A REAL-TIME ALGORITHM DESIGN AND PROTOTYPING PLATFORM FOR MIMO RESEARCH

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ABSTRACT

In this paper, we present the design of a comprehensive real-time algorithm development platform for MIMO communication systems based upon the highly customizable FlexRIO hardware platform by National Instruments. By using a commercial off-the-shelf system with a programming environment familiar to many in industry and academia, we seek to reduce costly development time and instead enable researchers to focus on algorithm development and analysis tasks. As a demonstration of the FlexRIO's capabilities, we present our preliminary findings on an experimental bit error rate (BER) performance comparison between a 2×1 OFDM system employing Alamouti space-time coding and another 1×1 OFDM system which does not. A detailed examination of the two systems' wireless channel characteristics and their impact on BER performance is also presented.

***Index Terms*—Real-time, software defined radio, wireless testbed, rapid prototyping, MIMO, OFDM, experimental investigation, National Instruments, FlexRIO, Ettus Research.**

I. INTRODUCTION

Multi-Input Multi-Output (MIMO) techniques have become a key technology in the evolution of broadband wireless access systems by exploiting extra spatial degrees of freedom afforded by the use of multiple antennas at both sides of the communications link. In order to fully realize the benefits of MIMO technologies for 4G communication systems, innovative ideas and techniques must be developed. For in practice radio frequency (RF) impairments and mutual coupling between antennas largely limit the performance of MIMO systems. Furthermore, effective and novel real-time algorithms that balance complexity/performance tradeoffs must be implemented. Thus, we propose a comprehensive real-time algorithm development platform for MIMO communications that pairs on widely available RF chipsets and components from National Instruments (NI) including LabVIEW and the firm's FlexRIO hardware.

By providing a common platform built with commercial off-the-shelf components, we seek to reduce development time and enable researchers to focus on algorithm development and analysis tasks. A similar testbed developed by researchers in China consisting of NI's off-the-shelf products the PXI-5670 RF vector signal generator and PXI-5660 RF vector signal analyzer, but does not support real-time DSP operations [1]. Another recent FPGA based real-time testbed that supports baseband DSP operations is available, but lacks the means to up/down-convert signals to/from RF [2]. In this paper, we present the initial design of a complete turn-key, real-time development platform and application to the design and prototyping of real-time algorithms aimed at mitigating the effects of RF impairments/antenna coupling, suppress multi-user interference, and explore the benefits of polarization diversity.

The proposed development platform is built upon NI's product family of FlexRIO hardware designed for real-time applications requiring high speed synchronous data acquisition from multiple input/output sources. Also capable of interfacing with many of the wireless RF transceiver boards offered by Ettus Research[1] as part of the GNU Radio[2] project, the FlexRIO platform is well suited for real-time MIMO applications over a broad spectrum of RF frequencies.

The development process of the proposed real-time prototyping platform is tiered into three stages. Initially, algorithms intended to execute on the FlexRIO hardware are first simulated offline on a PC. Secondly, the greater portion of the algorithms are implemented on the FlexRIO embedded microprocessor for increased system throughput though still not fully real-time. Lastly, algorithms are implemented completely in hardware, that is in the FlexRIO's high speed FPGA's for true real-time performance. In this way, the final real-time system can be developed in stages of increasing complexity followed by design verification/validation along the way in order to manage the many difficulties associated with debugging.

In this paper, we present a near real-time multiple-in-

[1] http://www.ettusresearch.com
[2] http://gnuradio.org/

single-out (MISO) system for the experimental bit error rate (BER) performance evaluation of a 2×1 OFDM system employing the Alamouti space-time block code (STBC) [3] and a 1×1 OFDM system that does not in order to determine if measurable improvements in BER can be gained by using the Alamouti STBC over a SISO system that does not. A full real-time version of the system will be presented in future publications.

II. HARDWARE ARCHITECTURE

As shown in Fig. 1, the transmit and receive chains of our multiple antenna testbed consists of the following NI FlexRIO family of devices.

- PXIe-8130 PXI express embedded real-time controller[3]
- PXIe-7965R FPGA module[4]
- NI 5781 baseband transceiver[5]
- Ettus Research XCVR2450 wireless transceiver board[6]

For our initial wireless experiments reported here, the majority of the base band digital signal processing (DSP) is performed on the 8130 real-time controller (RT) running a real time OS and equipped with an AMD Turion 2.3GHz dual core processor with 2GB of dual channel RAM. At both the transmitter and receiver, the RT performs various DSP functions such as QPSK modulation/demodulation, Alamouti space-time block encoding/decoding, OFDM multiplexing/demultiplexing, OFDM symbol generation, frequency offset estimation, channel estimation, etc.

The 7965R FPGA module built around the Xilinx Virtex-5 SX95T FPGA has 512MB of onboard DDR2 DRAM, access to 132 single-ended digital IO lines and 16 DMA channels that support data rates of more than 800MBps. For these experiments, the 7965R is used primarily to configure/control the 5781 baseband transceiver module that is equipped with dual 100MSps 14 bit analog to digital converters (ADC) and dual 100MSps 16 bit digital to analog converters (DAC), in addition to transferring digital/analog signals between the RT and 5781 for DAC/ADC conversion. For future wireless experiments, we plan to make use of the Virtex-5's many capabilities by transferring most of the DSP functions presently running on the RT to the 7965R for increased system throughput and lower processing latency.

Signal up-conversion to RF and down-conversion to baseband is performed by the XCVR2450 transceiver board, built around the popular Maxim MAX2829 dual band transceiver chip, operates on both the 2.4 to 2.5GHz and 4.9 to 5.9GHz bands and provides up to 100mW of transmit power [4], [5]. Photographs of the transmitter and receiver are shown in Fig. 2.

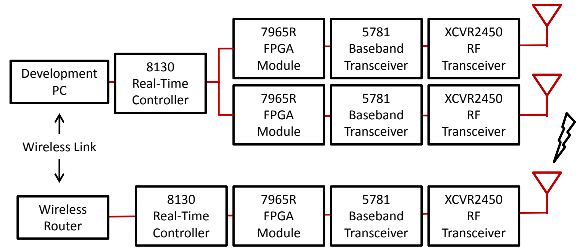

Fig. 1. Block diagram of dual antenna transmitter (top) and single antenna receiver (bottom).

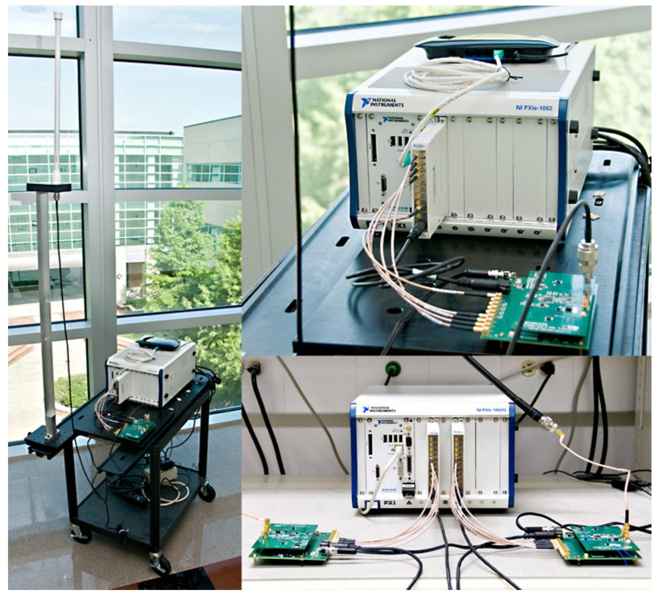

Fig. 2. (Left) Single antenna receiver on mobile cart. (Upper Right) Enlarged view of the single antenna receiver. (Lower Right) Dual antenna transmitter.

III. LABVIEW PROGRAMMING ENVIRONMENT

All of the software executing to the FlexRIO platform, i.e. RT and 7965R, is developed in the NI LabVIEW programming environment. NI's real-time[7] and FPGA[8] software modules for LabVIEW allow developers to create their application specific programs for the FlexRIO hardware in much the same way they would a LabVIEW virtual instrument (VI) running on a PC.

Once complied on the development PC, executable bit files are downloaded to their respective transmitter/receiver RT and 7965R modules for experimentation. As shown in Fig. 1, the development PC does so across a wired Ethernet connection to the transmitter RT, while a wireless communication link is used between the development PC and receive RT via an 802.11n wireless router. As shown in Fig. 2, no longer

[3]http://sine.ni.com/nips/cds/view/p/lang/en/nid/203930
[4]http://sine.ni.com/nips/cds/view/p/lang/en/nid/208167
[5]http://sine.ni.com/nips/cds/view/p/lang/en/nid/208378
[6]http://www.ettusresearch.com/downloads/ettus_ds_transceiver_dbrds_v6c.pdf
[7]http://sine.ni.com/nips/cds/view/p/lang/en/nid/2381
[8]http://www.ni.com/fpga/

Parameter	Value
Total bandwidth	7.3242 MHz
Sampling frequency	25 MHz
FFT size	2048
Bandwidth per subcarrier	12.207 kHz
Number of subcarriers	600
Number of data subcarriers	392
Number of pilot subcarriers	196
Number of nulls near DC	12
Length of cyclic prefix	512 samples
Length of OFDM symbol	2018 samples
Modulation	QPSK

Fig. 3. OFDM system parameters.

tethered by an Ethernet cable, a wireless communications link provides greater flexibility in the placement of the receiver in order to conduct more experiments over a larger selection of locales and richer set of fading environments.

IV. WIRELESS SYSTEMS UNDER TEST

For these experiments, we test the bit error rate (BER) performance of a 2×1 and 1×1 OFDM system, both of which have the system specifications listed in Fig. 3. The 2×1 system uses Alamouti space-time encoding [3] while the 1×1 does not. At the receiver, both system employ the following algorithms.

- Time domain synchronization
- Frequency offset estimation/correction
- Zero forcing channel estimation & linear interpolation

The 1×1 system uses zero forcing to simply invert the channel while the 2×1 receiver uses Alamouti space-time decoding to correct the effects of the channel.

Shown in Fig. 4 (a) are time domain plots of the transmit signals from antennas 1 (top) and 2 (bottom). The transmit frame consists of 4 distinct signals that have been concatenated together: 1) preamble for time domain synchronization, 2) the OFDM symbol for the 2×1 system, 3) the OFDM symbol for the 1×1 system on antenna 1, and 4) the OFDM symbol for the 1×1 system on antenna 2. Furthermore, the transmit signals of the 2×1 system are scaled such that the total power from both antennas is equal to that of the single antenna system. Frames are continuously transmitted in this structure in order to test the performance of both systems under similar channel conditions.

A sample of the frequency response of the receive signal amplitude is shown in Fig. 4 (b). From this figure, the channel response appears to be relatively flat for our indoor environment, but from Fig. 4 (c), the amplitude of the channel estimates for antenna 2 undergo slightly more attenuation at the outer edges of the signal spectrum than they do near the center (excluding DC), roughly 1dB more. In this case, the amplitude of the channel estimates for antenna 1 are approximately 2dB lower than those of antenna 2 and are relatively flat across the frequency band. Lastly, in Fig. 4 (d), is a sample of the recovered receive signal constellation of the 2×1 system after time domain synchronization, frequency offset estimation/correction, and Alamouti decoding.

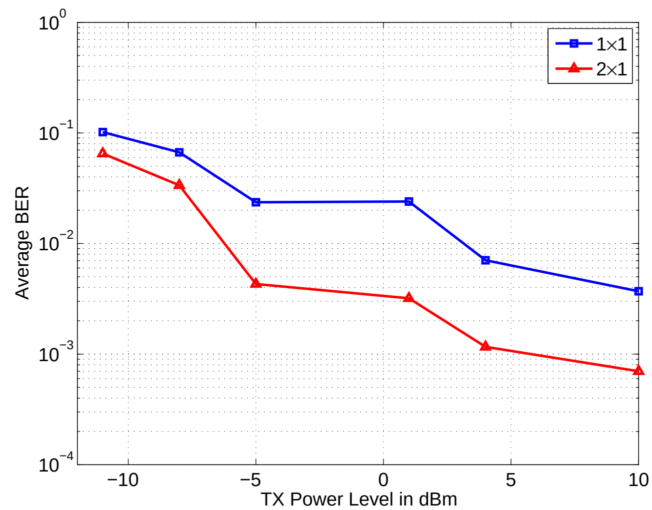

Fig. 5. BER vs. TX power for the 2x1 and 1x1 systems.

V. EXPERIMENTAL RESULTS

In this section, we present the BER performance results of our experiments. Experiments were conducted over a single location within our laboratory in order to test the performance of the two systems within an indoor environment with the transmitter and receiver placed roughly 20ft apart from each other. Transmissions were made on a carrier frequency of 2.492GHz, unused by the department's wireless LAN, thus providing an interference free band over which to conduct our experiments.

Both transmitters are configured to output equal amounts of power within the baseband as well as the passband in order to avoid biasing the outcome of the experimental results. Variations in the 2×1 wireless channel are achieved by moving the position of the receive antenna along a rail 2 ft. in length mounted on the mobile receiver cart. For the real hardware system, it should be guaranteed that the system works in the range where receiver's thermal noise is the main noise source and changing TX power also changes receive SNR.

Shown in Fig. 5 are the average BER performance curves as functions of transmit power for the two systems. The BER curve for the 1×1 system shown in the plot is the average taken over both 1×1 systems, that is one transmitted from antenna 1 and another transmitted from antenna 2. As can be seen, the 2×1 system outperforms the 1×1 system

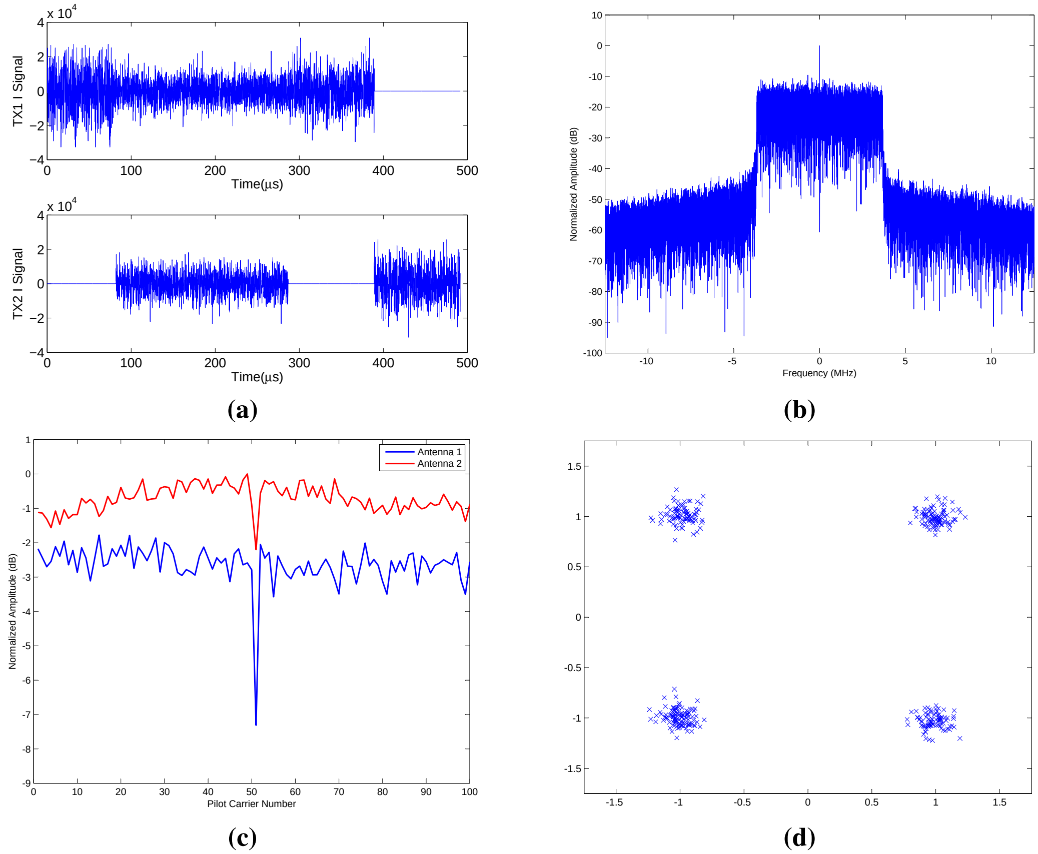

Fig. 4. (a) Time domain transmit frame for both antennas, (b) receive signal spectrum, (c) channel estimation plots for both transmit antennas, (d) decoded signal constellation.

due to the diversity gain achieved by 2×1 system. For instance, the 2×1 system requires approximately 9dBm less transmit power than the 1×1 system in order to achieve an average BER of 8×10^{-3}. Thus, on average, that is over many statistically varying fading environment, the 2×1 Alamouti scheme achieves a lesser average BER for a given unit of transmit power than the 1×1 system, as can be expected.

In order to understand how the 2×1 Alamouti scheme achieves such improvements in transmit power, we refer to the definition of the received SNR for both the 2×1 and the 1×1 systems [6] respectively defined as

$$\gamma_{2\times1} := \left(|h_1|^2 + |h_2|^2\right) \frac{E_s}{2N_0} \tag{1}$$

$$\gamma_{1\times1,a} := |h_1|^2 \frac{E_s}{N_0} \tag{2}$$

$$\gamma_{1\times1,b} := |h_2|^2 \frac{E_s}{N_0} \tag{3}$$

where $\gamma_{1\times1,a}$ refers to the 1×1 system transmitted from antenna 1 and $\gamma_{1\times1,b}$ refers to the 1×1 system transmitted from antenna 2. For the Alamouti scheme, the signal power of each antenna has been divided by 2 in order to ensure both systems transmit equal total power. Then for any given E_s/N_0, the SNR for the MISO system is less than or equal to the SNR of the SISO system associated with the stronger channel, but greater than or equal to the SISO system associated with the weaker channel,

$$\min(\gamma_{1\times1,a}, \gamma_{1\times1,b}) \leq \gamma_{2\times1} \leq \max(\gamma_{1\times1,a}, \gamma_{1\times1,b}). \tag{4}$$

Furthermore, for any fixed h_1 and h_2, the error probability for QPSK is given by $P_b(\gamma) = Q(\sqrt{2\gamma})$, where the Q function is a concave function with respect to $\sqrt{2\gamma}$ and monotonically decreases on the interval $(0, +\infty)$. Since $\sqrt{2\gamma_{2\times1}} > \frac{1}{2}(\sqrt{2\gamma_{1\times1,a}} + \sqrt{2\gamma_{1\times1,b}})$, it is always true that

$$P_b\left(\gamma_{2\times1}\right) \leq \frac{1}{2}\left(P_b\left(\gamma_{1\times1,a}\right) + P_b\left(\gamma_{1\times1,b}\right)\right). \tag{5}$$

Therefore, given random channel gains, h_1 and h_2, of equal distributions, the BER performance of the 2×1 system is always better than the 1×1 system.

Shown in Fig. 6 are plots of the cumulative distribution functions (CDF) and the probability density functions (PDF) for $\gamma_{2\times1}$, $\gamma_{1\times1,a}$, and $\gamma_{1\times1,b}$ taken over 200 frames for a single transmit power. We can see that $\gamma_{1\times1,a}$ and $\gamma_{1\times1,b}$ have similar PDF's in which the probability of achieving very lower SNR values close to zero are much greater than

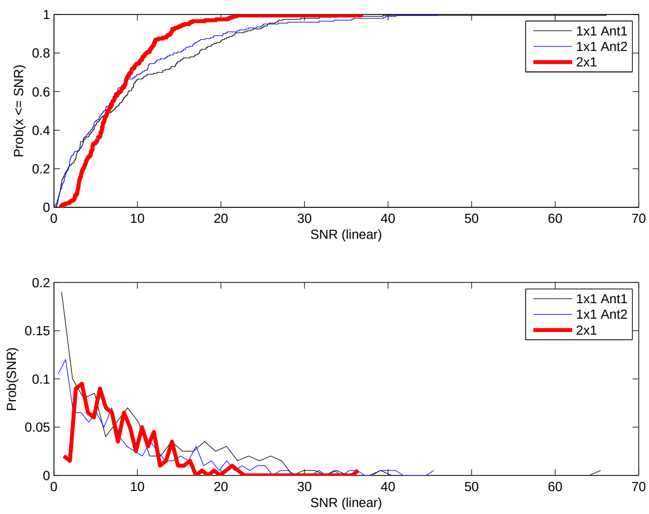

Fig. 6. Cumulative distribution functions (CDF) and probability density functions (PDF) for $\gamma_{2\times1}$, $\gamma_{1\times1,a}$, and $\gamma_{1\times1,b}$ when $\overline{\gamma_{2\times1}} = 8.8dB$, $\overline{\gamma_{1\times1,a}} = 9.65dB$, and $\overline{\gamma_{1\times1,b}} = 9.43dB$.

those for the 2×1 system. This increased probability of entering into a deep fade in SNR for the 1×1 system accounts for its greater average BER. The Alamouti scheme which in effect averages the receive SNRs of the two transmit branches, has an SNR distribution with lesser probabilities of entering into deep fades as well as lesser probabilities of achieving greater SNR values - concentrating higher probabilities about its mean SNR value of 7.59, thereby reducing the number of bit errors incurred.

VI. CONCLUSION

We have presented the design of MIMO testbed with real-time capabilities that has been used in the experimental investigation on the BER performance comparison between a 2×1 Alamouti/OFDM system and a 1×1 OFDM system employing no spatial multiplexing. Our initial deployment of the testbed, although not fully real-time, has given us the ability to closely examine the dependance of the two systems upon the characteristics of the wireless channel studied in our experiments. Our experiments show that on average and over very many statistically varying channels, systems employing Alamouti space-time block coding can achieve significant gains in BER performance over single antenna systems.

In the next phase of our ongoing study of MIMO communication systems, we plan to move the majority of DSP functions presently running on the RT embedded processor onto the 7965R's FPGA in order to conduct similar experiments on a fully real-time system. Once complete, we plan to examine the performance of these and other MIMO systems over a more extensive set of indoor locations in order to analyze the average performance of such systems over a richer set of fading environments.

VII. REFERENCES

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