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Performance Evaluation of Spatial Modulation and QOSTBC for MIMO Systems†

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Abstract

Multiple-input multiple-output (MIMO) systems require simplified architectures that can maximize design parameters without sacrificing system performance. Such architectures may be used in a transmitter or a receiver. The most recent example with possible low cost architecture in the transmitter is spatial modulation (SM). In this study, we evaluate the SM and quasi-orthogonal space time block codes (QOSTBC) schemes for MIMO systems over a Rayleigh fading channel. QOSTBC enables STBC to be used in a four antenna design, for example. Standard QO-STBC techniques are limited in performance due to self-interference terms; here a QOSTBC scheme that eliminates these terms in its decoding matrix is explored. In addition, while most QOSTBC studies mainly explore performance improvements with different code structures, here we have implemented receiver diversity using maximal ratio combining (MRC). Results show that QOSTBC delivers better performance, at spectral efficiency comparable with SM.

Keywords – Spatial Modulation, Space Time Block Codes, Quasi-orthogonal Space Time Block Codes, MIMO
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1. Introduction

Since the demand for ever higher data rates is a major driver in research on telecommunications services for mobile devices, modern (and future) telecommunication standards are being proposed based on multiple-input multiple-output (MIMO) antenna configurations. In long-term evolution (LTE) and LTE-Advanced (LTE-A) for example, data rates on the Gigabit scale are being sought [1]. The MIMO scheme exploits the probability that no two channel paths will have equally bad impairments, thus increasing the number of transmitting and/or receiver elements can improve the probability of correctly receiving transmitted information over a fading channel. For instance, if p is the probability that the instantaneous signal-to-noise ratio (SNR) falls below a critical value on each antenna branch (usually called the outage probability [2]), then $p^{(N_R)}$ is the probability that the instantaneous SNR is below the same critical value on all N_R-receiver branches for independently faded channels [3]. Since mobile receivers are generally compact, diversity techniques are best utilised in the transmitter.

MIMO schemes increase both transmitter and receiver diversity beyond one antenna. Many different transmitter diversity techniques have been studied by researchers [4]. Maximal ratio combining (MRC) is an optimum combining method for flat fading channels with additive white Gaussian noise (AWGN) [4] and is applied in the receiver. Examples of popular transmitter diversity techniques include spatial multiplexing and space-time block coding (STBC). Most recently, the spatial modulation (SM) technique [5, 6] has been introduced. In SM, multiple antenna systems are designed with only one radio frequency (RF) chain in the transmitter. This technique is explored in this study and will be compared with QOSTBC alongside STBC. The standard QOSTBC scheme is limited by non-zero off-diagonal terms in its detection matrix. Here, a QOSTBC scheme that does not have this limitation is used. In this paper, this will be referred to as interference-free QOSTBC.

Spatial modulation (SM) is an attractive multi-antenna transceiver technique for MIMO system deployment. It improves spectral efficiency and has no inter-channel interference (ICI) at the receiver, provided the pulse shaping period does not overlap amongst antennas [7]. SM reduces transmitter complexity and cost since only one transmitting antenna is activated during a transmission period, thus reducing the number of RF-chains to one. When SM was introduced, it was compared with STBC which uses up to 4-receiver antennas [8]. STBC improves power efficiency by maximizing spatial diversity, and improves capacity from diversity gain, which reduces error probabilities over the same spectral efficiency [6, 8]. QOSTBC thus improves signal quality reception and overall system performance consequent on this fact.

In this study, SM, STBC and QOSTBC will be compared in terms of their bit error ratios (BER). Each of these is

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discussed in Section 2 alongside system models and the results are shown in Section 3, with conclusions following in Section 4.

2. System Models

This work involves different system architectures, namely SM, STBC and QOSTBC, whose respective models are now discussed. QOSTBC is a class of STBC used to enable more than two transmitting antenna diversity with a full spatial rate. SM on the other hand is a three-dimensional signal modulation scheme that enables multi-antenna transmitter design with only one RF-chain.

2.1 Spatial Modulation

Signal modulation involves mapping a fixed amount of information into one symbol. Each symbol represents a constellation point in the complex two dimensional signal plane [6]. Extending this plane to three dimensions yields what has been referred to as spatial modulation [6, 8], a three-dimensional signal mapping (modulation) scheme that activates only one transmitting antenna out of many at one time.

In signal modulation, for instance using *M*-PSK as explored in this study, the number of bits that can be transmitted is given by

$$m = \log_2(M) \tag{1}$$

On the other hand, SM permits the mapping/transmission of more bits (n) as a consequence of the number of transmitting elements:

$$n = \log_2(N_T) + m \tag{2}$$

where N_T is the number of transmitting elements. By (2), the data rate is increased by $\log_2(N_T)$. This is done by mapping the information in a q-vector of n bits into a new s-vector of N_T bits in each timeslot such that only one element in the resulting vector is non-zero.

The position of the element in the s-vector chooses the transmitting antenna element over which the symbol will be transmitted (or that can be made active) in a transmission timeslot. Let the active antenna be designated as s_l; notice that

$$\boldsymbol{s_l} \in [1, \cdots, \boldsymbol{N_t}] \tag{3}$$

Since data are encoded in information symbol and antenna number (as in (3)), the estimation of antenna number is essential. For a noiseless system of the form $\boldsymbol{y} = \boldsymbol{hx}$, where $\boldsymbol{h}$ is the channel matrix, the estimate of the transmitted symbol can be expressed as [8]

$$\boldsymbol{g}(k) = \boldsymbol{h}^{\boldsymbol{H}}(k)\, y(k) \tag{4}$$

where h^H is the Hermitian transpose of $\boldsymbol{h}$. The antenna number can then be estimated as [6]

$$\hat{\boldsymbol{l}} = \arg\max_{\forall \boldsymbol{i}} \left(\left| \boldsymbol{g_i}(\boldsymbol{k}) \right| \right) \qquad \boldsymbol{i} = 1, \cdots, \boldsymbol{N_t} \tag{5}$$

Then, based on the estimated antenna index, the estimate of the transmitted symbol is given by

$$\hat{s} = D\left(g_{i=\hat{l}}(k)\right) \tag{6}$$

where D is the constellation demodulator function [7]. The SM demodulator uses these two estimates to find the message respective to the antenna branch by performing an inverse mapping of the initial SM mapping table.

2.2 Maximal Ratio Combining (MRC)

MRC is an optimum receiver combining technique for a flat fading channel with additive white Gaussian noise (AWGN) [4], used to provide N_R–receiver diversity order. A schematic example of a system with MRC is shown in Figure 1.

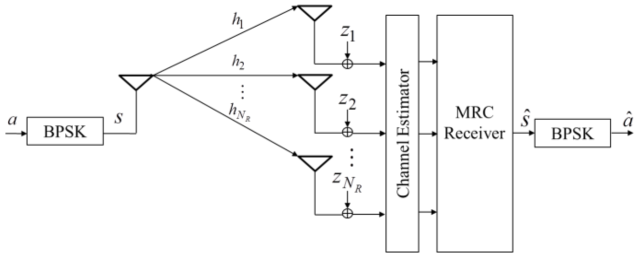

Figure 1: Schematic example of an MRC scheme

In the transmitter, randomly generated symbols, a, are mapped using BPSK. The resulting symbols are transmitted over $h_1, \cdots, h_{N_R}$ multipath channels. In the receiver, some AWGN respective to each receiver branch is added, namely $z_1, \cdots, z_{N_R}$. For a linear system, the received signal can be described in the form:

$$\boldsymbol{y} = \boldsymbol{hs} + \boldsymbol{z} \tag{7}$$

where y is a vector containing received symbols from each branch of the N_R receiver elements, defined as: $\boldsymbol{y} = [y_1, y_2, \cdots, y_{N_R}]^T$. $\boldsymbol{h} = [h_1, \cdots, h_{N_R}]^T$ is a Rayleigh multipath fading channel defined as ([9]):

$$h_i = \sum_{l=0}^{L-1} a_{i,l}(t) e^{-j\theta_{i,l}}, \quad \forall i = 1, \cdots, (N_T N_R) \tag{8}$$

Here $[\cdot]^T$ is the transpose of $[\cdot]$, $a_{i,l}$ is the path gain, and $\theta_{i,l}$ is the l^{th} phase of the multipath. Similarly, $\boldsymbol{z} = [z_1, \cdots, z_{N_R}]^T$ is the AWGN due to the i^{th} receiver antenna.

If the channel coefficients are perfectly available in the receiver, the detector attains optimal maximum likelihood (ML) decoding as [10]

$$\hat{s} = \arg\max_{\boldsymbol{s}} \prod_{i=1}^{N_R} P(y_i \mid h_i, \boldsymbol{s}) \tag{8a}$$

$$= \arg\min_{\boldsymbol{s}} \mathrm{Re}\left\{ \left(\sum_{\boldsymbol{i}=1}^{\boldsymbol{N_R}} \boldsymbol{h_i^*} \boldsymbol{y_i} \right) \boldsymbol{s}^* \right\} - \frac{1}{2} \left(\sum_{\boldsymbol{i}=1}^{\boldsymbol{N_R}} |\boldsymbol{h_i}|^2 \right) |\boldsymbol{s}|^2$$

where $P(\boldsymbol{y} \mid \boldsymbol{h}, \boldsymbol{S}) = \frac{1}{\pi} \exp\left(-|\boldsymbol{y} - \boldsymbol{hS}|^2 \right)$. The term $|\boldsymbol{y} - \boldsymbol{hs}|^2$ is the Euclidean distance metric for ML decoding [11]. PSK symbols have equal energy, thus the bias energy term in (8a) is dropped [11] so that [10]:

$$\hat{s} = \arg\min_{s} \mathrm{Re}\left\{\left(\sum_{i=1}^{N_R} \boldsymbol{h}_i^* \boldsymbol{y}_i\right) s^*\right\} \tag{8b}$$

where $(\cdot)^*$ is the conjugate of $(\cdot)$. The optimal decision rule linearly combines the received signals through different diversity branches after co-phasing and weighting them with their respective channel gains. If an equivalent channel is known, the MRC rule becomes [10, 12]

$$\hat{s} = \left(\sum_{i=1}^{N_R} \left|\boldsymbol{h}_i\right|^2\right) s + \sum_{i=1}^{N_R} \boldsymbol{h}_i^* \boldsymbol{z}_i \tag{9}$$

Although affected by $\boldsymbol{h}^*$, the noise terms are still Gaussian.

The effective instantaneous SNR with MRC is $\sum_{i=1}^{N_R} |h_i|^2 \rho$, where ρ is the average SNR per antenna branch. It can be seen that the SNR of N_R branch diversity with MRC is the sum of the instantaneous SNRs for each branch. In [2], it was shown that $\mathrm{BER} \propto (1/\rho)^{N_R}$ as presented in Figure 2 (BER is the bit error ratio).

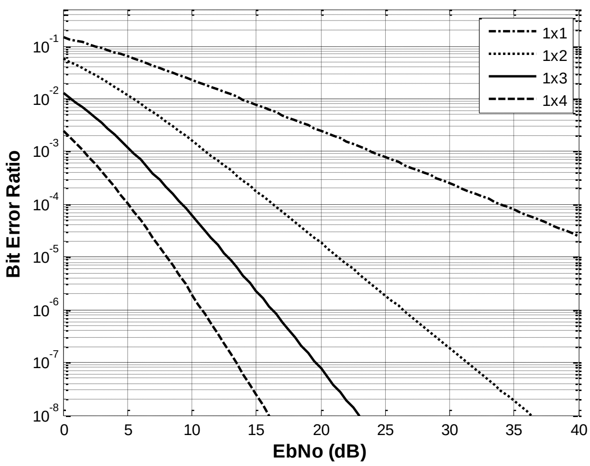

Figure 2: BER performance of BPSK system for MRC with an increasing number of antennas.

The plot in Figure 2 shows that an MRC system does not act as a single element with N_R times greater SNR. Due to the fact that independent faded symbol copies are received on each antenna branch, the slope of the BER changes as N_R increases (but falls off exponentially).

Thus from Figure 2, the MRC combining diversity technique provides significant improvement as the number of receiver antennas increases.

2.3 Orthogonal Space Time Block Codes

Space time block coding or STBC was introduced to improve the performance of multi-antenna systems over constrained bandwidth. It achieves full diversity and a full spatial rate (R_s) over two antenna spaces, for example [13],

$$\boldsymbol{S} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{10}$$

In (10), there are two antenna spaces (N_T) and two time slots (T) so that $R_s = N_T / T = 1$. The symbol s provides two antenna spaces, h_1 and h_2. In the first time slot, s_1 and s_2 will be transmitted over h_1 and h_2, respectively. Similarly, in the second timeslot $-s_2^*$ and s_1^* will be transmitted over h_1 and h_2, respectively. Thus, in the receiver,

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1 s_1 + h_2 s_2 \\ -h_1 s_2^* + h_2 s_1^* \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{11}$$

It is easier for the receiver to decouple the information-bearing symbol if an equivalent virtual channel matrix (EVCM) to the orthogonal codes of (10) can be constructed. Thus, we take the conjugate of the second row of signal received in the second timeslot in (11),

$$\begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} h_1 s_1 + h_2 s_2 \\ -h_1^* s_2 + h_2^* s_1 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2^* \end{bmatrix} \tag{12}$$

In a linear form, (12) can be rewritten as $\hat{\boldsymbol{y}} = \boldsymbol{h}_v \hat{\boldsymbol{s}} + \hat{\boldsymbol{z}}$, where $\hat{\boldsymbol{y}} = [y_1, y_2^*]^T$, $\hat{\boldsymbol{s}} = [s_1, s_2]^T$ and $\hat{\boldsymbol{z}} = [z_1, z_2^*]^T$. $\boldsymbol{H}_v$ is the channel, usually referred to as EVCM;

$$\boldsymbol{H}_v = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \tag{13}$$

In the receiver, the STBC code permits linear decoding as

$$\boldsymbol{H}_v^H \hat{\boldsymbol{y}} = \boldsymbol{H}_v^H \boldsymbol{H}_v \hat{\boldsymbol{s}} + \boldsymbol{H}_v^H \hat{\boldsymbol{z}}$$

where $\boldsymbol{H}_v^H$ is the Hermitian transpose of $\boldsymbol{H}_v$. Then $\boldsymbol{H}_v^H \boldsymbol{H}_v = \sum_{i=1}^{2} |h_i|^2 \boldsymbol{I}_2$ is the power gain, where $\boldsymbol{I}_2$ is a (2×2) identity matrix. Thus, the rows and columns of EVCM of the Alamouti code are orthogonal. The receiver decouples the transmitted signals s_1 and s_2. Using EVCM simplifies the implementation of the STBC scheme and also reduces the receiver complexity.

2.3.1 Maximum Likelihood for STBC Detection

It is assumed that channel state information (CSI) is known to the receiver. Thus, the channel coefficients h_1 and h_2 can be used in the decoding for a ML detector [14]. The detector is optimum if the ML detector can find the codewords $(\hat{s}_1, \hat{s}_2)$ that minimize the Euclidean distance metric between the estimated received codeword pairs and transmitted codewords (s_1, s_2). In STBC, the Euclidean distance metric for ML decoding is [11, 15]

$$d(s_1, s_2) = \left|y_1 - h_1 s_1 - h_2 s_2\right|^2 + \left|y_2 + h_1 s_2^* - h_2 s_1^*\right|^2 \tag{14}$$

The joint conditional PDF of y_1 and y_2 given the channels h_1 and h_2 over which the codewords s_1 and s_2 are transmitted can be expressed as [11]

$$P(y_1, y_2 \mid h_1, h_2, s_1, s_2) = \frac{1}{2\pi\eta^2} \exp\left\{-\frac{d(s_1, s_2)}{2\eta^2}\right\} \tag{15}$$

where η^2 is the variance of z_1 and z_2; these are equal for uncorrelated Gaussian random variables. To reduce the computational complexity in the detector, $|y_1|^2 + |y_2|^2$ terms that are not required in the decision will be dropped. Then expanding (15), it is found that

$$\begin{aligned} d(s_1, s_2) &= |s_1|^2 \lambda_h - 2\Re\left\{y_1^* h_1 s_1 + y_2 h_2 s_1^*\right\} \\ &\quad + |s_2|^2 \lambda_h - 2\Re\left\{y_1^* h_2 s_2 + y_2 h_1^* s_2\right\} \\ &= d(s_1) + d(s_2) \end{aligned} \tag{16}$$

where $\lambda_h = |h_1|^2 + |h_2|^2$.

For PSK symbols, signal points in the constellation have equal energy. Thus, the bias energy terms ($|s_1|^2 \lambda_h$ and $|s_2|^2 \lambda_h$) are ignored; the optimum ML detection further simplifies to

$$\begin{aligned} d_{psk}(s_1) &= \Re\left\{y_1^* h_1 s_1 + y_2 h_2 s_1^*\right\} \\ d_{psk}(s_2) &= \Re\left\{y_1^* h_2 s_2 + y_2 h_1^* s_2\right\} \end{aligned} \tag{17}$$

Only PSK symbols will be considered in this study.

2.3.2 MIMO-STBC

Suppose that there are N_R receiver antennas. Thus, each of h_1 and h_2 can be treated respectively as a vector of the form:

$$\begin{aligned} \boldsymbol{h}_1 &= [h_{11} \quad h_{21} \quad \cdots \quad h_{N_R 1}]^T \\ \boldsymbol{h}_2 &= [h_{12} \quad h_{22} \quad \cdots \quad h_{N_R 2}]^T \end{aligned} \tag{18}$$

We know that if the equivalent channel can be derived, then the MRC when there are N_R maximum receiving elements becomes [12]

$$\begin{aligned} \boldsymbol{r} &= \sum_{i=1}^{N_R} H_{v_i}^H \hat{y}_i \\ \boldsymbol{r} &= \sum_{i=1}^{N_R} \left(\boldsymbol{H}_{v_i}^{\boldsymbol{H}} \boldsymbol{H}_{v_i}\right)\hat{s} + \sum_{i=1}^{N_R} \boldsymbol{H}_{v_i}^{\boldsymbol{H}} \hat{\boldsymbol{z}}_i \end{aligned} \tag{19}$$

In all cases of N_R, $\boldsymbol{H}_{v_i}^{\boldsymbol{H}} \boldsymbol{H}_{v_i}$ is an identity matrix multiplied (as in the case N_R = 1) by the channel gains such as $\sum_{j=1}^{N_R} \sum_{i=1}^{2} |h_{i,j}|^2$. The noise term is rather amplified by $\boldsymbol{H}_{v_j}^{\boldsymbol{H}}$, $\forall j = 1, \cdots, N_R$. The degree of impact of $\boldsymbol{H}_{v_j}^{\boldsymbol{H}}$ on the noise term impacts the closeness of the Euclidean distance metric in the receiver; this depends on the fading of the channel. The complexity in the decoupling of the transmitted message in the receiver reduces to finding only $\hat{\boldsymbol{s}} = [s_1, s_2]^T$.

2.4 Quasi-orthogonal Space Time Block Codes

A major limitation in the use of STBC is that $N_T > 2$ is not supported. QOSTBC is a class of STBC that removes the two-transmit antenna limitation.

2.4.1 Standard QOSTBC

Standard QOSTBC achieves a full spatial rate but not full diversity [16]. In [11, 15, 17, 18], different methods for constructing QOSTBC have been described. QOSTBCs are STBCs with N_T > 2 and timeslots T = 2, 4 and 8 with complex entries; STBC codes with $R_s = N_T/T = 1$ are said to attain a full rate [11, 19].

An example of a full rate (R_s = 1) STBC code with N_T = 4 and T = 4 is given as [19, 20]

$$\boldsymbol{S} = \begin{bmatrix} \Omega_{12} & \Omega_{34} \\ \Omega_{34}^* & \Omega_{12}^* \end{bmatrix} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ s_3 & s_4 & s_1 & s_2 \\ -s_4^* & s_3^* & -s_2^* & s_1^* \end{bmatrix} \tag{20a}$$

where Ω represents the standard Alamouti STBC [21],

$$\Omega_{12} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \text{and } \Omega_{34} = \begin{bmatrix} s_3 & s_4 \\ -s_4^* & s_3^* \end{bmatrix} \tag{20b}$$

(20) is an example of QOSTBC. The rate of full-diversity codes is $R_s \le 1$ [22]. Unfortunately, standard QOSTBC codes do not attain full diversity and also do not permit linear processing due to coupling terms which lie off the leading diagonal of the detection matrix [20, 23].

As seen in (20), there are $\boldsymbol{h} = [h_1 \quad h_2 \quad h_3 \quad h_4]^T$ antenna spaces. Combining QOSTBC from (20) with the channel vector for N_R = 1,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} h_1 s_1 + h_2 s_2 + h_3 s_3 + h_4 s_4 \\ -h_1 s_2^* + h_2 s_1^* - h_3 s_4^* + h_4 s_3^* \\ h_1 s_3 + h_2 s_4 + h_3 s_1 + h_4 s_2 \\ -h_1 s_4^* + h_2 s_3^* - h_3 s_2^* + h_4 s_1^* \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \tag{21}$$

As with Alamouti STBC codes, EVCM can be formulated by taking the conjugates of the second and fourth rows in the received matrix, thus

$$\begin{bmatrix} y_1 \\ y_2^* \\ y_3 \\ y_4^* \end{bmatrix} = \begin{bmatrix} h_1 s_1 + h_2 s_2 + h_3 s_3 + h_4 s_4 \\ -h_1^* s_2 + h_2^* s_1 - h_3^* s_4 + h_4^* s_3 \\ h_1 s_3 + h_2 s_4 + h_3 s_1 + h_4 s_2 \\ -h_1^* s_4 + h_2^* s_3 - h_3^* s_2 + h_4 s_1 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2^* \\ z_3 \\ z_4^* \end{bmatrix} \tag{22}$$

so that

$$\begin{bmatrix} y_1 \\ y_2^* \\ y_3 \\ y_4^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3 & h_4 & h_1 & h_2 \\ h_4^* & -h_3^* & h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2^* \\ z_3 \\ z_4^* \end{bmatrix}$$

In compact form, (22) is of (7) form except that $\hat{\boldsymbol{y}} = \left[y_1, y_2^*, y_3, y_4^*\right]^T$, $\hat{\boldsymbol{s}} = \left[s_1, s_2, s_3, s_4\right]^T$ and $\hat{\boldsymbol{z}} = \left[z_1, z_2^*, z_3, z_4^*\right]^T$. The EVCM therefore becomes

$$\boldsymbol{H}_{\boldsymbol{v}_4} = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3 & h_4 & h_1 & h_2 \\ h_4^* & -h_3^* & h_2^* & -h_1^* \end{bmatrix} \quad (23)$$

Definition 1: The *Equivalent Virtual Channel Matrix, h_v, is a matrix that satisfies $\sum_{i=1}^{N} \|h_i\|^2$ **D**, where **D** is a sparse matrix with ones on its leading diagonal and at least $N^2/2$ zeros at its off-diagonal positions; its remaining (self-interference) entries are bounded in magnitude by 1.*

In the receiver, the EVCM can be used to simplify decoding. For instance, let the decoding method proceed as:

$$\hat{\boldsymbol{s}} = \boldsymbol{H}_{\boldsymbol{v}_4}^{\boldsymbol{H}} \times \hat{\boldsymbol{y}} = \boldsymbol{H}_{\boldsymbol{v}_4}^{\boldsymbol{H}} \boldsymbol{h}_{\boldsymbol{v}_4} \times \hat{\boldsymbol{s}} + \boldsymbol{H}_{\boldsymbol{v}_4}^{\boldsymbol{H}} \times \hat{\boldsymbol{z}} \quad (24)$$

$$\hat{\boldsymbol{s}} = \boldsymbol{D}_4 \times \hat{\boldsymbol{s}} + \boldsymbol{H}_{\boldsymbol{v}_4}^{\boldsymbol{H}} \times \hat{\boldsymbol{z}}$$

where $\boldsymbol{D_4}$ is the detection matrix for N_T=4 and N_R=1in the form,

$$\boldsymbol{D}_4 = \boldsymbol{H}_{\boldsymbol{v}_4}^{\boldsymbol{H}} \boldsymbol{H}_{\boldsymbol{v}_4} = \lambda_{\boldsymbol{h}} \times \begin{bmatrix} 1 & 0 & \underline{\beta} & 0 \\ 0 & 1 & 0 & \underline{\beta} \\ \underline{\beta} & 0 & 1 & 0 \\ 0 & \underline{\beta} & 0 & 1 \end{bmatrix} \quad (25)$$

$\boldsymbol{D_4}$ is a Grammian matrix with λ_h in the leading diagonal of the $\boldsymbol{D_4}$ ($N_T \times N_T$) matrix; $\lambda_h = \sum_{i=1}^{N_T} |h_i|^2, \ \forall i = 1, \cdots, N_T$ is the channel power/gain.

On the other hand, $\underline{\beta} = \dfrac{\beta}{\lambda_h}$ and $\beta = 2\Re\left(\dfrac{h_1 h_3^* + h_2 h_4^*}{\lambda_h}\right)$.

β is the self-interfering term that limits full-diversity performance expected of this type of QOSTBC systems. Alternative channel estimation for linear receivers, such as zero-forcing (ZF) [24], compensates for the β-term except for the noise elements. This yields sub-optimal results.

2.4.2 Interference-Free QOSTBC

Independently, two different researchers have proposed an interference-free QO-STBC; one method involves the use of Givens rotations [25] while the other uses eigenvalues [20, 23]. Both of these methods yield similar results. However, the eigenvalues approach is less complex and this will be reviewed in brief.

Definition 2 - *If $\boldsymbol{A} = (a_{ij})$ is a square matrix and x is a column matrix ($\boldsymbol{x_i}$); if $\boldsymbol{Ax} = \boldsymbol{v_i x}$, where v is a scalar, then v_i is an eigenvalue and x_i is an eigenvector. x_i can be formed into a square matrix $\boldsymbol{M} = \left[\boldsymbol{x}_1, \cdots, \boldsymbol{x}_{N_T}\right]$usually called a modal matrix. If the eigenvalue of A is the leading diagonal of a matrix **V**, then **V** = v_i**I**; both A and V share the same eigenvalues, **I** is an identity matrix. It follows that $\boldsymbol{AM} = \boldsymbol{VM}$.*

The goal of the eigenvalue computation is to eliminate the interfering terms. If ***A*** represents $\boldsymbol{D_4}$, then $\boldsymbol{D_4 M} = \boldsymbol{MV}$. Thus, $\boldsymbol{M}^{-1}\boldsymbol{D_4 M} = \boldsymbol{V}$; this is the principle of diagonalizing a matrix [26]. It follows that ***V*** contains the required diagonal terms of the diagonal matrix, $v_i\boldsymbol{I}$, with no interference terms.

Recall the decoding matrix of (25): its modal matrix from $\boldsymbol{M}^{-1}\boldsymbol{D}_4\boldsymbol{M} = v_i\boldsymbol{I}$ is

$$\boldsymbol{M}_{\boldsymbol{H}_{v_4}} = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \quad (26)$$

$\boldsymbol{M}_{\boldsymbol{H}_{v_4}}$ will be post-multiplied by the EVCM ($\boldsymbol{H}_{\boldsymbol{v}_4}$) for linear decoding in the receiver, such as

$$\boldsymbol{H} = \boldsymbol{h}_{\boldsymbol{v}_4} \times \boldsymbol{M}_{\boldsymbol{h}_{v_4}}$$

$$= \begin{bmatrix} h_1 + h_3 & h_2 + h_4 & h_3 - h_1 & h_4 - h_2 \\ h_2^* + h_4^* & -h_1^* - h_3^* & h_4^* - h_2^* & h_1^* - h_3^* \\ h_1 + h_3 & h_2 + h_4 & h_1 - h_3 & h_2 - h_4 \\ h_2^* + h_4^* & -h_1^* - h_3^* & h_2^* - h_4^* & h_3^* - h_1^* \end{bmatrix} \quad (27)$$

Thus, assuming a linear system of (7) form as, $\hat{\boldsymbol{y}} = \boldsymbol{H}\,\hat{\boldsymbol{s}} + \hat{\boldsymbol{z}}$.

If, at the receiver, we have

$$\boldsymbol{H}^{\boldsymbol{H}} \hat{\boldsymbol{y}} = \boldsymbol{H}^{\boldsymbol{H}} \boldsymbol{H}\,\hat{\boldsymbol{s}} + \boldsymbol{H}^{\boldsymbol{H}} \hat{\boldsymbol{z}} \quad (28a)$$

$\boldsymbol{H^H H}$ can be verified to permit linear decoding with no interfering terms, β, as follows

$$\boldsymbol{H}^{\boldsymbol{H}} \times \boldsymbol{H} = \lambda_{\boldsymbol{h}} \times \begin{bmatrix} 1+\underline{\beta} & 0 & 0 & 0 \\ 0 & 1+\underline{\beta} & 0 & 0 \\ 0 & 0 & 1-\underline{\beta} & 0 \\ 0 & 0 & 0 & 1-\underline{\beta} \end{bmatrix} \quad (28b)$$

Notice that $\boldsymbol{H}^{\boldsymbol{H}} \times \boldsymbol{H}$ provides $\boldsymbol{M}_{\boldsymbol{H}_{v_4}}^{-1} \boldsymbol{H}_{\boldsymbol{v}_4}^{\boldsymbol{H}} \boldsymbol{H}_{\boldsymbol{v}_4} \boldsymbol{M}_{\boldsymbol{H}_{v_4}}$. With ML detection, the receiver finds $(\hat{s}_1, \cdots, \hat{s}_4)$ whose Euclidean distance metric is closest to the transmitted symbols $(s_1, \cdots, s_4)$.

As an example, 4×1 and 3×1 QOSTBC systems are compared for interference-free and non-interference free cases. To do that, random 128×10^4 input symbols are generated and mapped using QPSK. The resulting symbols are demultiplexed into s_1, s_2, s_3 and s_4 so that they can be transmitted over antenna spaces h_1, h_2, h_3 and h_4, as shown in Figure 3.

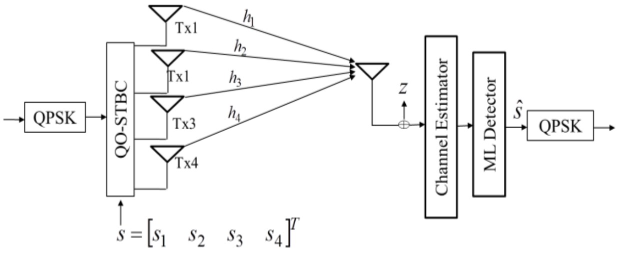

Figure 3: Architecture for Implementing QOSTBC

To enable QOSTBC, EVCM is constructed as (27) for 4×1 transmission; for 3×1 design, h_4 is set to zero. Noise terms (AWGN) are generated and added to each receiver branch respective to the transmitting branch. In the receiver, the linear decoding shown in (28) is performed to estimate the transmitted signals.

It is assumed that the channel state information (CSI) is known; the ML detection method is said to be optimum to find the transmitted data as [14]:

$$\hat{u} = \arg\min_{u} \|\hat{y} - H\,u\|^2,$$

where u is the transmitted data and $\hat{u}$ is the estimate. The receiver finds $(\hat{s}_1,\cdots,\hat{s}_4)$ whose Euclidean distance metric is closest to the transmitted symbols $(s_1,\cdots,s_4)$. This is an optimization (minimization) problem of the form

$$\hat{\boldsymbol{s}} = \arg\min_{\hat{\boldsymbol{s}}} \|\hat{\boldsymbol{y}} - \boldsymbol{H}\,\hat{\boldsymbol{s}}\|_{\boldsymbol{F}}^2 \qquad (29)$$

where $\hat{\boldsymbol{s}}$ is the estimated signal vector. If $\hat{\boldsymbol{s}} = (\boldsymbol{s}_1,\cdots,\boldsymbol{s}_4)$ were transmitted and $\hat{\boldsymbol{s}} = (\hat{\boldsymbol{s}}_1,\cdots,\hat{\boldsymbol{s}}_4)$ are received, then the error matrix is $\boldsymbol{e} = (s_1-\hat{s}_1,\cdots,s_4-\hat{s}_4)$. The fading channel is quasi-static for four consecutive timeslots; however, the noise terms are uncorrelated and statistically independent, with zero-mean and variance η^2. It follows that the probability that $\hat{\boldsymbol{s}} \neq \boldsymbol{s}$ was detected is [27]

$$P(\boldsymbol{s}\rightarrow\hat{\boldsymbol{s}}\,|\,\boldsymbol{H}) = Q\left(\sqrt{k\frac{SNR}{2}}\right) \qquad (30)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp\left(-\frac{t^2}{2}\right)dt$ is the complementary error function, $k = \|\boldsymbol{He}\|_{\boldsymbol{F}}^2$ is the Euclidean distance metric at the receiver and SNR is the ratio of transmitted and received powers per antenna. From the Chernoff upper bound [28], the pairwise error probability (PEP) approximates to

$$(\boldsymbol{s}\rightarrow\hat{\boldsymbol{s}}\,|\,\boldsymbol{H}) = Q\left(\sqrt{k\frac{SNR}{2}}\right) \leq \exp\left(-k\frac{SNR}{4}\right) \qquad (31)$$

where $\|\boldsymbol{He}\|_{\boldsymbol{F}}^2 = \|\boldsymbol{H}\|_{\boldsymbol{F}}^2\,\|\boldsymbol{e}\|_{\boldsymbol{F}}^2$, $\|\boldsymbol{U}\|_{\boldsymbol{F}}^2 = \boldsymbol{trace}\left(\boldsymbol{U}^{\boldsymbol{H}}\boldsymbol{U}\right)$ and $(\cdot)^{\boldsymbol{H}}$ is a Hermitian transpose of $(\cdot)$.

2.4.3 MIMO-QOSTBC

The maximum achievable diversity level for an $N_T \times N_R$ MIMO system is $N_T N_R$ [11], where N_T is the number of transmit elements and N_R is the number of receiver elements. In the ML detection case, the error matrix is $\boldsymbol{e} = (s_1-\hat{s}_1,\cdots,s_4-\hat{s}_4)$, then the rank of $\boldsymbol{E}_{i,j} = \boldsymbol{e}_{i,j}\boldsymbol{e}_{i,j}^{\boldsymbol{H}}$ is κ and its nonzero eigenvalues are $\{\alpha_l\}$. QOSTBC systems attain full diversity, when $\kappa = N_T$.

As in the STBC case, if there are N_R maximum receiver elements, then

$$\boldsymbol{R} = \sum_{i=1}^{N_R} \boldsymbol{H}_i^{\boldsymbol{H}}\,\hat{\boldsymbol{y}}_i$$
$$\boldsymbol{R} = \sum_{i=1}^{N_R}\left(\boldsymbol{H}_i^{\boldsymbol{H}}\boldsymbol{H}_i\right)\hat{\boldsymbol{s}} + \sum_{i=1}^{N_R}\boldsymbol{H}_i^{\boldsymbol{H}}\,\hat{\boldsymbol{z}}_i \qquad (31)$$

For an i.i.d Gaussian channel with many receiver elements (e.g. N_R), the average Chernoff bound simplifies to [27]

$$P(\boldsymbol{s}\rightarrow\hat{\boldsymbol{s}}) \leq \left(\frac{1}{\det\left(I_{N_T} + \frac{SNR}{4}E\right)}\right)^{N_R} \qquad (32)$$
$$= \left(\frac{1}{\prod_{l=1}^{\kappa}\left(1+\frac{\boldsymbol{SNR}}{4}\sigma_l^2\right)}\right)^{\boldsymbol{N_R}}$$

A major performance degradation in this case arises from the error matrix or σ_l^2 in the estimated noise power which is amplified by $\boldsymbol{H}^{\boldsymbol{H}}$.

An advantage in this case (interference-free QOSTBC) accrues from the gain contributed by $\boldsymbol{H}^{\boldsymbol{H}}\times\boldsymbol{H}$ which amplifies the amplitude of the received signals. This varies depending on the eigenvalue $(v_{i=1,\cdots,N_T})$ from $\boldsymbol{M}^{-1}\boldsymbol{D}_4\boldsymbol{M} = \boldsymbol{V}$. At high SNR, where $SNR/4 >> 1$, the error probability is bounded as [11]

$$P(\boldsymbol{s}\rightarrow\hat{\boldsymbol{s}}) \leq \left(\prod_{l=1}^{\kappa}\alpha_l\right)^{-N_R} \times \left(\frac{SNR}{4}\right)^{-\kappa N_R} \qquad (33)$$

The idea of using the rank criterion is to attain maximum possible diversity, $N_T N_R$. The nonzero eigenvalue term, however, provides information about the coding gain.

3. Simulation Results and Discussion

In this section, the simulation results are discussed. The results involve comparisons of the spatial modulation scheme as a method for MIMO transmission with STBC and QOSTBC schemes. Assuming a Raleigh fading channel, the receiver is equipped with the full knowledge of the channel state information and the antennas are reasonably separated to avoid correlation.

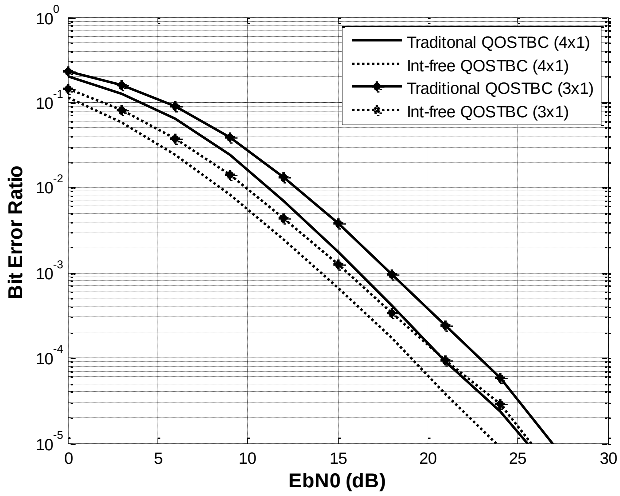

Figure 4: Comparison of Standard and Interference-free (Int-free) QOSTBC

To investigate a 3×1 QOSTBC design, the fourth antenna element is nulled (i.e., $h_4 = 0$). The process for 4×1 QOSTBC implementation is then repeated for 3×1 QOSTBC. In Figure 4, it is observed that interference-free (Int-free) QOSTBC achieves about 2 dB gain with respect to the standard QOSTBC for both 4×1 QOSTBC and 3×1 QOSTBC. The gain results from the elimination of the interfering terms described above.

3.1 Simulation of STBC and QOSTBC

To simulate the MIMO-STBC case, some 7×10^5 random input symbols, a, are generated and mapped using QPSK. The resulting symbols are demultiplexed into s_1, and s_2 so that they can be transmitted over antenna spaces h_1 and h_2, as shown in Figure 5.

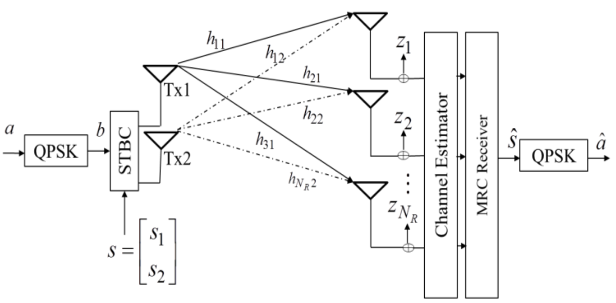

Figure 5: Architecture for Implementing STBC

Since there are N_R receiver antennas, each of h_1 and h_2 is treated respectively as a vector as in (18). In the receiver, the received information on each branch is demodulated and the channel detection performed. The information received from respective branches is combined by MRC. The resulting symbol $\hat{s}$ is demapped using QPSK. For other mapping orders, such as 8-PSK, 16-PSK, 32-PSK and 64-PSK, only QPSK has been substituted in Figure 5. The results are first compared with the data in [21]. The results in Figure 6 are comparable to those reported in Figure 4 of [21] for 2×1 and 2×2 MIMO systems.

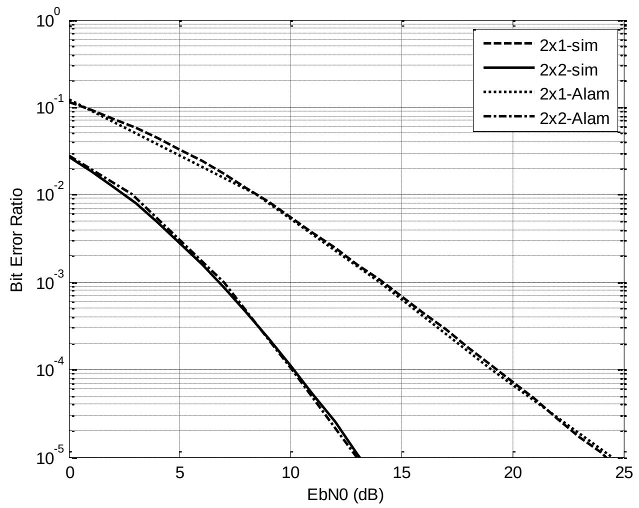

Figure 6: Results of 2×1 and 2×2 MIMO using STBC for the BPSK system

Similar to the STBC simulation case in Figure 5, QOSTBC is enabled after generating random symbols. The resulting symbols are demultiplexed into s_1, s_2, s_3 and s_4 so that they can be transmitted over antenna spaces h_1, h_2, h_3 and h_4. For MIMO-QOSTBC, each h_1, h_2, h_3 and h_4 is treated respectively as a vector of up to N_R receiver antennas. In the receiver, the channel is compensated. The information detected across each antenna branch is combined with another using MRC, then using QPSK, the received symbol estimate is demapped.

3.2 Simulation of SM

Similarly, to simulate the MIMO for the SM case, some $n\times10^5$ random input symbols (where n is from (2)), a, are generated and mapped using QPSK to yield b; this is the two-dimensional signal modulation. SM is a third dimension added to the default two-dimensional signal modulation. SM maps the symbols into a table of $\boldsymbol{s} \in C^{N_T \times L}$, where $C^{N_T \times L}$ is an $N_T \times L$ matrix with complex entries. N_T here denotes that there are N_T possible transmitting branches provided by the SM design. In each column of the matrix, only one element is nonzero which corresponds to the antenna index that can be activated at that time. The symbol corresponding to the selected branch is transmitted over the channel, and AWGN is added. The channel estimation proceeds and the antenna index that will be used to predict the transmitted information is derived.

3.3 Results and Discussions

The results are compared for all transmitter diversity schemes. For a fair comparison, the channel and noise terms are made similar. However, the mapping scheme orders vary but permit equally likely data rates. In [29], we discussed the cases of SM and STBC for up to an N_R = 4 MIMO system and QOSTBC for only to N_R = 2. In this study, we include QOSTBC for up to an N_R = 4 MIMO system.

A. Comparison of Analytical and Simulation Results

To validate our results we show first a comparison of analytical and simulation results with the standard QO-STBC in Figure 7.

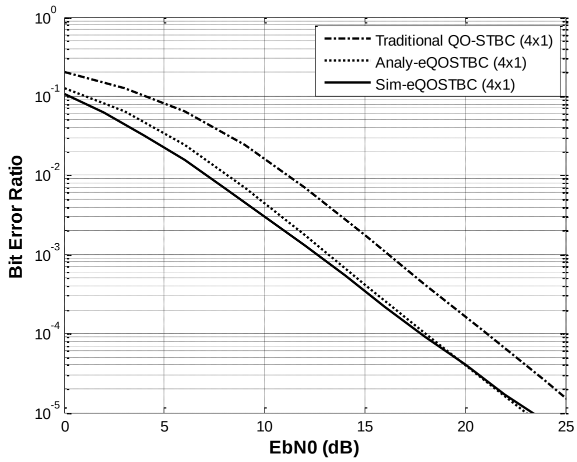

Figure 7: Performance comparison of analytical and simulation results

The simulation results shown in Figure 7 are for a 4×1 QOSTBC diversity scheme. It can be found that the simulation result of eQOSTBC and the analytical result of eQOSTBC reasonably agree up to about $10^{-4.5}$ BER, where both results perfectly aligned. The variation at the start of the plot can be attributed to the parameter setting. Meanwhile, the interference terms in the detection matrix of the standard QOSTBC degrade its performance. Hence, the eQOSTBC outperforms the standard QOSTBC both analytically and in simulations. Both results of eQOSTBC outperform the standard QOSTBC scheme by about 2 dB, for instance, at $10^{-4.5}$ BER.

B. Two Bits Transmission

For further evaluations, we transmit two bits using SM, STBC and QOSTBC. The two bits from the SM scheme are provided by two transmit antennas and the BPSK scheme sequel to $n = \log_2(N_T) + m$ of (2) with four receiving elements. On the other hand, the two bits for STBC and QOSTBC are consequent on (1). The results are shown in Figure 8. At relatively low transmission power, it is found from Figure 8 that transmitting with 2 antennas and receiving with 4 antennas for the STBC scheme is better by some 1 dB at 10^{-2} BER than transmitting with 4 antennas and receiving by 4 antennas using the QOSTBC scheme. Increasing the transmission power thus improves the performance of QOSTBC up to 7.5 dB where both schemes performed equally; further increase in power however shows better performance for QOSTBC than for STBC.

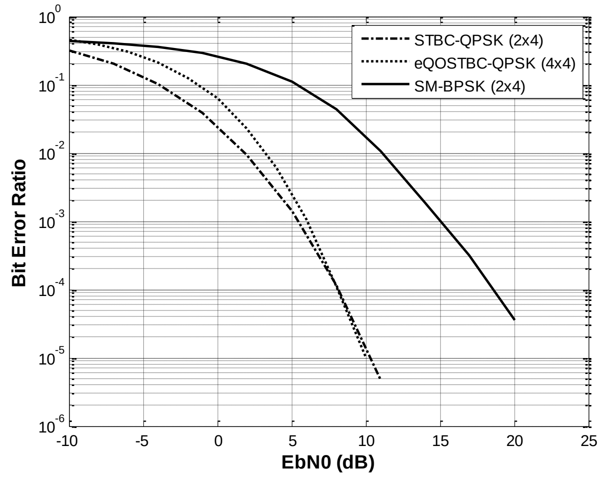

Figure 8: Comparison of two bits transmissions using SM, STBC and QOSTBC

The interfering terms (β) discussed in (25) and then eliminated in (28b) impact the signal amplitude as they affect the gain λ_h. The results here show that results can be improved by simply increasing the transmission power. However, comparing the results of QOSTBC and SM schemes, it is found that the QOSTBC scheme outperforms the SM by about only 9 dB at 10^{-3} BER and then by about 11 dB at 10^{-5} BER. This would increase for increased symbol lengths.

C. Three Bits Transmission

In Figure 9, we compare the results of the SM, STBC and QOSTBC schemes for three bits transmission. The three bits transmission investigation is typical of those reported in Figure 3 of [6].

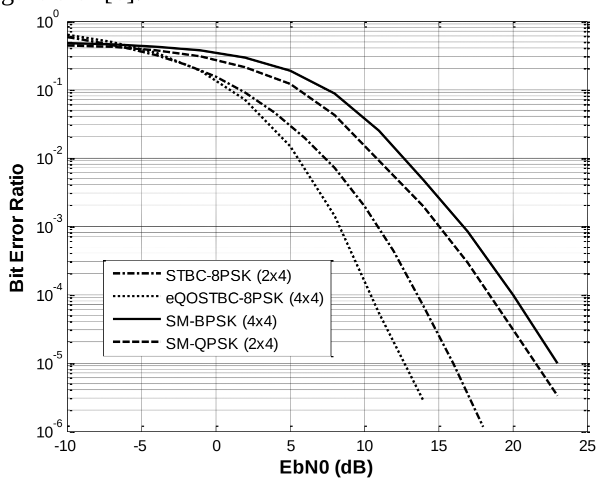

Figure 9: Comparison of three bits transmissions using SM, STBC and QOSTBC

As in [6], it can be seen that transmitting on 2 antennas and receiving on 4 antennas using the SM scheme for QPSK is better than transmitting on 4 antennas and receiving on 4 antennas using BPSK by about 1 dB. On the other hand, comparing the STBC and QOSTBC schemes, it is found that 4×4 QOSTBC performs better than 2×4 of the 8PSK scheme by about 3 dB at 10^{-5} BER. Then comparing them with the SM scheme, it is found that both STBC outperform SM scheme (2×4-QPSK) by about 6 dB at 10^{-5} BER while QOSTBC outperforms SM scheme (2×4-QPSK) by about 8 dB respectively. The benefit of the discussed QOSTBC scheme is its ability to attain full diversity and a full spatial rate resulting from the elimination of the coupling terms.

D. *Four Bits Transmission*

Again, we compare the performance of STBC and QOSTBC with the SM scheme when four bits are transmitted. The results are shown in Figure 10. Both 4×4-QPSK and 2×4-8PSK SM schemes perform similarly with 2×4-16PSK of STBC at 10^{-2} BER although with a performance marginally better than STBC. On the other hand, 4×4-16PSK QOSTBC clearly outperforms the other schemes at 10^{-3} BER by about 4 dB, for example.

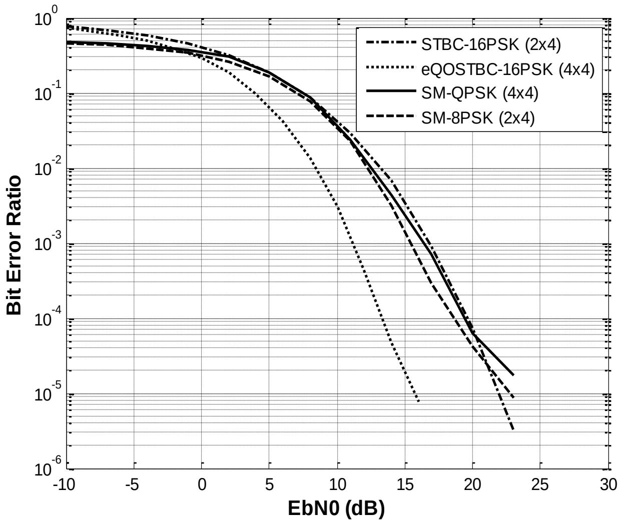

Figure 10: Comparison of four bits transmissions using SM, STBC and QOSTBC

E. *Six Bits Transmission*

Finally, transmitting six bits using SM is investigated as in [6] and [8]. We then compare the results with that of transmitting six bits with the STBC and QOSTBC schemes. The results are shown in Figure 11.

In agreement with references [6] and [8], Figure 11 clearly shows that using the SM schemes to transmit six bits is more economical, in terms of transmission power, than using the STBC scheme. However, SM shows improved performance as the signal modulation order increases. The SM scheme transmission of six bits using 4×4-16PSK outperforms 2×4-32PSK progressively. On the other hand, comparing the QOSTBC and SM schemes, the 4×4-64PSK of the QOSTBC scheme outperforms all other SM schemes and the STBC scheme. Specifically, the 4×4-64PSK QOSTBC scheme outperforms the best performing SM (16PSK that uses 4×4 antennas) among all SM schemes of six bits transmission, by about 3 dB at 10^{-4} BER.

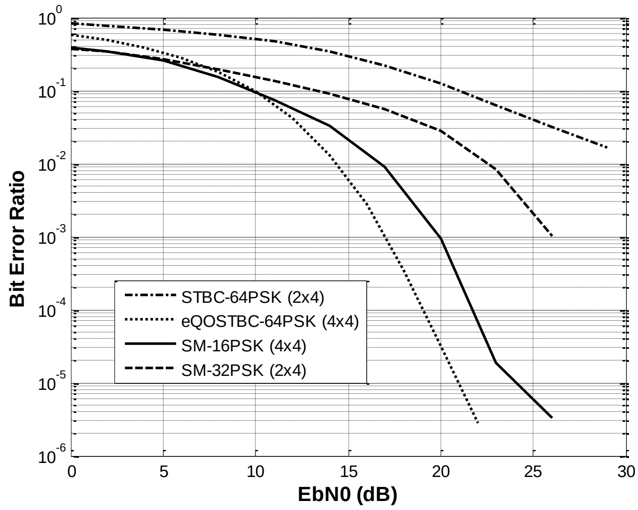

Figure 11: Comparison of six bits transmissions using SM, STBC and QOSTBC

F. *Evaluation of QO-STBC for N_R Receivers*

The interference-free QOSTBC provides information into the performance of the scheme with an increasing number of receivers, as shown in Figure 12.

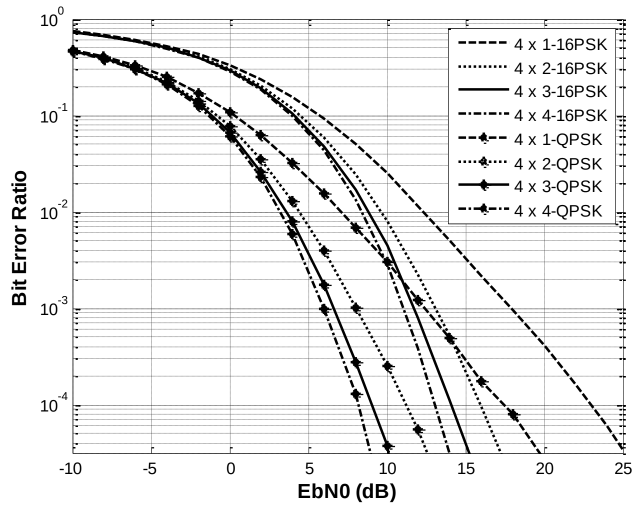

Figure 12: Evaluation of receiver diversity order for N_R QOSTBC system

While the SM performance improvement stems largely from the mapping scheme rather than on the number of transmitting antennas, the QO-STBC scheme exploits the diversity gain of the transmitting antennas spaces when compared to the STBC scheme. For instance, in Figure 12, it is observed that as the number of the receiving antennas increases, the diversity gain increasingly diminishes for both mapping schemes shown (QPSK and 16PSK). The self-interfering terms (β) in (25) even though eliminated in (28) further impact the true gain λ_h .

However, mobile nodes are not suited (in terms of size and battery life) in supporting a large number of antennas, for example, and the slope of the 4×2 MIMO BER plot reflects appreciable space and time coding gain better (in terms of difference between N_R = 2 and 1 compared to N_R = 3 and 2) than the rest N_R = 3 and 4. Thus, interference-free QOSTBC is an excellent technique for MIMO configuration in modern and future wireless communication applications. It transfers the complexity of the multiple antenna design algorithm from the receiver to the transmitter; transmitters, such as base stations, are more flexible in supporting complex algorithms than the receivers (such as mobile devices). By EVCM, the QOSTBC scheme studied simplifies the decoupling of the transmitted information in the receiver.

4. Conclusion

In this study, three different diversity schemes for MIMO systems were studied. These schemes include spatial modulation, STBC and QOSTBC. In the study, we explored the performance of these diversity techniques at low and relatively high spectral efficiencies. Most QOSTBC studies emphasise performance improvement with different code structures; here we implemented the scheme to include receiver diversity using MRC. Up to $4\times N_R$ can be implemented and only 4×4 QOSTBC with MRC has been investigated. The study showed that over all, the MIMO QOSTBC (for instance 4×4) scheme performed better than SM while the MIMO-STBC technique performed worst at relatively high spectral efficiency but best at low spectral efficiency. From the study, it can be said that the strength of the SM diversity scheme is in the signal modulation order, that is, the performance of the SM diversity scheme improves as the signal modulation order increases up to four bits transmission (as investigated above). At relatively low spectral efficiency (e.g. up to four bits transmission), the modulation order (with lower transmitter antenna diversity) mostly impacted the performance of the SM scheme while at relatively high spectral efficiency (e.g. at six bits transmission), lower modulation (against higher modulation order) was improved by more transmitter antenna diversity. Notwithstanding, using the QOSTBC scheme with four receiver antennas, the performance of the SM diversity scheme is poorer. Finally, where a higher signal modulation order is required, then a higher number of transmitting elements must be preferred.

Acknowledgement

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