Analyzing the Benefits of Pattern Diversity for MIMO Wireless Systems

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***Abstract*—We investigate the benefits of pattern diversity from using reconfigurable antenna arrays relative to conventional non-reconfigurable arrays that use signal processing techniques such as antenna grouping. The performance of various MIMO antenna mode selection algorithms are experimentally analyzed and benchmarked. Our performance evaluation is based on a measurement campaign employing a software-defined-radio MIMO testbed. Our findings demonstrate relative performance improvements from using pattern diversity at certain conditions.**

***Index Terms*—Pattern Reconfigurable Antennas, MIMO Systems, and Antenna Selection Techniques**

I. Introduction

MIMO technology can be implemented using different signal processing techniques. These techniques have varying characteristics and are used for different scenarios. One simple approach is called spatial multiplexing – a component of the BLAST architectures [1] – [2] – transmits multiple independent signals over the same frequency at the same time. Thus, different data signals are sent on the same time-frequency resource from different antennas so that spectrum efficiency is multiplied without expending more frequency resource. Other techniques such as spatial diversity, use redundancy to achieve transmitter diversity by sending orthogonal information set at two different timeslots from two different antennas. These signals are transmitted from the same source but have passed through statistically independent channels. Another technique known as Beamforming or spatial filtering, uses antenna arrays and advance signal processing algorithms to perform weighted processing on every physically separated antenna in the array. This is intended to maximize the power of the desired signals while minimizing or nulling the power of the interfering signals by controlling the relative magnitudes and phases of the signals.

Although high spectral efficiency can be achieved from spatial multiplexing, reliability of data transmission gets worse especially when there is a correlation between the transmission antennas. In contrast, combining gain can be obtained by sacrificing spectral efficiency using the beamforming mode. Therefore, in order to reap the gains in spectral efficiency through spatial multiplexing and transmit beamforming, antenna grouping algorithms have been used [3], [5], and [6]. These antenna grouping algorithms are hybrids of the two MIMO processing techniques. In this paper, we investigate various mode selection algorithms which select between antenna grouping, beamforming, and pattern diversity techniques. Several mode selection criteria are first introduced and a representative set of these algorithms are implemented in a software-defined radio platform. The results obtained from field measurements are then benchmarked against those obtained using algorithms that leverage pattern diversity in reconfigurable antennas for MIMO.

In this work we propose a model that leverage the pattern diversity gain derived from using reconfigurable antenna arrays to improve system performance; and benchmark it against models [3], [5], and [6] that use non-reconfigurable antenna arrays. We present the system-level implementation of these models/algorithms in a MIMO testbed relative to their respective simulation-based implementations. The main implication of our work is the demonstration of the benefits of pattern reconfigurable antenna arrays to motivate their integration in portable MIMO wireless systems – systems that are too small to employ conventional antenna arrays due to space/design limitations. This integration is possible due to the fact that a single reconfigurable antenna structure is used to act as a multiple element array in lieu of several physical antenna elements.

A. Related Works

The work in [3] proposes a multimode antenna selection algorithm that dynamically adjusts both the number of substreams and the mapping of substreams to antennas, for a fixed data rate, to the channel conditions. It also discusses a dual-mode selection algorithm that switches between spatial multiplexing and beamforming. It also derives several expressions that characterize the various criteria for selecting the number of substreams and the optimal mapping of substreams to transmit antennas. In [5], an adaptive algorithm that selects between beamforming, multimode antenna selection and spatial multiplexing is presented. This model extends the work in [3] to demonstrate capacity gains derived from adaptively switching between MIMO schemes. The work in [6] introduces several mode selections criteria and a low complexity criterion which is derived from a low complexity antenna grouping algorithm.

The relevant preliminary work for the pattern reconfigurable antennas is presented in [7] – [10]. These antennas are capable of dynamically changing their electrical and radiation characteristics to suit the conditions of the wireless chan-

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nel. The changing radiation patterns lead to pattern diversity gains that improve system performance. This is in contrast to conventional non-reconfigurable arrays which depend on signal processing techniques such as antenna grouping and beamforming to achieve performance gains. Previous works in [7] and [10], propose adaptive algorithms for antenna pattern selection.

In Section II, we present the MIMO system models that employ reconfigurable antenna arrays and conventional arrays and, briefly discuss the selection criteria of various antenna mode selection algorithms. In Section III, we describe the experimental setup and implementation parameters, and then, analyze the experimental performance results in Section IV. Section V gives a brief conclusion.

II. System Model

We consider a MIMO-OFDM system illustrated in Fig. 1 that transmits R bits per channel use. Fig. 2 shows the same system employing reconfigurable antennas. The system consists of Q transmit and P receive antennas sending data across K subcarriers. The system consists of serial to parallel spatial multiplexer that produces G substreams, a precoding mapper that maps these streams to transmit antennas, a channel matrix that is function of the of the wireless environment, and a space-time receiver that uses the estimate of the channel state information to decide on the transmitted bit stream. The feedback channel is used to send a low-rate feedback comprising of the precoding matrix index, antenna mode index and the adaptive modulation and coding index.

The symbol vector $\mathbf{s}^t_{q,k}$ produced from the spatial multiplexer during each symbol period t for a given subcarrier is denoted by $\mathbf{s}^t_{q,k} = [s^t_{1,k},\ s^t_{2,k},\ ...,\ s^t_{Q,k}]$. R bits are demultiplexed into Q different bit streams and modulated using the same constellation. The number of bits per substream is R/G so that R bits are transmitted irrespective of the value of G. This symbol vector is precoded by a $Q \times G$ precoding matrix $\mathbf{W}_{Q,g}\ \epsilon\ \omega(G,Q)$ where $\mathbf{W}_{Q,g}$ represents a substream-to-antenna group g mapping. It is the g^{th} entry in $\omega(G,Q)$, the ordered set of $Q \times G$ matrices constructed by all combinations of G columns of the identity matrix $\mathbf{I}_Q$. The cardinality $|\omega(G,Q)| = \binom{Q}{G}$. For a $Q = 2$, $\omega(1,2) = \left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\}$, $\omega(2,2) = \left\{ \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right\}$ The columns of the mapping matrices are simply selection diversity vectors that select the antenna to transmit the corresponding substream. This ordered set is $\omega(G,Q) = \left\{ \mathbf{W}_{Q,1}, \mathbf{W}_{Q,2}, ..., \mathbf{W}_{Q,\binom{Q}{G}} \right\}$.

Assuming that the transmitter has no knowledge of the forward-link channel, the optimal values of the parameter G (the number of substreams and the precoding group g are determined at the receiver and fedback to the transmitter. Suppose, the OFDM symbol transmitted from the q^{th} ($q = 1, ..., Q$) transmit antenna on the k^{th} ($k = 1, ..., K$) OFDM subcarrier is represented by $\mathbf{s}_{q,k}$. During the t symbol period, the received sequence at the p^{th} ($p = 1, ..., P$) receive antenna is given by

$$\mathbf{y}_{p,k} = \sqrt{\frac{\varepsilon_s}{Q}} \mathbf{H}_{p,q,k} \mathbf{W}_{Q,g} \mathbf{s}_{q,k} + \mathbf{n}_{p,k}, \tag{1}$$

where $\mathbf{H}_{p,q,k}\mathbf{W}_{Q,g}$ is the equivalent channel. After precoding, the q^{th} transmit antenna transmits the g^{th} of $\mathbf{W}_{Q,g}\mathbf{s}_{q,k}$.

For the system in Fig. 2 that uses reconfigurable antenna arrays with J antenna configurations or patterns, the system is modeled by:

$$\mathbf{y}^j_{p,k} = \sqrt{\frac{\varepsilon_s}{Q}} \mathbf{H}^j_{p,q,k} \mathbf{W}\ \mathbf{s}_{q,k} + \mathbf{n}_{p,k}, \tag{2}$$

where $\mathbf{y}^j_{p,k}$ is the P x 1 received vector at the p^{th} receive antenna, $\mathbf{H}^j_{p,q,k}$ is the P x Q channel response matrix between the q^{th} transmit and the p^{th} receive antenna for the k^{th} subcarrier and the j^{th} antenna configuration, and $\mathbf{n}_{p,k}$ is the P x 1 Additive White Gaussian Noise (AWGN) at the p^{th} receive antenna for the k^{th} subcarrier. J is the total number of antenna configurations and ε_s is the transmit energy. In both system models, the transmission bandwidth is assumed to be much less than the coherence bandwidth of the channel and that the symbol period is much less than the coherence time. A zero-delay limited capacity feedback link is assumed to be available from the receive to the transmitter. The receiver uses a Zero-Forcing linear equalizer.

A. System Model I: Review of the Antenna Mode Selection Criteria

While several criteria have been discussed in detail in [3] and [6], in this section, we only present two such criteria: i) Post-Processing SNR-based selection criterion for dual-mode antenna selection, and ii) Eigenmode-Based Selection for multimode antenna grouping. In the former case, the system switches between two antenna modes of space diversity and spatial multiplexing; the system is either using the sub-arrays to send independent data streams or sending redundant copies of the same stream through all the sub-arrays. In the latter case, the multimode selection introduces the possibility of selecting certain sub-arrays for transmission and not using the rest. It uses either spatial multiplexing or space diversity on various antenna groups that are adaptively selected based on the eigenmode of the equivalent channel matrix.

1) Post-Processing SNR-based Selection: It has been established in [3] that the performance of spatial multiplexing with a Zero-Forcing linear receiver is a function of the effective SNR for each stream is given by

$$SNR^{(ZF)}_p = \gamma_0 \frac{1}{[\mathbf{H}^H_{p,q,k}\mathbf{H}_{p,q,k}]^{-1}} \tag{3}$$

The ergodic capacity for the spatial multiplexing with linear receivers is then given by [5]

$$C_{(SM)} = \sum_{p=1}^{P} E\left[log_2(1 + SNR^{(ZF)}_p) \right] \tag{4}$$

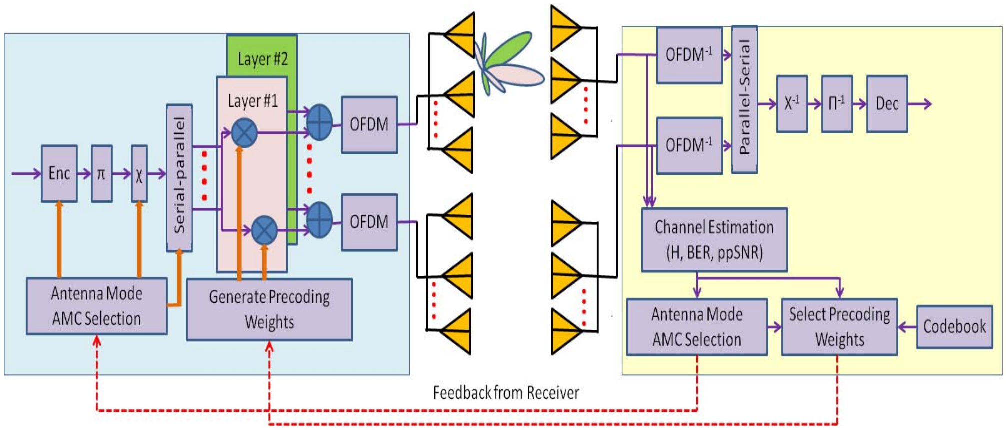

Fig. 1. Closed-loop Single User MIMO Transmission System using Code-book-based Precoding and Antenna Grouping

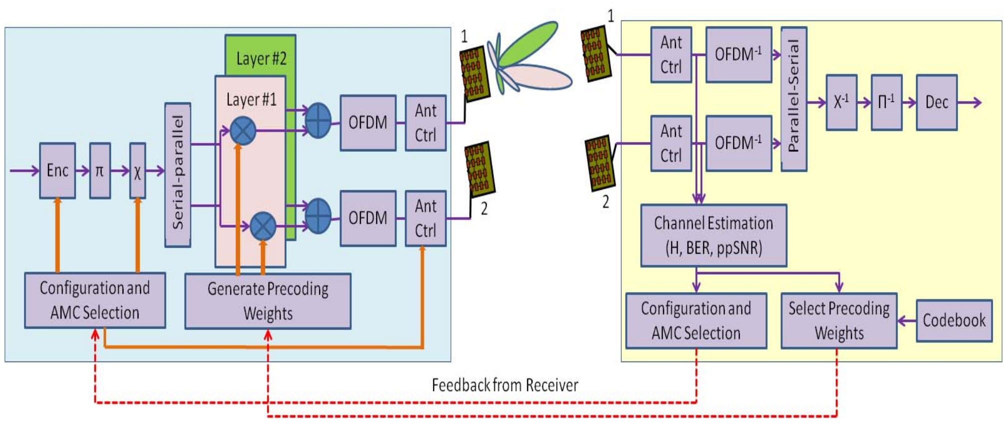

Fig. 2. Closed-loop Single User MIMO Transmission System using Code-book-based Precoding and Reconfigurable Antennas

Similarly, the performance of spatial diversity with a Zero-Forcing receiver is dependent on the equivalent channel matrix $\mathbf{H}_{p,q,k}\mathbf{W}_{1,g}$ and is given by

$$SNR^{(ZF)} = \gamma_0 \parallel \mathbf{H}_{p,q,k}\mathbf{W}_{1,g} \parallel^2 \quad (5)$$

And, the corresponding ergodic capacity for the spatial diversity with linear receivers is then given by [5]

$$C_{(SD)} = E\left[\frac{1}{2}\sum_{p=1}^{P} log_2\left(1 + SNR_p^{(ZF)}\right)\right] \quad (6)$$

These values of SNR determine the performance of the system as measured by the average probability of vector symbol error. Also, $SNR^{(ZF)}$ is related to the singular value decomposition vector as below

$$\max_{1\leq g\leq Q} \quad SNR^{(ZF)}(Q,g) \leq \frac{\varepsilon_s}{N_0}\lambda_{max}^2(\mathbf{H}_{p,q,k}) \quad (7)$$

where $SNR(Q,g)$ denote the post-processing SNR for a stream given the precoding matrix $\mathbf{W}_{Q,g}$. Another parameter of importance is $d_{min}^2(Q,R)$, which denotes the squared minimum Euclidean distance of the constellation used for transmission on one of the Q substreams. This parameter is often used to derive the probability of detection error in maximum-likelihood detection of the signal. This is modeled by either of these equations:

$$Pr(error|\mathbf{H}_{p,q,k}) \leq (2^R - 1)Q\left(\sqrt{\frac{\varepsilon_s}{2N_o}d_{min}^2(\mathbf{H}_{p,q,k})}\right) \quad (8)$$

$$Pr(error|\mathbf{H}_{p,q,k}) \leq (2^R - 1)Q\left(\sqrt{SNR(G,g)d_{min}^2(Q,R)}\right) \quad (9)$$

Based on the above derivations in [3] by Heath et al., the following approximation provides a selection criterion that chooses spatial multiplexing over space diversity if

$$d_{min}^2(Q,R) \min_{1\leq g\leq Q} \quad SNR(Q,1) \geq d_{min}^2(1,R) \max_{1\leq g\leq Q} SNR(1,g) \quad (10)$$

Else, choose space diversity transmission from the best transmit antenna.

2) Eigenmode-based Selection: The eigenmode-based selection criterion is used for the multimode transmission where both the number of substreams and the antenna subset are optimally chosen. By considering a Zero-Forcing receiver, the same work in [3] leverages a result from matrix theory to derive the criterion for multimode selection by using the singular value of $\mathbf{H}_{p,q,k}\mathbf{W}_{Q,g}$. The eigenmode selection rule solves for $\{G^{*}, g*\}$ that maximize the minimum singular value; this requires he computation of $\lambda_{min}(\mathbf{H}_{p,q,k}\mathbf{W}_{Q,g})$ for all possible $\mathbf{W}_{Q,g} \; \epsilon \; \omega(G,Q)$. The eigenmode-based selection criterion first choose G^{*} such that

$$G^{*} = arg \max_{1 \leq G \leq Q} \lambda_{G}(\mathbf{H}_{p,q,k}) d^{2}_{min}(G,R) \quad (11)$$

and then find the g^{*} that solves

$$g^{*} = arg \max_{1 \leq g \leq \binom{Q}{G^{*}}} \lambda^{2}(\mathbf{H}_{p,q,k}\mathbf{W}_{G^{*},g}), \quad (12)$$

B. System Model II: Antenna Configuration Selection Criteria

This system model uses post processing SNR (ppSNR) as the metric of configuration selection. The algorithm selects an optimal configuration J^{*} that yields the highest average ppSNR. This process requires channel training and is carried out during one of the following training intervals: i) Initial training interval, and ii) Re-training Interval. The initial training interval is necessary when no prior channel training has been done. Conversely, the re-training interval prior to some initial training is only used in order to abate the effects of channel fading over time and for up-to-date channel adaptation.

i) Initial training interval: In this interval, initial channel training is carried out over all the J possible configurations; several training packets are transmitted using QPSK modulation for each of the J possible configurations. After each training packet transmission, the ppSNR is calculated by taking the mean of the subcarrier ppSNR values. The average ppSNR of a specific configuration is then obtained by taking the mean of the transmissions at that configuration. The algorithm then selects configuration j^{*} that with the highest average ppSNR. We sort these average ppSNR values and store the top 5 along with their corresponding configurations.

In this interval, there is need to transmit multiple training packets at a given configuration in order to obtain a meaningful statistic of the Channel Quality Indicator (CQI) from post processing. However, a major challenge arises in selecting the period of the training interval: the use of a long training interval will lead to parameter adaptation based on out-dated channel characteristics; meanwhile a short interval fails to yield a realistic statistic. Determining the optimal training period requires further analysis that deviates from the main focus of this work. Therefore, a fixed training period was used to obtain a CQI statistic from post processing the channel measurements. Similarly, in an attempt to minimize the re-training interval time we selected a subset of the total configuration for the re-training phase.

ii) Re-training Interval: during this interval we re-train over the top 5 configurations stored in interval i); and transmit a training packet per configuration - thus, a total of 5 training packets. We then select the configuration that yields the highest average ppSNR out of these top 5 configurations.

III. Experimental Implementation

A. Measurement Setup

The experimental setup used two stations. Each station is equipped with a laptop, a Wireless open-Access Radio Platform (WARP) board [12], and two Reconfigurable antennas. A WARP board has two radio cards, each with one antenna slot. Each of the WARP boards are equipped with a Field-Programmable Gate Array (FPGA) that allows for flexible configuration to different 802.11 standards. The laptop runs the software that drives the WARP radios and the reference code for signal processing. The WARP based testbed therefore, provides a flexible software-defined-radio platform for implementing the PHY/MAC protocols.

We implement a 2x2 MIMO link established by the two stations in concert with OFDM because of its ability to cope with severe channel conditions such as frequency-selective fading due to multipath. The transmission packets are based on the 802.11n OFDM format. The total bandwidth of 20 MHz is divided into 64 subcarriers: 48 for data and 16 for pilot symbols and preamble. Each OFDM symbol has 80 samples (64 samples for each subcarrier plus 16 samples for cyclic prefix). Based on the manufacturer's specification for WARP radio transmission rate of 10^{7} samples per second, the sampling rate is approximately 8μs per OFDM symbol [14].

Data are encoded using punctured convolutional codes and modulated at a carrier frequency of 2.484 GHz using one of the four signal constellations: BPSK, QPSK, 16QAM, and 64QAM. The convolutional encoder uses a constraint length of and code generator polynomials of 133, and 171 (in octal numbers). The puncturing matrices for the relevant coding rates (1/2, 2/3, 3/4) are specified. All transmissions consisted of a 24 byte header which includes a Cyclic Redundancy Check (CRC) modulated with BPSK and bits were coded at rate 1/2. The header carries a fixed channel training sequence [13] and a payload of 1KB is followed by a 4 byte CRC check.

IV. Performance Results

Several algorithms were considered for implementation: i) Proposed model using pattern reconfigurable antennas illustrated in Fig. 2. The proposed spatially adaptive algorithm is implemented as part of this model. ii) The model in Fig. 1 using conventional arrays. With this model three algorithms: The waterfilling spatial technique [4], multimode [5], and dual-mode [11], approaches are implemented.

Fig. 3 presents the ergordic capacity curves for the different techniques with Zero-Forcing receivers. The results were based on channel measurements in an indoor environment. In the figure, we can see that at SNRs below 5dB the proposed technique generates the highest capacity, with respect to the other approaches. For SNRs less than 10dB it outperforms both multimode antenna selection and the waterfilling spatial technique. This advantage can be attributed to the pattern diversity gain associated with the use of the reconfigurable antennas. At low SNRs, the spatial diversity techniques also performs better than the other techniques except the proposed

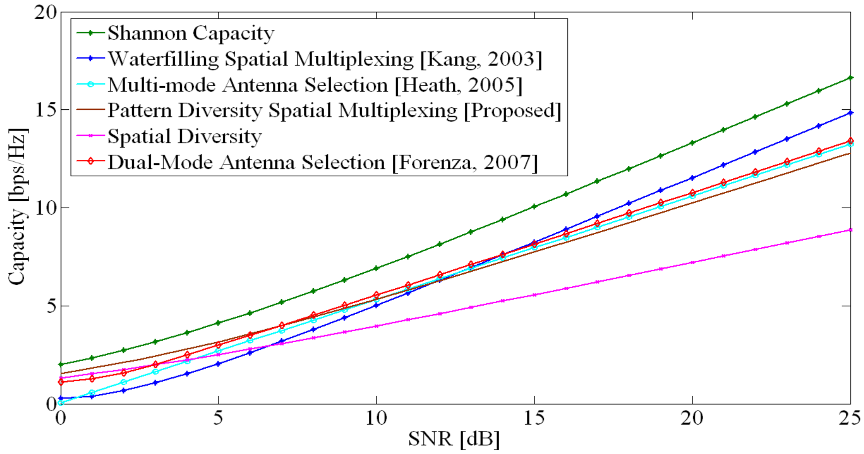

Fig. 3. Average Capacity for Single User MIMO Transmission System; Shannon Capacity, Waterfilling Technique, Antenna Selection Approaches, Pattern Diversity Scheme

model. However, at higher SNRs it consistently performs below the other models. This emphasizes the fact that spatial diversity is preferable for systems that value robustness over spectral efficiency.

At SNR range higher than 10dB, the all the models perform closely except the that for the waterfilling technique. The slight advantage of the waterfilling technique can be attributed to the optimal power allocation between antenna elements of the transmission array. Also, the 1dB gap between the antenna grouping algorithms with the pattern diversity based technique can be explained by the spatial diversity advantage realized from selecting the optimal antenna grouping scheme. The minor difference between the dual-mode and multimode schemes may be attributed to the fact that implemented system uses only two transmit and receive antenna arrays. We believe the use of a larger number of antenna array elements would have influenced the performance of the two schemes.

V. Conclusion

In this paper, we analyzed and presented a low-complexity model that leverages the pattern diversity of reconfigurable antennas and benchmarked it against a model that uses conventional antenna arrays with signal processing techniques that apply antenna grouping. Our findings show that at low SNRs, pattern diversity provides a better diversity gain relative to the antenna grouping techniques. However, at higher SNRs, the antenna grouping techniques have a slight edge over pattern diversity due to their ability to leverage both diversity and spectral efficiency.

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