseband-to-passband with a high dynamic range and a broad frequency range from 400 MHz to 6 GHz. The output is followed by a power amplifier to create enough signal level.

The receiver RF front-end consists of the following modules for each channel: a low noise amplifier (LNA), an RF bandpass filter, a quadrature demodulator, two variable pass filters, two variable gain amplifiers and a common local oscillator for all channels. The maximum gain of the LNA is 25 dB and the noise figure is as low as 3.5 dB. At the output of the LNA, a receive bandpass filter operating from 3.5 GHz to 4.5 GHz is exploited to reject noise outside the frequency range. The RF demodulator covers a frequency range of 400 MHz to 6 GHz and provides typical 3-4 dB of conversion gain. At each I or Q output of the demodulator, a variable gain amplifier is combined using a power amplifier and a variable attenuator.

D. Experimental Setup

UWB MIMO channel measurement is performed using frequency domain technique to get channel transfer functions \( h_{mn}(f) \) in a confined metal rectangular environment, the size of which is 7 feet by 7 feet by 4.5 feet and layout is given in Fig. 4(a). The channel transfer function data is collected by Vector Network Analyzer (VNA) - Agilent N5230A (300 kHz - 13.5 GHz), which measures the \( S_{21} \) parameter of the device under test, namely the propagation channel. It sweeps from 3.5 GHz to 4.5 GHz using 1001 tones with frequency step of 1 MHz. Two identical LNAs are used between receiver ports of VNA and receive antennas. Meanwhile, the cables, amplifiers and connectors are calibrated before channel measurement to compensate for frequency dependent losses.

Channel measurement is performed one by one between transmit antenna array and receive antenna array. The transmit antennas and receive antennas are blocked with a metal plate as Fig. 4(a) shows, so there is no line-of-sight (LOS) transmission. The distance between the transmitter array and the receiver array is 6.5 feet. The distance between the antennas in the transmitter array is 10 inches, while the distance between the antennas in the receiver array is 16 inches. The antennas are placed at 4 feet above the ground. The multipath propagation channels are represented by Fig. 4(b), the average channel delay spread is more than 200 ns. Some critical test parameters are listed as Table I.

![Experimental setup](image)

Table I. Critical system test parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Bandwidth (approximately)</td>
<td>550 MHz</td>
</tr>
<tr>
<td>Receiver first stage noise figure</td>
<td>5.9 dB</td>
</tr>
<tr>
<td>Transmitted power to one antenna</td>
<td>1.14 dBm (1.3 mW)</td>
</tr>
<tr>
<td>Equivalent path loss (approximately)</td>
<td>36.2 dB</td>
</tr>
<tr>
<td>Received power at one antenna</td>
<td>-23.04 dBm</td>
</tr>
</tbody>
</table>

IV. SYSTEM VALIDATION

In the transmitter, TiR templates are prepared from a rectangle-windowed channel transfer functions measured by VNA. MIMO-TiR processing extracts the desired I&Q waveforms for each transmit antenna based on achieved baseband TiR matrix template. Then the waveforms are quantized by D/A converters with 8-bits quantization at 1 Gsps sampling rate, where optimization algorithm under maximum correlation criterion is exploited to approximate the original template \( h_{mn}(−t) \). The transmitted MIMO waveforms are formulated earlier, \( A_{mn} \)'s are set to be the same for all antenna branches.

A. Temporal Focusing and Array Again

With TiR signal processing, waveforms are transmitted every 300 ns repeatedly to observe the temporal focusing...
property and array again of the real-time UWB MIMO testbed. Two experiments have been carried out: (1) comparison between MISO system and single-input single-output (SISO) system; and (2) comparison between MIMO system and MISO system. All the received signals are digitized in the receiver with 3Gsp/s A/D converters. The two received I waveforms and two received Q waveforms are combined in FPGA chips separately. This paper only shows received I results with 8-bits A/D quantization values. The MIMO processed results are sent to DDR2 memories, then be fetched by DMA engine to PXIe bus for display.

Fig. 5 shows the received sharp peaks from two receive antennas and the coherently combined result in MIMO configuration: it can be seen that the MIMO system contributes 3 dB gain over the MISO system. It has also been observed that MISO system contributes about 3 dB gain over the SISO system. Thus, a 6 dB energy gain over the SISO system is experimentally achieved in the 2 × 2 UWB MIMO testbed. However, if the antennas are moved a certain distance away, such as 0.5 feet, or the center frequency is shifted a few MHz, no sharp peaks will be observed. The agreement between theoretical results and real-time experimental results has validated the system implementation.

![Fig. 5](image)

Fig. 5. Array again of the UWB MIMO system. (a) MISO case at receive antenna 1 (MISO1). (b) MISO case at receive antenna 2 (MISO2). (c) MIMO coherently combined result.

B. SIR Evaluation Based on Measured Data

The developed testbed serves as a general UWB MIMO experimental research platform, not aiming at a specific modulation scheme or a MIMO radar application scenario. But inter-symbol (or inter-waveform) interference is common for all cases especially in harsh RF environments. We use SIR as a performance metric to test the system configured for high data rate transmission. It is observed that system performance is dominated by the ISI at relatively high data rate so that thermal noise can be ignored. Average SIRs are measured at different data rates with BPSK modulation. Two comparisons have been made: (1) UWB MIMO-TiR vs. UWB MIMO without TiR; and (2) UWB MIMO-TiR vs. UWB MISO-TiR. One of the features of a TiR system is that the receiver can be rather simple (at the cost of more processing at the transmitter). The receiver is configured as a "peak-sampler" in SIR estimation. Fig. 6 shows the SIRs performances in different experimental scenarios, with data rate ranging from 10 to 600 megabit per second (Mbps). It can be observed from Fig.6 that TiR processing is indeed in favor of high data rate transmission:

if using 3-dB SIR as a threshold, the data rates of MISO-TiR and MIMO-TiR configurations are around 300 Mbps and more than 500 Mbps, respectively, while the one without TiR is not able to reach 100 Mbps. In addition to the judgment using received peak values, the advantage of MIMO over MISO is validated in terms of SIR gain shown in Fig.6(b). As expected, at very low data rate, all SIRs converge to a high value.

![Fig. 6](image)

Fig. 6. SIRs performances. (a) UWB MIMO-TiR vs. non-TiR; (b) UWB MIMO-TiR vs. UWB MISO-TiR.

V. CONCLUSION

The paper presents the design and implementation of a real-time experimental UWB MIMO radio testbed. Temporal focusing and energy-collection gain with MIMO-TiR technology are experimentally verified. Multi-channel UWB RF front-ends, multi-channel A/D and D/A converters supporting multi-GHz sampling rate have been manipulated with high-end FPGAs, leading to up to 16 GByte/s aggregated throughput. It is expected that the testbed will be used in support of research in the areas of UWB imaging, UWB sensing, wideband physical-layer security and high-speed wireless communications.

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