High Rate Space-Time Codes for Millimeter-Wave Systems with Reconfigurable Antennas

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***Abstract*—In this paper, we propose a high-rate space-time block code (STBC) for millimeter-wave wireless communication systems that are equipped with reconfigurable multiple-input multiple-output (MIMO) antennas. We assume that each reconfigurable antenna element has the capability of forming its beam and can independently change the characteristics of its radiation pattern[1]. We exploit this feature of the antenna elements to construct the proposed space-time block code where each coded symbol is sent over independent beams. As a result, the received coded symbols at different receive antennas will have different power levels, a desired property that can be used in data detection. We show that the proposed code achieves a coding rate of two and requires a low-complexity maximum likelihood (ML) detector. We carry out computer simulations that demonstrate the performance of the proposed code and shows its superiority in compared to previous rate-2 STBC counterparts. We also comment on the generalization of the proposed STBC for higher MIMO dimensions.**

***Index Terms*—Multiple-input multiple-output (MIMO), reconfigurable antennas, space-time block coding.**

I. Introduction

The millimeter-wave (mmWave) technology operating at frequencies in the 30 and 300 GHz range is considered as a potential solution for the 5th generation (5G) wireless communication systems to support multiple Gigabits per second data rates [3], [4]. The large communication bandwidth available at mmWave frequencies allows users to transmit more data at a given time compared with microwave-band wireless systems with stringent bandwidth, where the communication spectrum of each user is about a few MHz or less. Large propagation path loss is, however, the main drawback of the signal transmission in the mmWave band that can adversely affect the bit-error-rate (BER) performance of the system and reduce the coverage areas of the transmitted signal [5]. One remedy to this problem is to use reconfigurable antennas. Such antennas can adjust their radiation pattern characteristics, such as shape, beamwidth, direction, or polarization, in response to real-time system requirements or environmental conditions. There are several works in the literature on performance analysis of MIMO systems employing reconfigurable antennas at low microwave frequency bands [6]–[11].

From the physical layer perspective, if reconfigurable antennas are used in mmWave systems, new signal processing algorithms need to be designed to benefit from the antennas capabilities. Essentially, the previous microwave-band signal processing algorithms which are developed based on the assumption of omni-directional signal propagation and rich scatterer environment may not remain optimal for mmWave systems [12]. This can be attributed to the propagation characteristics of the signal that are particular to the mmWave band, which are quite different than those encountered in the microwave band [13]. At the mmWave frequencies, multipath is insignificant, while attenuation from atmospheric precipitation is more important [14].

The space-time block codes (STBCs) is one of the key building blocks of wireless communication systems that their performance will be impacted by signal propagation behavior in mmWave systems. The STBCs have been designed based on the well accepted notion that the transceiver is equipped with omni-directional antennas, while in the mmWave systems, the radiation pattern of the antennas need to be directive to compensate for the large path loss at mmWave frequencies. Therefore, the STBCs designed for conventional MIMO systems ignore the antenna gain and directivity in the mmWave systems. Naturally, a more effective STBC design approach should exploit the directive radiation pattern of the antennas utilized in mmWave systems.

In this paper, we propose a high-rate space-time block code for a 2×2 MIMO system equipped with reconfigurable antenna elements. The proposed code uses the properties of the reconfigurable antennas to enhance the coding rate, while reducing the computation complexity of the receiver. In particular, we design a STBC code based on the rotated quasi-orthogonal coding principles [15]–[18]. At each time slot, the system transmits multiple rotated symbols each intended for a particular desired direction and receive antenna. The deployment of reconfigurable antennas at the transmitter enables the system to amplify the transmitted signal towards the desired receive antenna, while placing nulls towards the remaining directions [19]. By using this mechanism, the system suppresses the interference from the undesired beams at the receiver. This is feasible if the antenna elements at the transmitter and

[1]Composite right-left handed (CRLH) leaky-wave antenna (LWA) is an example of reconfigurable antennas with such characteristics [1], [2].

receiver sides are separated sufficiently. For example, the optimal antenna spacing for a uniformly spaced 2×2 LoS MIMO system operating at 60 GHz with a transmitter-receiver distance of 10m to 30m is 16cm to 27cm on both sides, respectively [20]. For such a 2×2 MIMO system, we show that the proposed code achieves a coding rate of *two*. We also demonstrate that the decoding complexity of ML detection can be reduced to $\mathcal{O}(M^2)$ from $\mathcal{O}(M^4)$, where M is the cardinality of the signal constellation.

For comparison purposes, we study the performance of the recent rate-2 STBCs, including the *Matrix C* [21] and *maximum transmit diversity (MTD)* [22] codes, under the same system settings. The Matrix C code is a threaded algebraic space-time code [23], which is known to be one of the efficient STBCs of size 2×2. However, this code has a high decoding complexity which grows with the fourth power of the modulation order for maximum likelihood (ML) decoding. In [22], the authors proposed a high-rate STBC, referred to as MTD code, designed based on the linear combination of two Alamouti codes. The MTD code has lower ML complexity compared to Matrix C. However, the MTD code only designed for systems with omni-directional radiation pattern antennas and restricted to MIMO systems with two transmit antennas. Our proposed code, however, can be generalized to systems with more than two antennas and are designed to exploit the directivity of the reconfigurable antennas in mmWave systems. Our computer simulations demonstrate the performance of the proposed code and shows its superiority in compared to previous rate-2 STBC counterparts.

The rest of this paper is organized as follows. In Section II, we describe the system and signal model. In Section III, we introduce the proposed high-rate STBC for 2×2 MIMO systems and present a low complexity ML decoder for the proposed STBC. Simulation results are presented in Section IV, and concluding remarks are appeared in Section V.

Notation: Throughout this paper, we use capital boldface letters, $\mathbf{X}$, for matrices and lowercase boldface letters, $\mathbf{x}$, for vectors. $(\cdot)^T$ denotes transpose operator. $\mathbf{A} \circ \mathbf{B}$ denotes the Hadamard product of the matrices $\mathbf{A}$ and $\mathbf{B}$ and $||\mathbf{A}||_F$ represents the Frobenius norm of the matrix $\mathbf{A}$. Moreover, $\text{diag}(a_1, a_2, \cdots, a_n)$ represents a diagonal $n \times n$ matrix whose diagonal entries are $a_1, a_2, \cdots, a_n$. Finally, $\mathbb{C}$ denotes the set of complex valued numbers.

II. System Model and Definitions

We consider a single-user mmWave system with N_t and N_r transmit and receive antennas, respectively, where the transmitter is equipped with directive reconfigurable antennas to overcome the signal power degradation due to high pathloss in mmWave systems. We assume that the channels are quasi-static and flat fading and the channel coefficients remain constant over the duration of one codeword.

The proposed space-time block code, $\mathbf{C} \in \mathbb{C}^{N_t \times T}$, can be expressed as

$$\mathbf{C} \triangleq [\mathbf{c}_1, \mathbf{c}_2, \cdots, \mathbf{c}_T], \tag{1}$$

where T is the number of time slots and $\mathbf{c}_t \triangleq [c_1(t), c_2(t), \cdots, c_{N_t}(t)]^T \in \mathbb{C}^{N_t \times 1}$ is transmitted codeword from N_t antennas during the t-th time slot. The index j in $c_j(t)$ refers to the j-th transmit antenna. The received signal over T time slots is represented by $\mathbf{Y} \in \mathbb{C}^{N_r \times T}$ and can be given as

$$\mathbf{Y} = \mathbf{H}_g(\phi)\boldsymbol{\mathcal{C}} + \mathbf{Z}, \tag{2}$$

where

$$\boldsymbol{\mathcal{C}} \triangleq \text{diag}\{\mathbf{c}_1, \mathbf{c}_2, \cdots, \mathbf{c}_T\}, \tag{3}$$

and $\mathbf{H}_g(\phi) \triangleq \left[\mathbf{H}_g(1, \phi), \cdots, \mathbf{H}_g(T, \phi)\right] \in \mathbb{C}^{N_r \times TN_t}$ is the channel matrix and $\mathbf{Z} \in \mathbb{C}^{N_r \times T}$ is a zero-mean complex white Gaussian noise matrix consisting of statistically independent components of identical power N_0. The entries of $\mathbf{H}_g(\phi)$ can be computed as the Hadamard product of the independent and identically distributed (i.i.d.) Rayleigh channel matrix, $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$, and the antenna gain matrix, $\mathbf{G}(t, \phi) \in \mathbb{C}^{N_r \times N_t}$, i.e.,

$$\mathbf{H}_g(t, \phi) = \mathbf{H} \circ \mathbf{G}(t, \phi). \tag{4}$$

where $\mathbf{H} \triangleq \left[\mathbf{h}_1, \cdots, \mathbf{h}_{N_t}\right]$ with $\mathbf{h}_j \triangleq [h_{1,j}, \cdots, h_{N_r,j}]^T$ and $\mathbf{G}(t, \phi) \triangleq \left[\mathbf{g}_1(\phi_{1,t}), \mathbf{g}_2(\phi_{2,t}), \cdots, \mathbf{g}_{N_t}(\phi_{N_t,t})\right]$ with $\mathbf{g}_j(\phi_{j,t}) \triangleq [g_{1,j}(\phi_{j,t}), g_{2,j}(\phi_{j,t}), \cdots, g_{N_r,j}(\phi_{j,t})]^T$.

Definition 1:(**Transmission rate**) If N_s information symbols in a codeword are transmitted over T channel use, the transmission symbol rate is defined as

$$r_s = \frac{N_s}{T}, \tag{5}$$

and the bit rate per channel use is then given by

$$r_b = r_s \log_2 M, \tag{6}$$

where M is the cardinality of the signal constellation. Note that a STBC is said to be full-rate when the number of transmitted symbols per channel use (pcu) is equal to the number of transmit antennas, i.e., when $r_s = N_t$ [22].

Definition 2:(**Maximum likelihood decoding complexity**) The maximum likelihood (ML) decoding metric that is to be minimized over all possible values of codeword $\mathbf{C}$ is given by

$$\hat{\boldsymbol{\mathcal{C}}} = \arg\min_{\mathbf{C}} ||\mathbf{Y} - \mathbf{H}_g\boldsymbol{\mathcal{C}}||_F^2. \tag{7}$$

If we assume that there are N_s symbols to be transmitted in each codeword, then the ML decoder complexity will be M^{N_s} for joint data detection. As we will show in sequel, we can reduce the ML complexity to $M^{N_s/2}$ due the proposed code structure.

III. Proposed 2×2 STBC Design

To simplify the presentation, we consider a 2×2 MIMO system. We take the information symbols $\{s_1, s_2, s_3, s_4\}$ to construct a 2×2 matrix code that is transmitted during $T = 2$ time slots from $N_t = 2$ transmit antennas. The proposed STBC is built based on the principles of rotated quasi-orthogonal codes, where half of the transmitted symbols are chosen from a signal constellation set $\mathcal{A}$ and the other half are chosen from a rotated constellation set $e^{j\theta_1}\mathcal{A}$ with the rotation angle of θ_1 [15]–[17]. The rotation angle is chosen to ensure that every constellation point is uniquely distinguishable and to maximize the coding gain. For $N_t = 2$ transmit antennas, the proposed codeword $\mathbf{C}$ in (1) is given by

$$\begin{bmatrix} c_1(1) & c_2(1) \\ c_1(2) & c_2(2) \end{bmatrix}^T = \Theta \begin{bmatrix} s_1 & s_3 \\ s_2 & s_4 \end{bmatrix}, \tag{8}$$

where $\Theta = \mathbf{U}_2 \times \mathrm{diag}\{1, e^{j\theta_1}\}$ and $\mathbf{U}_2$ is an 2×2 Hadamard matrix. Hence, we can rewrite (8) as

$$\begin{bmatrix} c_1(1) & c_1(2) \\ c_2(1) & c_2(2) \end{bmatrix} = \begin{bmatrix} s_1 + e^{j\theta_1}s_2 & s_1 - e^{j\theta_1}s_2 \\ s_3 + e^{j\theta_1}s_4 & s_3 - e^{j\theta_1}s_4 \end{bmatrix}. \tag{9}$$

In this representation, θ_1 denotes the rotation angle, which can be selected based on different optimization criteria. For example, it can be chosen such that the diversity or the coding gain of the proposed STBC is maximized.

Remark 1: *The proposed code can be extended for more than two transmit antennas. For example, a 4×4 block code can be constructed for transmission of 16 symbols using 4 transmit reconfigurable antennas during 4 time slots. The number of receive antenna required in this case will be 4.*

To proceed further, let us explain the function of reconfigurable antenna elements during the signal transmission. One of the requirements in mmWave wireless system is to use highly focused "pencil beam" antennas [24] to compensate the large pathloss at mmWave frequencies. Reconfigurable antennas with highly directive beams can be used to serve this purpose. To model the antenna radiation pattern, we consider a rectangular function as a proper abstraction to capture the direction steerability and beamwidth characteristics of the antenna [25]. Using this model, the directive antenna gain between the j-th transmit antenna and the i-th receive antenna, $g_{i,j}(\phi_j, t)$, can be given by

$$g_{i,j}(\phi_{j,t}) = \begin{cases} \sqrt{\frac{2\pi}{B_{3dB}}}, & \phi^p_{j,t} - \frac{B_{3dB}}{2} \le \phi_{j,t} < \phi^p_{j,t} + \frac{B_{3dB}}{2} \\ g_c, & \text{otherwise} \end{cases} \tag{10}$$

where $\phi^p_{j,t}$ is the j-th transmit antenna pointing angle during the t-th time slot transmission, B_{3dB} is the 3-dB antenna beamwidth and g_c is the antenna sidelobe level. Note that the pointing angle $\phi^p_{j,t}$ can be estimated using a single reconfigurable antenna [26]. Considering the radiation pattern (10), we illustrate in Fig. 1 how the transmitted signals will arrive at the receiver during the first time slot ($t = 1$). For more clarity, we present these signals by equations (11)-(14) where $y_i(t)$ denote the received signal at antenna i during time slot t. In these equations, $h_{i,j}$ is the channel fading coefficient between the j-th transmit and the i-th receive antenna, $g_{i,j}(\phi_{j,t})$ is the antenna gain at the receive antenna i from the transmit antenna j during the t-th time slot, and $z_i(t)$ is the additive Gaussian noise with zero-mean and variance N_0. $h_{i,j}$'s are modeled as independent identical distributed (i.i.d.) complex Gaussian variables with zero-mean and unit variance.

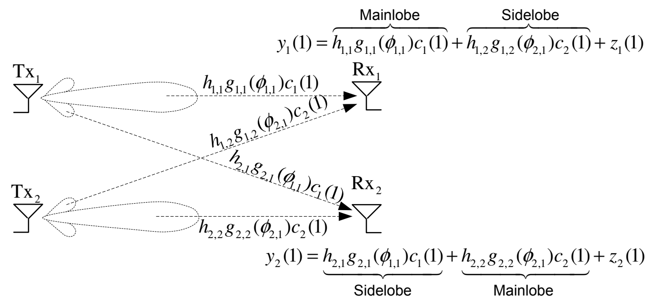

Fig. 1. The received signals at the first and second antennas during the first time slot ($t = 1$).

If highly directive reconfigurable antennas with low sidelobe levels, say about -20dB [27] are used, the received signal from the sidelobe can be combined with the link noise to produce a single noise term. For example, the new noise term associated with the first receive antenna and the first time slot is given

$$\tilde{z}_1(1) = h_{1,2}\, g_{1,2}(\phi_{2,1})\, c_2(1) + z_1(1). \tag{15}$$

Similarly, we can express the other new noise terms and rewrite the received signal defined in (11)-(14) as

$$y_1(1) = h_{1,1}\, g_{1,1}(\phi_{1,1})\, (s_1 + e^{j\theta_1}s_2) + \tilde{z}_1(1), \tag{16}$$
$$y_2(1) = h_{2,2}\, g_{2,2}(\phi_{2,1})\, (s_3 + e^{j\theta_1}s_4) + \tilde{z}_2(1), \tag{17}$$
$$y_1(2) = h_{1,2}\, g_{1,2}(\phi_{2,2})\, (s_1 - e^{j\theta_1}s_2) + \tilde{z}_1(2), \tag{18}$$
$$y_2(2) = h_{2,1}\, g_{2,1}(\phi_{1,2})\, (s_3 - e^{j\theta_1}s_4) + \tilde{z}_2(2). \tag{19}$$

For decoding, consider the following two squared cost functions:

$$f_1(s_1, s_2) = |y_1(1) - h_{1,1}\, g_{1,1}(\phi_{1,1})\, (s_1 + e^{j\theta_1}s_2)|^2 + |y_1(2) - h_{1,2}\, g_{1,2}(\phi_{2,2})(s_1 - e^{j\theta_1}s_2)|^2, \tag{20}$$

$$f_2(s_3, s_4) = |y_2(1) - h_{2,2}\, g_{2,2}(\phi_{2,1})\, (s_3 + e^{j\theta_1}s_4)|^2 + |y_2(2) - h_{2,1}\, g_{2,1}(\phi_{1,2})\, (s_3 - e^{j\theta_1}s_4)|^2. \tag{21}$$

Assuming known channel coefficients and antenna gain at the receiver, the symbols $\{s_1, s_2, s_3, s_4\}$ can be jointly detected using an ML decoder as follows:

$$(\hat{s}_1, \hat{s}_2, \hat{s}_3, \hat{s}_4) = \underset{s_1,s_2,s_3,s_4}{\mathrm{argmin}} \big(f_1(s_1, s_2) + f_2(s_3, s_4)\big). \tag{22}$$

The computational complexity of the receiver in this case is $\mathcal{O}(M^4)$. However, considering the structure of the cost functions $f_1(s_1, s_2)$ and $f_2(s_3, s_4)$, we observe that the minimization problem (22) can be broken into two independent sub-minimization problems, because f_1 only depends on s_1 and s_2 and f_2 depends on s_3 and s_4, hence, we can write:

$$(\hat{s}_1, \hat{s}_2) = \underset{s_1,s_2}{\mathrm{argmin}}\, f_1(s_1, s_2), \tag{23}$$

$$y_1(1) = \overbrace{h_{1,1}\, g_{1,1}(\phi_{1,1})\,(s_1 + e^{j\theta_1} s_2)}^{\text{mainlobe}} + \underbrace{h_{1,2}\, g_{1,2}(\phi_{2,1})\,(s_3 + e^{j\theta_1} s_4)}_{\text{sidelobe}} + z_1(1), \tag{11}$$

$$y_2(1) = \overbrace{h_{2,1}\, g_{2,1}(\phi_{1,1})\,(s_1 + e^{j\theta_1} s_2)}^{\text{sidelobe}} + \underbrace{h_{2,2}\, g_{2,2}(\phi_{2,1})\,(s_3 + e^{j\theta_1} s_4)}_{\text{mainlobe}} + z_2(1), \tag{12}$$

$$y_1(2) = \overbrace{h_{1,2}\, g_{1,2}(\phi_{2,2})\,(s_1 - e^{j\theta_1} s_2)}^{\text{mainlobe}} + \underbrace{h_{1,1}\, g_{1,1}(\phi_{1,2})\,(s_3 - e^{j\theta_1} s_4)}_{\text{sidelobe}} + z_1(2), \tag{13}$$

$$y_2(2) = \overbrace{h_{2,2}\, g_{2,2}(\phi_{2,2})\,(s_1 - e^{j\theta_1} s_2)}^{\text{sidelobe}} + \underbrace{h_{2,1}\, g_{2,1}(\phi_{1,2})\,(s_3 - e^{j\theta_1} s_4)}_{\text{mainlobe}} + z_2(2). \tag{14}$$

and

$$(\hat{s}_3, \hat{s}_4) = \underset{s_3, s_4}{\operatorname{argmin}}\, f_2(s_3, s_4). \tag{24}$$

Therefore, instead of minimizing the cost function in (22) over all possible values of (s_1, s_2, s_3, s_4), one can simultaneously minimize the cost functions in (23) and (24) over (s_1, s_2) and (s_3, s_4), respectively.

Remark 2: *The ML decoding complexity of the proposed code is $\mathcal{O}(M^2)$ since only two symbols are jointly decoded at a time. Moreover, for this code the diversity order of 2 can be achieved in a 2×2 MIMO configuration, which is because of highly directive signal propagation in mmWave systems. Table I compares the ML decoding complexity and diversity order of the proposed code with those of Matrix C, MTD, Alamouti and V-BLAST schemes for a 2×2 MIMO system equipped with reconfigurable antenna elements. The complexity of the proposed code can be reduced to $\mathcal{O}(M)$ using a conditional ML decoding technique. This will be further investigated in our future works.*

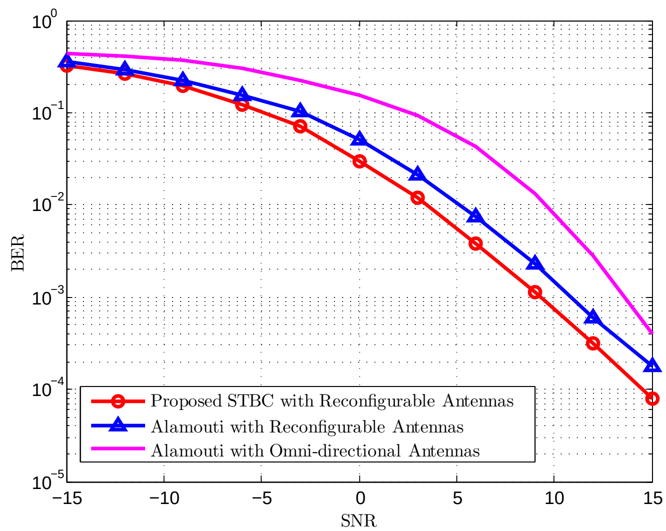

Fig. 2. Bit error rate performance of the proposed STBC with $N_r = 2$ and spectral efficiency of 4 bits pcu in Rayleigh fading channels.

IV. Simulation Results

In this section, we present our computer simulation results to verify the performance of the proposed STBC scheme. We compare the bit-error-rate (BER) performance of the proposed code with that of the Alamouti code. We also make some comparisons with that of the previous rate-2 STBC codes. In all experiments, we consider a 2×2 MIMO structure, where the antennas at the transmitter side are directive reconfigurable antennas with 3dB beamwidth of $B_{3dB} = 40°$ and sidelobe level of -17dB, unless otherwise indicated. The receive antennas are assumed to be omni-directional.

Fig. 2 compares the BER performance of the proposed STBC code with the Alamouti code. We implement the Alamouti code in two different ways. In the first implementation, we consider omni-directional antenna at both the transmitter and the receiver. In the second implementation, we use directive reconfigurable antenna at transmitter and omni-directional antenna at the receiver similar to the setting used for our proposed code. Fig. 2 shows the results for a spectral efficiency of 4 bits per channel use, i.e., we use QPSK modulation for our proposed code and 16QAM modulation for the Alamouti code. This follows from the fact that the proposed STBC achieves a rate of 2 symbols per time slot while the Alamouti codes achieve a rate of 1 symbol per time slot. Considering this setting the receiver in both cases receives equal amount of bits per channel use. As shown in this figure, the proposed code outperforms the Alamouti code with omni-directional and directive antennas. In particular, at a bit error rate of 10^{-3}, the performance improvement compared to the Alamouti coding scheme with omni-directional and directive antennas is nearly 4 and 3 dB, respectively.

It is observed form the results in Fig. 2 that the diversity order provided by the Alamouti code is higher than the proposed code, i.e., in high SNR the slop of the BER curve of the Alamouti code is larger than the proposed code. This is

TABLE I. Comparison of diversity order and ML decoding complexity of STBCs

Coding Scheme	Symbol rate (r_s)	Diversity order	ML decoding complexity
Proposed code	2	2	$\mathcal{O}(M^2)$
Matrix C [21]	2	2	$\mathcal{O}(M^4)$
MTD [22]	2	2	$\mathcal{O}(M^2)$
Alamouti [28]	1	2	$\mathcal{O}(M)$
V-BLAST [29]	2	1	$\mathcal{O}(M^2)$

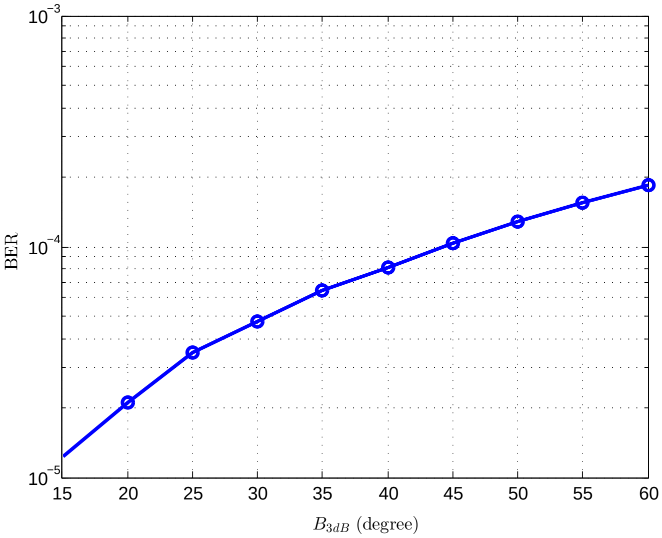

Fig. 3. Bit error rate performance versus beamwidth for a reconfigurable MIMO system using the proposed STBC code with $N_r = 2$ and spectral efficiency of 4 bits pcu in Rayleigh fading channels.

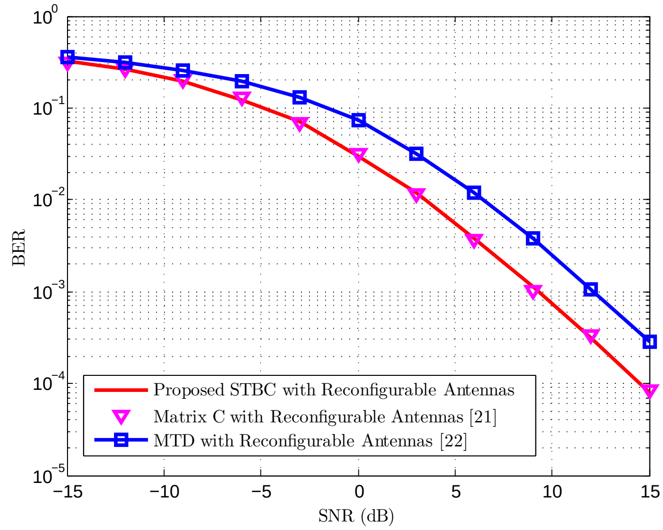

Fig. 4. Bit error rate performance of the proposed STBC code with $N_r = 2$ and spectral efficiency of 4 bits pcu in Rayleigh fading channels.

because, the diversity order of the Alamouti code is 4 while the diversity order of the proposed code is 2. However, this is insignificant because in practice the system will operate in low to medium SNR regions where the proposed code outperforms the Alamouti code.

Fig. 3 shows the BER performance of the proposed code against the antenna beamwidth at SNR of 15dB. As it is expected, the BER performance of the system deteriorates as the antenna beamwidth become larger. For mmWave systems, the use of directive antennas with beamwidth of 7.8° has been reported by now [30]. As shown in this figure, for this range of beamwidth the system can achieve a BER value close to 10^{-5}.

In Fig. 4, we compare the BER performance of the proposed STBC code with that of the *Matrix C* and *MTD* codes presented in [21] and [22], respectively. It is clear from these results that the proposed code outperforms *MTD* code over all SNR values. Moreover, the proposed code obtains an identical performance as *Matrix C* code. Nevertheless, as shown in Table I, the the decoding complexity of the proposed code is $O(M^2)$ whereas that of the *Matrix C* code is $O(M^4)$. Note that for the fairness, we used a similar system settings for all these codes and the proposed code i.e., the antenna elements at the transmitter are directive reconfigurable and at the receiver are omni-directional ones.

V. Conclusions

We proposed a high rate space-time coding technique for mmWave MIMO systems employing antennas with reconfigurable radiation patterns. The proposed code is constructed based on the principle of quasi-orthogonal space-time coding scheme. We showed that ML decoding complexity of the proposed code can be reduced from $\mathcal{O}(M^4)$ to $\mathcal{O}(M^2)$, where M is the size of signal constellation used at the transmitter. We provided simulation results that demonstrated the performance of the proposed coding scheme and showed its superiority compared to that of recent rate-2 STBC schemes.

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