Generalised Spatial Modulation

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***Abstract*—In this paper, a generalised technique for spatial modulation (SM) is presented. Generalised spatial modulation (GSM) overcomes in a novel fashion the constraint in SM that the number of transmit antennas has to be a power of two. In GSM, a block of information bits is mapped to a constellation symbol and a spatial symbol. The spatial symbol is a combination of transmit antennas activated at each instance. The actual combination of active transmit antennas depends on the random incoming data stream. This is unlike SM where only a single transmit antenna is activated at each instance. GSM increases the overall spectral efficiency by base–two logarithm of the number of antenna combinations. This reduces the number of transmit antennas needed for the same spectral efficiency. The performance of GSM is analysed in this paper, and an upper bound on the bit–error–ratio (BER) performance is derived. In addition, an algorithm to optimise the antenna combination selection is proposed. Finally, the performance of GSM is validated through Monte Carlo simulations. The results are compared with traditional SM. It is shown that for the same spectral efficiency GSM performs nearly the same as SM, but with a significant reduction in the number of transmit antennas.**

***Index Terms*—Spatial modulation, generalised spatial modulation, MIMO.**

I. Introduction

Multiple-input multiple-output (MIMO) systems offer a significant increase in spectral efficiency, in comparison to single antenna systems [1]. An example is the Vertical Bell Labs layered space-time (V-BLAST) architecture [2], where the spectral efficiency increases linearly with the number of transmit antennas. However, transmitting from all antennas at the same time, on the same frequency, causes inter-channel interference (ICI) at the receiver.

Spatial Modulation (SM) is a spatial multiplexing MIMO technique that is proposed in [3] to increase the spectral efficiency and to overcome inter–channel interference (ICI). This is attained by activating only a single transmit antenna at each instance to transmit a certain data symbol, where the active antenna index and the data sent depend on the incoming random data bits. Thereby, an overall increase in the spectral efficiency by base–two logarithm of the number of transmit antennas is achieved. Note that, the number of transmit antennas must be a power of two. A detector that jointly estimates the active antenna index and the sent data symbol is required at the receiver side. The optimal SM decoder is proposed in [4] and SM combined with trellis-coded modulation (TCM) is recently proposed in [5]. Furthermore, space shift keying (SSK) with partial channel state information is presented in [6], and a general framework for performance analysis of SSK for multiple input single output (MISO) systems over correlated Nakagami-m fading channels is shown in [7]. It is shown in [3]–[5] that ICI avoidance results in better BER performance and a significant reduction in detection complexity, as compared to V-BLAST, for instance. However, the logarithmic increase in spectral efficiency and the requirement that the number of antennas must be a power of two would require large number of antennas.

Fractional bit encoded spatial modulation (FBE-SM) is proposed in [8] to overcome the limitation in the number of transmit antennas. FBE-SM is based on the theory of modulus conversion and allows an arbitrary number of transmit antennas. However, the system suffers from error propagation.

An alternative approach to limit the number of transmit antennas is proposed in this paper. Generalised spatial modulation (GSM) activates more than one transmit antenna at a time to simultaneously transmit a data symbol. In GSM the transmitted information is conveyed in the activated combination of transmit antennas and the transmitted symbol from a signal constellation. As a result, the number of transmit antennas required to achieve a certain spectral efficiency is reduced by more than a half in GSM as compared to SM, and generalised space shift keying modulation (GSSK) proposed in [9]. Transmitting the same data symbol from more than one antenna at a time, retains the key advantage of SM, which is the complete avoidance of ICI at the receiver. Moreover, GSM offers spatial diversity gains and increases the reliability of the wireless channel, by providing replicas of the transmitted signal to the receiver [10]. Nonetheless, the activated transmit antennas must be synchronised to avoid inter-symbol interference (ISI). At the receiver, a maximum likelihood (ML) detection algorithm is considered to estimate the activated combination of transmit antennas and the transmitted constellation symbol.

A tight analytical upper bound for the BER performance of GSM is derived in this paper and analytical results are validated through Monte Carlo simulation results. Moreover, GSM performance is shown to be very close to the performance of SM but with major reduction in the required number of transmit antennas.

The remainder of this paper is organised as follows: Section II presents GSM system model and the optimal detection technique. Section III presents the analytical BER derivation for GSM and proposes the selection process for the optimal antenna combinations. The receiver complexity is discussed in

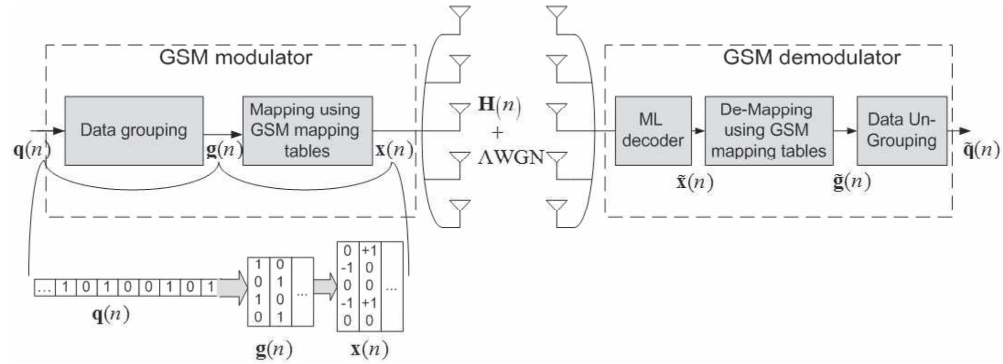

Fig. 1. Generalised spatial modulation system model. At each instance, four bits are transmitted. Three bits are encoded in the indices of the combination of transmit antennas and one bit is conveyed in the signal domain using BPSK modulation.

section IV. Monte Carlo Simulation results are presented in Section V, and the paper is concluded in Section VI.

II. GSM System Model

GSM uses more than one transmit antenna to send the same complex symbol. Hence, a set of antenna combinations can be formed, and used as spatial constellation points. The number of possible antenna combinations is $N_c^{'} = \binom{N_t}{N_u}$, where N_t is the number of transmit antennas and N_u is the number of active antennas at each instance. However, the number of antenna combinations that can be considered for transmission must be a power of two. Therefore, only $N_c = 2^{m_\ell}$ combinations, can be used, where $m_\ell = \lfloor \log_2 \binom{N_t}{N_u} \rfloor$, and $\lfloor \cdot \rfloor$ is the floor operation.

The GSM system model is depicted in Fig. 1 and an example of data mapping and transmission for two instances is also shown. The incoming data bits are mapped to a spatial symbol and a data symbol according to the mapping table shown in Table I. The mapping procedure maps the first m_ℓ bits to the antenna combinations, and the remaining bits (m_s) are modulated using M-QAM modulation, where $M = 2^{m_s}$. In the example, $N_t = 5$ and $N_u = 2$ are assumed. The resultant antenna combinations are listed in Table I. For instance, the data bits to be transmitted at the first instance in Fig. 1 $\mathbf{g}(n) = \begin{bmatrix} 0 & 1 & 0 & 1 \end{bmatrix}$ are mapped to $\mathbf{x}(n) = \begin{bmatrix} +1 & 0 & 0 & +1 & 0 \end{bmatrix}$. Each column vector of $\mathbf{x}(n)$ is transmitted at a specific instance from the existing five transmit antennas where only two antennas are activated at any given time. If SM is used instead with the same modulation order, the number of transmit antennas must be increased to eight to maintain the same spectral efficiency. In general, the number of bits that can be transmitted using GSM is given by,

$$m = m_\ell + m_s = \left\lfloor \log_2 \binom{N_t}{N_u} \right\rfloor + \log_2 M \tag{1}$$

The GSM modulated signal is transmitted over an $N_r \times N_t$ MIMO Rayleigh flat fading wireless channel, $\mathbf{H}$, and, thus, the entries of $\mathbf{H}$ are modeled as complex independent and identically distributed (i.i.d.) Gaussian random variables with zero–mean and unit–variance, where N_r is the number of receive antennas.

TABLE I
GSM Mapping Table for $N_t = 5$, $N_u = 2$ and BPSK Modulation, where $(\cdot,\cdot)$ indicates the indices of the active antennas

Grouped Bits	Antenna Combination (ℓ)	Symbol (s)
0000	(1,2)	-1
0001	(1,2)	+1
0010	(1,3)	-1
0011	(1,3)	+1
0100	(1,4)	-1
0101	(1,4)	+1
0110	(1,5)	-1
0111	(1,5)	+1
1000	(2,3)	-1
1001	(2,3)	+1
1010	(2,4)	-1
1011	(2,4)	+1
1100	(3,5)	-1
1101	(3,5)	+1
1110	(4,5)	-1
1111	(4,5)	+1

The received signal at any given time is,

$$\mathbf{y} = \mathbf{h'}_\ell s + \mathbf{v} \tag{2}$$

where $s \in M$-QAM is the transmitted symbol, from the antenna combination $\ell = (\ell_1, \ell_2, \dots, \ell_{N_u}) \in \Phi$, ℓ_n indicates the index of the n-th antenna in the antenna combination ℓ, and Φ is the set of used antenna combinations. An optimal algorithm for the selection of Φ is proposed in next section. Furthermore the vector $\mathbf{h'}_\ell = \sum_{n=1}^{N_u} \mathbf{h}_{\ell_n}$ contains the summation of the active antennas channel vectors, and $\mathbf{h}_{\ell_n}$ is the channel vector from the active transmit antenna ℓ_n to all receive antennas. $\mathbf{v}$ is an AWGN vector with zero–mean and variance σ_n^2 per dimension at the receiver input.

At the receiver, the spatial symbol and the data symbol are jointly decoded using the ML principle, as follows,

$$\begin{aligned}[\tilde{\ell}, \tilde{s}] &= \arg\max_{\ell,s} p_{\mathbf{y}}(\mathbf{y}|\mathbf{x}, \mathbf{H}) \\ &= \arg\min_{\ell,s} \sum_{i=1}^{N_r} |y_i - h'_{\ell,i} s|^2 \end{aligned} \tag{3}$$

where,

$$p_{\mathbf{y}}\left(\mathbf{y}|s,\ell,\mathbf{H}\right)=\frac{1}{\left(\pi\sigma_n^2\right)^{N_t}}\exp\left(-\frac{\left\|\mathbf{y}-\mathbf{h'}_{\ell}s\right\|_{\mathrm{F}}^2}{\sigma_n^2}\right) \quad (4)$$

is the probability density function (PDF) of $\mathbf{y}$ conditional on s,ℓ and $\mathbf{H}$, $\|\cdot\|_{\mathrm{F}}^2$ is the Frobenius norm.

III. Analytical derivation and optimal combination selection

A. Analytical BER calculation of GSM

The analytical performance of GSM is estimated using the well-known union bounding technique [11]. The average BER in GSM is,

$$\Pr_{\text{e,bit}}\leq \mathrm{E}_{\mathbf{x}}\left[\sum_{\tilde{\ell},\tilde{s}}\frac{N\left(x_{\ell,s},x_{\tilde{\ell},\tilde{s}}\right)\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right)}{2^m}\right] \quad (5)$$

where $x_{\ell,s}$ indicates the symbol s transmitted from the antenna combination ℓ, $N\left(x_{\ell,s},x_{\tilde{\ell},\tilde{s}}\right)$ is the number of bits in error between $x_{\ell,s}$ and $x_{\tilde{\ell},\tilde{s}}$, and $\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right)$ denotes the probability of deciding on $x_{\tilde{\ell},\tilde{s}}$ given that $x_{\ell,s}$ is transmitted.

The probability $\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right)$ can be computed by using (3) as follows,

$$\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right)=\Pr\left(\sum_{i=1}^{N_r}\left|D_i(\ell,s)\right|^2>\sum_{i=1}^{N_r}\left|D_i(\tilde{\ell},\tilde{s})\right|^2\right) \quad (6)$$

where

$$D_i(\ell,s)=y_i-h'_{\ell,i}s, \quad (7)$$

and,

$$y_i=v_i+h'_{\ell,i}s, \quad (8)$$

where $v_i\sim\mathcal{CN}(0,\sigma_n^2)$. Substituting (8) into (7) result in,

$$D_i(\ell,s)=v_i \quad (9)$$

and

$$D_i(\tilde{\ell},\tilde{s})=v_i+h'_{\ell,i}s-h'_{\tilde{\ell},i}\tilde{s} \quad (10)$$

Hence, $D_i(\ell,s)\sim\mathcal{CN}(0,\sigma_n^2)$, $D_i(\tilde{\ell},\tilde{s})\sim\mathcal{CN}(0,\sigma^2_{D_{\tilde{\ell},\tilde{s}}})$, and,

$$\begin{aligned}\sigma^2_{D_{\tilde{\ell},\tilde{s}}} &= \sigma_n^2+\left(|s|^2+|\tilde{s}|^2\right)d(\ell,\tilde{\ell})+|s-\tilde{s}|^2\left(N_u-d(\ell,\tilde{\ell})\right)\\ &= \sigma_n^2+2\,\mathrm{Re}\{s\tilde{s}^*\}d(\ell,\tilde{\ell})+|s-\tilde{s}|^2N_u \quad (11)\end{aligned}$$

where $\mathrm{Re}(\cdot)$ is the real part of a complex variable and $d(\ell,\tilde{\ell})$ is the number of elements where ℓ and $\tilde{\ell}$ differ from each other.

Let,

$$\kappa_{D_{\ell,s}}=\sum_{i=1}^{N_r}\left|\frac{D_i(\ell,s)}{\sigma_n/\sqrt{2}}\right|^2 \quad (12)$$

and

$$\kappa_{D_{\tilde{\ell},\tilde{s}}}=\sum_{i=1}^{N_r}\left|\frac{D_i(\tilde{\ell},\tilde{s})}{\sigma_{D_{\tilde{\ell},\tilde{s}}}/\sqrt{2}}\right|^2 \quad (13)$$

be the summation of N_r squared complex Gaussian random variables, with zero mean and variance equal to 1, *i.e.* $\kappa_{D_{\ell,s}}$ and $\kappa_{D_{\tilde{\ell},\tilde{s}}}$ are a central chi–squared random variables with $2N_r$ degrees of freedom [11].

Substituting (12) and (13) in (6) gives,

$$\begin{aligned}\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right) &= \Pr\left(\frac{\sigma_n^2}{2}\kappa_{D_{\ell,s}}>\frac{\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}{2}\kappa_{D_{\tilde{\ell},\tilde{s}}}\right)\\ &= \Pr\left(\frac{\kappa_{D_{\tilde{\ell},\tilde{s}}}}{\kappa_{D_{\ell,s}}}<\frac{\sigma_n^2}{\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}\right) \quad (14)\end{aligned}$$

Both $\kappa_{D_{\tilde{\ell},\tilde{s}}}$ and $\kappa_{D_{\ell,s}}$ are chi–square distributed random variables and have the same degree of freedom. Let,

$$\varphi=\frac{\kappa_{D_{\tilde{\ell},\tilde{s}}}}{\kappa_{D_{\ell,s}}} \quad (15)$$

which follows an F–distribution with degrees of freedom $\varsigma_1=\varsigma_2=2N_r$. Substituting (15) in (14),

$$\begin{aligned}\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right) &= \Pr\left(\varphi<\frac{\sigma_n^2}{\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}\right)\\ &= F_\varphi\left(\frac{\sigma_n^2}{\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}\right). \quad (16)\end{aligned}$$

$F_\varphi(\cdot)$ is the cumulative distribution function (CDF) of the F–distributed random variable given by,

$$F_\varphi(x)=I_{\frac{\varsigma_1x}{\varsigma_1x+\varsigma_2}}\left(\varsigma_1/2,\varsigma_2/2\right), \quad (17)$$

where $I_x(a,b)$ is the regularised incomplete beta function given by,

$$I_x(a,b)=\frac{B(x;a,b)}{B(a,b)}=\frac{1}{B(a,b)}\int_0^x t^{(a-1)}\left(1-t\right)^{(b-1)}dt \quad (18)$$

with

$$B(a,b)=\int_0^1 t^{(a-1)}\left(1-t\right)^{(b-1)}dt \quad (19)$$

From (16) and (17) it follows that,

$$\Pr\left(x_{\ell,s}\rightarrow x_{\tilde{\ell},\tilde{s}}\right)=I_{\frac{\sigma_n^2}{\sigma_n^2+\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}}\left(N_r,N_r\right) \quad (20)$$

Substituting (20) in (5) yields,

$$\begin{aligned}\Pr_{\text{e,bit}} &\leq \mathrm{E}_{\mathbf{x}}\left[\sum_{\tilde{\ell},\tilde{s}}\frac{N\left(x_{\ell,s},x_{\tilde{\ell},\tilde{s}}\right)I_{\frac{\sigma_n^2}{\sigma_n^2+\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}}\left(N_r,N_r\right)}{2^m}\right]\\ &\leq \sum_{\ell,s}\sum_{\tilde{\ell},\tilde{s}}\frac{N\left(x_{\ell,s},x_{\tilde{\ell},\tilde{s}}\right)I_{\frac{\sigma_n^2}{\sigma_n^2+\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}}\left(N_r,N_r\right)}{2^{2m}} \quad (21)\end{aligned}$$

It is shown later in section V, that (21) gives a tight approximation to the GSM BER performance.

B. Optimal set of antenna combinations selection

The optimal antenna combination Φ_{opt} is found by minimising the average BER given in (21).

$$\tilde{\Gamma}_{\text{opt}} = \arg\min_{\Gamma} \Pr_{\text{e,bit}} \tag{22}$$

where Γ is the set of parameters (N_t, N_u, Φ).

From (21), it can be noted that only $N(x_{\ell,s}, x_{\tilde{\ell},\tilde{s}})$ and $\sigma^2_{D_{\tilde{\ell},\tilde{s}}}$ depend on Γ. Moreover, it can be found that the relation between I and $\sigma^2_{D_{\tilde{\ell},\tilde{s}}}$ is,

$$I_{\frac{\sigma_n^2}{\sigma_n^2+\sigma^2_{D_{\tilde{\ell},\tilde{s}}}}}(N_r, N_r) \propto \frac{1}{\sigma^2_{D_{\tilde{\ell},\tilde{s}}}} \tag{23}$$

Hence, the optimisation in (22) can be simplified to,

$$\tilde{\Gamma}_{\text{opt}} = \arg\min_{\Gamma} \sum_{\ell,s} \sum_{\tilde{\ell},\tilde{s}} \frac{N\left(x_{\ell,s}, x_{\tilde{\ell},\tilde{s}}\right)}{\sigma^2_{D_{\tilde{\ell},\tilde{s}}}} \tag{24}$$

Fig. 2 shows GSM BER performance using (21) for different set of parameters (Γ), where $m = 5$ and $N_r = 8$. On the one hand, it can be seen from Fig. 2 that the larger N_t is, the better the performance. On the other hand, as it will be shown in the next section, increasing N_t increases the complexity. Furthermore, increasing N_u increases the possibility of having the same antenna in different antenna combinations, which will reduce $d(\ell, \tilde{\ell})$, and consequently degrades GSM performance.

To further elaborate on this, it can be seen from Fig. 2 that there is an optimum number of transmit antennas. Generally a low number of transmit antennas (*e.g.* $N_t = 4$) results in a worse performance. However, increasing the number of transmit antennas does not necessarily improve the performance. For example, the performance of GSM with $N_t = 5$ is better than with $N_t = 6, 7$ or 8.

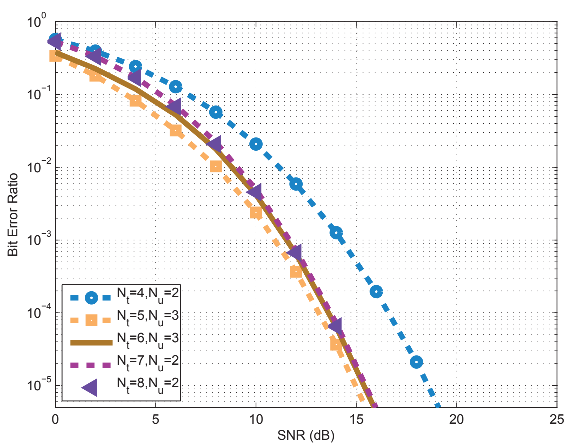

Fig. 2. GSM BER bounds for different Γ

Another interesting observation in Fig. 2 is that a different set of parameters might give very similar performance. In other words, there might not be a unique solution for the optimisation problem in (24) which provides useful flexibility for choosing Γ.

IV. Receiver Complexity

In this section the receiver complexity for GSM is compared to the complexity of the SM optimal decoder given in [4, eq. (4)], using the number of complex operations needed at the receiver. A complex operation is a complex multiplication or addition.

The optimum SM receiver is given by,

$$[\tilde{\ell}_{\text{SM}}, \tilde{s}_{\text{SM}}] = \arg\min_{\ell,s} ||\mathbf{g}_{\ell s}||^2 - 2\,\text{Re}\{\mathbf{y}^H \mathbf{g}_{\ell s}\} \tag{25}$$

where $\mathbf{g}_{\ell s} = \mathbf{h}_\ell s$. The complexity of SM optimal decoder in (25) is equal to $N_t M(3N_r + 1)$, where the first term $||\mathbf{g}_{\ell s}||^2$ needs $N_r + 1$ complex operations, and the second term $\mathbf{y}^H \mathbf{g}_{\ell s}$ needs $2N_r$ complex operations, giving a total of $3N_r + 1$ complex operations to compute the equation $(||\mathbf{g}_{\ell s}||^2 - 2\,\text{Re}\{\mathbf{y}^H \mathbf{g}_{\ell s}\})$, which is evaluated $N_t M$ times.

The GSM receiver has a complexity of $N_r N_c M(N_u + 2)$ complex operations, where the squared euclidean distance $|y_i - h'_{\ell,i} s|^2$ needs $N_u + 2$ complex operations, which is calculated $N_r N_c M$ times. Note that $h'_{\ell,i}$ requires a $N_u - 1$ complex summations.

The ratio of GSM receiver complexity to the complexity of SM optimal decoder for the same m_ℓ is,

$$R = \frac{N_r N_C M(N_u + 2)}{N_t M(3N_r + 1)} = \frac{N_r(N_u + 2)}{3N_r + 1} \tag{26}$$

where $N_t = N_c = 2^{m_\ell}$. This is plotted in Fig. 3 for $N_r = 8$. It can be seen that the complexity of GSM increases with the increase of N_u, but this increase is compensated by the substantial reduction in the number of transmit antennas.

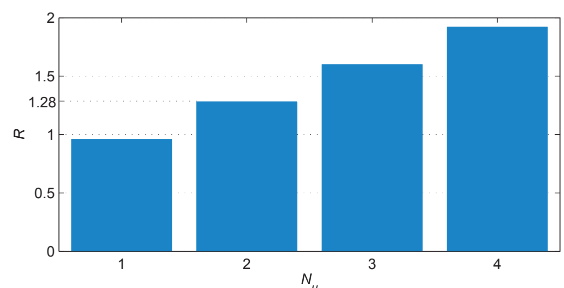

Fig. 3. The ratio of GSM receiver complexity to the complexity of SM optimal decoder

For example, let $m = 6$ bis/s/Hz, $M = 4$ and $N_r = 8$. GSM would have $\sim 28\%$ increase in complexity in comparison to SM, when $N_u = 2$. However, the number of transmit antennas required by GSM is less than half the number of transmit antennas required for SM, where $N_t = 7$ for GSM, and $N_t = 16$ for SM.

Another observation which can be made from Fig. 3 is that for $N_u = 1$ the complexity of GSM is less than the complexity of SM. This is because, the GSM ML receiver proposed here is less complex than the SM optimal decoder. Note that, GSM with only one active antenna resembles traditional SM.

V. Simulation Results

In the following, Monte Carlo simulation results for at least 10^6 channel realisations are considered in order to compare the performance of GSM with the performance of SM. In the analysis, two different set of parameters (Γ) are considered, to achieve a spectral efficiency of $m = 6$ bits/s/Hz, using $M = 4$ and $M = 8$ QAM and $N_r = 4$.

The BER performance versus signal to noise ratio (SNR) for $M = 4$ is depicted in Fig. 4, where for GSM $N_t = 7$ and $N_u = 2$ and for SM $N_t = 16$. The performance of GSM is nearly identical to the performance of SM. The better performance of SM is mainly due to the higher probability of error when detecting two active antennas instead of only one. However, SM requires more than twice the number of transmit antennas to achieve the same spectral efficiency as compared to GSM. The result also validates the derived analytical bound and shows that, indeed, it is very tight.

The results for $M = 8$ are depicted in Fig. 5 where $N_t = 5$ and $N_u = 2$ are considered for GSM and $N_t = 8$ for SM. Again, GSM and SM have nearly the same performance, with a slightly better performance of SM at high SNR.

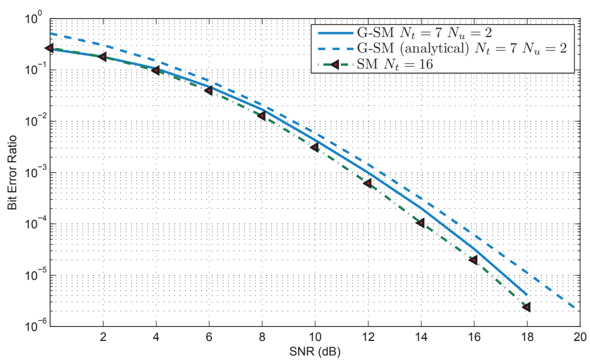

Fig. 4. BER performance versus SNR, for M=4

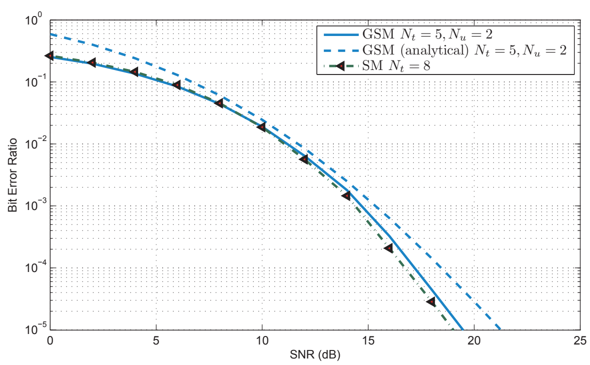

Fig. 5. BER performance versus SNR, for M=8

VI. Summary and Conclusions

In this paper SM was generalised by sending the same symbol from more than one transmit antenna at a time. Hence, SM is no longer limited to a number of transmit antennas which strictly has to follow a power of two. Instead an arbitrary number of transmit antennas can be used. Moreover, higher spectral efficiency can be achieved with a much lower number of transmit antennas, as compared to SM. These, enhancements are achieved at the cost of a slight increase in the complexity. This complexity increase depends on the number of active antennas. The smaller the number of active transmit antennas the less the complexity increase. In general, however, the increase in complexity is outweighed by the significant reduction in the number of transmit antennas. In this context, it is important to highlight that the BER performance of SM and GSM are almost identical. Moreover, GSM retains one of the key advantages of SM, namely that ICI is avoided while spatial multiplexing gains are obtained. Furthermore, this paper proposed a novel receiver based on the ML principle to determine the complete information bits, *i.e.*, the antenna combination used and the transmitted complex symbol. In addition, an algorithm to optimise the selection of the set of antenna combinations, was proposed. Finally, the analytical BER performance for GSM was derived, along with its complexity.

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