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Enhanced Transmit Antenna Selection Using OSTBC Scheme with SVD-Based Hybrid Precoding for 5G Millimeter-wave Communications

Taissir Y. Elganimi, Mohammed S. Alshawish
Electrical and Electronic Engineering Department
University of Tripoli
Tripoli, Libya
e-mail: {t.elganimi, m.alshawish}@uot.edu.ly

Moustafa M. Abdalla
Electrical and Electronic Engineering Department
Azzaytuna University
Tarhuna, Libya
e-mail: m.abdalla@ee.uot.edu.ly

***Abstract*—Transmit Antenna Selection using Orthogonal Space-Time Block Codes (TAS-OSTBC) aided Millimeter-wave (mmWave) communications is proposed in this paper. The TAS transmitter is characterized by a lower number of Radio Frequency (RF) chains than the number of transmit antennas, hence it is capable of reducing both the energy consumption as well as the transmitter cost. The proposed scheme combines TAS-OSTBC system with Hybrid Analog-Digital Beamforming for 60 GHz mmWave communications and using Hadamard transform. The computer simulation results demonstrate that the TAS-OSTBC scheme with fully digital SVD-based precoding has better Bit Error Rate (BER) performance than that of the conventional TAS system with OSTBC scheme. Furthermore, the error performance is significantly improved by applying Uniform Linear Array (ULA) antennas which improve the system performance as the number of array elements increases due to providing a beamforming gain. It is also found that the BER performance is further improved by applying Hadamard transform with an SNR improvement of about 3dB over the conventional systems without using Hadamard transform.**

Keywords-millimeter-wave; transmit antenna selection; analog beamforming; SVD-based hybrid precoding; Hadamard transform

I. INTRODUCTION

In Multiple-input Multiple-output (MIMO) systems, the data rate enhancement is normally associated with extra complexity, size and high cost in the system hardware design since a Radio Frequency (RF) chain is required to be connected to each antenna port. To circumvent this issue, a subset of antennas can be selected for transmission. Such technique is called Antenna Selection (AS) which can reduce the cost and attain many of the advantages of MIMO systems. Transmit Antenna Selection (TAS) is one of MIMO categories where a subset of the transmit antennas are activated for transmission, and retaining a full diversity benefits as if all the transmit antennas were in use [1]. The most well-known TAS scheme where an Orthogonal Space-Time Block Code (OSTBC) is used along with the optimal subset of transmit antennas has been proposed by Gore and Paulraj in [1]. A rapid development has been gained and a closer research attention has been paid for TAS systems since it was proposed. However, in order to exploit the benefits of TAS and OSTBC systems, both have been combined to improve the multiplexing gain and the diversity gain simultaneously, and to reduce the number of RF chains in order to reduce the transmitter cost [2]. In this system, OSTBC signal matrices are transmitted over a selected subset of transmit antennas, which is a practical technique for achieving a full diversity order. However, two transmit antennas out of total N_T antennas are selected for transmission [3, 4], and hence only two RF chains are required.

In the classic spatial multiplexing MIMO systems, the number of RF chains at the transmitter has to be equal to the number of transmit antennas. However, it is impractical to employ a full-digital precoding architecture with a dedicated RF chain for each antenna due to the high cost, the space restrictions and the high energy consumption. Nevertheless, hybrid analog-digital beamforming technique relying on both analog beamforming and digital precoding techniques was proposed in [5, 6]. A high number of antenna elements are divided into beamforming subarrays, and each beamformer is connected to a single RF chain. Therefore, hybrid beamforming technique is proposed to achieve the gain of a large number of antenna elements while consuming less energy by using lower number of RF chains than antennas.

Against this backcloth, the main contribution of this paper is that the Singular Value Decomposition (SVD)-based precoding is applied in TAS with OSTBC scheme, and the performance is evaluated in terms of the Bit Error Rate (BER). Also, the Analog Beamforming (ABF) is employed and combined with the fully digital SVD-based precoding into a hybrid precoding regime for the emerging 60 GHz Millimeter-wave (mmWave) communications that have a potential capability for achieving coverage improvement and reducing the number of RF chains in the Fifth Generation (5G) wireless systems. As well as imposing Hadamard criteria on the TAS-OSTBC systems with hybrid beamforming is considered in order to further improve the error performance.

To this end, the rest of this paper is organized as follows. In section II, the channel model is introduced and the system model of the proposed scheme is presented. Section III presents the way of applying both the fully digital SVD-based precoding and ABF, and combining both of them in the proposed scheme of TAS-OSTBC with Hybrid Analog-Digital Beamforming (HBF) and using Hadamard Transform. Simulation results of the BER performance and

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comparisons are demonstrated and discussed in section IV. Finally, the conclusion of this paper is provided in section V.

II. SYSTEM AND CHANNEL MODELS

The schematic of our TAS-OSTBC system with hybrid precoding and using Hadamard transform is shown in Fig. 1. In this scheme, there are only two RF chains and N_T transmit antennas, while a full-RF structure is required in the conventional spatial multiplexing scheme with N_T RF chains. However, TAS is the effective way where it can be made optimal in the sense of minimizing the error probability or maximizing the transmission rate. The former approach is adopted in this paper [7], where only two transmit antennas out of N_T antennas are selected and activated for the transmission of OSTBC signal matrices, and the other antennas are silent.

In this paper, the mmWave communications is considered with the mmWave MIMO channel that consists of N_T transmit antennas and N_R receive antennas. The quasi-static flat Rayleigh fading channel is assumed where ABF arrays are employed, and the Channel State Information (CSI) is perfectly available at the receiver.

In TAS system with Q antennas are used among N_T transmit antennas, the effective channel can be represented by Q columns of $H \in \mathbb{C}^{N_R \times N_T}$. Let p_i denote the index of the i-th selected column, $i = 1, 2, ..., Q$, then, the corresponding effective channel will be modeled by $N_R \times Q$ matrix, which is denoted by $H_{\{p_1,p_2,\dots,p_Q\}} \in \mathbb{C}^{N_R \times Q}$. Let $x \in \mathbb{C}^{Q \times 1}$ denote the space-time coded or spatially multiplexed stream that is mapped into Q selected antennas. Then, the received signal y is represented as [8]:

$$y = \sqrt{\frac{E_x}{Q}}\, H_{p_1,p_2,\dots,p_Q} x + n \tag{1}$$

where $n \in \mathbb{C}^{N_R \times 1}$ is the noise vector whose elements (noise samples) are independent zero mean circularly symmetric complex Gaussian random variables with variance $N_O/2$ per dimension ($N_O/2$ is the two-sided noise power spectral density). The factor $1/\sqrt{Q}$ assures that the available symbol energy E_x is shared among the Q active antennas [8].

III. SVD-BASED HYBRID PRECODING IN TAS WITH OSTBC SCHEME USING HADAMARD TRANSFORM

In this section, the fully digital SVD-based precoding technique and the criteria of generating ABF weights using Uniform Linear Array (ULA) antennas are reviewed. The receiver of the proposed scheme of TAS-OSTBC using Hadamard transform with hybrid precoding is also presented.

A. Fully Digital SVD-Based Precoding

The SVD of the channel matrix $H \in \mathbb{C}^{N_R \times N_T}$ is denoted as [6]:

$$H = USV^H \tag{2}$$

where $U \in \mathbb{C}^{N_R \times N_R}$ and $V \in \mathbb{C}^{N_T \times N_T}$ are orthogonal and unitary matrices, and V^H is the Hermitian transpose of V. The matrix $S \in \mathbb{C}^{N_R \times N_T}$ is a diagonal matrix where the largest singular values of H are on its diagonal. In other words, it is a real-valued diagonal matrix of the positive square roots of the eigenvalues of the matrix $H^H H$ sorted in descending order.

In the fully digital SVD-based precoding scheme with the digital precoder V at the transmitter and the digital combiner U^H at the receiver, the transmitted signal is multiplied by the precoder matrix V, and the received signal is multiplied by the matrix U^H. Moreover, in MIMO systems with the fully digital SVD-based precoding scheme, the digital precoder at the transmitter is designed in order to eliminate the inter-symbol interference, while the digital combiner at the receiver or the digital post-coder which is also called as receiver shaping is designed to successfully reconstruct the transmitted symbols.

In TAS systems with OSTBC scheme, two transmit antennas are selected to minimize the error probability and to reduce the number of RF chains. Then the effective channel $H_{SVD\{p_1,p_2\}}$ with SVD-based precoding scheme becomes with two columns of $H_{SVD} = U^H USV^H V = S$ chosen. In this case, the received signal equation of TAS-OSTBC systems utilizing the SVD-based precoding technique becomes as follows:

$$y = \sqrt{\frac{E_x}{2}} H_{SVD\{p_1,p_2\}} x + U^H n \tag{3}$$

B. Generation of ABF Weights

In this paper, the ABF is controlled based on the Angle of Departure (AoD) θ_{AoD} at the transmitter. More specifically, this paper adopts ULA antennas where the ABF weight w_{T_i} with L_T elements at each transmit antenna is modeled as follows [9]:

$$w_{T_i} = \frac{1}{\sqrt{L_T}}\left[1 \;\; e^{j\delta_T{}^{(i)}} \;\; e^{j2\delta_T{}^{(i)}} \;\; \dots\dots \; e^{j(L_T-1)\delta_T{}^{(i)}}\right]^T \tag{4}$$

where $\delta_T{}^{(i)}$ represents the electrical phase shift between each two antenna elements along the transmit antenna array that is expressed as $d.(2\pi/\lambda).\sin\left(\theta_{AoD}{}^{(i)}\right)$, and $\theta_{AoD}{}^{(i)}$ denotes the AoD towards the i-th ABF of the transmitter, λ is the transmission wavelength, and d is the antenna spacing between each two antenna elements in each ABF with the constraint of $d \leq \lambda/2$ in order to achieve a beneficial beamforming gain.

This ABF weight is known as the ABF weight vector with L_T complex conjugate coefficients at the transmitter, and this vector contains the information about all antenna elements and the Direction of Arrival (DoA) of the transmitted signals.

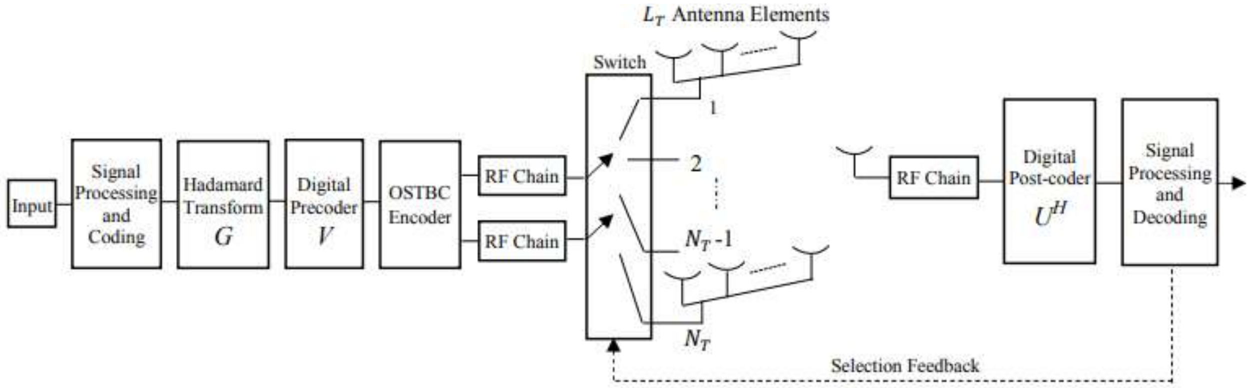

Figure 1. Block diagram of transmit antenna selection with OSTBC scheme aided mmWave MIMO with hybrid beamforming and Hadamard transform.

C. Hadamard Transform (HDT)

Hadamard transform is a square matrix whose rows are mutually orthogonal with entries of $+1$ s and -1 s. This means that each pair of rows in the Hadamard matrix has matching entries in exactly half of their columns and mismatched entries in the remaining columns, and each pair of rows represents two perpendicular vectors [10]. For instance, the Hadamard matrix of 2×2 order is expressed as follows [11]:

$$G = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{5}$$

D. SVD-Based Hybrid Precoding for TAS-OSTBC System Using Hadamard Transform

Combining hybrid precoding with TAS-OSTBC system can be obtained by employing ABF with the fully digital SVD-based precoding in TAS-OSTBC system with considering that the channel matrix is available at the transmitter. Therefore, the received signal of TAS-OSTBC with hybrid precoding includes the ABF weight vector and its Hermitian transpose operation is expressed as follows:

$$y = \sqrt{L_T} \sum_{i=0}^{L_T-1} \sqrt{\frac{E_x}{2}} {w_T}_i^{\,H} H_{SVD\{p_1,p_2\}} {w_T}_i x + U^H n \tag{6}$$

In TAS-OSTBC scheme with hybrid precoding, the received signal is normalized with the factor $1/\sqrt{L_T}$, and the effective channel matrix which is expressed as $\sqrt{L_T}\sum_{i=0}^{L_T-1} {w_T}_i^{\,H} H_{SVD\{p_1,p_2\}} {w_T}_i$ is taken into consideration in the linear processing and Maximum Likelihood (ML) detection at the receiver side where the symbols are decoded using the ML decision criteria described in [3].

In the case of imposing Hadamard matrix on TAS-OSTBC scheme with hybrid precoding, the effective channel matrix is expressed as $\sqrt{L_T}\sum_{i=0}^{L_T-1} {w_T}_i^{\,H} H_{SVD\{p_1,p_2\}} G {w_T}_i$, where $G = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ is the Hadamard matrix of 2×2 order due to activating only two transmit antennas in this system. Therefore, the received signal of this scheme is expressed as follows:

$$y = \sqrt{L_T} \sum_{i=0}^{L_T-1} \sqrt{\frac{E_x}{2}} {w_T}_i^{\,H} H_{SVD\{p_1,p_2\}} G {w_T}_i x + U^H n \tag{7}$$

IV. PERFORMANCE RESULTS AND COMPARISONS

To underline the benefits of the proposed scheme of applying the SVD-based hybrid precoding in the joint Hadamard transform and TAS-OSTBC system, the BER performance is evaluated in this section. Initially, the simulation results of the fully digital SVD-based precoding scheme for TAS-OSTBC system using Hadamard transform are presented. The error performance of employing ULA antennas at the transmitter of TAS-OSTBC systems is also given. Moreover, combining both ABF at the transmitter and the fully digital SVD-based precoding techniques into a hybrid beamforming regime in TAS-OSTBC systems is considered where the employment of omnidirectional antenna elements was assumed. As well as the effect of using Hadamard transform on the BER performance of these systems is evaluated. Throughout the simulation, the system model of all schemes is limited to 4-QAM technique only, and the corresponding transmission wavelength was $\lambda = 0.5\ cm$ when ABF is employed where a carrier frequency of $60\ GHz$ is considered. It is also assumed that the antenna array elements are separated by half the wavelength $\lambda/2$, and a flat Rayleigh fading channel is used with assuming that the impulse response is perfectly known at the transmitter.

A. Joint Hadamard Transform and TAS-OSTBC System with Fully Digital SVD-Based Precoding

The BER performance of TAS-OSTBC 4×1 scheme with SVD-based precoding is compared with the conventional TAS-OSTBC, Alamouti STBC 2×1 and SISO systems as shown in Fig. 2. It is obvious from this figure that the fully digital SVD-based precoded TAS-OSTBC system employing 4 -QAM (Quadrature Amplitude Modulation) technique with 4 transmit antennas and only 2 RF chains outperforms all the other schemes. This shows that there is a

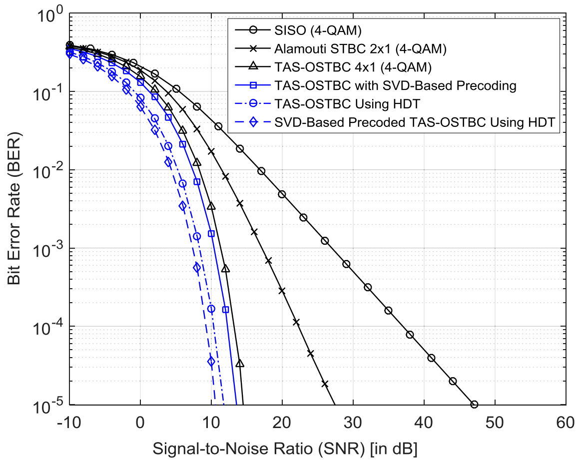

Figure 2. BER performance of TAS-OSTBC 4 × 1 scheme employing 4-QAM with fully digital SVD-based precoding and Hadamard transform.

diversity gain of almost 33 dB, 13 dB and 1 dB at the BER of 10^{-5} obtained from the fully digital SVD-based precoded TAS-OSTBC system as compared to SISO, Alamouti STBC 2×1 and the conventional TAS-OSTBC systems, respectively. As well as imposing Hadamard transform on TAS-OSTBC scheme and the fully digital SVD-based precoded TAS-OSTBC system improves the error performance by about 3 dB at the BER of 10^{-5}. This improvement is obtained because the new constellation points affect the real and imaginary values of the information signal. This is due to the use of Hadamard matrix of 2×2 order because of activating only 2 transmit antennas in these systems. Therefore, this SNR gain can be expressed as $10 \log n$, where n is the number of RF chains.

Fig. 3 depicts the TAS-OSTBC scheme with the fully digital SVD-based precoding employing 4, 8, 16 and 32 transmit antennas and 4-QAM technique. It can be clearly seen from this figure that there is a diversity gain achieved from increasing the number of transmit antennas, and a performance improvement obtained from employing SVD-based precoding in TAS-OSTBC systems. Thus, the fully digital SVD-based precoding scheme provides important SNR gains with respect to the conventional systems. This SNR improvement increases as the number of transmit antennas increases. For instance, it is clear that there is an SNR improvement of about 1 dB, 2.7 dB, 5 dB and 6.7 dB at the BER of 10^{-5} are obtained when 4, 8, 16 and 32 transmit antennas are employed, respectively.

B. *TAS-OSTBC Using Hadamard Transform with Analog Beamforming*

Fig. 4 compares the error performance of TAS-OSTBC aided mmWave MIMO with ABF, the TAS-OSTBC schemes using Hadamard transform and ABF, and the conventional TAS-OSTBC systems. It is clearly noticeable from these results that there is an SNR gain achieved from employing ABF, and it increases as the number of antenna array elements increases. For instance, a beamforming gains of about 3 dB, 4.7 dB, 6 dB, 9 dB and 12 dB are obtained by employing ABF at the transmitter with $L_T = 2, 3, 4, 8$ and 16 array elements over the conventional TAS-OSTBC scheme, respectively. This SNR gain can be expressed approximately as $10 \log L_T$ with respect to the conventional TAS-OSTBC system using single element antennas. Additionally, it is also noticeable that the SNR improvement obtained from imposing Hadamard transform on these schemes is about 3 dB in all cases because of activating only two transmit antennas.

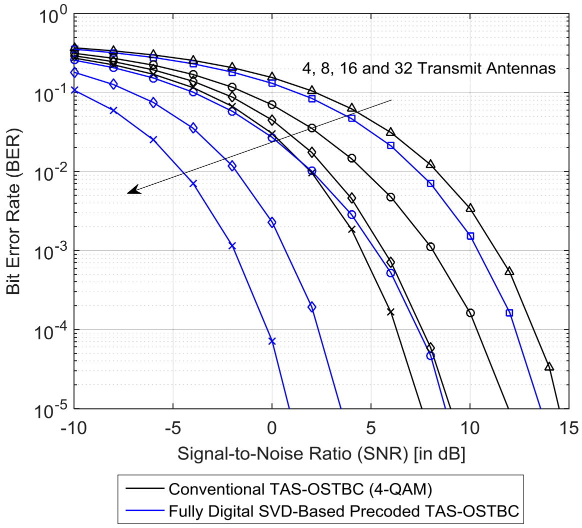

Figure 3. BER performance of TAS-OSTBC employing 4-QAM and 4, 8, 16 and 32 transmit antennas with fully digital SVD-based precoding.

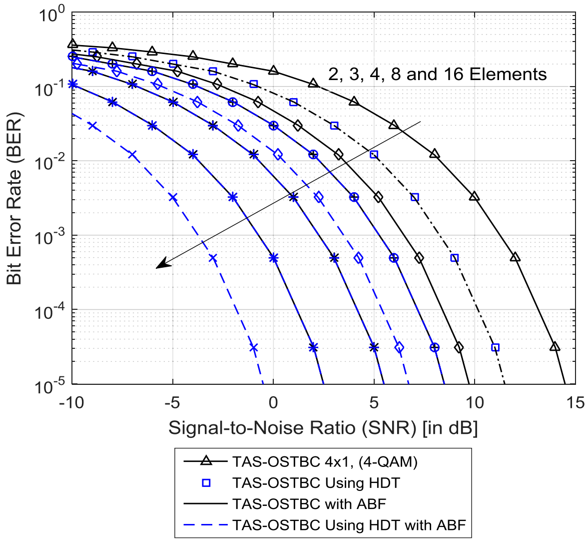

Figure 4. BER performance of TAS-OSTBC employing 4-QAM and 4 transmit antennas with analog beamforming and Hadamard transform.

C. *TAS-OSTBC Using Hadamard Transform with SVD-Based Hybrid Precoding*

Lastly, Fig 5 shows the error performance of joint Hadamard transform and TAS-OSTBC 4×1 scheme with

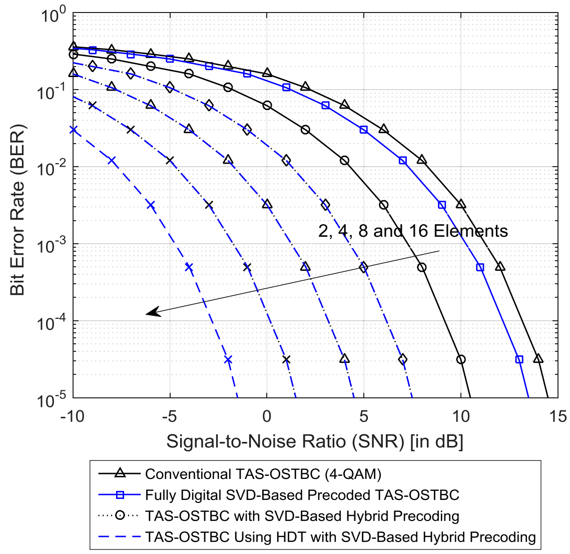

Figure 5. BER performance of SVD-based hybrid precoding in TAS-OSTBC using Hadamard transform employing 4-QAM and 4 transmit antennas.

SVD-based hybrid precoding. As expected, a performance improvement is observed as the number of array elements increases, and the SNR improvement that obtained by increasing the number of array elements over the conventional TAS-OSTBC system is more than the gain that obtained from employing only ABF at the transmitter. This is due to employing the fully digital SVD-based precoding which adds another diversity gain of about 1 dB in the case of $N_T = 4$ in addition to the ABF gain ($10 \log L_T$). Moreover, the BER performance is further enhanced with using Hadamard transform by about 3 dB in all schemes.

V. CONCLUSION

In this paper, employing both Hadamard transform and hybrid beamforming in TAS-OSTBC scheme are explored while it is clear that the benefits of the proposed techniques can be extended to larger scale systems and 5G mmWave communications with less number of RF chains and significant performance improvements. The proposed system benefits from the transmit diversity gain of OSTBC scheme, from the gain obtained due to using the fully digital SVD-based precoding, and from the SNR gain of both ABF and imposing Hadamard transform on these systems.

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