Space-Frequency Block Code for MIMO-OFDM Communication Systems with Reconfigurable Antennas

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Abstract—We propose a space-frequency (SF) block coding scheme for a multiple-input multiple-output (MIMO) orthogonal frequency-division multiplexing (OFDM) system using antennas with reconfigurable radiation patterns. In this system, each element of the antenna array at the transmitter side is assumed to be reconfigurable so that it can independently change the physical characteristics of its radiation pattern. The proposed block code is full rate and benefits from spatial, frequency, and reconfigurable radiation pattern state diversity over frequency-selective fading channels. We provide simulation results to demonstrate the performance of the proposed block coding technique and make comparisons with that of the previous SF coding schemes in MIMO-OFDM systems. The results indicate that the proposed code achieves higher diversity and coding gain compared to other available SF codes.

Index Terms—Frequency-selective fading channels, multiple-input multiple-output-orthogonal frequency-division multiplexing (MIMO-OFDM) systems, space-frequency (SF) coding, reconfigurable antennas.

I. INTRODUCTION

Reconfigurable antennas can be used in multiple-input multiple-output (MIMO) communication systems to increase the capacity and reliability of wireless links [1]–[5]. In a reconfigurable MIMO system, the characteristics of each antenna radiation pattern can be changed by placing switching devices such as Microelectromechanical Systems (MEMS), varactor diodes, or field-effect transistor (FET) within the antenna structure [6]–[8]. As a result, a system employing reconfigurable antennas is able to alter the propagation characteristics of the wireless channel into a form that leads to a better signal quality at the receiver. In fact, by using reconfigurable antennas and designing a proper code, we can achieve an additional diversity gain that can further improve the performance of wireless communication systems.

There are several works in the literature on designing efficient codes for reconfigurable MIMO systems in order to take advantage of the antenna reconfigurability. In [5], authors have proposed a MIMO system equipped with reconfigurable antennas at the receiver that can achieve a diversity order that equals to the product of the number of transmit antennas, the number of receive antennas and the number of reconfigurable states of the receive antennas. They have shown that this diversity gain is achievable only under certain channel propagation conditions and using an appropriate coding technique. Later on, in [9] authors extended the concept by using reconfigurable elements at both transmitter and receiver sides. In their work, they have introduced a state-switching transmission scheme, called space-time-state block coding (STS-BC), to further utilize the available diversity in the system over flat fading wireless channels. However, their coding scheme does not exploit the frequency diversity offered by the multipath propagation channels between each transmit and receive antenna pair.

To obtain frequency diversity in multipath environment, a space-frequency (SF) block code was first proposed by authors in [10], where they used the existing space-time (ST) coding concept and constructed the code in frequency domain. Later works [11]–[16] also used similar strategies to develop SF codes for MIMO-OFDM systems. However, the resulting SF codes achieved only spatial diversity, and they were not able to obtain both spatial and frequency diversities. To address this problem, a subcarrier grouping method has been proposed in [17] to further enhance the diversity gain while reducing the receiver complexity. In [13], a repetition mapping technique has been proposed that obtains full-diversity in frequency-selective fading channels. Although their proposed technique achieves full-diversity order, it does not guarantee full coding rate. Subsequently, a block coding technique that offers full-diversity and full coding rate was derived [19], [20]. However, the SF codes proposed in the above studies and other similar works on the topic are not able to exploit the state diversity available in reconfigurable multiple antenna systems.

In this paper, we propose a coding scheme for reconfigurable MIMO-OFDM systems that achieves multiple diversity gains, including, space, frequency, and state. Basically, the proposed scheme consists of a code that is sent over transmit antennas, OFDM tones, and radiation states. In order to obtain state diversity, we configure each transmit antenna element to independently switch its radiation pattern to a direction that can be selected according to different optimization criteria, e.g., to minimize the correlation among different radiation
states. We construct our proposed code based on the fundamental concept of rotated quasi-orthogonal space-time block codes (QOSTBC) \[21\]–\[23\]. By using the rotated QOSTBC, the proposed coding structure provides rate-one transmission (i.e., one symbol per frequency subcarrier per radiation state) and leads to a simpler Maximum Likelihood (ML) decoder. As the simulation results indicate, our proposed code outperforms the existing space-frequency codes substantially.

The rest of this paper is organized as follows. In Section II we introduce the channel and system model for a reconfigurable MIMO-OFDM system. In Section III we briefly discuss the code design for reconfigurable multiple antenna systems. Simulation results are presented in Section IV, and finally conclusions are drawn in Section V.

Notation: Throughout this paper, we use capital boldface letters for matrices, and lowercase boldface letters for vectors. \((\cdot)^T\) denotes transpose of a vector. \(\mathbb{C}\) stands for the set of complex valued numbers. Operator \(\text{diag}(a_1, a_2, \cdots, a_n)\) represents a diagonal \(n \times n\) matrix whose diagonal entries are \(a_1, a_2, \cdots, a_n\). \([\cdot]\) stands for the floor operation and \(\mathbf{I}_N\) represents the \(N \times N\) identity matrix. Operator \(\text{col}\{\cdot\}\) stacks up the matrices on top of each other.

II. CHANNEL AND SYSTEM MODELS FOR RECONFIGURABLE MIMO-OFDM SYSTEMS

Consider a MIMO-OFDM system with \(M_t\) reconfigurable elements at the transmitter where each of these elements is capable of electronically changing its radiation pattern and creating \(P\) different radiation states as shown in Fig. 1. In this system, we assume the receiver antenna array consist of \(M_r\) omni-directional elements with fixed radiation patterns. Moreover, we consider an \(N_c\)-tone OFDM modulation and frequency-selective fading channels with \(L\) independent propagation paths between each pair of transmit and receive antenna in each radiation state. The channel gains are quasi-static over one OFDM symbol interval. The channel impulse response between transmit antenna \(i\) and receive antenna \(j\) in the \(p\)-th radiation state can be modelled as

\[
h_{p}^{i,j}(\tau) = \sum_{l=0}^{L-1} \alpha_{p}^{i,j}(l) \delta(\tau - \tau_{l,p}),
\]

where \(\tau_{l,p}\) is the \(l\)-th path delay in the \(p\)-th radiation state, and \(\alpha_{p}^{i,j}(l)\) is the complex amplitude of the \(l\)-th path between the \(i\)-th reconfigurable transmit antenna and the \(j\)-th receive antenna in the \(p\)-th radiation state. The average total received power is normalized to one.

The frequency response of the channel at the \(n\)-th subcarrier between transmit antenna \(i\) and receive antenna \(j\) in the \(p\)-th radiation state is given by

\[
H_{p}^{i,j}(n) = \sum_{l=0}^{L-1} \alpha_{p}^{i,j}(l) e^{-j2\pi n\Delta f \tau_{l,p}},
\]

where \(\Delta f = 1/T_s\) is the subcarrier frequency spacing and \(T_s\) is the OFDM symbol duration. The space-frequency codeword transmitted during the \(p\)-th radiation state, \(\mathbf{C}_p \in \mathbb{C}^{M_t \times N_c}\), can be expressed as

\[
\mathbf{C}_p = \begin{bmatrix}
c_1(p) & c_1^2(p) & \cdots & c_1(N_c - 1) \\
c_2(p) & c_2^2(p) & \cdots & c_2(N_c - 1) \\
\vdots & \vdots & \ddots & \vdots \\
c_{M_t}(p) & c_{M_t}^2(p) & \cdots & c_{M_t}(N_c - 1)
\end{bmatrix},
\]

where \(c_i(n)\) denotes the data symbol transmitted by transmit antenna \(i\) on the \(n\)-th subcarrier during the \(p\)-th radiation state.

At the receiver, after cyclic prefix removal and FFT, the received frequency domain signal of the \(n\)-th subcarrier and \(p\)-th radiation state at the \(j\)-th receive antenna can be written as

\[
y_{p}(n) = \sqrt{\gamma M_t} H_{p}^{i,j}(n)c_{i}(n) + z_{p}(n),
\]

where \(H_{p}^{i,j}(n)\) is the frequency response of the channel at the \(n\)-th subcarrier between transmit antenna \(i\) and receive antenna \(j\) in the \(p\)-th radiation state as defined in \(2\), \(z_{p}(n)\) is the additive complex Gaussian noise with zero mean and unit variance at the \(n\)-th subcarrier, and \(\gamma\) is the received signal-to-noise ratio (SNR).

The received signal during the \(p\)-th radiation state \(y_{p} = [y_{p}^T(0) \ y_{p}^T(1) \ \cdots \ y_{p}^T(N_c - 1)]^T\) with \(y_{p}(n) = [y_{p}^1(n) \ y_{p}^2(n) \ \cdots \ y_{p}^{M_r}(n)]^T\), can be written as

\[
y_{p} = \sqrt{\gamma M_t} \mathbf{H}_p \mathbf{C}_p + \mathbf{z}_p,
\]

where

\[
\mathbf{H}_p = \text{diag}\{\mathbf{H}_p(0), \ \mathbf{H}_p(1), \ \cdots, \ \mathbf{H}_p(N_c - 1)\}
\]

is the channel matrix, \(\mathbf{c}_p = \text{vec} (\mathbf{C}_p)\) is the transmitted codeword, and \(\mathbf{z}_p \in \mathbb{C}^{N \times M_t} \times 1\) is the noise vector during the \(p\)-th radiation state. In \(6\), \(\mathbf{H}_p(n)\) is an \(M_r \times M_t\) channel matrix with entries defined in \(2\).

The SF codeword over all \(P\) radiation states can be represented as

\[
\mathbf{C} = [\mathbf{C}_1, \ \mathbf{C}_2, \ \cdots, \ \mathbf{C}_P],
\]

where \(\mathbf{C}_p\) is given in \(3\). The received signals over all radiation states is defined by \(\mathbf{y} = [y_1^T \ y_2^T \ \cdots \ y_P^T]^T \in \mathbb{C}^{PN \times M_t} \times 1\) and can be represented by

\[
\mathbf{y} = \sqrt{M_t} \mathbf{H}_c \mathbf{z},
\]

where \(\mathbf{c} = \text{vec}(\mathbf{C}), \ \mathbf{H} = \text{diag}\{\mathbf{H}_1, \ \mathbf{H}_2, \ \cdots, \ \mathbf{H}_P\} \in \mathbb{C}^{PN \times M_t} \times PN \times M_t\) is the overall channel matrix, and \(\mathbf{z} = [\mathbf{z}_1^T \ \mathbf{z}_2^T \ \cdots \ \mathbf{z}_P^T]^T \in \mathbb{C}^{PN \times M_t} \times 1\) is the noise vector.
III. SPACE-FREQUENCY CODE DESIGN FOR RECONFIGURABLE MIMO-OFDM SYSTEMS

In this section, we present our proposed coding scheme for a reconfigurable antenna system, where each transmit antenna can independently change its radiation pattern direction. In particular, we construct the code based on the principle of a quasi-orthogonal coding structure for an arbitrary number of transmit antennas and radiation pattern states. In each radiation state, we consider a coding strategy where the SF codeword is a concatenation of $G_m^p$ as follows:

$$C_p = \{G_1^p G_2^p \cdots G_M^p \odot_N 0_{N_c-ML_i}\}, \quad (9)$$

where $M = \lfloor \frac{N_c}{LM_i} \rfloor$ and $0_N$ is the all-zeros $N \times N$ matrix. In this expression, $0_N$ will disappear if $N_c$ is an integer multiple of $LM_i$. In this work, for simplicity, we assume $N_c = LM_i q$, for some integer $q$. Each $G_m^p$ matrix, $m \in \{1, 2, \cdots, M\}$, takes the following form:

$$G_m^p = \text{col}\{X_1, X_2, \cdots, X_L\}, \quad (10)$$

where $X_t$ is the $M_t \times M_t$ block coding matrix which is equivalent to an Alamouti code structure for $M_t = 2$. To maintain simplicity in our presentation, we design the code for $M_t = 2$ transmit antennas, however, extension to $M_t > 2$ is possible by following the similar procedure. In the case of having two transmit antennas, $X_t = A(x_1, x_2)$, where

$$A(x_1, x_2) = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix}, \quad (11)$$

and therefore $G_m^p$ can be expressed as

$$G_m^p = \begin{bmatrix} A(S_{2(p-1)L+1}^m, S_{2(p-1)L+2}^m) \\ A(S_{2(p-1)L+3}^m, S_{2(p-1)L+4}^m) \\ \vdots \\ A(S_{2L-1}^m, S_{2L}^m) \end{bmatrix}. \quad (12)$$

In (12), $S_1^m$ is a set of combined symbols, computed as

$$[S_1^m \ S_2^m \ \cdots \ S_{2L-1}^m]^T = \Theta [s_1^m \ s_2^m \ \cdots \ s_{2L-1}^m]^T,$$

$$[S_1^m \ S_2^m \ \cdots \ S_{2L}^m]^T = \Theta [s_1^m \ s_2^m \ \cdots \ s_{2L}^m]^T, \quad (13)$$

where $\{s_1^m, \ldots, s_{2L}^m\}$ is a block of symbols belonging to a constellation $A$, $\Theta = U \times \text{diag}\{1, e^{j\theta_1}, \ldots, e^{j\theta_{2L-1}}\}$ and $U$ is a $PL \times PL$ Hadamard matrix. The $\theta_i$'s are the rotation angles. Different optimization strategies can be used to find the optimal values of rotation angles $\theta_i$'s, such that they maximize the coding gain. The objective function in this optimization is defined as the minimum Euclidean distance between constellation points.

As an example, consider a reconfigurable MIMO-OFDM system with $M_t = 2$ transmit antennas, $P = 2$ radiation states, and $L = 2$ multipaths. In this scenario, the transmitted codewords $C_1$ and $C_2$ given in (14) are constructed according to

$$C_1 = \frac{1}{4} \begin{bmatrix} \mathbf{S}_1^1 \ -\mathbf{S}_2^1 \ \mathbf{S}_3^1 \ -\mathbf{S}_4^1 \ \cdots \ \mathbf{S}_1^M \ -\mathbf{S}_2^M \ \mathbf{S}_3^M \ -\mathbf{S}_4^M \end{bmatrix},$$

$$C_2 = \frac{1}{4} \begin{bmatrix} \mathbf{S}_1^1 \ -\mathbf{S}_6^1 \ \mathbf{S}_7^1 \ -\mathbf{S}_8^1 \ \cdots \ \mathbf{S}_1^M \ -\mathbf{S}_6^M \ \mathbf{S}_7^M \ -\mathbf{S}_8^M \end{bmatrix}. \quad (14)$$

Fig. 1. Block diagram of a Reconfigurable MIMO-OFDM system employing reconfigurable antennas at the transmitter.
to (9). The entries of $C_p$ are computed using (13). As a result, we obtain $C_T^1$ as

\[
\begin{bmatrix}
    s_1 + s_1^* - s_5 - s_7^* & s_2 + s_4^* + s_6 + s_8 \\
    -s_2 - s_3 + s_5^* - s_6 & s_1^* + s_3^* + s_5^* + s_4 \\
    s_1 - s_3 + s_4^* - s_7^* & s_2 - s_4 + s_6 - s_5^* \\
    -s_2^* + s_4^* - s_6 + s_8^* & s_1^* - s_3^* + s_5^* - s_7^*
\end{bmatrix}
\]

and $C_T^2$ as

\[
\begin{bmatrix}
    s_1^* + s_1 - s_5^* - s_7 & s_2^* + s_4 + s_6 - s_8 \\
    -s_2^* - s_3 - s_5^* + s_7^* & s_1^* + s_3^* - s_5^* - s_7^* \\
    s_1^* - s_3^* - s_4 + s_7^* & s_2^* - s_4^* + s_6^* - s_5^* \\
    -s_2^* + s_4^* + s_6^* - s_8^* & s_1^* - s_3^* + s_5^* + s_7^*
\end{bmatrix}
\]

where $s_i = e^{j \theta_i} s_i$, $\tilde{s}_i = e^{j \theta_i} s_i$, and $\hat{s}_i = e^{j \theta_i} s_i$. Note that the above codeword provides rate-one transmission (i.e., one symbol per OFDM tone per radiation state).

IV. SIMULATION RESULTS

In this section, we present simulation results for both conventional and reconfigurable MIMO-OFDM systems. The reconfigurable multiple antenna system employs antenna elements capable of dynamically changing their radiation pattern directions at the transmitter, where in this work, we consider that each element has $P = 2$ radiation states. The conventional MIMO-OFDM system uses omni-directional antenna elements with fixed radiation pattern at both transmitter and receiver ends. For both systems, we consider $M_t = 2$ antennas at the transmitter and $M_r = 1$ antenna at the receiver and an OFDM modulation technique with $N_c = 128$ subcarriers as well as a cyclic prefix equal to or longer than the maximum channel delay spread. In our simulations, we consider that the receiver has perfect channel state information. We also assume that the symbols are chosen from a BPSK constellation, leading to a spectral efficiency of 1 bit/sec/Hz if the cyclic prefix overhead is ignored. The average symbol power per transmit antenna is set to be $E_s = 1/2M_t$ and the noise variance is $\sigma_n^2 = 1/\gamma$. We carry out the simulations for a 2-ray equal power channel model for two different delay spreads. Furthermore, for a reconfigurable antenna system, we assume the same delay spread for both radiation states.

Fig. 2 shows the bit error rate (BER) performance of the proposed code in multipath propagation channels with a delay spread of $\tau = 5\mu s$. As shown in this figure, the proposed code outperforms those of [19] and [20]. In particular, at a bit error rate of $10^{-5}$, the performance improvement compared to [19] and [20] is nearly 7 and 6 dB, respectively. This performance improvement demonstrates the superiority of our proposed scheme which is due to the extra diversity gain offered by the use of reconfigurable antenna elements.

V. CONCLUSIONS

We proposed a space-frequency coding technique for MIMO-OFDM systems using antennas with reconfigurable radiation patterns. The proposed code is constructed based on the principle of quasi-orthogonal coding scheme and consists of a block of transmitted symbols expanding over space, frequency, and radiation state dimensions. We provided simulation results to demonstrate the performance of the proposed...
coding scheme and make comparisons with that of the previous SF coding schemes. In these experiments, it has been shown that the proposed code provides additional diversity and coding gains compared to the previously designed SF codes in MIMO-OFDM systems.

REFERENCES

[1] B. Cetiner, E. Akay, E. Sengul, and E. Ayanoglu, “A MIMO system with multifunctional reconfigurable antennas,” IEEE Antennas Wireless Propag. Lett., vol. 5, pp. 463–466, 2006.

[2] D. Piazza, N. Kirsch, A. Forenza, R. Heath, and K. Dandekar, “Design and evaluation of a reconfigurable antenna array for MIMO systems,” IEEE Trans. Antennas Propagat., vol. 56, pp. 869–881, Mar. 2008.

[3] J. Frigon, C. Caloz, and Y. Zhao, “Dynamic radiation pattern diversity (DRPD) MIMO using CRLH leaky-wave antennas,” in Proc. IEEE Radio and Wireless Symp., 2008, pp. 635–638.

[4] X. Li and J. Frigon, “Capacity analysis of MIMO systems with dynamic radiation pattern diversity,” in Proc. IEEE VTC Spring 2009, 2009, pp. 1–5.

[5] A. Grau, H. Jafarkhani, and F. De Flaviis, “A reconfigurable multiple-input multiple-output communication system,” IEEE Trans. on Wireless Commun., vol. 7, pp. 1719–1733, May 2008.

[6] W. Weedon, W. Payne, and G. Rebeiz, “MEMS-switched reconfigurable antennas,” in Antennas and Propagation Society International Symposium, 2001. IEEE, vol. 3, 2001, pp. 654–657.

[7] C. Caloz and T. Itoh, Electromagnetic metamaterials: transmission line theory and microwave applications. Wiley-IEEE Press, 2005.

[8] C. won Jung, M.-j. Lee, G. Li, and F. De Flaviis, “Reconfigurable scan-beam single-arm spiral antenna integrated with RF-MEMS switches,” IEEE Trans. Antennas Propagat., vol. 54, pp. 455–463, Feb. 2006.

[9] F. Fazel, A. Grau, H. Jafarkhani, and F. De Flaviis, “Space-time-state block coded MIMO communication systems using reconfigurable antennas,” IEEE Trans. on Wireless Commun., vol. 8, pp. 6019–6029, Dec. 2009.

[10] R. S. Blum, Y. G. Li, J. H. Winters, and Q. Yan, “Improved space-time coding for MIMO-OFDM wireless communications,” IEEE Trans. Commun., vol. 49, pp. 1873–1878, Nov. 2001.

[11] Z. Hong and B. L. Hughes, “Robust space-time codes for broadband OFDM systems,” in Proc. IEEE Wireless Commun. Networking Conf. (WCNC), vol. 1, 2002, pp. 105–108.

[12] K. F. Lee and D. B. Williams, “A space-frequency transmitter diversity technique for OFDM systems,” in Proc. IEEE Global Commun. Conf. (GLOBECOM), vol. 2, Nov. 2000, pp. 1000–1004.

[13] F. Fazel and H. Jafarkhani, “Quasi-orthogonal space-frequency and space-time-frequency block codes for MIMO OFDM channels,” IEEE Trans. on Wireless Commun., vol. 7, pp. 184–192, Jan. 2008.

[14] N. Sharma and C. B. Papadias, “Improved quasi-orthogonal codes through constellation rotation,” in Finnish Wireless Commun. Workshop (FWWC), Oct. 2001, pp. 59–60.

[15] W. Su, Z. Safar, M. Olfat, and K. R. Liu, “Obtaining full-diversity space-frequency codes from space-time codes via mapping,” IEEE Trans. Signal Process., vol. 51, no. 11, pp. 2905–2916, Nov. 2003.

[16] W. Su, Z. Safar, and K. R. Liu, “Full-rate full-diversity space-frequency codes with optimum coding advantage,” IEEE Trans. Inf. Theory, vol. 51, pp. 229–249, Jan. 2005.

[17] W. Su and X.-G. Xia, “Signal constellations for quasi-orthogonal space-time block codes with full diversity,” IEEE Trans. Inf. Theory, vol. 50, pp. 2331–2347, Oct. 2004.