Hybrid Spatial Modulation Scheme with Arbitrary Number of Transmit Antennas

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Abstract. Spatial Modulation (SM) is a single RF chain Multi-Input-Multi-Output (MIMO) scheme that has significantly improved the spectral efficiency. A major limitation of SM is the constraint on the number of transmit antennas, where the number of transmit antennas must be a power of two. Generalized SM (GSM) is proposed to further improve the spectral efficiency of SM by activating multiple transmit antennas simultaneously. However, activating multiple antennas increases the energy consumption at the transmitter. To this end, a hybrid scheme is proposed in this paper that allows for arbitrary number of transmit antennas to be installed. For a given number of transmit antennas, the proposed scheme achieves higher spectral efficiency than SM. Also, for a given spectral efficiency, the proposed scheme consumes energy less than GSM, and causes a negligible loss in the error performance compared to SM and GSM.

Keywords: MIMO · Space modulation · Spatial modulation

1 Introduction

The growing demand for high data rates and the crowded spectrum bands motivate the research towards promising spectral efficient systems. One of these systems is Multiple-Input-Multiple-Output (MIMO) systems that enhance the overall spectral efficiency as they permit the simultaneous use of multiple antennas at transmitter and receiver [1]. However, a major problem of MIMO systems is the Inter-Channel Interference (ICI) between the transmit antennas [2]. To this end, Spatial Modulation (SM) has been proposed in order to overcome the ICI problem in MIMO systems [3].

In SM, only a single transmit antenna is activated at each transmission time. The index of the activated transmit antenna is selected based on a part of the transmitted block. For a system with N_t transmit antennas, and a signal modulation of order M, SM can transmit $\log_2 N_t M$ bits at each transmission time [4,5]. In each transmitted block, the first $\log_2 M$ bits are modulated and transmitted using a single transmit antenna that is selected based on the last $\log_2 N_t$

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bits. As such, ICI is totally avoided as only one transmit antenna is activated. Moreover, compared to other MIMO schemes, using a single RF chain reduces the energy consumption at the transmitter [6,7].

It is clear that N_t must be a power of two in order to have an integer value of the transmitted block length [8]. Thus, in the case that N_t is not a power of two, some transmit antennas will not be used. Generalized SM (GSM) has been proposed to release the constraint, and improve the attainable spectral efficiency [9]. GSM allows for activating multiple transmit antennas at each time. Although GSM can significantly enhance the spectral efficiency and allows for arbitrary number of transmit antennas to be installed, it magnifies the energy consumption at the transmitter since multiple antennas must be activated [10,11]. Energy consumption is a major concern in wireless systems especially for mobile users with limited power resources [12].

In the literature, several works have addressed the problem, and proposed solutions to solve the limitation on the number of transmit antennas in SM systems. In [13], a simple scheme is proposed to overcome the problem and enhance the performance under low Signal-to-Noise Ratio (SNR) conditions. Specifically, in case that N_t is not a power of two, it will be rounded to the nearest power of two value larger than N_t. Consequently, the data will be transmitted in blocks, each of $\lceil \log_2 N_t M \rceil$ bits. Each block is mapped to the antenna with minimum hamming distance in order to minimize the impact on the bit error rate (BER) performance. However, the proposed scheme shows a poor performance in high SNR range. Another solution using Fractional Bit Encoding (FBE) is reported in [14]. It is based on the modulus conversion method in order to allow for the usage of any arbitrary number of transmit antennas. FBE scheme achieves a fractional bit rate larger than that achieved by the conventional SM. However, its complexity cost and the high vulnerability to the propagation errors are the main drawbacks of [14]. Alternatively, an efficient scheme is proposed in [15], where different transmit antennas use different modulation orders. Specifically, the modulation order of the symbols emitted from each antenna and the length of the antenna index are adapted such that the block length is fixed for all symbols.

In this paper, a hybrid scheme of SM and GSM is proposed in order to improve the achievable spectral efficiency compared to SM, and to reduce energy consumption compared to GSM. The proposed scheme implies that if the number of transmit antennas is not a power of two, combinations of two antennas can be used in order to increase the achievable spectral efficiency with a slight increase in the BER. For example, if a transmitter has only 3 antennas, the proposed scheme implies that one combination of two different antennas can act as a fourth antenna. This way, the system will be able to provide one more bit to the spectral efficiency achieved by the conventional SM. The proposed scheme can be seen as a switching process between conventional SM and GSM. For a given number of transmit antennas, the proposed scheme achieves higher spectral efficiency than SM. Also, for a given spectral efficiency, the proposed scheme consumes energy less than GSM, and causes a negligible loss in the BER performance compared to

SM and GSM. The contributions of this works extend to include mathematical analysis of the achievable error performance and the saved energy as compared to the GSM scheme.

2 System Model

A MIMO communication system between two users (a transmitter and a receiver) is considered. The transmitter is equipped with N_t transmit antennas, while the receiver is equipped with N_r receive antennas. The channel matrix between the transmitter and the receiver is denoted by $\mathbf{H}$. The entries of $\mathbf{H}$ (i.e, h_{ji}, $j = 1, 2, ...N_r$, $i = 1, 2, ...N_t$) are assumed independently and identically distributed complex Gaussian random variables with zero mean and unity variance (i.e, $h_{ji} \sim \mathcal{CN}(0, 1)$). Also, we assume that the additive white Gaussian noise to the received signal at a specific receive antenna has zero mean and N_o variance. As such, the SNR at the receiver, denoted by γ is equal to $\gamma = \frac{1}{N_o}$.

Without loss of generality, we consider that the channel response matrix $\mathbf{H}$ is perfectly available at the receiver before each transmission time. This can be attained by a channel estimation process accomplished prior to data transmission between the communicating users. At the transmitter, the transmitted symbol can be conveyed by two different modulation schemes, namely, SM and GSM. In what follows, we give a brief description of both schemes.

2.1 Conventional SM Scheme

In the conventional SM scheme, the length of the transmitted block in bits (k_{SM}) is determined based on the number of transmit antennas N_t and the modulation order M. Specifically, k_{SM} is expressed as follows

$$k_{SM} = \begin{cases} \log_2 N_t + \log_2 M & \text{if } N_t = 2^i \\ \lfloor \log_2 N_t \rfloor + \log_2 M & \text{if } N_t \neq 2^i. \end{cases} \tag{1}$$

where $i = 1, 2, 3, ...$, and $\lfloor . \rfloor$ represents the flooring operator.

In SM, the first $\log_2 M$ bits of each block is modulated using the adopted modulation scheme, and transmitted through a single transmit antenna selected based on the last $\lfloor \log_2 N_t \rfloor$ bits of the transmitted block. Thus, the transmission vector $\mathbf{X}$ can be modeled as an $N_t \times 1$ vector with all-zero elements except one element which is set to the modulated signal. The index of the nonzero element of $\mathbf{X}$ corresponds to the index of the active transmit antenna.

A special case of SM is called Space Shift Keying (SSK) [16]. In SSK schemes, $M = 1$, and hence, no signal modulation is performed at the transmitter. Consequently, in SSK, data are transmitted by sending a fixed signal from a single transmit antenna whose index is determined based on the transmitted data block.

As k_{SM} must be an integer, (1) states that the conventional SM can only use a number of transmit antennas that is a power of two. Otherwise (i.e. if the number of transmit antennas is not a power of two), the largest power of two that is less than N_t should be used. Therefore, the conventional SM scheme cannot benefit from all the available transmit antennas when their number is not a power of two. Therefore, in such a case, an attainable spectral efficiency will be lost since a subset of the transmit antennas cannot be used.

2.2 GSM Scheme

Aiming at increasing the spectral efficiency of SM systems, GSM has been proposed in [9]. In GSM, the transmitter allows more than one transmit antenna to be activated at each transmission round. The core idea is to transmit through a combination of multiple transmit antennas. Assuming that the number of active antennas is N_a, the number of combinations of N_a is equal to $\binom{N_t}{N_a}$ possible combinations.

The length of transmitted block in GSM (k_{GSM}) is given as follows:

$$k_{GSM} = \begin{cases} \log_2 \binom{N_t}{N_a} + \log_2 M & \text{if } \binom{N_t}{N_a} = 2^i \\ \left\lfloor \log_2 \binom{N_t}{N_a} \right\rfloor + \log_2 M & \text{if } \binom{N_t}{N_a} \neq 2^i. \end{cases} \tag{2}$$

where $i = 1, 2, 3, ...$

Similar to SM schemes, in GSM, the first $\log_2 M$ bits of each block is modulated using the signal modulation scheme, while the the last $\left\lfloor \log_2 \binom{N_t}{N_a} \right\rfloor$ bits determine the N_a transmit antennas (among the N_t antennas) to send the modulated signal. Therefore, the transmission vector $\mathbf{X}$ in GSM includes N_a nonzero elements whose values are set to the modulated signal.

Compared to SM, GSM is able to achieve higher data rate as a longer data block can be delivered at every transmission round. However, the cost is paid by the need to activate N_a transmit antennas. Moreover, activating multiple transmit antennas will definitely increase the energy consumption at the transmitter [17].

3 The Proposed Scheme

The motivation behind the proposed scheme is to overcome the constraint on the number of the transmit antennas in SM. The proposed scheme grants the system designer more freedom to install any number of transmit antennas as long as the overall size of the transmitter is acceptable. It is assumed that the transmitter can switch between SM to GSM modes and via versa in order to convey longer symbols than the conventional SM.

The proposed scheme implies that the transmitted data are divided into blocks, each block contains k_{HSM} bits. Thus, the block length k_{HSM} can be expressed as follows:

$$k_{HSM} = \begin{cases} \log_2 N_t + \log_2 M & \text{if } N_t = 2^i \\ \lceil \log_2 N_t \rceil + \log_2 M & \text{if } N_t \neq 2^i. \end{cases} \tag{3}$$

where $i = 1, 2, 3, ...$, and $\lceil . \rceil$ represents the ceiling operator.

Notice that in the case $N_t = 2^i$ (i.e., a power of two), the proposed scheme works exactly as the conventional SM scheme. However, in the case of $N_t \neq 2^i$ (i.e., not a power of two), the transmitter will apply a hybrid mode between SM and GSM schemes. In other words, if N_t is not a power of two, the number of possible data block $2^{k_{HSM}}$ is grouped into two groups of blocks. The first group contains N_tM blocks, and each of them is transmitted using a single transmit antenna as in conventional SM scheme. On the other hand, the second group contain $2^{k_{HSM}} - N_tM$ blocks, where each of them is transmitted using a combination of two antennas as in GSM scheme. The following example explains how the proposed scheme works.

3.1 Numerical Example

Assume that a transmitter is equipped with $N_t = 5$ transmit antennas: $\{A_1, A_2, ..., A_5\}$. Also, assume that M is equal to one (SSK scheme). Conventionally, since 5 is not a power of two, the number of exploited transmit antennas is the largest power of two that is less than 5. Hence, only 4 antennas will be used. Using (1), the block length in the conventional SM is $k_{SM} = 2$ bits. Thus, the transmitted data will be divided into 2-bit blocks, and each block will be mapped to a different antenna, as shown in Table 1. It is worth noting that the fifth antenna (A_5) is not used in the conventional SM scheme.

If we consider GSM with $N_a = 2$ active antennas, the block length is $k_{GSM} = 3$ bits which is computed using (2). Thus, we have $2^3 = 8$ different possible data blocks, where each block is transmitted to a different combination of two transmit antennas, as shown in Table 1.

Following the proposed scheme, based on (3), the block length is $k_{HSM} = 3$ bits. Thus, the number of the possible different data blocks is $2^3 = 8$ blocks. As such, 5 (out of 8) blocks will be transmitted using a single transmit antenna, while the rest of the blocks (3 out of 8) will be transmitted using two transmit antennas for each. Notice that the three two-antennas combinations listed in Table 1 are randomly selected. Although an opportunistic combination selection can enhance the overall performance, such an enhancement is very marginal given the extra complexity accompanied by the selection procedure.

Comparing the three schemes, it is clear that the conventional SM is the most energy efficient among others, since it always uses a single transmit antenna. However, the conventional SM achieves the lowest spectral efficiency where it transmits only 2 bits at each transmission round. On the other hand, the spectral efficiency of the GSM scheme achieves the highest spectral efficiency (3 bits), while its energy efficiency is the worst since it always activates two transmit antennas. However, the proposed scheme is able to attain the best spectral efficiency (3 bits, as in GSM), with an improved energy efficiency compared to GSM systems. The improvement in energy efficiency stems from the fact that the proposed scheme does not always require two active transmit antennas.

For the seek of elaborating, let us assume that the energy consumed in SM is denoted by E_{SM}, and the energy consumed in GSM systems is denoted by E_{GSM}. Both values can be related to each other as follows

$$E_{GSM} = (1 + \rho)E_{SM}, \tag{4}$$

where ρ is a coefficient related to the extra energy consumption due to activating multiple transmit antennas in GSM schemes. Notice that $0 < \rho < 1$ in order to ensure that the extra energy consumption in GSM is less than using another RF chain. As such, the energy consumed in the proposed hybrid scheme, denoted by E_{HSM}, can be represented as follows

$$E_{HSM} = \alpha E_{SM} + (1 - \alpha)E_{GSM}, \tag{5}$$

where α is the probability that the proposed scheme uses a single transmit antenna. The probability α is related to the number of available transmit antennas N_t as follows

$$\alpha = \frac{N_t}{N_t^*}, \tag{6}$$

where N_t^* is the nearest power-of-two number equal or larger than N_t. Notice that if N_t is a power of two, the probability α is equal to 1, and hence, the proposed scheme will completely act like the conventional SM scheme.

Substituting (4) and (6) in (5), the energy consumption of the proposed scheme can be given as follows

$$\begin{aligned} E_{HSM} &= \frac{N_t}{N_t^*}E_{SM} + \frac{N_t^* - N_t}{N_t^*}(1 + \rho)E_{SM} \\ &= \frac{1}{N_t^*}E_{SM}\big(N_t + (N_t^* - N_t)(1 + \rho)\big) \\ &= \frac{1}{N_t^*}E_{SM}\big((1 + \rho)N_t^* - \rho N_t\big) \end{aligned} \tag{7}$$

The percentage of saved energy due to the proposed scheme as compared to the GSM scheme, denoted by E_s, is defined as follows

$$E_s\% = \frac{E_{GSM} - E_{HSM}}{E_{GSM}} \times 100\% = \frac{\rho N_t}{(1 + \rho)N_t^*} \times 100\%, \tag{8}$$

3.2 BER Performance

The average error probability for the proposed SM scheme can be formulated using the union bound technique [18] as follows

$$\text{BER} \leq \frac{1}{k_{HSM}2^{k_{HSM}}} \sum_{i=1}^{2^{k_{HSM}}} \sum_{j \neq i} D_{\mathbf{x}_i,\mathbf{x}_j} \text{PEP}_{\mathbf{x}_i,\mathbf{x}_j} \tag{9}$$

where $D_{\mathbf{X}_i,\mathbf{X}_j}$ is hamming distance (the number of different bits) between the transmission vectors $\mathbf{X}_i$ and $\mathbf{X}_j$, and $\text{PEP}_{\mathbf{X}_i,\mathbf{X}_j}$ is the pairwise error probability between the two vectors $\mathbf{X}_i$ and $\mathbf{X}_j$. The pairwise error probability is defined as the probability that $\mathbf{X}_i$ is detected given that $\mathbf{X}_j$ is transmitted.

For Rayleigh fading channel, the pairwise error probability is also upper bounded as follows [19]

$$\text{PEP}_{\mathbf{X}_i,\mathbf{X}_j} \leq \frac{1}{2\det(\mathbf{I}_{N_r N_t} + \frac{1}{2\sigma_n^2}\mathbf{\Psi})} \tag{10}$$

where $\mathbf{I}_{N_r N_t}$ is the identity square matrix, $\mathbf{\Psi} = \mathbf{I}_{N_r} \otimes \mathbf{\Delta}\mathbf{\Delta}^H$, $\mathbf{\Delta} = \mathbf{X}_i - \mathbf{X}_j$, the superscript ^{H} denotes the complex conjugate operator, $\otimes$ denotes the Kronecker product, and $det(\cdot)$ denotes the determinant operator. Therefore, the average BER of the proposed scheme over Rayleigh fading channels can be expressed by substituting (10) in (9) as follows

$$\text{BER} \leq \frac{1}{k_{HSM} 2^{k_{HSM}}} \sum_{i=1}^{2^{k_{HSM}}} \sum_{j \neq i} \frac{D_{\mathbf{X}_i,\mathbf{X}_j}}{2\det(\mathbf{I}_{N_r N_t} + \frac{1}{2\sigma_n^2}\mathbf{\Psi})} \tag{11}$$

Notice that the above upper bound can be used for SM and GSM scheme with careful substitution of the transmission vectors $\mathbf{X}$'s. Also, the average power of each transmission vector should be normalized to one.

Table 1. Symbol-Antenna mapping in the three schemes ($N_t = 5$)

SM		GSM ($N_a = 2$)		Proposed	
Symb.	Ant.	Symb.	Ants	Symb.	Ants
00	A_1	000	A_1 & A_2	000	A_1
01	A_2	001	A_2 & A_3	001	A_2
10	A_3	010	A_3 & A_4	010	A_3
11	A_4	011	A_4 & A_5	011	A_4
		100	A_5 & A_1	100	A_5
		101	A_2 & A_4	101	A_1 & A_2
		110	A_3 & A_5	110	A_3 & A_4
		111	A_1 & A_4	111	A_5 & A_1

4 Simulation Results

In this section we present Monte Carlo simulations in order to show the performance of the proposed hybrid SM scheme compared to the conventional SM and GSM schemes. The comparison metrics are the spectral efficiency, and the average BER.

The spectral efficiency versus the number of transmit antennas (N_t) for the three schemes are shown in Fig. 1. The number of active antennas in GSM is assumed $N_a = 2$. Compared to SM, the proposed scheme provides higher spectral efficiency when N_t is not a power of two, while in the case that N_t is a power of two (see at $N_t = 2, 4, 8$), both schemes achieve the same spectral efficiency. On the other hand, the proposed scheme achieves less spectral efficiency than GSM for a given number of transmit antennas. However, the performance improvement of GSM will be in the cost of the energy consumption.

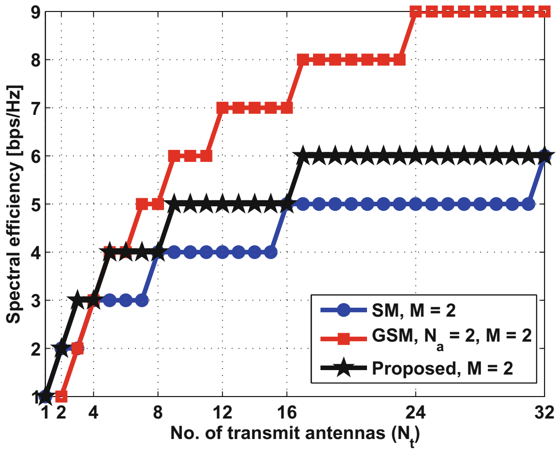

Fig. 1. The achievable spectral efficiency versus the number of available transmit antenna (N_t) for SM, GSM (with $N_a = 2$) and the proposed scheme.

The average BER for the proposed scheme versus the average SNR is shown in Fig. 2. $N_t = 3$, $M = 4$ and different values of N_r have been assumed. The analytical results obtained using the upper bound derived in (11) are added as well. At moderate and high SNR values, both the analytical and simulation curves match each other, which validates the derived formula in (11).

The average BER versus the average SNR for the three considered schemes is shown in Fig. 3. Specifically, SM with $N_t = 8$ and QPSK, GSM with $N_t = 5$, $N_a = 2$ and QPSK, and the proposed scheme with $N_t = 5, 6, 7$, and QPSK. The spectral efficiency of all schemes is 5 bps/Hz. The number of receive antennas is assumed $N_r = 3$. The performance of all schemes are almost equal. However, we zoomed in the average BER at $SNR = 9$ dB in the square shown in Fig. 3. As expected the conventional SM scheme achieves the best performance among all the considered schemes. For the proposed scheme, the achieved BER approaches the one achieved by the conventional SM as N_t approaches the power of two (i.e., 8). Moreover, the proposed scheme records better average BER values compared to GSM scheme.

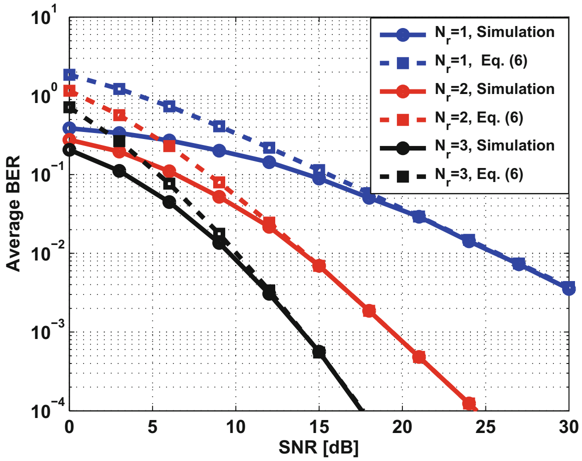

Fig. 2. Simulation and analytic results of the average BER versus the SNR for the proposed scheme. ($N_t = 3$, $M = 4$ (QPSK)).

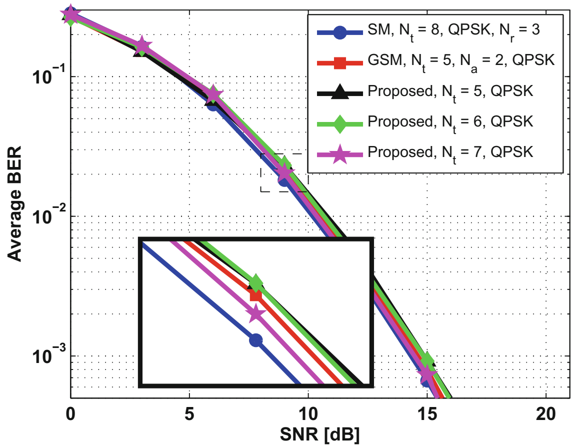

Fig. 3. The average BER versus the SNR for the three considered schemes. ($N_r = 3$).

5 Conclusions

In this paper, a hybrid SM scheme is proposed that allows for an arbitrary number of transmit antennas to be installed. The core idea of the proposed scheme is based on using a combination of two antennas in the case that the number of transmit antennas is not a power of two. The proposed scheme can be viewed as a combination between the conventional SM and GSM schemes. For a given number of transmit antennas, the proposed scheme achieves a moderate spectral efficiency between the conventional SM and GSM schemes. In addition, the proposed scheme consumes less energy compared to the GSM scheme. On the other hand, for a given spectral efficiency, the BER performance of the proposed scheme is almost identical to the BER achieved by the conventional scheme.

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