Performance Optimization of Open-Loop MIMO Systems With Orthogonal Space–Time Block Codes

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Abstract—**In order to obtain full spatial diversity available in a multiple-input multiple-output (MIMO) system, orthogonal space–time block codes (OSTBC) are employed due to their low decoding complexity. However, the drawback of OSTBC is that the code rate decreases with increasing number of transmit antennas. Using a recent result on the properties of Gaussian quadratic forms, we show that an OSTBC for an odd number of transmit antennas is always outperformed in terms of different performance measures, namely, the outage probability, the outage mean-squared error (MSE), and the raw bit-error rate (BER), by an OSTBC for an even number of transmit antennas, which has a strong impact on the design and application of OSTBC.**

Index Terms—**Bit-error rate (BER), mean-squared error (MSE), number of transmit antennas, orthogonal space–time block codes (OSTBC), outage.**

I. Introduction

IN WIRELESS communications, one applies multiple antennas in order to increase the reliability of wireless systems. Thus, many techniques that utilize the spatial domain were proposed and analyzed. Due to their low decoding complexity, orthogonal space–time block codes (OSTBC) gained a lot of interest in the research community. They have been proposed in [1]–[3]. In [4]–[6] (and others), the performance of OSTBC was analyzed for different scenarios. One big disadvantage of OSTBC is that the higher the number of transmit antennas, the lower the code rate that can be supported [2], [7]. Thus, in order to achieve high spectral efficiency, higher modulation orders have to used in order to compensate the rate loss (since all degrees of freedom are used to obtain diversity). Note, however, that higher constellations complicate amplification, synchronization, and detection. Recently, this rate loss or rate reduction was characterized completely for OSTBC without linear processing of information symbols [8]. Note that the rate reduction derived in [8] has been conjectured in [7] to hold for OSTBC with linear processing of information symbols as well.

On the one hand, it was conjectured in [9] that the optimal transmit strategy for minimizing the outage probability is to use only a subset of the transmit antennas and distribute the power equally among this subset. The conjecture was proven later on in [10], showing that for fixed transmission rate and increasing signal-to-noise ratio (SNR), more and more antennas should be used. On the other hand, OSTBC suffer from rate reduction with increasing number of transmit antennas. In this letter, we show that both effects lead to a suboptimality of an odd number of transmit antennas with respect to the different performance measures.

It is important to note that different from [10], here we apply OSTBC, which has an dramatic impact on the optimization. Based on different performance measures, we show that an OSTBC for an odd number of transmit antennas, say, $k+1$ with even k, is always outperformed by an OSTBC for an even number of transmit antennas, either by k or $k+2$, which has a rather interesting impact on the design and application of OSTBC. This is in contrast to [10], where the objective function (outage probability) may also be minimized by an odd number of transmit antennas. The suboptimality of an odd number of transmit antennas was also shown in [11], where the analysis was restricted to the outage probability. Here we extend the work performed in [11] to other performance measures, namely, the MSE and the bit-error rate (BER). We also present a much simpler approach than in [11], which is based on a power series expansion, to verify our claims.

II. System Model

We consider a system with n_T transmit and n_R receive antennas. Our system model is defined by $\mathbf{Y}=\mathbf{G}_{n_T}\mathbf{P}^{1/2}\mathbf{H}+\mathbf{N}$, where $\mathbf{G}_{n_T}$ is the $(T\times n_T)$ transmit matrix, $\mathbf{Y}=[\mathbf{y}_1,\ldots,\mathbf{y}_{n_R}]$ is the $(T\times n_R)$ receive matrix, $\mathbf{H}=[\mathbf{h}_1,\ldots,\mathbf{h}_{n_R}]$ is the $(n_T\times n_R)$ channel matrix, $\mathbf{P}=\mathrm{diag}(\mathbf{p})$ is the power allocation matrix, and $\mathbf{N}=[\mathbf{n}_1,\ldots,\mathbf{n}_{n_R}]$ is the complex $(T\times n_R)$ additive white Gaussian noise (AWGN) matrix, where an entry $\{n_{ti}\}$ of $\mathbf{N}(1\le i\le n_R)$ denotes the complex noise at the ith receiver for a given time $t(1\le t\le T)$. The real and imaginary parts of n_{ti} are independent and $\mathcal{N}(0,n_T/(2\mathrm{SNR}))$ distributed. The channel matrix $\mathbf{H}$ is a complex Gaussian random matrix with independent zero-mean unit variance entries $\sim\mathcal{CN}(0,1)$. The channel matrix is assumed to be constant for a block of T symbols and changes independently from block to block. It is further assumed that the transmitter has no channel state information (CSI), and the receiver has perfect CSI.

III. Preliminaries

A. Code Construction and Rate Reduction

A space–time block code is defined by its transmit matrix $\mathbf{G}_{n_T}$ given as $\mathbf{G}_{n_T}=\sum_{j=1}^{q}\mathbf{A}_j\mathrm{Re}(s_j)+i\mathbf{B}_j\mathrm{Im}(s_j)$. The symbols $\{s_j\}_{j=1}^{q}$ are elements of the vector $\mathbf{s}=[s_1,\ldots,s_q]^T$ of length q with $s_1,\ldots,s_q\in\mathcal{C}$, where $\mathcal{C}\subseteq\mathbb{C}$ denotes a complex modulation signal set with unit average power, e.g., M-PSK.

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The $\mathbf{A}_j, \mathbf{B}_j, 1 \leq j \leq q$ are $T \times n_T$ matrices that satisfy specific properties; see, e.g., [5].

The code rate r_c of a space–time code is defined as $r_c = q/T$. For an OSTBC with n_T transmit antennas, it was shown recently [8] that the maximum achievable rate is given by

$$r_c(n_T) = \frac{\left\lfloor \frac{n_T+1}{2} \right\rfloor + 1}{2\left\lfloor \frac{n_T+1}{2} \right\rfloor}. \tag{1}$$

It is obvious from (1) that r_c is a decreasing function with n_T. Furthermore, it holds that

$$\lim_{n_T \to \infty} r_c(n_T) = 1/2. \tag{2}$$

Note that the rate reduction function in (1) is a step function of the number of transmit antennas k, i.e., for the code rate r_c, it holds that $r_c(k+1) = r_c(k+2)$ with k even. This has an important impact on the optimization of the objective function such as the outage probability. The result of the optimization shows the fundamental difference to [10], since by using OSTBC, only even numbers of transmit antennas minimize the outage probability. To this end, in our analysis, we have to distinguish between odd and even numbers of transmit antennas, which was not necessary in [10].

After matched filtering with $\mathbf{A}_k^H \mathbf{H}^H$ and $i\mathbf{B}_k^H \mathbf{H}^H$, respectively, the effective signal model induced by OSTBC is

$$\tilde{\mathbf{y}} = \|\mathbf{P}^{1/2}\mathbf{H}\|_F \mathbf{s} + \tilde{\mathbf{n}} \tag{3}$$

with vector $\mathbf{s}, \tilde{\mathbf{y}}$, and $\tilde{\mathbf{n}}$ of length q, where $\tilde{\mathbf{n}}$ is additive Gaussian noise with i.i.d. entries.

B. *Properties of Gaussian Quadratic Forms*

We present the theorems from [10] for completeness, which we need in the following sections. Consider the quadratic form $Q_n = \sum_{i=1}^n \lambda_i |z_i|^2$, where the real and imaginary part of z_i are i.i.d. normal distributed variables, and λ_i are eigenvalues of some covariance matrix $\mathbf{R}$. $\mathbf{R}$ is positive semidefinite, implying $\lambda_i \geq 0, 1 \leq i \leq n$. Note that $\mathbb{E}(Q_n) = \mathrm{tr}(\mathbf{R}) = \sum_{k=1}^n \lambda_k = 1$. Furthermore, let χ_d^2 be a random variable that is χ^2 distributed with d degrees of freedom. The main theorem proved in [10] is as follows.

Theorem 3.1:

$$\inf_{\{Q_n \geq 0 | \mathbb{E}(Q_n)=1\}} P(Q_n \leq x) = \begin{cases} P\left\{\frac{1}{d}\chi_d^2 \leq x\right\}, & \forall x \in [x(d), x(d-1)], d=1,2,\ldots,n-1 \\ P\left\{\frac{1}{n}\chi_n^2 \leq x\right\}, & \forall x \in [0, x(n-1)], \end{cases} \tag{4}$$

where $x(0) = \infty$ by definition.

IV. Outage Performance

OSTBC have been analyzed from an average and outage performance point of view. Scenarios with delay constraints or where a certain level of reliability has to be guaranteed are better captured through an outage analysis. For coded systems, the outage probability itself serves as a lower bound on the frame error performance [12]. The outage probability P_{out} achievable with OSTBC is defined as the probability that the mutual information is smaller than a certain transmission rate R, i.e., with

$$P_{\text{out}}(R, n_T, \rho, r_c) = \Pr(I \leq R) \tag{5}$$

where I is the mutual information corresponding to the effective channel induced by OSTBC, given as

$$I = r_c \log\left(1 + \frac{1}{N_0}\sum_{j=1}^{n_T} p_j \sum_{i=1}^{n_R} |h_{j,i}|^2\right). \tag{6}$$

Note that the effective channel induced by OSTBC may be described as a single-input, single-output (SISO) channel with $\|\mathbf{H}\|_F^2$ as the channel gain. Using (6) in (5) results in

$$f(\rho, \tilde{R}_{n_T}, \lambda, \mathbf{p}) = \Pr\left(\|\mathbf{P}^{1/2}\mathbf{H}\|_F^2 \leq N_0\left(2^{\frac{R}{r_c}} - 1\right)\right) \tag{7}$$

with the SNR $\rho = P/N_0$, the power allocation vector $\mathbf{p}$, and the effective rate $\tilde{R}_{n_T} = R/r_c(n_T)$.

A closely related instantaneous performance measure to the instantaneous capacity is the MSE. For this effective SISO channel, the relation between the mutual information, the SINR, and the MSE is described by $I = \log(1 + \mathrm{SINR}) = -\log(\mathrm{MSE})$. The rate reduction by the code rate r_c carries over to the MSE by $\mathrm{MSE}(r_c) = \mathrm{MSE}^{r_c}$. Hence, the outage MSE is given by

$$M(\rho, \mathrm{MSE}, \lambda, \mathbf{p}) = \Pr\left(\|\mathbf{P}^{1/2}\mathbf{H}\|_F^2 \leq \frac{\mathrm{MSE}^{-\frac{1}{r_c}} - 1}{\rho}\right). \tag{8}$$

Comparing (7) with (8) shows that both outage performance measures have a similar structure.

A. *Optimal Power Allocation*

First, consider the following problem statement: The transmitter has no CSI, and the channel is spatially uncorrelated. What is the optimal power allocation under sum transmit power constraint $\mathrm{tr}\mathbf{P} \leq P$?

Let the transmitter have n_T transmit antennas, and the effective transmission rate is $\tilde{R}_{n_T}$. By Theorem 3.1, there are $n_T - 1$ SNR values such that the optimal power allocation is to allocate equal power to a subset of l antennas out of n_T. The SNR range in which only one antenna is active for outage probability minimization is given by

$$\underline{\rho} = \frac{P}{N_0} = \frac{2(2^{\tilde{R}} - 1)}{-2\mathcal{L}_w(-1, -1/2\exp(-1/2)) - 1}. \tag{9}$$

$\mathcal{L}_w$ is the Lambert W function. Its value for the parameters -1 and $-1/2\exp(-1/2)$ approximately is -1.756. As a result, the single-antenna region can be written as $\underline{\rho} = (2^{\tilde{R}} - 1)/1.258$. For outage MSE minimization, the single-antenna region can be written as $\underline{\tilde{\rho}} = (\mathrm{MSE}–1)/1.258$.

In Theorem 3.1, it is shown that the minimum of the quadratic form is achieved for all regions $[x(d), x(d-1)]$ by a χ^2 distribution with d degrees of freedom. In our case, the range $x(d)$ is parameterized by the SNR ρ. The optimality of the equal power allocation for high SNR values is proved in Corollary 3.2. It follows that the outage probability in (7) as a function of l is given as

$$P_{\text{out}}(R, l, \rho) = 1 - \frac{\Gamma\left(ln_R, \left(2^{R/r_c(l)} - 1\right)\frac{l}{\rho}\right)}{\Gamma(ln_R)}, 1 \leq l \leq n_T. \tag{10}$$

Correspondingly, the outage MSE as a function of the number of active antennas l is given by $M_{\text{out}}(\mathrm{MSE}, l, \rho) =$

$1 - \frac{\Gamma\left(l n_R, \left(\mathrm{MSE}^{-\frac{1}{r_c}} - 1\right)\frac{l}{\rho}\right)}{\Gamma(l n_R)}, 1 \leq l \leq n_T$. Further, from [11, Theorem 4] and (2), it follows that the SNR value at which equal power allocation over all n_T transmit antennas is optimal converges to $\bar{\rho}^* = 2^{2R} - 1$. In the following analysis, we restrict ourself to the MISO case ($n_R = 1$). Note, however, that the results also hold for the more general MIMO case ($n_R > 1$).

Applying the power series expansion to (10) at $\bar{\rho}^*$ for $n_R = 1$ and truncating it after the linear term results in (11)–(13), shown at the bottom of the page, where z_k, z_{k+1}, and z_{k+2} is the linear approximation of the outage probability in (10) for $k, k+1$, and $k+2$ transmit antennas with $2 \leq k \leq n_T$ and k even. Note that since $r_c(k+1) = r_c(k+2)$, it follows that $\tilde{R}_{k+1} = \tilde{R}_{k+2}$. By comparing (11)–(13), observe that the constant terms $C(z_k), C(z_{k+1}), C(z_{k+2})$ have the following order $C(z_{k+1}) > C(z_{k+2}) > C(z_k)$. Furthermore, since the slope of z_{k+2} is steeper than that of the other curves, it follows that the intersection point between the linear functions z_k and z_{k+2} is at smaller SNR values in comparison to the intersection point of z_k and z_{k+1}. The same line of argument can be applied to (15). Thus, it is suboptimal to use an OSTBC for an odd number of transmit antennas with respect to outage probability and outage MSE.

V. BER Performance

Using the signal-space concept proposed in [13] for the instantaneous BER for M-PSK and M-QAM given as

$$P_{e,\mathrm{MPSK}} \approx 2\alpha \sum_{i=1}^{\max(M/4,1)} Q\left(\sin\left(\frac{(2i-1)\pi}{M}\sqrt{2\gamma_s}\right)\right)$$

where $\alpha = (1/\max(\log_2 M, 2))$ and

$$P_{e,\mathrm{MQAM}} \approx \frac{4\left(1 - \frac{1}{\sqrt{M}}\right)}{\log_2 M} \sum_{i=1}^{\sqrt{M}/2} Q\left((2i-1)\sqrt{\frac{3}{M-1}\gamma_s}\right)$$

respectively, where $\gamma_s = P/(r_c N_0)\|\mathbf{H}\|_F^2$ is the instantaneous SNR. Averaging over all channel realizations results in

$$\mathrm{BER}_{\mathrm{MPSK}} \approx \alpha \sum_{i=1}^{\max(\frac{M}{4},1)} \left(1 - \sum_{k=0}^{n_T n_R - 1} \mu_i \left(\frac{1-\mu_i^2}{4}\right)^k \binom{2k}{k}\right) \tag{14}$$

with $\mu_i = \sqrt{\frac{\sin^2(2i-1)\frac{\pi}{M}\frac{\rho}{r_c}}{1+\sin^2(2i-1)\frac{\pi}{M}\frac{\rho}{r_c}}}$ for M-PSK. For high SNR, the first term, i.e., $i = 1$, will dominate the BER performance such that the terms for $i > 1$ may be neglected resulting in the closed-form expression derived in [14]. Similarly, we have

$$\mathrm{BER}_{\mathrm{MQAM}} \approx 2\alpha \sum_{i=1}^{\max(\frac{M}{4},1)} \left(1 - \left(1 - \frac{1}{\sqrt{M}}\right) \times \left(1 - \sum_{k=0}^{n_T n_R - 1} \mu_i \left(\frac{1-\mu_i^2}{4}\right)^k \binom{2k}{k}\right)\right) \tag{15}$$

with $\mu_i = \sqrt{\frac{(2i-1)^2 3\frac{\rho}{r_c}}{2(M-1)+(2i-1)^2 3\frac{\rho}{r_c}}}$ for M-QAM, respectively.

VI. Simulations

In this section, some simulation results are shown in order to support the theoretical claims from the previous section. We would like to stress that in order to have a fair comparison, we analyze all the OSTBC at the same spectral efficiency or transmission rate R. In Fig. 1, the outage probability for OSTBC for $n_T = 2, n_T = 3$, and $n_T = 4$ transmit and one receive antennas is depicted. In addition to that, the power series expansions given by (11)–(13) are shown (dotted lines). Note that the code rates of the OSTBC for $n_T = 4$ and $n_T = 3$ equal $r_c = 3/4$, whereas $r_c = 1$ for $n_T = 2$. From the figure, we observe that for small SNR values, the OSTBC for $n_T = 2$ performs best. The intersection point of the OSTBCs with $n_T = 2$ and $n_T = 4$ is approximately at the above-mentioned $\bar{\rho}^*$, at which using $n_T = 4$ is optimal. Therefore, the OSTBC for $n_T = 3$ is outperformed by the OSTBC with even number of transmit antennas (either $n_T = 2$ or $n_T = 4$) for all SNR values as predicted by the analysis of the power series expansion. Obviously, the approximated series expansion becomes more inaccurate the further the SNR deviates from $\bar{\rho}^*$. The most important aspect, however, is that it is tight at $\bar{\rho}^*$, showing that at the intersection point of the OSTBCs with $n_T = 2$ and $n_T = 4$, the outage probability with $n_T = 3$ is higher. Trivially, the outage probability for $n_T = 4$ is for $\mathrm{SNR} > \bar{\rho}^*$ lower than for $n_T = 3$, since the diversity gain shows its effect (cf. [11, Theorem 4]).

Note that the same behavior is also observed for higher number of transmit and receive antennas.

$$z_k = -\frac{k\left(\frac{(2^{\tilde{R}_k}-1)k}{\bar{\rho}^*}\right)^{k-1} e^{\frac{(2^{\tilde{R}_k}-1)k}{\bar{\rho}^*}}(2^{\tilde{R}_k}-1)k}{k!(\bar{\rho}^*)^2} \times (\rho - \bar{\rho}^*) + \underbrace{1 - \frac{k\Gamma(k, \frac{(2^{\tilde{R}_k}-1)k}{\bar{\rho}^*})}{k!}}_{C(z_k)} \tag{11}$$

$$z_{k+1} = -\frac{(k+1)\left(\frac{(2^{\tilde{R}_{k+1}}-1)(k+1)}{\bar{\rho}^*}\right)^{k} e^{\frac{(2^{\tilde{R}_{k+1}}-1)(k+1)}{\bar{\rho}^*}}(2^{\tilde{R}_{k+1}}-1)(k+1)}{(k+1)!(\bar{\rho}^*)^2}(\rho - \bar{\rho}^*) + \underbrace{1 - \frac{(k+1)\Gamma((k+1), \frac{(2^{\tilde{R}_{k+1}}-1)(k+1)}{\bar{\rho}^*})}{(k+1)!}}_{C(z_{k+1})} \tag{12}$$

$$z_{k+2} = -\frac{(k+2)\left(\frac{(2^{\tilde{R}_{k+2}}-1)(k+2)}{\bar{\rho}^*}\right)^{k+1} e^{\frac{(2^{\tilde{R}_{k+2}}-1)(k+2)}{\bar{\rho}^*}}(2^{\tilde{R}_{k+2}}-1)(k+2)}{(k+2)!(\bar{\rho}^*)^2}(\rho - \bar{\rho}^*) + \underbrace{1 - \frac{(k+2)\Gamma((k+1), \frac{(2^{\tilde{R}_{k+2}}-1)(k+2)}{\bar{\rho}^*})}{(k+2)!}}_{C(z_{k+2})} \tag{13}$$

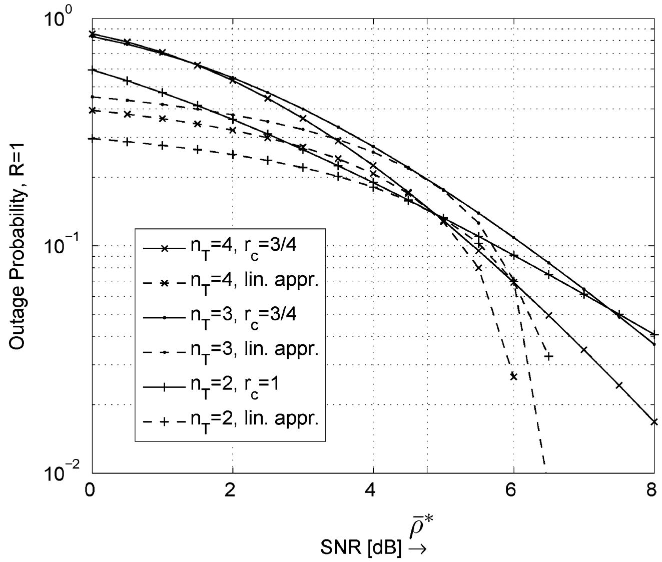

Fig. 1. Outage probability of OSTBC with $n_R = 1$ receive and $n_T = 2, 3,$ and 4 transmit antennas, transmission rate $R = 1$.

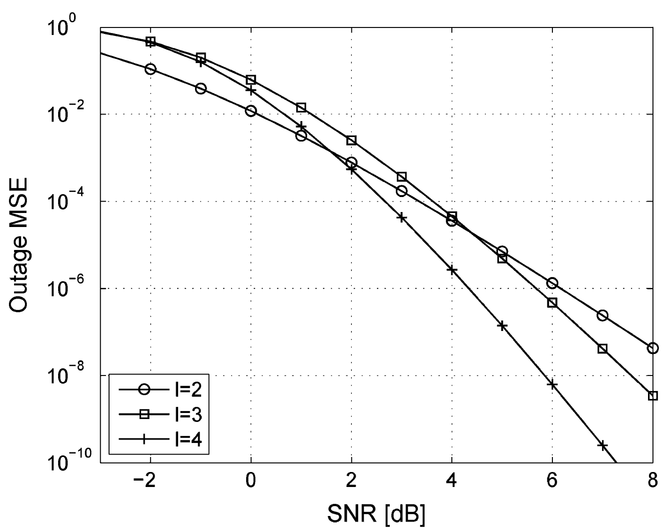

Fig. 2. Outage MSE of OSTBC with $n_R = 4$ receive and $l = 2, 3,$ and 4 active transmit antennas, envisaged $\mathrm{MSE} = 0.4$.

In Fig. 2, the outage MSEs for OSTBC for $l = 2, 3, 4$ active antennas, $n_R = 4$, and $\mathrm{MSE} = 0.4$ are plotted over the SNR. The behavior is similar to the outage probability curves in Figs. 1 and 2. To minimize the outage MSE, at about 1.5 dB, you should switch from two to four transmit antennas, omitting three transmit antennas.

In Fig. 3, the BER for the OSTBC $\mathcal{G}2(r_c = 1), \mathcal{H}3(r_c = 3/4)$, and $\mathcal{H}4(r_c = 3/4)$ [2] for a transmission rate of 3 bit/s/Hz are depicted. From the figure, we observe the same behavior as in the outage performance analysis, i.e., for low SNR values, the OSTBC for $n_T = 2$ provides the best performance and is then outperformed by the OSTBC for $n_T = 4$ transmit antennas. The OSTBC for $n_T = 3$, i.e., $\mathcal{H}3$, is always outperformed by either the $\mathcal{G}2$ or $\mathcal{H}4$, respectively.

The behavior becomes more obvious by using OSTBC with even lower code rates than achievable for a certain number of

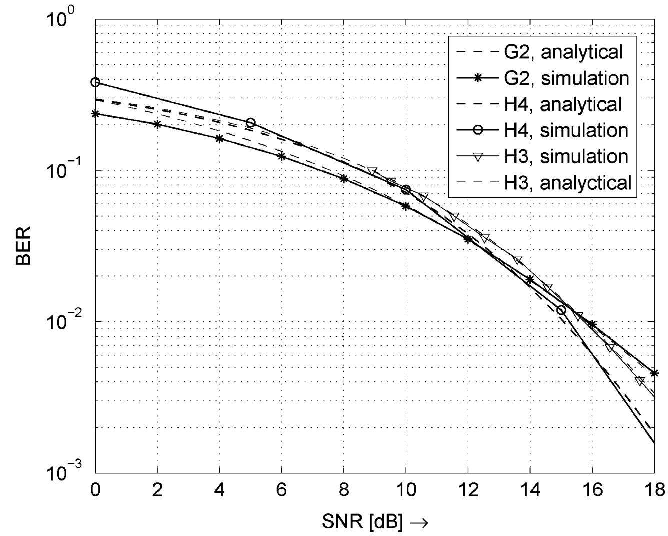

Fig. 3. BER for the OSTBC $\mathcal{H}4, \mathcal{H}3$, and $\mathcal{G}2$ for 3 bit/s/Hz.

transmit antennas (e.g., using $\mathcal{G}3(r_c = 1/2)$ instead of $\mathcal{H}3$ and $\mathcal{G}4(r_c = 1/2)$ instead of $\mathcal{H}4$ [2]).

Finally, we would like to point out that both the analytical expression in Sections IV and V and the numerical examples in Section VI support the main statement of this letter that the objective function is not minimized by using an odd number of transmit antennas.

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