Enhanced Spatial Modulation With Multiple Signal Constellations

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***Abstract*—In this paper, we introduce a new spatial modulation (SM) technique using one or two active antennas and multiple signal constellations. The proposed technique, which we refer to as Enhanced SM or ESM, conveys information bits not only by the index(es) of the active antenna(s), but also by the constellations transmitted from each of them. The main feature of ESM is that it uses a primary signal constellation during the single active antenna periods and some other secondary constellations during the periods with two active transmit antennas. The secondary signal constellations are derived from the primary constellation by means of geometric interpolation in the signal space. We give design examples using two and four transmit antennas and QPSK, 16QAM, and 64QAM as primary modulations. The proposed technique is compared to conventional SM as well as to spatial multiplexing (SMX), and the results indicate that in most cases, ESM provides a substantial performance gain over conventional SM and SMX while reducing the maximum-likelihood (ML) decoder complexity.**

***Index Terms*—MIMO system, spatial modulation.**

I. Introduction

MULTIPLE-input multiple-output (MIMO) technologies are now commonplace in wireless communications systems to increase throughput, performance, or both. The basic principle of these technologies is well described in [1], and a comprehensive survey can be found in [2]. The main limitation of MIMO systems is related to their implementation complexity, which increases with the number of antennas. In some MIMO systems, cost and energy consumption considerations lead to the implementation of a smaller number of radio-frequency (RF) chains in the transmitter than the number of transmit (TX) antennas. This is often the case in mobile and fixed user equipment, because the number of antennas is dictated by the performance requirements of the downlink signal, and cost and energy consumption limitations may not allow the implementation of as many RF chains.

When the number of RF chains in the transmitter is smaller than the number of TX antennas, we essentially have two options to exploit the inherent antenna redundancy: The classic approach is to use antenna switching to improve system performance. Indeed, if the channels are known at the transmitter side, the antennas corresponding to the best channels can be selected for transmission. This is called switching diversity, and it is well known that this technique can approach the performance of optimum diversity [3]. The second approach, which is called spatial modulation (SM), does not aim at creating diversity. Instead, the active antenna indices in this technique are used to transmit information. The first papers on SM considered a single active antenna [4]–[6]. In that simple case, selection of 1 out of N_T TX antennas requires $\log_2(N_T)$ bits, assuming that N_T is an integer power of 2. Next, m information bits are used to transmit one symbol from that antenna, assuming that the signal constellation has $M = 2^m$ points. In summary, such a scheme transmits $m + \log_2(N_T)$ bits per channel use (*bpcu*). The SM technique was simplified in [7] by using only the spatial constellation diagram (the index of the active antenna) to transmit information bits. This scheme is known as space-shift keying (SSK). Further work on SM and SSK generalized these techniques by relaxing the single RF-chain constraint and allowing more than one antenna to transmit simultaneously. The resulting schemes are known as Generalized SM (GSM) [8]–[11] and Generalized SSK (GSSK) [7], [12], [13] in the literature. Further work on the subject introduced space-time block coding (STBC) to improve system performance as in conventional MIMO systems. Examples of this type of work can be found in [14]–[16].

In terms of spectral efficiency, it should be noted that SM is quite poor compared to *Spatial Multiplexing* (SMX) that is commonly used in wireless communications standards. SMX consists of transmitting independent data streams from all TX antennas simultaneously [1]. For example, with 2 TX antennas, conventional SM (with one RF chain) transmits $m + 1$ *bpcu*, whereas SMX transmits $2m$ *bpcu* (where m is the number of bits per symbol of the constellation used). Similarly, with 4 TX antennas, SM transmits $m + 2$ *bpcu*, whereas SMX transmits $4m$ *bpcu*. This inherent throughput loss of conventional SM is the main motivation for this paper to introduce a new SM scheme, which we refer to as *Enhanced SM* (ESM).

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ESM was devised by combining several ideas. The first one is to transmit symbols from a primary constellation when a single TX antenna is activated and to transmit symbols from a secondary constellation when two TX antennas are activated. The second idea is to define a set of secondary constellations whose size is half of the primary constellation size to transmit the same number of bits during the single active antenna periods and the two active antenna periods. The third idea is to design the secondary constellations through geometric interpolation in the signal space in such a way as to maximize the minimum Euclidean distance between transmitted signal vectors.

The concept of using multiple signal constellations is the basic deviation of ESM from conventional MIMO schemes including single-RF SM and Generalized SM. Here, instead of the active antenna index, or the indices of active antennas, information bits are transmitted by antenna and constellation combinations. The number of those combinations is the double or the quadruple of the number of active antenna indices (or index combinations) in conventional SM systems, and this increases the number of bits transmitted per channel use by 1 or 2, when the signal constellation of conventional SM is used as primary constellation in ESM. Alternatively, when the signal constellations are selected in such a way that ESM operates at the same spectral efficiency as conventional SM, ESM achieves higher performance. The idea of increasing the number of combinations to increase spectral efficiency also appears in the recently introduced Quadrature SM (QSM) [17]. This SM scheme decomposes the complex symbol to be transmitted into its real and imaginary components, and it transmits them independently using one or two antennas. The number of antenna combinations in this scheme is N_T^2, and therefore the spectral efficiency is $m + 2\log_2(N_T)$. However, as will be seen in Section VI, this scheme suffers from a reduced minimum squared Euclidean distance and gives lower performance than our proposed ESM scheme.

The remainder of this paper is organized as follows. In Section II, we give a brief description of the system model used. In Section III, we present a brief review of conventional SM and of SMX. Next, in Section IV, we present the basic principle of the proposed ESM technique and describe several examples for 2 and 4 TX antennas, before pointing out its generalizations to higher numbers of antennas. In Section V, we give an analysis of the pairwise error probability (PEP) performance and of the receiver complexity. Finally, Monte Carlo simulation results are reported in Section VI, and our conclusions are given in Section VII.

Notation: Matrices and column vectors are shown in boldface uppercase and lowercase letters, respectively. x_i is the ith entry of vector $\mathbf{x}$. Transpose and Hermitian are denoted by $(\cdot)^T$ and $(\cdot)^H$, respectively. The Frobenius norm is denoted by $\|\cdot\|$. $\mathcal{R}$ denotes the set of real values, and $\mathcal{C}$ denotes the complex-value set. The cardinality of a set that measures the number of elements of the set is denoted by $|\cdot|$. The expectation is defined as $\mathbb{E}[\cdot]$. The floor function that maps a real number to its integer part is denoted by $\lfloor\cdot\rfloor$. The number of k-combinations from a given n elements is denoted by $\mathbb{C}_k^n$. The distribution of a circularly symmetric complex Gaussian random vector $\mathbf{z}$ with mean μ and covariance $\mathbf{\Sigma}$ is denoted by $\mathbf{z} \sim \mathcal{N}_c(\mu, \mathbf{\Sigma})$.

II. System Model

Considering a MIMO system operating on Rayleigh fading channels, the received signal is given by:

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}. \tag{1}$$

In (1), $\mathbf{H}$ is the $N_R \times N_T$ channel matrix, N_R denotes the number of the receive antennas, N_T is the number of the TX antennas, $\mathbf{s}$ is the $N_T \times 1$ transmitted signal vector with normalized power, i.e., $\mathbf{s} = \frac{\mathbf{x}}{\sqrt{E_s}}$, and $\mathbf{n}$ is the additive white Gaussian noise (AWGN). We assume that the entries of the channel matrix $\mathbf{H}$ are independent and identically distributed (i.i.d.) complex circularly symmetric Gaussian variables of the form $\mathcal{N}_c(0, 1)$. We also assume that the entries of AWGN, $\mathbf{n}$, are i.i.d. Gaussian noise of the form $\mathcal{N}_c(0, N_0)$. The transmit power is normalized, i.e., $\mathbb{E}[\mathbf{s}^H\mathbf{s}] = 1$, $\mathbb{E}[\mathbf{x}^H\mathbf{x}] = E_s$, and the average signal-to-noise ratio (SNR) is defined as SNR $= 1/N_0$. Note that the main difference between SM and conventional MIMO is that in the former not all TX antennas are activated simultaneously, which means that there are some zero elements in the transmit signal vector $\mathbf{x}$.

III. A Brief Review of SMX and Conventional SM

A. SMX

For SMX with N_T transmit antennas, the transmitted symbol vector $\mathbf{x}$ can be written as:

$$\mathbf{x} \in \left\{ \begin{bmatrix} \mathcal{C} \\ \vdots \\ \mathcal{C} \end{bmatrix} \right\} = \mathcal{C}^{N_T}, \tag{2}$$

where the entries $\mathcal{C}$ represent the complex signal constellation used. When this MIMO scheme uses a signal constellation with $M = 2^m$ points, it transmits mN_T bits per channel use, and the total power per transmitted symbol vector is N_T times the average power per symbol of the signal constellation.

B. Conventional SM

In conventional SM with N_T TX antennas (out of which only one antenna is active at a time), the transmitted symbol vectors $\mathbf{x}$ are of the form:

$$\mathbf{x} \in \left\{ \begin{bmatrix} \mathcal{C} \\ 0 \\ \vdots \\ \cdot \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \mathcal{C} \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \cdots, \begin{bmatrix} 0 \\ \vdots \\ \cdot \\ 0 \\ \mathcal{C} \end{bmatrix} \right\}, \tag{3}$$

where, as previously, the entry $\mathcal{C}$ denotes the symbol constellation used, and the zero entries correspond to the silent TX elements. Assuming that this scheme uses a signal constellation with $M = 2^m$ points, a total of $m + \lfloor\log_2(N_T)\rfloor$ information bits are sent per channel use: $\lfloor\log_2(N_T)\rfloor$ bits select the index of the active antenna and m bits select a particular symbol from the signal constellation to be transmitted from that antenna. For example, with the QPSK signal constellation, SM transmits 3 *bpcu* when $N_T = 2$, and it transmits 4 *bpcu* when $N_T = 4$.

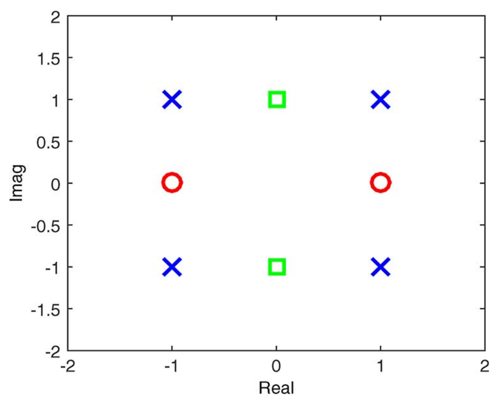

Fig. 1. An illustration of the constellations used: The crosses represent QPSK and the circles (resp. squares) represent the BPSK0 (resp. BPSK1) signal constellation.

Note that the corresponding numbers for SMX are 4 *bpcu* with $N_T = 2$ and 8 *bpcu* with $N_T = 4$.

Clearly, when both transmission schemes use the same signal constellation, SM transmits significantly less information than SMX, and this motivated us to search for an enhanced SM scheme that increases the transmitted data rate. In the following section, we describe the general principle and the construction of the introduced ESM scheme for $N_T = 2$ and $N_T = 4$ before outlining its generalizations to a higher number of antennas. In terms of signal constellations, we start with QPSK as primary modulation, and then we describe ESM designs using 16QAM and 64QAM.

IV. Enhanced SM

A. ESM-QPSK

1) 2-TX Antennas: With two TX antennas and QPSK as primary modulation, the transmitted signal vector in our proposed ESM technique is of the form:

$$\mathbf{x} \in \left\{ \begin{bmatrix} \mathcal{C}_4 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \mathcal{C}_4 \end{bmatrix}, \begin{bmatrix} \mathcal{B}_2^0 \\ \mathcal{B}_2^0 \end{bmatrix}, \begin{bmatrix} \mathcal{B}_2^1 \\ \mathcal{B}_2^1 \end{bmatrix} \right\}, \tag{4}$$

where $\mathcal{C}_4$ denotes the QPSK signal constellation used as primary constellation, and $\mathcal{B}_2^0$ and $\mathcal{B}_2^1$ represent two secondary signal constellations given by $\mathcal{B}_2^0 = \{\pm 1\}$ and $\mathcal{B}_2^1 = \{\pm i\}$. Clearly, the first two elements in the signal space given by (4) are those of conventional SM with QPSK signal constellation and they correspond to the transmission of a QPSK symbol from the first and the second antenna, respectively. The third and the fourth signal elements correspond to the simultaneous transmission of symbols from both antennas, but those symbols take their values from a secondary constellation, which carries only 1 bit. The purpose of this is to have the same number of transmitted bits as with the first and the second elements of the signal space. We refer to the secondary signal constellations as BPSK0 and BPSK1, respectively. The three signal constellations used in this design are shown in Fig. 1, and the four antenna/constellation combinations, which respectively determine the four signal space elements in (4), are illustrated in Table I. This scheme transmits 4 *bpcu*, because selection of one combination out of four requires two bits, and two other bits are required to select either a QPSK symbol, or two symbols from one of the secondary constellations (BPSK0, BPSK1). Compared to conventional SM with the same modulation and number of TX antennas, we have thus increased the number of bits per channel use by one.

TABLE I
Enhanced SM, 2TX-4 bpcu

	TX1	TX2
C1	QPSK	0
C2	0	QPSK
C3	BPSK0	BPSK0
C4	BPSK1	BPSK1

Two main features of the proposed ESM scheme are very evident from the description above: The first is the increased number of combinations compared to conventional SM by the inclusion of a set of secondary modulations in addition to the primary modulation. The second feature is that the size of the secondary modulations is exactly half of the primary modulation size and therefore the number of transmitted bits is the same for all combinations. At this point, it is important to describe a third feature, which is related to the derivation of the secondary signal constellations. The principal criterion in this derivation is to maximize the minimum Euclidean distance between the three constellations involved without increasing the transmitted signal power.

As evidenced from Fig. 1, the minimum Euclidean distance is the same for all three signal constellations used in the design. It is given by $\delta_0 = 2$. Obviously, δ_0 is also the minimum distance between two signal vectors corresponding to the same combination. Next, δ_0 is also the minimum distance between a signal vector from combination C1 and a signal vector from combination C2. The same applies to the minimum distance between a signal vector from combination C3 and a vector from combination C4. However, the distance between a signal vector from $C1 \cup C2$ and a signal vector from $C3 \cup C4$ is $\delta_0/\sqrt{2}$. This is the minimum distance of the entire signal space, but this 3-dB reduction of the minimum Euclidean distance is limited to ESM which uses QPSK as primary modulation. The ESM designs described in the following subsections with 16QAM and 64QAM as primary modulations do not have such a problem.

2) 4-TX Antennas: As indicated earlier, with $N_T = 4$ and the QPSK signal constellation, conventional SM transmits 4 *bpcu*, because two bits determine the active antenna index and two other bits determine a QPSK symbol to be transmitted from that antenna. In this case, our ESM uses 16 combinations of active antennas and constellations transmitted from these antennas, which are shown in Table II. The first four combinations in this table are those of conventional SM. They simply correspond to the transmission of a QPSK symbol from one of the four TX antennas. Next, we have 6 combinations for transmission of two simultaneous BPSK0 symbols from two TX antennas, and as many combinations for simultaneous transmission of two BPSK1 symbols. Therefore, ESM transmits 6 *bpcu*, compared to the 4 *bpcu* capacity of conventional

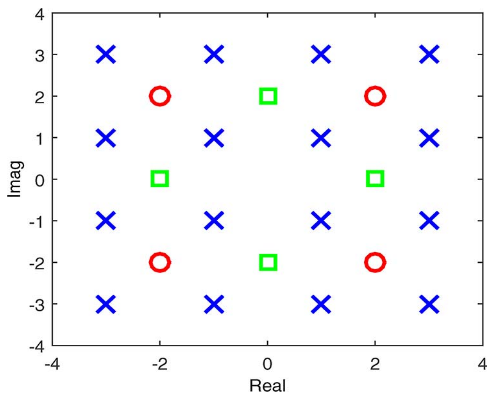

Fig. 2. An illustration of the constellations used: The crosses represent 16QAM and the circles (resp. squares) represent the QPSK0 (resp. QPSK1) signal constellations.

SM: 4 information bits are needed to select one of those 16 combinations, and 2 bits are used to select a QPSK symbol, or a pair of BPSK0 symbols, or a pair of BPSK1 symbols.

B. ESM-16QAM

Conventional SM with 16QAM modulation and 2 TX antennas consists of selecting one of the two TX antennas using one information bit and transmitting a 16QAM symbol from that antenna. The throughput is 5 *bpcu*.

For ESM, we use the following constellation combinations, which provide 6 *bpcu* transmission:

$$\mathbf{x} \in \left\{ \begin{bmatrix} \mathcal{C}_{16} \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \mathcal{C}_{16} \end{bmatrix}, \begin{bmatrix} \mathcal{Q}_4^0 \\ \mathcal{Q}_4^0 \end{bmatrix}, \begin{bmatrix} \mathcal{Q}_4^1 \\ \mathcal{Q}_4^1 \end{bmatrix} \right\}, \tag{5}$$

where $\mathcal{C}_{16}$ denotes the 16QAM signal constellation used as primary modulation, and $\mathcal{Q}_4^0$ and $\mathcal{Q}_4^1$ represent two reduced-size signal constellations defined as $\mathcal{Q}_4^0 = \{\pm 1 \pm i\}$ and $\mathcal{Q}_4^1 = \{\pm 1, \pm i\}$. We refer to the secondary signal constellations as QPSK0 and QPSK1, respectively. These constellations are shown in Fig. 2. The antenna/modulation combinations used in ESM are those of Table I, when QPSK, BPSK0 and BPSK1 are replaced by 16QAM, QPSK0 and QPSK1, respectively.

It should be noted that the average transmit power in the proposed ESM scheme is slightly larger than in the corresponding conventional SM scheme. Indeed, conventional SM transmits one 16QAM symbol from the selected active antenna, and the average transmit power is $E_s = 10$. This also holds for the first two combinations in ESM. But the third combination of ESM transmits two QPSK0 symbols and the corresponding average power is 16. Finally, the fourth combination transmits two QPSK1 symbols and the corresponding average power is 8. Therefore, the overall average power is $E_s = 11$, which represents a 0.4 dB increase with respect to conventional SM.

The design methodology of the secondary modulations used in ESM-16QAM follows the same rules as in ESM-QPSK. More specifically, their size is half of the size of the primary modulation, so that transmitting two symbols in parallel from a secondary modulation corresponds to the same number of bits per channel use as the transmission of a symbol from a primary modulation. Next, the points of the QPSK0 and QPSK1 constellations are placed at the centers of the square grid representing the original 16QAM constellation to maximize the minimum Euclidean distance between symbol vectors belonging to combinations based on the primary modulation and those belonging to combinations that are based on the secondary modulations. It can be easily verified by hand that the minimum distance δ_0 of the 16QAM modulation is also the minimum distance of the signal vector space in this design.

TABLE II
ENHANCED SM, 4TX-6 bpcu

	TX1	TX2	TX3	TX4
C1	QPSK	0	0	0
C2	0	QPSK	0	0
C3	0	0	QPSK	0
C4	0	0	0	QPSK
C5	BPSK0	BPSK0	0	0
C6	BPSK0	0	BPSK0	0
C7	BPSK0	0	0	BPSK0
C8	0	BPSK0	BPSK0	0
C9	0	BPSK0		BPSK0
C10	0	0	BPSK0	BPSK0
C11	BPSK1	BPSK1	0	0
C12	BPSK1	0	BPSK1	0
C13	BPSK1	0	0	BPSK1
C14	0	BPSK1	BPSK1	0
C15	0	BPSK1	0	BPSK1
C16	0	0	BPSK1	BPSK1

Extension of ESM-16QAM to the 4-TX case follows the same process as with ESM-QPSK, i.e., by substituting in Table II 16QAM, QPSK0, and QPSK1 for QPSK, BPSK0, and BPSK1, respectively. Using 16QAM and 4 TX antennas, ESM transmits 8 *bpcu*, and the resulting scheme is denoted 4TX8b. This is to be compared to the 6 *bpcu* spectral efficiency of conventional SM with the same number of TX antennas and the 16QAM modulation.

C. ESM-64QAM

To achieve higher throughputs, we now describe ESM schemes using higher-level signal constellations. The design process is similar to that with the previous constellations, but here we have more degrees of freedom, and we will describe two different ESM schemes using 64QAM as primary modulation and two TX antennas. The first one of those, referred to as 2TX8b, is based on the following signal space:

$$\mathbf{x} \in \left\{ \begin{bmatrix} \mathcal{C}_{64} \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \mathcal{C}_{64} \end{bmatrix}, \begin{bmatrix} \mathcal{A}_8^0 \\ \mathcal{A}_8^0 \end{bmatrix}, \begin{bmatrix} \mathcal{A}_8^1 \\ \mathcal{A}_8^1 \end{bmatrix} \right\} \triangleq \mathcal{S}_{2TX8b}, \tag{6}$$

where $\mathcal{C}_{64}$ denotes the 64QAM signal constellation used as primary modulation, and $\mathcal{A}_8^0$ and $\mathcal{A}_8^1$ represent two different secondary signal constellations of 8 points each. The secondary signal constellations are respectively given by $\mathcal{A}_8^0 = \{\pm 2 \pm 2i, \pm 4i, \pm 4\}$ and $\mathcal{A}_8^1 = \{\pm 2, \pm 2i, 4 + 2i, -4 - 2i, 2 - 4i, -2 + 4i\}$. These constellations are referred to as 8-Level Amplitude-Phase-Keying-Type 0 (8APK0) and 8-Level

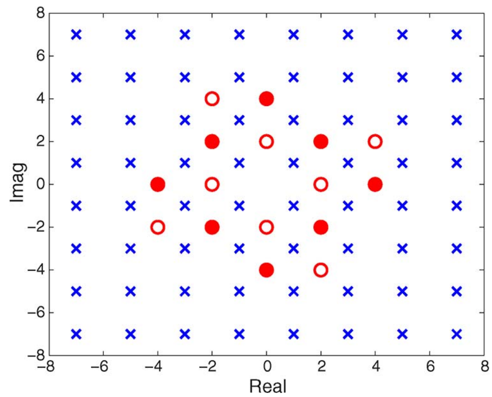

Fig. 3. An illustration of the constellations used: The blue crosses represent 64QAM, and the heavy/empty red circles represent the 8APK0/8APK1 signal constellations.

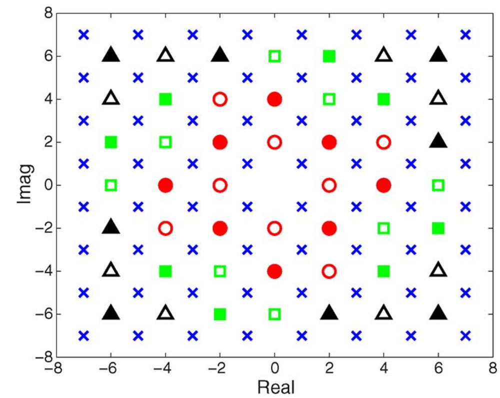

Fig. 4. An illustration: the crosses are 64QAM, the heavy/empty circles are the 8APK0/8APK1, the heavy/empty squares are the 8APK2/8APK3, and the heavy/empty triangles are 8APK4/8APK5 signal constellations.

Amplitude-Phase-Keying-Type 1 (8APK1), respectively, and the resulting ESM scheme is referred to as 2TX8b, because it transmits 8 bpcu. It can be verified that the average transmit signal power in this ESM scheme is $E_s = 33$. The constellations used are shown in Fig. 3, where the signal points in 8APK0 and 8APK1 are placed close to the origin with the purpose of average power reduction. The combinations are the same as those of Table I when QPSK, BPSK0 and BPSK1 are replaced by 64QAM, 8APK0 and 8APK1, respectively.

Another ESM scheme based on two TX antennas and 64QAM as primary modulation is the 2TX9b scheme in which the transmitted signal vector $\mathbf{x}$ takes its values from the signal space given below:

$$\mathbf{x} \in \left\{ \mathcal{S}_{2TX8b}, \begin{bmatrix} \mathcal{A}_8^2 \\ \mathcal{A}_8^2 \end{bmatrix}, \begin{bmatrix} \mathcal{A}_8^3 \\ \mathcal{A}_8^3 \end{bmatrix} \begin{bmatrix} \mathcal{A}_8^4 \\ \mathcal{A}_8^4 \end{bmatrix}, \begin{bmatrix} \mathcal{A}_8^5 \\ \mathcal{A}_8^5 \end{bmatrix} \right\}. \tag{7}$$

In addition to the signal space of 2TX8b, this one includes 4 other combinations. They correspond to the transmission in parallel of two symbols taking their values from one of 4 other secondary constellations. So, in summary, compared to 2TX8b this design doubles the number of combinations and involves 6 secondary constellations instead of 2. We denote the 4 secondary signal constellations used in this design as 8-APK2, 8-APK3, 8-APK4, and 8-APK5, respectively. These signal constellations are shown in Fig. 4. A simple inspection indicates that the average transmit signal power in this scheme is $Es = 59.5$. The 8 combinations of TX antenna and the constellations transmitted from them are explicitly shown in Table III.

Extension of 2TX8b to 4 TX antennas is straightforward. We simply replace QPSK, BPSK0, and BPSK1 in Table II by 64QAM, 8APK0, and 8APK1, respectively. The resulting scheme is referred to as 4TX10b, because it transmits 10 bpcu. However, extension of 2TX9b to 4 TX antennas is not straightforward. In 4TX11b, there are 32 combinations of the antennas and constellations requiring 5 bits for combination selection, and each combination transmits 6 bits, leading to a throughput of 11 bpcu. Note that we have 40 combinations if we follow the same extension as in 4TX10b, which is more than what is required. From those, we choose 32 combinations as follows: $C1 - C4$ with 64QAM transmitted from a single antenna, $C5 - C10$ with 8APK0 transmitted from two antennas, $C11 - C16$ with 8APK1, $C17 - C22$ with 8APK2, $C23 - C28$ with 8APK3, $C29 - C30$ with 8APK4, and $C31 - C32$ with 8APK5. Note that the 8APK4 and 8APK5 signal constellations whose average power is higher than the other signal constellations are only used in two combinations each, whereas the 8APK0-8APK3 constellations are used in 6 combinations each. The purpose of this is to limit the average transmit power. The resulting average signal power is 51.75.

TABLE III
ENHANCED SM, 2 TX, 9 bpcu

	TX1	TX2
C1	64QAM	0
C2	0	64QAM
C3	8APK0	8APK0
C4	8APK1	8APK1
C5	8APK2	8APK2
C6	8APK3	8APK3
C7	8APK4	8APK4
C8	8APK5	8APK5

D. Generalizations

In the previous subsections, we described ESM using primary modulations from QPSK to 64QAM, for a number of transmit antennas $N_T = 2$ and $N_T = 4$. Since our reference was conventional SM with a single active antenna ($N_A = 1$), the primary modulation was used for transmission from a single antenna, and the (half-size) secondary modulations were used for simultaneous transmission from two antennas.

First, generalization of the proposed technique to $N_T > 4$ is straightforward. The number of combinations to select one active antenna out of N_T transmit antennas is N_T. For convenience, we consider the number of transmit antennas N_T to be an integer power of 2. In this case, selection of one transmit antenna in conventional SM requires exactly $\log_2(N_T)$ bits. Like conventional SM, ESM features N_T combinations with one active transmit antenna. But ESM also features $\mathbb{C}_2^{N_T} = N_T(N_T - 1)/2$ active antenna combinations for transmitting two symbols in parallel from the first secondary modulation. It also involves as many combinations for transmitting two symbols from the other secondary modulation. Therefore, the total number of active antennas and modulation combinations in ESM is $N_T + \mathbb{C}_2^{N_T} + \mathbb{C}_2^{N_T} = N_T^2$. Selection of one combination out of N_T^2 requires $2\log_2(N_T)$ bits. In other words, the number of bits required to select one combination is the double of that in the case of conventional SM. For example, with $N_T = 8$, the number of bits for active antenna selection in conventional SM is 3, and the number of bits for selection of a particular antenna/modulation combination is 6 in ESM.

Generalization to larger numbers of active antennas ($N_A > 1$) too is quite simple. Consider a generalized SM (GSM) system with N_T transmit antennas, two of which are active ($N_A = 2$). The total number of antenna combinations is $\mathbb{C}_2^{N_T}$, but note that this number is not an integer power of 2. For addressing the active antenna combinations with an integer number of bits, the number of combinations used in generalized SM is the largest integer power of 2 that is smaller than $\mathbb{C}_2^{N_T}$. In the simplest case, the signal vector space L in the corresponding ESM system is composed of 3 subspaces: $L = L_1 \cup L_2 \cup L_3$. The first one is the signal vector space of Generalized SM, in which the number of combinations is given above ($|L_1| = \mathbb{C}_2^{N_T}$). The second subspace L_2 corresponds to the simultaneous transmission of 4 symbols using 4 active antennas and the first secondary modulation. The number of combinations in this subspace is $\mathbb{C}_4^{N_T} = N_T(N_T-1)(N_T-2)(N_T-3)/24$. The third subspace L_3 corresponds to the transmission of 4 symbols using 4 active antennas and the other secondary modulation. The number of combinations in this subspace is the same as the number of combinations in the second subspace. Therefore, the total number of combinations in this ESM scheme is:

$$\begin{aligned} |L| &= \mathbb{C}_2^{N_T} + \mathbb{C}_4^{N_T} + \mathbb{C}_4^{N_T} \\ &= \frac{N_T(N_T-1)}{2}\left[1 + \frac{(N_T-2)(N_T-3)}{6}\right]. \end{aligned} \tag{8}$$

For $N_T = 8$, $|L| = 28(1+5) = 168$. The largest integer power of 2 that is smaller than this number is 128. We therefore include 128 combinations in the signal space, which require 7 bits for selection of a particular combination. The corresponding numbers in Generalized SM are 16 combinations and 4 address bits.

In fact, the signal space can be significantly expanded by realizing that when 4 transmit antennas are simultaneously active, 2 of them can transmit symbols from the first secondary constellation while the other 2 antennas transmit symbols from the other secondary constellation. This expansion does not involve any reduction of the minimum distance. The additional number of combinations corresponding to this signal space expansion is given by:

$$\begin{aligned} |L_4| &= \mathbb{C}_2^{N_T}\mathbb{C}_2^{N_T-2} \\ &= \frac{N_T(N_T-1)(N_T-2)(N_T-3)}{4}. \end{aligned} \tag{9}$$

For $N_T = 8$, $|L_4| = 420$, and therefore the addition of this subspace leads to $|L| = 588$. The integer power of 2 that is immediately below this number being 512, 512 combinations are included in the signal space and the number of bits needed to select a particular combination is 9. This ESM scheme increases the number of address bits by 5.

Further expansions of the signal space are possible by transmitting from one antenna a symbol taken from the primary constellation and transmitting in parallel two symbols from a secondary constellation. It can be easily verified that those expansions do not reduce the minimum Euclidean distance of the signal space, and therefore, the asymptotic performance at high SNR must be essentially the same.

E. Quadrature SM

In an attempt to improve the spectral efficiency of SM, the so-called Quadrature SM (QSM) technique was recently proposed in [17]. In this technique, the complex symbols to be transmitted are split into their real and imaginary parts, and active antenna assignment to these two parts is made independently of each other. When the real and imaginary parts are transmitted from the same antenna, only one transmit antenna becomes active, and when the two components are transmitted from separate antennas, the number of active antennas is two. In a QSM system with N_T transmit antennas, the number of antenna combinations is N_T^2 which is identical to the number of antenna/constellation combinations in our ESM scheme. In other words, like our ESM scheme, QSM increases the number of antenna combinations and the spectral efficiency with respect to conventional SM.

In terms of performance, QSM turns out to suffer from a reduced minimum Euclidean distance compared to our proposed ESM. Indeed, whereas signal space expansion in ESM is made without reducing minimum distance with respect to conventional SM except when QPSK is used as primary modulation, QSM involves an inherent 3 dB loss in all cases. To see this, it is sufficient to consider two different antenna combinations corresponding to the transmission of an innermost point of the QAM signal constellation. Without loss of generality, we can consider the point $(1+i)$ and the signal vectors $(1, i, 0, 0, \cdots, 0)$ and $(1, 0, i, 0, \cdots, 0)$. These two vectors differ in their second and third components only. The Euclidean distance between these two vectors is $\delta_0/\sqrt{2}$, which represents a 3 dB loss compared to the minimum Euclidean distance of SM.

V. Performance and Complexity Analysis

A. Performance Analysis

When the channel state information (CSI) is perfectly known at the receiver, the maximum-likelihood (ML) decoder estimates the transmitted symbol vector according to:

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}\in\mathbb{S}} \|\mathbf{y} - \mathbf{H}\mathbf{s}\|^2, \tag{10}$$

where $\mathbb{S}$ denotes the constellation of the normalized transmitted symbols, and the minimization is performed over all possible transmitted symbol vectors. We define the pairwise error probability (PEP) as the probability that the ML decoder decodes a symbol vector $\mathbf{s}'$ instead of the transmitted symbol vector $\mathbf{s}$.

The average PEP (APEP) can be computed by using the union bound as follows:

$$APEP \leq \frac{1}{|\mathbb{S}|} \sum_{\mathbf{s} \in \mathbb{S}} \sum_{\mathbf{s}' \in \mathbb{S}} PEP(\mathbf{s} \to \mathbf{s}'). \tag{11}$$

For Rayleigh fading channels, the PEP is given by [18]:

$$\begin{aligned} &PEP(\mathbf{s} \to \mathbf{s}') \\ &= \mathbb{E}_{\mathbf{H}} \left[\mathcal{Q} \left(\sqrt{\frac{\gamma_{s \to s'}}{2N_0}} \right) \right] \\ &= \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \mathcal{L}_{\gamma_{s \to s'}} \left(\frac{1}{4N_0 \sin^2(\theta)} \right) d\theta \\ &= \left(\frac{1-\mu}{2} \right)^{N_R} \sum_{k=0}^{N_R - 1} \mathbb{C}_k^{N_R - 1 + k} \left(\frac{1+\mu}{2} \right)^k, \end{aligned} \tag{12}$$

where $\mathcal{Q}(\cdot)$ denotes the Gaussian $\mathcal{Q}$-function, $\gamma_{s \to s'} = \|\mathbf{Hs} - \mathbf{Hs}'\|^2$ represents a random variable with the chi-squared distribution, $\mathcal{L}_{\gamma_{s \to s'}}$ is the Moment-Generating Function (MGF) of $\gamma_{s \to s'}$, $\mu = \sqrt{\tau/(4N_0 + \tau)}$, and $\tau = \|\mathbf{s} - \mathbf{s}'\|^2$. At high SNR, the asymptotic system performance is determined by the worst-case PEP, which corresponds to the minimum value of the squared Euclidean distance between symbol vectors in the signal space:

$$\begin{aligned} L_{min}^2 &= \min_{\mathbf{s} \neq \mathbf{s}'} \|\mathbf{s} - \mathbf{s}'\|^2 \\ &= \frac{1}{E_s} \min_{\mathbf{x} \neq \mathbf{x}'} \|\mathbf{x} - \mathbf{x}'\|^2. \end{aligned} \tag{13}$$

To analyze asymptotic performance (at high SNR), it is instructive to compare the different MIMO schemes at hand (SMX, SM, and ESM) in terms of the squared minimum Euclidean distance between transmit symbol vectors, denoted as L_{min}^2. The comparisons were made at identical spectral efficiency and the results are represented in Table IV. The first part of the table corresponds to MIMO schemes with 2 TX antennas, and the second part corresponds to schemes with 4 TX antennas. Different columns correspond to different spectral efficiencies. Labeling of the MIMO schemes in this table is based on the number of TX antennas and the number of bits per channel use. For instance, 4TX8b means 4 TX antennas and 8 *bpcu*. For each one of the presented MIMO schemes, the signal constellations used can be easily determined using the descriptions provided in Sections III and IV. For example, in the 4TX8b column of the table, SM uses 64QAM, SMX uses 16QAM, and ESM uses 16QAM as primary modulation. For QSM, the signal constellations used can be found in the legend of the simulation plots shown in Section VI. For instance, in the 4TX8b case, QSM uses 16QAM as indicated in Fig. 11.

The squared minimum Euclidean distances which appear in this table are given in the form of a fraction or using a decimal representation. The reason is that some of the considered schemes use the 8PSK signal constellation, and the distance is best expressed using decimal representation in this case. In contrast, fractional number representation of the distances is more convenient for the schemes based on QAM signal constellations, and this holds for most cases which appear in

TABLE IV
THE MINIMUM SQUARED EUCLIDEAN DISTANCE, L_{min}^2

	2TX4b	**2TX6b**	**2TX8b**	**2TX9b**
SM	0.5858	4/20	4/82	4/170
SMX	4/4	0.2929	4/20	4/30
ESM	2/2	0.3636	4/33	4/59.5
QSM	2/2	2/10	2/42	2/82
	4TX6b	**4TX8b**	**4TX10b**	**4TX11b**
SM	4/10	4/42	4/170	4/330
SMX(2TX)	0.2929	4/20	4/40	4/62
ESM	2/2	4/11.5	4/28.5	4/51.75
QSM	2/2	2/10	2/42	2/82

the table. In all schemes using QAM signal constellations, the comparison in terms of squared minimum distances is rather straightforward. For example, the average transmit signal vector powers in the 2TX8b case are 82 for SM, 20 for SMX, 33 for ESM, and 42 for QSM, respectively (when the minimum distance is set to 2 in all of the signal constellations). Therefore, the squared minimum Euclidean distances are 4/82, 4/20, 4/33, and 2/42, respectively, when the transmitted average signal power is normalized by 1. These values appear in the 2TX8b column of the table. Note that SMX is restricted to two active antennas, because our assumption is that the number of RF chains is limited to 2 as in the proposed ESM schemes. The conventional SM schemes considered here actually involve a single RF chain, because the number of active antennas is 1. As for QSM, the number of active antennas is 2 as in ESM, but the authors of [17] claim that this technique can be implemented using a single RF chain. Comparing the distances displayed in Table IV, we can see that ESM has a significantly larger L_{min}^2 than SM in all cases. It also has a larger L_{min}^2 than QSM except in the trivial case where ESM uses QPSK as primary modulation (the 2TX4b and 2TX6b cases in the table). Finally, ESM provides a larger L_{min}^2 than SMX in the 4-TX cases due to restricting the system to 2 RF chains. These results indicate that ESM reduces the worst-case PEP compared to SM, SMX, and QSM and leads to the best system performance in most cases.

In terms of worst-case PEP, the gain of a scheme with a squared minimum distance of L_{min}^2 over a scheme with a squared minimum distance of $L_{min}'^2$ is given by:

$$\mathcal{G} = 10 \log_{10} \left(\frac{L_{min}^2}{L_{min}'^2} \right) \tag{14}$$

For example, the expected gain of ESM over conventional SM in the case of 2TX4b is given by:

$$\mathcal{G}_{SM,ESM} = 10 \log_{10}(1/0.5858) = 2.32 \text{ dB}$$

Note that with QPSK as primary modulation, bit mapping is important in ESM, because the squared minimum distance in the signal space arises between symbol vectors that belong to different combinations, e.g., between C1 and C3 in Table I and between C1 and C5 in Table II, and this distance is smaller than the minimum distance of QPSK. In this case, separately labeling the signal constellations and the active antennas patterns is not optimum for ESM. However, this is an isolated case, and the

Euclidean distance is preserved with higher level modulations, e.g., with 16QAM as primary modulation and QPSK0/QPSK1 as secondary modulations.

B. Receiver Complexity Analysis

In this section, we show that in addition to improving performance over conventional SM, the proposed ESM also reduces the complexity of the ML decoder. Reduction of the receiver complexity will be demonstrated by explicitly evaluating the respective complexities of SM and ESM in the 4TX8b case before summarizing the complexity figures of the two transmission schemes for different spectral efficiencies. In this analysis, we define complexity as the number of complex multiplications required per ML decoder decision.

For 4TX8b SM, the ML decoder needs to compute $\mathbf{w}_{ij} = \mathbf{y} - \mathbf{h}_i s_j$, where $\mathbf{h}_i$ with $i = 1, 2, \cdots, 4$ denotes the i-th column of the channel matrix $\mathbf{H}$, and s_j with $j = 1, 2, \cdots, 64$ denotes a 64QAM symbol. This step involves 256 complex multiplications. Next, it needs to compute the squared modulus of each one of the $\mathbf{w}_{ij}$ terms, and this step involves another 256 complex multiplications. In other words, the total number of complex multiplications in this scheme is 512 per channel use.

In the case of 4TX8b ESM, we need to consider separately 3 groups of antenna/constellation combinations. First, in combinations C1 - C4, a 16QAM symbol is transmitted from one of the 4 TX antennas. For those combinations, the ML decoder needs to compute $\mathbf{w}_{ij} = \mathbf{y} - \mathbf{h}_i s_j$, with $i = 1, 2, 3, 4$ and $j = 1, 2, \cdots, 16$, and this involves 64 complex multiplications. Next, in combinations C5 - C10, two QPSK0 symbols are transmitted from two active antennas. For those combinations, the ML decoder needs to compute $\mathbf{w}_{ijkl} = \mathbf{y} - \mathbf{h}_i s_j^0 - \mathbf{h}_k s_l^0$, with $i, k = 1, 2, 3, 4$ and where s_j^0 and s_l^0 $(j, l = 1, 2, 3, 4)$ denote two symbols taken from the Q_4^0 signal constellation. The number of complex multiplications involved in this step is only 16. Finally, in combinations C11 - C16, two QPSK1 symbols are transmitted from two active antennas. For those combinations, the ML decoder needs to compute $\mathbf{w}_{ijkl} = \mathbf{y} - \mathbf{h}_i s_j^1 - \mathbf{h}_k s_l^1$, with $i, k = 1, 2, 3, 4$ and where s_j^1 and s_l^1 $(j, l = 1, 2, 3, 4)$ denote two symbols taken from the Q_4^1 signal constellation. Here, the number of complex multiplications is also 16. So, the total number of complex multiplications involved in the steps above is 96, although the number of $\mathbf{w}_{ij}$ and $\mathbf{w}_{ijkl}$ values computed is 256 (64 values corresponding to combinations C1 - C4, 96 values corresponding to combinations C5 - C10, and 96 values corresponding to combinations C11 - C16). Next, the decoder needs to compute the squared modulus of all $\mathbf{w}_{ij}$ and $\mathbf{w}_{ijkl}$ values to determine the 256 metrics involved. So, the total number of complex multiplications per decoding step in the ML decoder is 352, which is significantly smaller than the corresponding number in SM. In this particular case, the decoder complexity reduction with respect to conventional SM is 31.2%.

The complexity analysis reported above for the 4TX8b case was also made for all SM and ESM schemes which appear in Table IV, and the results are reported in Table V. The results indicate that ESM significantly reduces the ML decoder complexity compared to conventional SM, particularly in the case of 4 TX antennas. Note that in the 4TX10b case, the ML decoder complexity of ESM is 34.4% smaller than that of conventional SM.

TABLE V
RECEIVER COMPLEXITY ($N_r = 1$)

	2TX4b	2TX6b	2TX8b	2TX9b
SM	32	128	512	1024
ESM	32	112	416	836
	4TX6b	**4TX8b**	**4TX10b**	**4TX11b**
SM	128	512	2048	4096
ESM	96	352	1344	2912

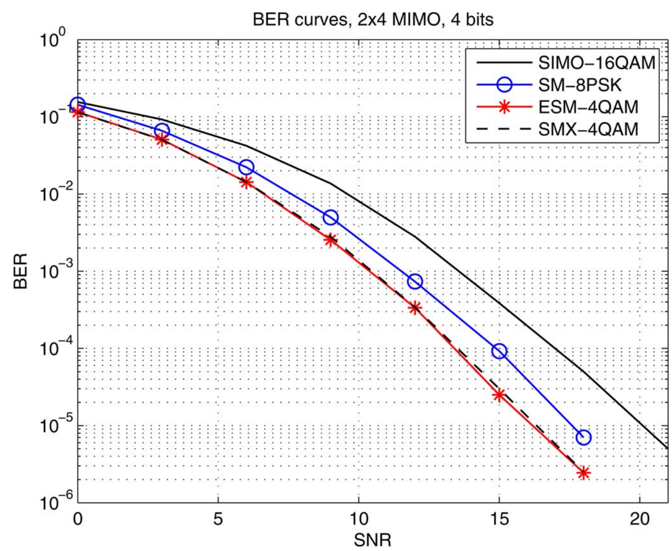

Fig. 5. The BER performance of 2TX4b.

VI. SIMULATION RESULTS

We report here the results of Monte Carlo simulations, which were obtained using Rayleigh fading MIMO channels with 4 receive antennas ($N_R = 4$) and assuming perfect CSI at the receiver. We also assume perfect synchronization and rectangular pulse shaping. That is, we neglect the problems of antenna switching with Nyquist pulse shaping, which may be challenging in practice. This problem was addressed in some recent papers, which proposed solutions such as employing a multiple-RF antenna switching architecture [19] or simply using a large roll-off factor in the pulse shaping filters to ensure that the power is concentrated in a short period of time [20].

In the simulations, symbol vectors were randomly generated and transmitted over the channel, ML detection was performed using the received noisy signal samples, and symbol vector error events were counted. The obtained symbol vector error rate (SVER) was used to compare the respective performances of conventional SM and ESM. Unlike bit error rate (BER) performance evaluation, the SVER does not need to define the bit mapping, and the simulations are much quicker. In the first part of the simulations, we compared the BER and the SVER performance results of SM, SMX, and ESM in the 2TX4b case. The BER results are reported in Fig. 5. The constellation

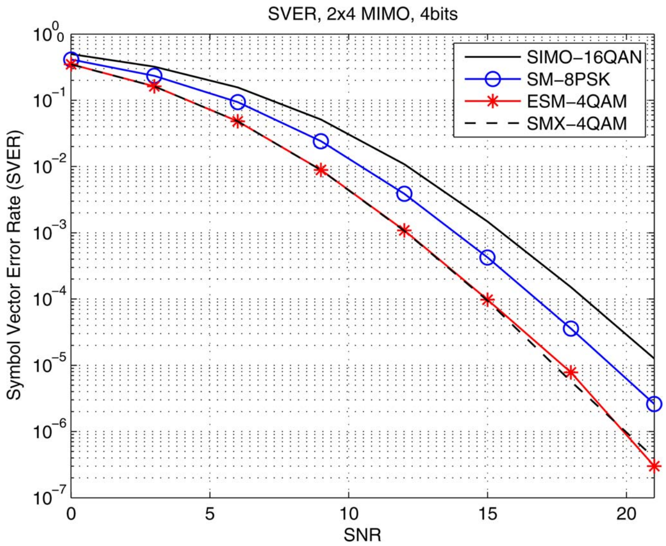

Fig. 6. The SVER performance of 2TX4b.

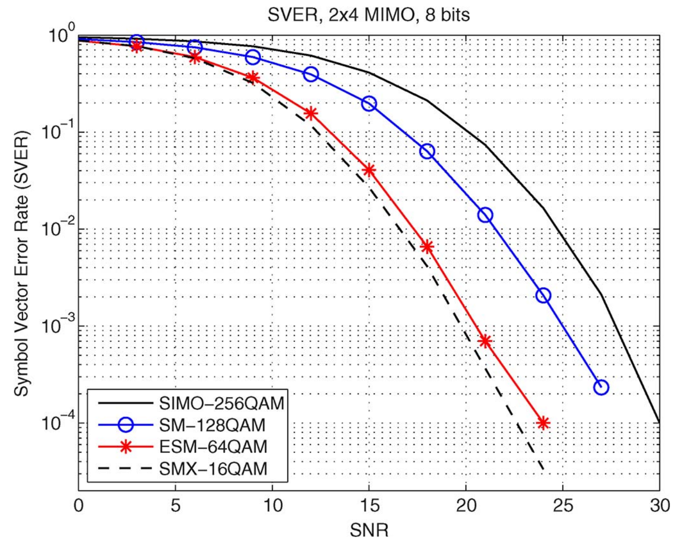

Fig. 8. The SVER performance of 2TX8b.

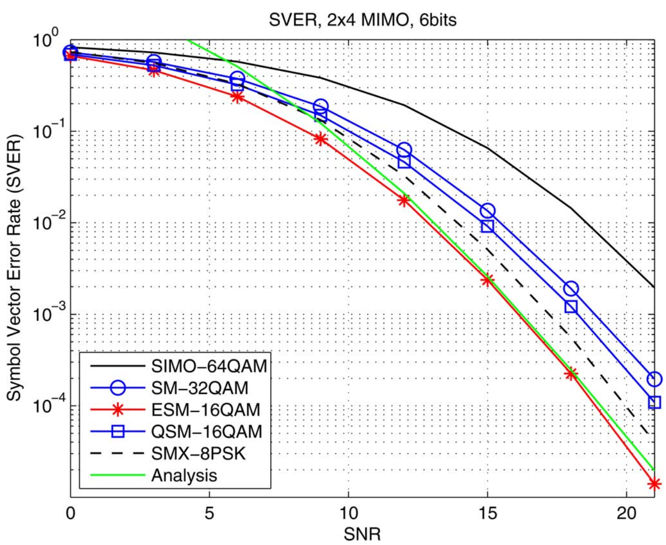

Fig. 7. The SVER performance of 2TX6b.

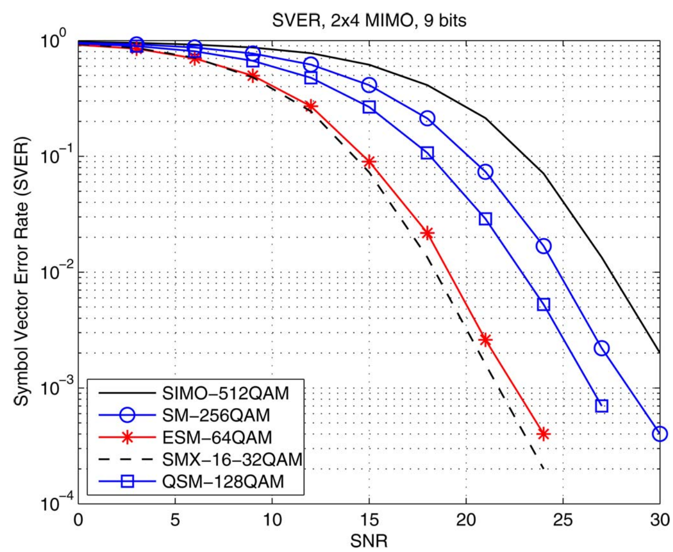

Fig. 9. The SVER performance of 2TX9b.

used in each scheme is given in the legend. For example, SM uses 8PSK and is denoted SM-8PSK, SMX uses 4QAM and is denoted SMX-4QAM, and finally ESM uses 4QAM as primary modulation, and it is denoted ESM-4QAM. These results show that ESM gains 1.5 dB over conventional SM and gives the same performance as SMX at $BER = 10^{-4}$. Next, the SVER performance of the 3 MIMO schemes at hand was evaluated, and the results are given in Fig. 6. Comparison of Fig. 5 and Fig. 6 shows that the gains in terms of SVER performance perfectly match those given in terms of BER. On the basis of this observation, SVER performance evaluations were used in all subsequent comparisons of the MIMO schemes under investigation, because they are simpler to evaluate than BER performance and they provide very accurate performance comparisons.

The SVER curves corresponding to 2TX6b are presented in Fig. 7. As predicted by the L^2_{min} analysis of the previous section, the simulation results confirm that ESM outperforms all other MIMO schemes at hand. Specifically, ESM gains more than 1 dB over SMX, 2 dB over QSM, and close to 3 dB over SM at $SVER = 10^{-3}$. In this figure, we also give the analytic bound of ESM obtained using (11) to show its tightness in the high SNR region.

Next, in Fig. 8, we show the SVER performance of 2TX8b schemes in which ESM uses 64QAM as primary modulation. The results indicate that ESM gains around 4 dB over QSM and 5 dB over SM, but loses close to 1 dB with respect to SMX at $SVER = 10^{-3}$. The average SNR loss of ESM with respect to SMX is mainly due to the fact that combinations $C1 - C2$ use the 64QAM signal constellation while SMX uses 16QAM in that case.

In Fig. 9, the SVER curves of 2TX9b show that ESM gains around 4 dB over QSM and 6 dB over SM and has about 0.8 dB loss compared to SMX at $SVER = 10^{-3}$. Again, the average SNR loss of ESM with respect to SMX can be attributed to the use of 64QAM in combinations $C1 - C2$, while SMX uses one

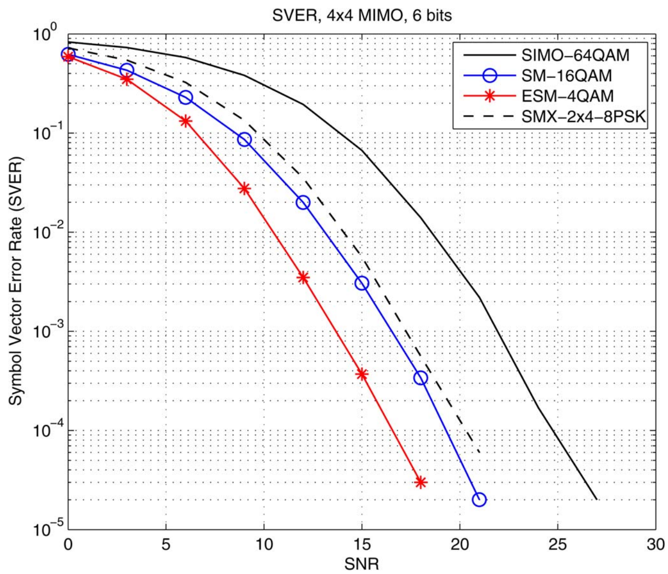

Fig. 10. The SVER performance of 4TX6b.

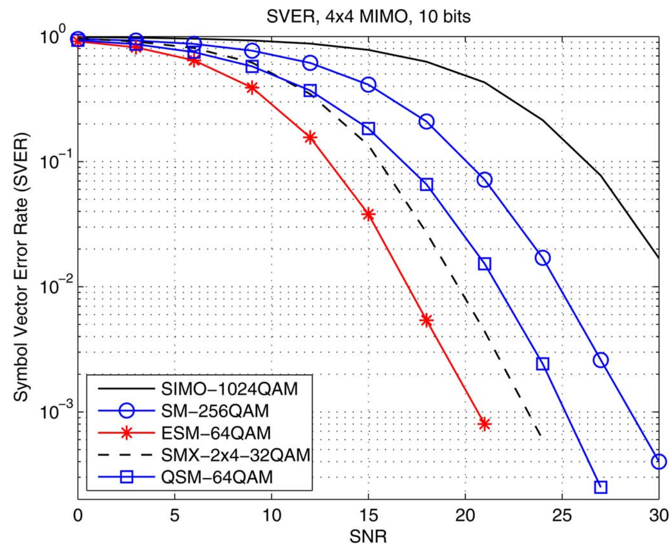

Fig. 12. The SVER performance of 4TX10b.

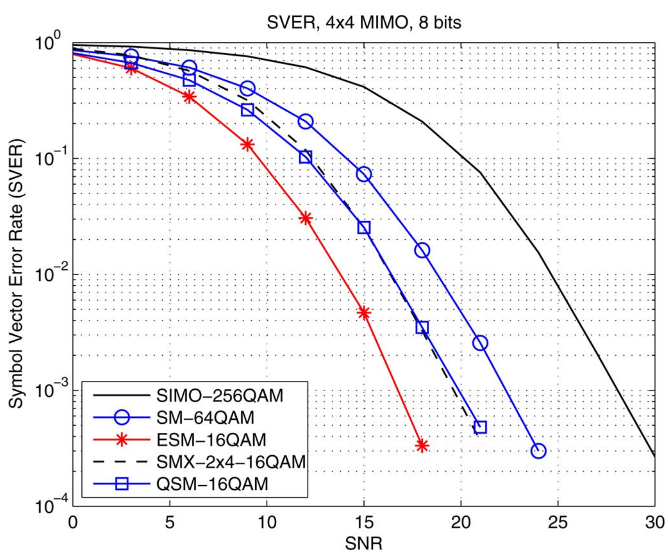

Fig. 11. The SVER performance of 4TX8b.

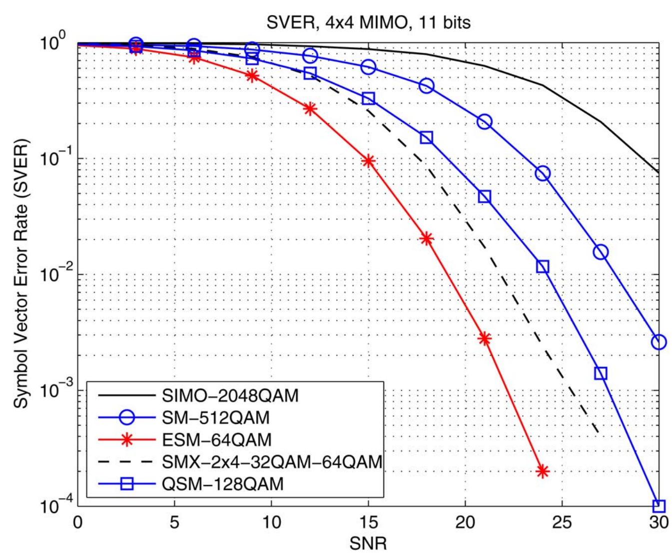

Fig. 13. The SVER performance of 4TX11b.

16QAM stream and one 32QAM stream in parallel to achieve a spectral efficiency of 9 *bpcu*.

In Fig. 10, the SVER curves of 4TX6b show substantial improvements of the SM family (both SM and ESM) over SMX. Specifically, ESM gains around 3 dB over SM and approximately 4 dB over SMX at $SVER = 10^{-3}$. This means that SM gains about 1 dB over SMX while using fewer RF chains. Similarly, the SVER curves of 4TX8b are shown in Fig. 11, which indicates that ESM gains around 3 dB over SMX and QSM and approximately 6 dB over SM at $SVER = 10^{-3}$. In other words, SM loses 3 dB over SMX in this case.

Fig. 12 shows the SVER performance results of 4TX10b in which ESM uses 64QAM as primary modulation. Here, ESM gains around 3 dB over SMX, 5 dB over QSM, and more than 7.5 dB over conventional SM at $SVER = 10^{-3}$. Finally, the SVER performances of the 4TX11b schemes are depicted in Fig. 13, which shows that ESM gains around 3 dB over SMX, 5 dB over QSM, and as much as 9 dB over SM at $SVER = 10^{-2}$. The substantial gain of ESM over SM in the 4TX11b case can be explained by the fact that SM requires 512QAM for transmitting 11 bpcu, while ESM only needs 64QAM as primary modulation to achieve the same spectral efficiency.

A final investigation in this work concerned the relation between the expected gains from the minimum distance analysis and the gains achieved with a finite number of receive (RX) antennas. The results are reported in Fig. 14. The specific numbers of RX antennas used here are 2, 4, 8, 16, 32, and 64. The average SNR gains which appear in this figure are those of ESM over SM. The expected gains corresponding to the 2TX4b and 4TX6b cases are indicated by the dotted line and the solid line, respectively. The curve with crosses gives the gain as a function of the number of RX antennas for the 2TX4b case. It shows that the expected gain of 2.32 dB can be approached when the number of RX antennas increases. Specifically, the gain is virtually to 2 dB with 8 RX antennas and 2.3 dB with 16 RX antennas. A similar observation can be made for the 4TX6b

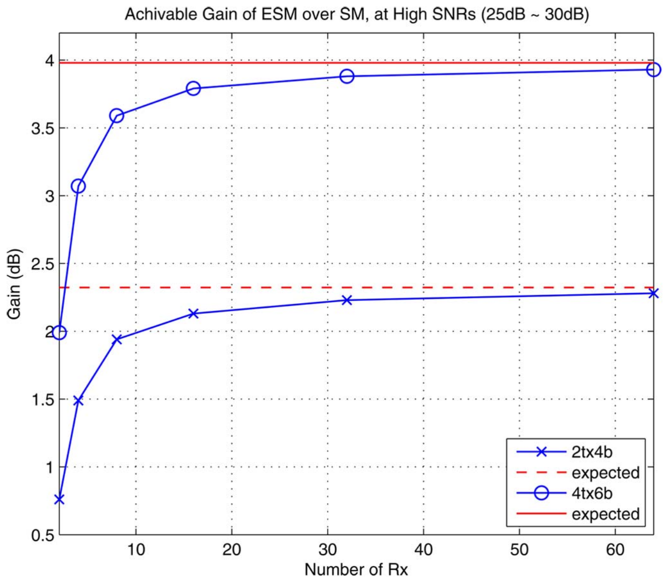

Fig. 14. The impact of the number of RX antennas.

case. Here, the expected gain (the solid-line curve) is 4 dB, and the curve with circles, which gives the gain as a function of the number of RX antennas indicate that the gain achieved with 8 RX antennas is 3.6 dB and the gain with 16 RX antennas is 3.8 dB.

VII. Conclusion

In this paper, we have introduced an Enhanced SM scheme by enabling one or two active TX antennas and using multiple signal constellations. Compared to conventional SM, this scheme transmits one or two additional information bits per channel use. On Rayleigh fading channels, both the closed-form performance analysis and the simulation results showed that the proposed technique outperforms conventional SM when the signal constellations are selected so as to have the same number of bits per channel use. The proposed technique was also compared to SMX restricted to 2 RF chains and to the recently introduced QSM scheme. It was found that with two TX antennas ESM potentially gains up to 6 dB over conventional SM, up to 4 dB over QSM, and up to 2 dB over SMX. It was also found that with four TX antennas, ESM leads to higher gains: it gains up to 9 dB over SM, up to 5 dB over QSM, and some 3 dB over SMX with 2 RF chains. Finally, the receiver complexity analysis of ML detection revealed that while ESM achieves a substantial performance gain over conventional SM, it also significantly reduces the complexity of the optimum decoder.

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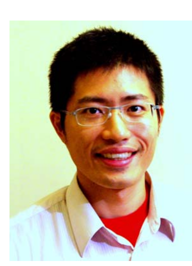

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