State-Selection in a Space-Time-State Block Coded MIMO Communication System Using Reconfigurable PIXEL Antennas

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Abstract—In this paper, we propose a novel Multiple-Input Multiple-Output (MIMO) wireless communication system employing reconfigurable PIXEL antennas at the receiver. We design a Space-Time-State Block Coding scheme for the PIXEL-based reconfigurable MIMO system and propose optimal and ad hoc state-selection algorithms that achieve maximum diversity gains. Moreover, we prove that in state-selection schemes, contrary to antenna selection, there is no benefit in selecting more than one state. Furthermore, we discuss the gains of state-selection over the state-switching scheme proposed in [1]. Finally, we evaluate the theoretical findings through simulations. These simulations are conducted using a realistic channel model, that takes into account the radio-electric characteristics (radiation pattern, gain, efficiency, etc.) of the PIXEL antennas.

I. INTRODUCTION

In [1], we proposed a space-time block coding scheme for an ORIOL-based reconfigurable Multiple-Input Multiple-Output (MIMO) wireless communication system, where both the transmitter and the receiver employ reconfigurable antennas. The ORIOL antenna [2], is capable of creating 2 partially correlated channel propagation scenarios. This capability is then combined with an appropriate codification of the transmitted signal to improve the diversity order of current MIMO communication systems using a state-switching scheme. In state-switching, the transmit and receive reconfigurable antennas periodically switch their radiation states, creating a block fading channel model. In this work, we employ PIXEL antennas [3] which are capable of producing up to 5 uncorrelated channel propagation scenarios, therefore offering higher diversity gains. Based on a Generalized Block-Diagonal Quasi-Orthogonal Space-Time Block Code [4]–[9], we propose a general coding scheme for any number of channel propagation states. We refer to this coding scheme as Space-Time-State Block Code (STS-BC) because in addition to exploiting the time and space dimensions it also takes into account the radiation state diversity offered by the use of reconfigurable antennas, thus effectively becoming a 3-dimensional code. The STS-BC applied over state-switching can be used in an open-loop configuration with reconfigurable antennas at the transmitter without the need for feedback and is capable of achieving a diversity gain equal to the product of number of transmit and receive antennas and the total number of propagation states offered by the reconfigurable system [1]. When reconfigurable antennas are employed at the receiver, although state-switching is still applicable, we propose a state-selection scheme to provide improved performance gains in terms of average received Signal to Noise Ratio (SNR). The state-selection scheme can also be used with lower order STS-BCs to combine the benefits of higher diversity with lower decoding complexity and delay. Notice that a simple state-selection scheme was proposed in [10], where the authors proposed choosing the best channel state, i.e. the one resulting in the largest received SNR, prior to data transmission using the Alamouti code. In this work, we further develop this idea. Also, in this paper, we use a channel model that takes into consideration practical aspects of the propagation environment, such as the intra- and inter-channel correlation coefficients, gain response of the antennas, etc. These parameters are obtained through electromagnetic simulations of the PIXEL antennas.

The rest of this paper is organized as follows. In Section II, we introduce the PIXEL antenna and its structure. We develop the system model in Section III taking into account various practical issues pertaining to propagation channel. In Section IV we design an STS-BC for 5 states that is capable of achieving the maximum theoretical diversity gains in combination with state-switching. In Section V, we propose both optimal and ad hoc state-selection criteria and prove that the optimal and ad hoc selection criteria are equivalent and result in single-state selection. We further quantify the selection gain and compare state-switching and state-selection schemes. Section VI presents actual measurements of the system parameters and simulation results for various state-switching and state-selection schemes. Finally, some concluding remarks are made in Section VII. Notation: Throughout this paper we use bold letters to represent matrices, and $(\cdot)^T$, $(\cdot)^*$ and $(\cdot)^H$ to denote transpose, complex conjugate and hermitian, respectively. Moreover, we use $\mathbb{C}^{M \times N}$ to denote the set of $M \times N$ matrices over the field of complex numbers.

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and ⊗ to represent the Kronecker product of two matrices. Note that $\mathbb{R}$ represents the set of real numbers.

II. PIXEL ANTENNA

The PIXEL antenna is a multifunctional MEMS-reconfigurable antenna which provides two functionalities: reconfiguration of its modes of radiation and reconfiguration of the operating frequency. The PIXEL antenna [3] offers higher reconfigurable capabilities compared to the ORIOL antenna [2], at the cost of additional design and operational complexity. It works based on the principle that different radiation modes and operating frequencies can be excited by changing the dimension (radius) of a circular patch and the relative location of the feed line within the patch [11]. In particular, the antenna uses a $13 \times 13$ matrix of metallic pixels interconnected through MEMS switches in which circular patches of different radius are mapped on it. On the other hand, the antenna is fed through a coaxial line which is connected to the pixeled surface at a fixed location. The PIXEL antenna can excite up to five distinct radiation patterns which are orthogonal in an ideally scattered channel. Fig. 1 shows the $\theta$- and $\phi$-component of the far-field radiation patterns in the azimuth plane, associated with the five modes of the PIXEL antenna [3].

![PIXEL antenna patterns](image)

Fig. 1. $\theta$- and $\phi$-component of the far-field radiation patterns, in the azimuth plane, associated with the five modes excited using the PIXEL antenna.

III. SYSTEM MODEL

For this paper, we assume that we have two monopole antennas at the transmitter ($M_T = 2$) and a single reconfigurable PIXEL antenna at the receiver ($M_R = 1$). Assume that the switching time in between radiation states is much smaller than the symbol duration, therefore negligible. Let $\Psi$ denote the total number of Channel Propagation States (CPSs) for a reconfigurable system. Note that as mentioned in Section II, by using the PIXEL antenna we have $\Psi = 5$. Notice that in [1], the number of CPSs are limited to two due to the fact that the ORIOL antenna can only radiate using two distinct polarization bases. The channel matrix during the $\psi^{th}$ CPS, where $\psi \in \{1, \ldots, 5\}$, is defined as

$$H_\psi = \begin{bmatrix} h_0^\psi \\ h_1^\psi \end{bmatrix},$$

where $h_i^\psi$ denotes the channel coefficient between the $i^{th}$ transmit antenna and the single-port of the receive PIXEL antenna during state $\psi$. We assume we have a Rayleigh fading channel, therefore $h_i^\psi$'s are zero-mean complex Gaussian random variables. Now, we define $R_{pq} = E\{H_p^* H_q\}$ as the inter channel propagation state correlation matrix. Throughout this paper we assume that no channel state information is available at the transmitter but the receiver is assumed to have perfect channel knowledge. Suppose we transmit a codeword $C_\psi \in \mathbb{C}^{T \times M_T}$, over $T$ time slots, during the $\psi^{th}$ state of the channel, where $\psi \in \{1, \ldots, \Psi\}$. The receive equation for the scenario discussed above is given by

$$Y = CH + N,$$

where, $C = \text{diag}\{C_1, C_2, \ldots, C_\Psi\} \in \mathbb{C}^{\Psi \times T \times M_T}$ is the transmitted codeword, $Y \in \mathbb{C}^{\Psi \times T \times M_R}$ is the received matrix, $H \in \mathbb{C}^{\Psi \times M_T \times M_R}$ is the channel matrix and $N \in \mathbb{C}^{\Psi \times T \times M_R}$ is a zero-mean circularly symmetric Gaussian noise matrix. Eq. (2) can be expanded as,

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_\Psi \end{bmatrix} = \begin{bmatrix} C_1 & 0 & \ldots & 0 \\ 0 & C_2 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & C_\Psi \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_\Psi \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \\ \vdots \\ N_\Psi \end{bmatrix}.$$

where, $H_\psi$ is defined in Eq. (1). Note that the channel vector can be written as, $H = \mathcal{R}_H^{1/2} \tilde{H}$ where, $H$ is a zero-mean i.i.d complex vector with covariance $\mathcal{E}\{HH^H\} = I_{M_T \times M_R \Psi}$. For the PIXEL antenna, $\mathcal{R}_H$, the covariance of the channel vector, $H$, is given by,

$$\mathcal{R}_H = \mathcal{E}\{HH^H\} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} \\ R_{12}^H & R_{22} & R_{23} & R_{24} & R_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{15}^H & R_{25}^H & R_{35}^H & R_{45}^H & R_{55}^H \end{bmatrix}.$$

IV. STS-BC FOR RECONFIGURABLE MIMO SYSTEMS

For a reconfigurable system with $\Psi$ channel propagation states, let us denote the STS-BC codeword of period $\Psi$ by $\text{STS-\Psi}$, given by [4],

$$C_{\text{STS-\Psi}} = \frac{1}{\sqrt{2\Psi}} \begin{bmatrix} A(S_1, S_2) & 0 & \ldots & 0 \\ 0 & A(S_3, S_4) & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & A(S_{2^\Psi - 1}, S_{2^\Psi}) \end{bmatrix},$$

where, $C_\psi = A(S_{2^\psi - 1}, S_{2^\psi})$ for $\psi \in \{1, 2, \ldots, \Psi\}$ and

$$A(x_1, x_2) = \begin{bmatrix} x_1 \\ -x_2 \\ x_2 \\ x_1 \end{bmatrix}.$$
Also,
\[
[S_1 \ S_3 \ \ldots \ S_{2\psi-1}]^T = \Theta [s_1 \ s_3 \ \ldots \ s_{2\psi-1}]^T, \tag{6a}
\]
\[
[S_2 \ S_4 \ \ldots \ S_{2\psi}]^T = \Theta [s_2 \ s_4 \ \ldots \ s_{2\psi}]^T, \tag{6b}
\]
where, \(\Theta = U \times \text{diag}[1, e^{j\theta_1}, \ldots, e^{j\theta_{\psi-1}}] \) and \(U\) is a \(\psi \times \psi\) matrix which is either a Hadamard matrix (if it exists) or is constructed by deleting rows and columns from a Hadamard matrix. For the PIXEL antenna, the constructed matrix is equivalent to the optimal selection algorithm. The ad hoc selection scheme chooses the best channel propagation state.

Later, we prove that in fact the ad hoc selection algorithm achieves full-diversity for \(\psi\) states, in combination with an STS-P code, achieves full-diversity of \(M_T M_R \psi\).

### Proof:
Let us make the simplifying assumption that \(H_i\)'s are independent. The conditional pairwise error probability can be written as,
\[
P(C^1 \rightarrow C^2|H) = Q\left(\frac{\sqrt{\gamma}}{2} ||(C^2 - C^1)H||_F\right)
= Q\left(\frac{\sqrt{2}}{2} \sum_{p=1}^{P} ||(C^2_p - C^1_p)H_p||_F^2\right) \tag{11}
\]
Note that using the code structure given in (4),
\[
||C^2_p - C^1_p||_F^2 = x_p \sum_{n=1}^{N} \sum_{m=1}^{M} |h_{n,m}^p|^2,
\]
where, \(x_p = |D_{2p-1}|^2 + |D_{2p}|^2\) and \(D_i = S_i^2 - S_i\) for all \(i \in \{1, \ldots, 2P\}\). Let \(x_{\min} = \min\{x_1, \ldots, x_P\}\). Then,
\[
P_{\psi_{\min}} \sum_{p=1}^{P} ||H_p||_F^2 \leq x_{\min} \sum_{p=1}^{P} ||H_p||_F^2 \leq x_{\min} \sum_{p=1}^{P} ||H_p||_F^2 + \cdots + ||H_p||_F^2
\]
which results in,
\[
P(C^1 \rightarrow C^2) \leq Q\left(\frac{\gamma P}{2 \psi_{\min}} \sum_{p=1}^{P} ||H_p||_F^2\right) \tag{14}
\]
Now, using the chernoff upper bound and calculating the expected value with respect to \(h_{n,m}^p\)'s results in,
\[
P(C^1 \rightarrow C^2) \leq \left(1 + \frac{\gamma P}{2 \psi_{\min}} \right)^{\Psi M_T M_R}. \tag{15}
\]
Therefore, by using an ad hoc state-selection scheme one can achieve a diversity of \(\Psi M_T M_R\), which is the highest level of diversity offered by the system. Note that proof of full-diversity for STS-Q, where \(1 \leq \Psi \leq \Psi\) follows similarly.

### C. Single-state Selection
We show that the optimal and the ad hoc criteria are equivalent and that they select the single best state.

**Theorem 2**: The optimal selection criterion, based on maximizing the received SNR, is equivalent to selecting the single best channel propagation state.

**Proof**: It is easy to show that, \(\forall a_i \in \mathbb{R}, \) where \(i \in \{1, \ldots, m\},\)
\[
z = a_1^2 + \cdots + a_m^2 \leq \max_i a_i^2
\]
Using (16), one can show that
\[
\max_{i \in \{1, \ldots, \psi\}} \frac{||H_{i1}||^2 + \cdots + ||H_{iP}||^2}{||H_{i1}||^2 + \cdots + ||H_{iP}||^2} = \Psi \tag{17}
\]
where, \(||H_{\max}||^2 = \max_{j \in \{1, \ldots, \psi\}} ||H_{j}||^2\). Therefore, the optimal selection algorithm chooses the best channel state and fixes the channel for the period of \(P\) codewords.
Also, the ad hoc selection criterion results in,

\[
\max_{1 \leq i_1, \ldots, i_P \leq P} \max_{1 \leq t_1, \ldots, t_P \leq P} ||H_{i_1,t_1}||^2 + \cdots + ||H_{i_P,t_P}||^2 = P||H_{\text{max}}||^2 \]

Therefore, both the optimal and ad hoc selection schemes resort to selecting the single best state, \( H_{\text{max}} \), and fixing the channel in that state, over the duration of \( P \) codewords.

### D. State-selection vs. State-switching

The state-switching technique \[1\] in combination with an appropriate STS-BC, can be used for a MIMO system using reconfigurable transmit antennas to obtain space and state diversity gains. When reconfigurable antennas are placed at the receiver, one has the additional capability of employing the state-selection scheme proposed in this paper, in combination with STS-BC. Note that state-selection in addition to obtaining full-diversity benefits, can produce a Selection Gain (SG) over STS-5. Also, the ad hoc selection criterion results in, 

\[
SG = \frac{\mathcal{E}\left\{||H_{\text{max}}||^2\right\}}{\Psi \mathcal{E}\left\{\sum_{1 \leq i_1, \ldots, i_P \leq P} ||H_{i_1,t_1}||^2 + \cdots + ||H_{i_P,t_P}||^2\right\}}
\]

Note that state-selection differs from hybrid antenna selection/Maximum Ratio Combining (MRC) methods, in the sense that contrary to antenna selection, state-selection beyond one state does not increase the SNR any further. The difference comes from the fact that in antenna selection there is additional radiation energy that the additional antennas are able to capture, whereas in state-selection, selecting more than one state does not increase the received power beyond one state.

### VI. Simulation Results

The simulations are performed for a reconfigurable MIMO system, where \( M_T = 2 \) and \( M_R = 1 \). We assume that the transmit antennas are non-reconfigurable and are separated by a distance of \( 0.5\lambda \), therefore exhibiting no spatial correlation. The receiver is assumed to be a PIXEL antenna with \( \Psi = 5 \). In order to compute the elements of \( R_H \) we assume a propagation channel satisfying the Kronecker model. This channel model has been widely used in the literature and in several IEEE standards (such as IEEE 802.11n) \[12\]. Contrary to \[12\], we do not model the power delay profile (i.e., narrowband assumption) and Doppler effects, since we aim at measuring the performance gains due to the pattern/polarization diversity provided by the reconfigurable PIXEL antenna. The entries of the covariance matrix are computed from the simulated radiation patterns of the PIXEL antenna (shown in Fig. 1) and the receive signal power spectrum using

\[
X_{pq} = \int_{-\pi}^{\pi} \left( \Psi_{R_{\theta}}(\phi) \right)(\Psi_{R_{\phi}}(\phi))^* d\phi = \int_{-\pi}^{\pi} \left( \Psi_{R_{\theta}}(\phi) \right)(\Psi_{R_{\phi}}(\phi))^* d\phi
\]

where we have assumed that the elevation angle spread is generally small, compared with the azimuth spread, and the directions of arrival/departure are mostly localized over the azimuth directions \[13\]. In Eq. (20), \( \Psi_{R_{\theta}}(\phi) = \Psi_{R_{\phi}}(\phi) = 0 \) represents the \( \theta \)- and \( \phi \)-components of the azimuthal radiation pattern of the receive PIXEL antenna sent in the \( \rho \)th CPS, while the distribution for the azimuth profile \( \Psi_{\theta}(\phi) = \Psi_{\phi}(\phi) = 0 \) is generally assumed to be Laplacian \[12\]

\[
\Psi_{\theta}(\phi) = \frac{1}{\sqrt{2\pi}\sigma_{\phi}} e^{-\frac{|\phi - \phi_c|}{\sigma_{\phi}}}
\]

for \( \phi \in [-\pi, \pi] \), where \( \sigma_{\phi} \) is the standard deviation of the power azimuth spectrum and \( \phi_c \) is the mean angle-of-arrival of a particular cluster. In most studies, the resultant covariance matrix is usually normalized such that the magnitude of its entries is equal or smaller than one, thus producing the receive correlation matrix. However, by doing so, important information regarding the amount of received power on each state is lost. In order to avoid this simplification, \( R_H \) is computed from the Kronecker product of the transmit and receive correlation matrices, that is, \( R_H = X \otimes I_2 \). As a result, we not only include information on the statistical correlation among the distinct radiation states of the PIXEL antenna but also take into account the amount of receive power on each of its propagation states. This allows us to conduct a more realistic set of simulations including realistic antenna parameters such as the antenna gain, ohmic efficiency and matching efficiency.

Notice that because the two transmit monopoles are separated by a large distance \((0.5\lambda)\), the transmit covariance matrix is given by an identity matrix. In our simulations we consider the following three scenarios for the distribution of the azimuth profile, \( \Psi_{\theta}(\phi) \):

- case 1: \( \phi_c = 0^\circ \) and \( \sigma_{\phi} = 5 \),
- case 2: \( \phi_c = 0^\circ \) and \( \sigma_{\phi} = 60 \),
- case 3: \( \phi_c = 0^\circ \) and \( \sigma_{\phi} = 220 \).

In addition, the above cases are also compared with an ideal case consisting of an uncorrelated channel receiving an equivalent amount of power as that in cases 1, 2 or 3. The receive covariance matrices for the three aforementioned cases are given by Eqs. (22)-(24) in the next page.

Fig. 2 depicts the Bit-Error-Rate (BER) vs. SNR performance of STS-5 for cases 1, 2 and 3 as well as the corresponding uncorrelated cases. The channel gains for each ideal case are given by 37.8791 dB, 37.1345 dB and 35.4436 dB, for cases 1, 2 and 3, respectively. Fig. 3 shows the BER-SNR performance of an uncorrelated reconfigurable multi antenna system, with \( \Psi = 5 \) and \( \Psi = 2 \) for 1 bit/sec/Hz. We compare various state-switching and state-selection schemes and we characterize their performance according to three factors: diversity gain, coding gain and selection gain. As shown in this figure, for both state-switching and state-selection schemes, as the number of CPSs (\( \Psi \)) increases, a larger diversity order is achieved. For a fixed \( \Psi \), by using an STS-BC with a larger period \( P \), we obtain improvements through coding gain. Note, however, that using an STS with larger period results in...
higher decoding complexity and decoding delays. Both state-switching and state-selection schemes achieve full diversity therefore the slope of the BER curves in asymptotical high-SNR scenarios should eventually be the same. At the same diversity level, one can confers from the simulation results, in the low SNR region coding gain is a more dominant factor, while in high SNR region, selection gain becomes dominant.

![Figure 2: BER vs. transmit SNR for a PIXEL-based reconfigurable multi-antenna system using STS-5 code; 1 bit/sec/Hz using BPSK.](image)

![Figure 3: BER vs. transmit SNR for an ideal reconfigurable multi-antenna system; 1 bit/sec/Hz using BPSK.](image)

VII. CONCLUSION

In this paper, we proposed a novel MIMO wireless communication system employing reconfigurable PIXEL antennas at the receiver. In particular, we studied state-selection and showed both analytically and by simulations, that a combination of STS-BC and state-selection scheme is able to achieve maximum diversity gains as well as additional selection gains compared to state-switching. Thus, the best scheme for reconfigurable receive antennas is to use STS-BC codes in combination with selecting the best state and keeping the channel propagation state fixed for the duration of the STS-BC codeword. Note that using an STS-BC with a larger period results in higher coding gains and therefore improved performance but at the same time results in higher decoding complexity and delay. Furthermore, simulation results suggest that at low SNR, coding gain is a more dominant factor, while at high SNR, selection gain becomes dominant.

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