Improved Orthogonal Space-Time Block Codes with Multiple Transmit Antennas Using Hadamard Transform

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***Abstract*—In this paper, imposing the Hadamard Transform (HDT) on Orthogonal Space-Time Block Codes (OSTBC) schemes using multiple transmit antennas is proposed in order to increase the reliability and improve the error performance of wireless communications. It is referred to as joint Hadamard transform and OSTBC schemes with multiple transmit antennas. However, HDT is used to change the location of constellation points by converting the transmit symbols of OSTBC system, and hence extending the Euclidean distance between transmit symbols for a precise detection. Simulation results demonstrated that increasing the number of transmit antennas in OSTBC systems employing 8-PSK improves the Bit Error Rate (BER) performance as in the case of OSTBC 2×2 scheme where an SNR of about $13.5\ dB$ is required to achieve a BER of 10^{-6}, while only about $7\ dB$ in OSTBC 8×8 scheme is required to obtain the same error probability. It is also demonstrated that imposing the Hadamard criteria on the OSTBC 2×2, 4×4, and 8×8 schemes has showed a performance improvement of about $3\ dB$, $6\ dB$ and $9\ dB$, respectively, as compared to the conventional OSTBC systems.**

Keywords-OSTBC; MIMO; maximum likelihood; BER; SNR improvement; hadamard transform

I. INTRODUCTION

The major motivation in modern wireless communication systems such as the Fourth Generation (4G) and the Fifth Generation (5G) standards is the need to achieve high data rate at the user end. This motivates the development and study of Multiple-Input Multiple-Output (MIMO) systems and large-scale MIMO systems. However, conventional Single-Input Single-Output (SISO) transmission techniques focus on optimum wireless communication in frequency and time domain, where the main issue of these systems is using a single frequency and the time is being limited, and hence the latency and the bandwidth limitation are incurred in SISO wireless communication systems [1]. Moreover, it is shown in [2] that MIMO technology is considered as a solution to SISO's problem and used to improve the reliability and increase the capacity of the wireless communications, and to create spatial domain. In the conventional Spatial Multiplexing (SMX) systems which is one of MIMO techniques, the same transmitted symbols are transmitted simultaneously from all transmit antennas to increase the receiver gain by getting copies of the same information symbol, each of which is subjected to a different channel. Therefore, MIMO has been a promising technique for Long Term Evolution (LTE) and LTE-Advanced (LTE-A) that are developed by the Third Generation Partnership Project (3GPP) in order to achieve high data rates [3].

In wireless communication systems, determining the transmitted signal at the receiver is extremely difficult due to the attenuation in multipath wireless environment. Deploying multiple antennas is considered as the solution of this issue. However, due to the fact that the receivers are typically required to be small, receive diversity where multiple receive antennas are deployed at the remote station is impractical. Thus, it is motivated to consider transmit diversity.

Alamouti Space-Time Block Codes (STBC) scheme that proposed in [4] is a well-known MIMO technique that achieves full diversity, and presents the same diversity order of Maximal Ratio Receiver Combining (MRRC) [4]-[6]. It is an attractive approach of transmit diversity due to its simplicity of implementation and feasibility of having multiple antennas at the base station [7]. This promising paradigm has been studied extensively as a technique that is combating detrimental effects in wireless fading channels where it uses the theory of designing Orthogonal STBC (OSTBC) schemes with providing the maximum possible transmission rate allowed by the theory for real signal constellations designed by Tarokh in [5] besides achieving the full diversity. OSTBC schemes with multiple transmit antennas and the orthogonal transmission matrices that are presented in [5] were to design codes that provide full diversity by generalizing the theory of orthogonal designs. In these orthogonal schemes with $3, 4, 5, 6, 7$ and 8 transmit antennas, the full rate power is not attainable as proved in [5, Theorem 5.4.2] with the complex orthogonal design, and half of the full transmission rate is achieved for any number of antennas at the transmitter. Furthermore, Tarokh in his paper [5] has also proposed codes with $3/4$ of the full transmission rate with a different strategy in designing OSTBC schemes with three and four transmit antennas.

In [8], a novel method of joint Hadamard transform and Alamouti STBC scheme is proposed in order to enhance the error performance of wireless communications by delivering one information symbol contains two points of the modulated signal at one time slot without affecting the structure of Alamouti STBC scheme. In this scheme, new constellation points are obtained by multiplying the modulated signal into Hadamard transform, and it takes the

978-1-7281-3910-4/19/$31.00 ©2019 IEEE
DOI 10.1109/ICEEE2019.2019.00040

advantage of the possibility of transmitting two points of constellation into one symbol of Alamouti STBC scheme. Therefore, Alamouti STBC scheme uses these new constellation points as transmitted information symbols that are transmitted through the wireless channel. The energy symbol in this scheme is normalized as one symbol comprises two points of modulation similar to the conventional Alamouti STBC scheme [8].

In this paper, the construction of OSTBC schemes with multiple transmit antennas and the receiver design are considered and presented first, and the error performance of these schemes with multiple transmit antennas and a transmission rate of $1/2$ is evaluated and compared to Alamouti STBC systems over Rician fading channel. Then, the Alamouti STBC 2×2 scheme that uses two time slots for achieving channel cancellation as well as OSTBC 4×4 and 8×8 systems are extended to include the Hadamard transform property in order to achieve higher capacity, and hence better reliability without time delay [9], and to improve the error performance of the conventional systems.

The rest of this paper is organized as follows: the system models of Alamouti and OSTBC schemes using multiple transmit antennas and Hadamard transform are described in Section II. The joint Hadamard transform and OSTBC schemes with multiple transmit antennas is presented in Section III. Simulation results of the Bit Error Rate (BER) performance are discussed in Section IV. Finally, the conclusion of this paper is provided in section V.

II. OSTBC Schemes and Hadamard Transform

In this section, OSTBC schemes with multiple transmit antennas and Hadamard transform are described.

A. *Orthogonal STBC Schemes*

In general, OSTBC schemes are used for MIMO transmission to transmit multiple copies of a data stream from number of transmit antennas and to exploit the various received versions of the data in order to improve the reliability of the data transfer. It combines all the copies of the received signal in an optimal way to extract as much information from each of them as possible, and uses both spatial and temporal diversity and enables significant gains to be achieved. OSTBC schemes are usually represented by a transmission matrix X as expressed below, where each row represents a time slot and each column represents one antenna's transmissions over time [10].

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Within this matrix, x_{mn} is the modulated symbol to be conveyed in time slot m from antenna n.

An example of a full-rate and full-diversity complex STBC is Alamouti schemes [4], which are designed with two transmit antennas to transmit symbols to a single antenna or two receive antennas. It is defined by the following transmission matrix:

$$\begin{bmatrix} x_1 & x_2 \\ -x_2{}^* & x_1{}^* \end{bmatrix} \quad (2)$$

In Alamouti STBC 2×1 and 2×2 schemes, two signals are simultaneously transmitted from two antennas at a given symbol period. At some instant of time t, the signal transmitted from the first antenna is denoted by x_1 and from the second antenna is x_2. During the next symbol period at time $t + T_s$, the signals $-x_2^*$ and x_1^* are transmitted from the first and second antennas, respectively, where $*$ is the complex conjugate operation. Therefore, the transmission rate of these scheme is unity, which is defined as the ratio of the number of transmitted symbols x's to be entered an STBC encoder to the number of symbol periods [5]. This also demonstrates how Alamouti coding involves coding in both the spatial and time dimensions; hence, it is an example of a space-time codes [10].

OSTBC schemes that are presented and the orthogonal transmission matrices that are designed by Tarokh in [5] are considered in this paper. The main characteristic of these codes is the orthogonality property, where the transmission matrices are designed with orthogonal columns. In these schemes, the transmission is considered orthogonal which implies that the receive antenna receives two completely orthogonal streams. The rule of orthogonality of OSTBC schemes is given as follows [11]:

$$XX^H = \sum_{k=1}^{n_x} |x_k|^2 . I_{N_T} \quad (3)$$

where I_{N_T} is the N_T-dimensional identity matrix, $|x_k|$ stands for the modules of the complex number x_k of the transmitted data sequence with a set of n_x scalar complex symbols, and H represents the Hermitian transpose operation.

1) OSTBC Scheme with Three and Four Transmit Antennas

In the complex OSTBC 3×4 and 4×4 transmission matrices designed by Tarokh in [5], 4 symbols (x_1, x_2, x_3 and x_4) are transmitted in 8 time slots, and half of the full transmission rate is achieved, i.e., the transmission rate of these schemes is $1/2$, because the number of transmitted symbols is half the number of symbol periods. For instance, at the transmitter of OSTBC 3×4 scheme, the first transmit antenna transmits the original signal (x_1, x_2 and x_3), and another copy of this signal is transmitted from another antenna after a certain time interval T_s. This mechanism repeats itself for the third transmit antenna too. Similarly for the OSTBC 4×4 scheme with 4 symbols that are transmitted in 8 time slots.

At the receiver side, each antenna receives a signal and the conjugate form of it as described in [12]. As well as the combining rule for these OSTBC schemes, and the combined signals from the receive antennas that are sent to the Maximum Likelihood (ML) detector are also discussed in [12]. Then, the ML detector decides which symbol was sent based on the minimum distance criteria as presented in [4].

2) OSTBC Scheme with Five, Six, Seven and Eight Transmit Antennas

In the complex OSTBC 5×8, 6×8, 7×8 and 8×8 schemes with transmission matrices designed by Tarokh in [5], 8 symbols (x_1, x_2, x_3, x_4, x_5, x_6, x_7 and x_8) are transmitted in 16 time slots, and half of the full transmission rate is achieved, hence these schemes lose half of the theoretical bandwidth efficiency [5]. The received signals and the combining rules of all these schemes as well as the ML detection are following the same criteria that presented in [12].

B. Hadamard Transform (HDT)

The Hadamard transform is a square matrix whose rows are mutually orthogonal and every different row has $+1$s and -1s entries. 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 [13].

The Hadamard matrix of 2×2 order is expressed as [8]:

$$G_{2\times 2} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{4}$$

Generally, Hadamard matrices of $n \times n$ order have columns and rows are pairwise orthogonal and satisfy the following formula [14]:

$$G_{n\times n} G_{n\times n}{}^{H} = G_{n\times n}{}^{H} G_{n\times n} = nI_n \tag{5}$$

where I_n is the identity matrix of $n \times n$ order.

III. Joint Hadamard Transform and OSTBC Schemes with Multiple Transmit Antennas

Exploiting the Hadamard property of the Hadamard codes that already presented in [15 and references therein] for higher order matrices is an enhancement technique to enhance the performance of OSTBC schemes. It explores the ability of Hadamard matrices in further improving the error performance of OSTBC systems and shows that there is an SNR improvement obtained by using Hadamard matrices as compared to the conventional OSTBC systems. The general system model of the improved OSTBC schemes using Hadamard transform is as shown in Fig. 1.

A. OSTBC 2x2 Scheme with Hadamard Transform

In OSTBC 2×2 scheme, the modulated signal is sent to the OSTBC system, while in the case of using Hadamard matrices as in this paper, the output of the modulator is the input of the Hadamard transform, and then the signal is sent to the OSTBC encoder as shown in Fig. 1.

Let c_1 and c_2 are the two modulated symbols in OSTBC 2×2 scheme, therefore:

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} c_1 + c_2 \\ c_1 - c_2 \end{bmatrix} \tag{6}$$

This matrix is obtained by multiplying the Hadamard matrix to the modulated signal, and it is the matrix that encoded using the OSTBC encoder instead of the modulated signal as in the conventional system. Therefore, the first row $c_1 + c_2$ is equivalent to x_1 and the second row $c_1 - c_2$ is equivalent to x_2 in the transmission matrix of the conventional OSTBC 2×2 scheme which can be written as:

$$\begin{bmatrix} c_1 + c_2 & c_1 - c_2 \\ -(c_1 - c_2)^* & (c_1 + c_2)^* \end{bmatrix} \tag{7}$$

B. OSTBC 4x4 Scheme with Hadamard Transform

In OSTBC 4×4 scheme based on Hadamard transform, let the four modulated symbols are (c_1, c_2, c_3 and c_4). The output matrix of the Hadamard transform is the multiplication of the Hadamard matrix to the modulated signal as in (8). In this equation, the first row ($c_1 + c_2 + c_3 + c_4$), the second row ($c_1 - c_2 + c_3 - c_4$), the third row ($c_1 + c_2 - c_3 - c_4$) and the fourth row ($c_1 - c_2 - c_3 + c_4$) are equivalent to x_1, x_2, x_3 and x_4 in the transmission matrix of the conventional OSTBC 4×4 scheme, respectively.

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} = \begin{bmatrix} c_1 + c_2 + c_3 + c_4 \\ c_1 - c_2 + c_3 - c_4 \\ c_1 + c_2 - c_3 - c_4 \\ c_1 - c_2 - c_3 + c_4 \end{bmatrix} \tag{8}$$

C. OSTBC 8x8 Scheme with Hadamard Transform

In OSTBC 8×8 scheme using Hadamard transform, consider the eight modulated symbols are (c_1, c_2, c_3, c_4, c_5, c_6, c_7 and c_8). The matrix that obtained by multiplying the Hadamard matrix to the modulated signal is as written in (9), where the first row ($c_1 + c_2 + c_3 + c_4 + c_5 + c_6 + c_7 + c_8$), the second row ($c_1 - c_2 + c_3 - c_4 + c_5 - c_6 + c_7 - c_8$), the third row ($c_1 + c_2 - c_3 - c_4 + c_5 + c_6 - c_7 - c_8$), the fourth row ($c_1 - c_2 - c_3 + c_4 + c_5 - c_6 - c_7 + c_8$), the fifth row ($c_1 + c_2 + c_3 + c_4 - c_5 - c_6 - c_7 - c_8$), the sixth row ($c_1 - c_2 + c_3 - c_4 - c_5 + c_6 - c_7 + c_8$), the seventh row ($c_1 + c_2 - c_3 - c_4 - c_5 - c_6 + c_7 + c_8$) and the eighth row ($c_1 - c_2 - c_3 + c_4 - c_5 + c_6 + c_7 - c_8$) are equivalent to x_1, x_2, x_3, x_4, x_5, x_6, x_7 and x_8 in the transmission matrix of the conventional OSTBC 8×8 system, respectively.

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \end{bmatrix} =$$

$$\begin{bmatrix} c_1 + c_2 + c_3 + c_4 + c_5 + c_6 + c_7 + c_8 \\ c_1 - c_2 + c_3 - c_4 + c_5 - c_6 + c_7 - c_8 \\ c_1 + c_2 - c_3 - c_4 + c_5 + c_6 - c_7 - c_8 \\ c_1 - c_2 - c_3 + c_4 + c_5 - c_6 - c_7 + c_8 \\ c_1 + c_2 + c_3 + c_4 - c_5 - c_6 - c_7 - c_8 \\ c_1 - c_2 + c_3 - c_4 - c_5 + c_6 - c_7 + c_8 \\ c_1 + c_2 - c_3 - c_4 - c_5 - c_6 + c_7 + c_8 \\ c_1 - c_2 - c_3 + c_4 - c_5 + c_6 + c_7 - c_8 \end{bmatrix} \tag{9}$$

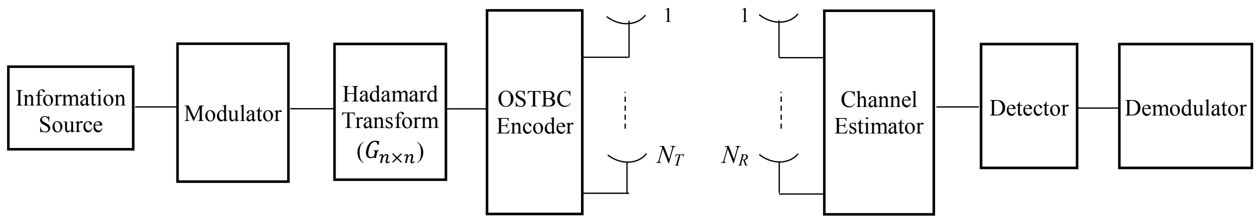

Figure 1. System model of OSTBC schemes with multiple transmit antennas using Hadamard transform.

D. Channel Model

In this paper, we focus on indoor communications, where a Line-of-Sight (LoS) component has the dominant effect as compared to the non-LoS paths. More specifically, the frequency flat Rician fading channel model is employed. The Rician fading channel matrix is given by [16, 17 and 18] as:

$$H = \sqrt{\frac{K}{K+1}} H_{LoS} + \sqrt{\frac{1}{K+1}} H_{NLoS} \quad \in \mathbb{C}^{N_R \times N_T} \qquad (10)$$

where K is the Rice factor denoting the power ratio between H_{LoS} and H_{NLoS}. It is found to be within the range of 8.34 to $12.04\ dB$ for the $60\ GHz$ indoor communication scenario. The H_{NLOS} denotes the random fast fading component, which obeys the zero mean complex valued Gaussian distribution and unit variance [19].

E. OSTBC-HDT Receiver

Equations (6), (8) and (9) illustrate that the constellation points can be changed easily to increase the Euclidean distance of the ML detector in order to distinguish the symbols from multiple transmit antennas. However, the transmitted signals are conveyed over an $N_R \times N_T$ wireless channel, and added to AWGN vector denoted as v which has a complex independent and identically distributed random variables with zero mean and unit variance. The received signal of OSTBC schemes using Hadamard transform is given as:

$$Y = HG_{n\times n}X + v \qquad (11)$$

where $H \in \mathbb{C}^{N_R \times N_T}$ represents the Rician fading channel matrix, $G_{n\times n}$ is the Hadamard matrix of $n \times n$ order, and n is the number of transmit antennas N_T.

The multiplication of the channel matrix $H \in \mathbb{C}^{N_R \times N_T}$ to the Hadamard matrix $G_{n\times n} \in \mathbb{C}^{N_T \times N_T}$ is known as the effective channel $H_e = HG_{n\times n} \in \mathbb{C}^{N_R \times N_T}$ which is taken into consideration in the ML detection at the receiver side where the Hadamard transform symbols are decoded using the ML decision criteria described in [4].

The ML detector leads to the best performance in terms of the error probability per symbol despite the fact of its complexity. It is the optimum detector in the sense of minimizing the probability of error.

IV. SIMULATION RESULTS

In this paper, the performance results of joint Hadamrad transform and OSTBC schemes with multiple transmit antennas is provided and evaluated in terms of the BER versus the Signal-to-Noise Ratio (SNR) as a measure of performance. However, the BER performance of OSTBC schemes with multiple transmit antennas up to 8 transmit antennas and a transmission rate of $1/2$ are simulated and compared to Alamouti STBC 2×1 and 2×2 systems with 8-PSK (8-Phase Shift Keying) modulation technique. In addition, the BER performance of OSTBC 2×1, 2×2, 4×4 and 8×8 schemes using Hadamard transform is presented and compared to the conventional OSTBC systems. The Rician fading channel is assumed with a Rice factor of $10\ dB$, and AWGN noise is considered.

The error performance of Alamouti STBC 2×1 and 2×2 schemes and OSTBC schemes with multiple transmit antennas employing 8-PSK modulation is depicted in Fig. 2. This figure reveals that there is a diversity gain between both Alamouti STBC 2×1 and Alamouti STBC 2×2 schemes of about $9\ dB$ at the BER of 10^{-6}. It is also obvious from this figure that the error performance improves as the number of transmit antennas increases.

Fig. 3 shows the simulation results of the BER performance of OSTBC 2×1 and 2×2 schemes using Hadamard transform as compared to that of the conventional schemes with 8-PSK modulation scheme. This figure clearly demonstrates that there is an improvement of approximately $4\ dB$ and $3\ dB$ are obtained in OSTBC 2×1 and 2×2 schemes with Hadamard transform over the conventional OSTBC 2×1 and 2×2 schemes, respectively.

Moreover, Fig. 4 compares the BER performance of the presented scheme of OSTBC 4×4 system using Hadamard transform as compared to that of the conventional OSTBC 4×4 system employing 8-PSK modulation scheme. It is clear from this figure that there is an improvement of approximately $6\ dB$ is obtained in OSTBC 4×4 scheme using Hadamard transform as compared to the conventional OSTBC 4×4 scheme.

Lastly as shown in Fig. 5, the BER performance of the presented scheme of OSTBC 8×8 system with Hadamard transform is compared to that of the conventional OSTBC 8×8 scheme with 8-PSK modulation technique. This figure shows that there is a noticeable SNR improvement of about $9\ dB$ is obtained in OSTBC 8×8 scheme using Hadamard transform over the conventional OSTBC 8×8 scheme.

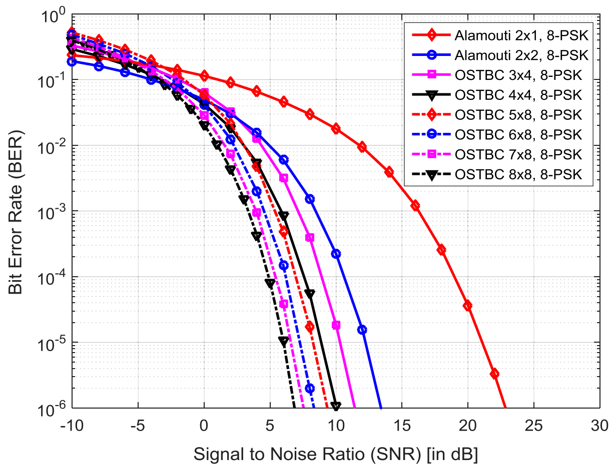

Figure 2. BER performance of Alamouti and OSTBC schemes with multiple transmit antennas employing 8-PSK over Rician fading channel with $K = 10dB$.

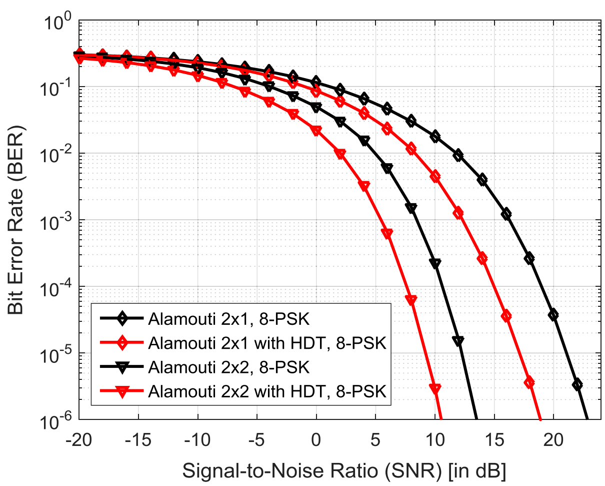

Figure 3. BER performance of Alamouti STBC 2×1 and 2×2 schemes with Hadamard transform over Rician fading channel with $K = 10dB$.

To conclude, it has been shown from the simulation results of this paper that applying Hadamard transform in OSTBC schemes using multiple transmit antennas improves the error performance of wireless transmission because it gives a lower BER than that of the conventional OSTBC schemes without applying Hadamard transform. This explores the ability of Hadamard matrices in further improving the error performance of OSTBC systems due to the significant effect of the new constellation points on both the real and imaginary values of the information signal [8].

Finally, it is noticeable from these results that the SNR improvement (in decibel) obtained from using Hadamard transform in Alamouti STBC 2×1 scheme is about $4\ dB$ as compared to the conventional scheme, while in OSTBC systems with $N_R = N_T = n$ it can be expressed as $10\, log_{10}(n)$ at all values of BER.

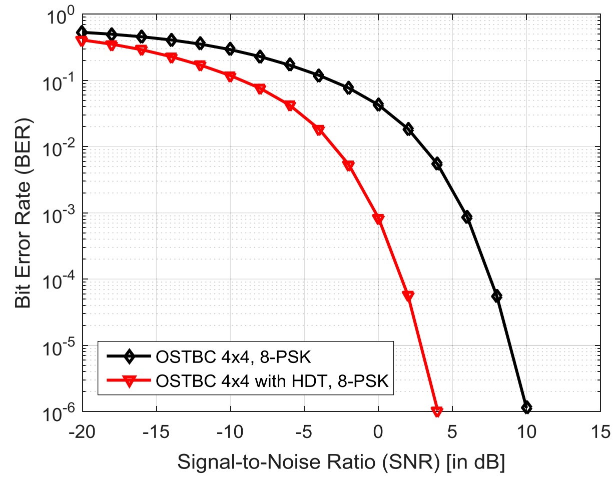

Figure 4. BER performance of OSTBC 4×4 scheme with Hadamard transform over Rician fading channel with $K = 10dB$.

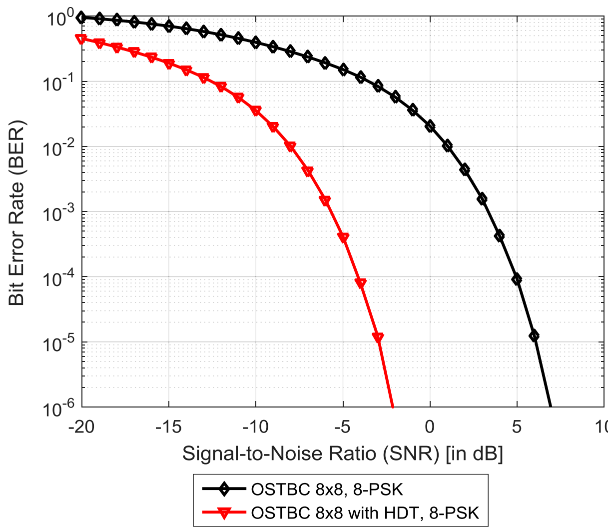

Figure 5. BER performance of OSTBC 8×8 scheme with Hadamard transform over Rician fading channel with $K = 10dB$.

V. Conclusion

The proposed scheme of joint Hadamard transform and OSTBC schemes using multiple transmit antennas is presented in this paper in order to enhance the system performance. The BER performance of OSTBC schemes with multiple transmit antennas (more than two antennas) employing 8-PSK modulation technique is simulated, and applying the Hadamard transform in these schemes is also validated and compared with the conventional OSTBC systems. The simulation results showed that the BER performance of OSTBC schemes with multiple transmit antennas is improved as the number of transmit antennas increased. It is also seen that the error performance of the wireless transmission using OSTBC schemes is further enhanced by using Hadamard transform because it shows a noticeable improvement of the system BER over the conventional OSTBC systems without applying the Hadamard transform. Moreover, an SNR improvement of about $4\ dB$, $3\ dB$, $6\ dB$ and $9\ dB$ is achieved by imposing the Hadamard transform on OSTBC 2×1, 2×2, 4×4 and 8×8 schemes over the conventional OSTBC schemes, respectively. Therefore, using the Hadamard transform could be easily imposed and integrated into existing wireless communication systems as it does not change the behavior of the conventional schemes but it adds some manipulations to the input of OSTBC schemes.

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