

A High Spectral Efficiency Generalized Spatial Modulation Scheme for MIMO Fading Channels

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Abstract—The Multiple-antenna technique called MIMO (Multiple-Input-Multiple-Output) constitutes a key technology for modern and future wireless communications, which trade-off superior error performance and higher data rates for increased system complexity and cost. As an extension to the classical MIMO schemes, a novel technique called Spatial Modulation(SM) can even enhance the capability of MIMO systems by exploiting the index of the transmit antenna(TA)s to convey information bits. In this paper, a Generalized SM MIMO (GSM MIMO) scheme is proposed, which uses more than one active antennas for each transmission. Parallel signal symbols are transmitted simultaneously on each of the active antennas per channel use (pcu). Most importantly, distinct combinations of active antennas can also be used to convey information symbols. In this proposed scheme, the number of transmit antennas can be an arbitrary positive integer greater than one, while eliminating the limit on TA number as in original SM MIMO. And the spectrum efficiency (SE) can be much higher than SMX schemes like V-BLAST. A suboptimal MMSE-based detection algorithm is also proposed to reduce the high complexity of the optimal Maximum-Likelihood (ML) detector. The performance of the proposed scheme is evaluated in an uncorrelated Rayleigh flat fading channel through Monte-Carlo simulations.

Keywords-Multiple Antennas; Multiple Input Multiple Outout(MIMO) systems; Spatial Modulation(SM);Generalized SM(GSM)

I. INTRODUCTION

MIMO communications constitute promising techniques for the design of future wireless communication systems for their capability of providing high data rates without increasing the spectrum utilization and the transmit power, and of providing diversity gain as well, thus lay very important foundations for physical-layer standards like WiMAX(Worldwide Interoperability for Microwave Access) [1]and LTE-A(Long Term Evolution – Advanced)[2]. In MIMO systems, all TAs are active at any time instance. By appropriately choosing the transmission/precoding matrices, both multiplexing and transmit-diversity gains can be obtained, thus resulting in SE optimization. However, this does not naturally lead to energy efficiency (EE)

optimization[3], which is key to future communication systems requiring low energy-consumption techniques.

In [4], a novel MIMO scheme named SM MIMO was first proposed by Mesleh et al. , in which only one antenna out of N_T transmit antennas is active every transmission, and the index of the active antenna conveys $\log_2(N_T)$ information bits alongside the $\log_2(M)$ bits(M is the size of signal constellation, or modulation order) carried on the signal symbol transmitted on it for each channel use. This scheme requires only one RF link, thus has high energy efficiency. The receiving algorithm can also be simplified greatly. In [5], Jeganathan et al. proposed an optimal detector for the SM. A Sphere decoder (SD) was used for SM in [6] which reduces the complexity of the SM optimal detector, yet can also achieve a bit error rate close to the optimal SM.

One disadvantage of the original SM MIMO is that it requires the number of TAs N_T to be 2^p , where p is a positive integer. The other disadvantage is that the number of bits per channel use is in proportion to the base-2 logarithm of N_T , in contrast to $N_T \log M$ of the V-BLAST scheme. Thus SM MIMO requires much more TAs for the same number of bits per transmission as in V-BLAST[7]. Meanwhile, SM can achieve only 1 degree of transmit diversity.

Many variants to SM MIMO have been proposed since [4], such as generalized space shift keying (GSSK)[8] and space shift keying (SSK) [9] proposed by Jeganathan et al. , in which combinations of active antennas or the active antenna index are the only way to convey information bits. In [10] and [11], generalized SM (GSM), which extended the SM idea to allow combinations of multiple active antennas to transmit the same signal symbols, were proposed.

In this paper, the author propose a new MIMO transmission scheme to extend the GSM MIMO concept in [10] and [11], to exploiting spatial multiplexing nature of the underlying multi-antenna architecture. Unlike the GSM, this proposed scheme uses K ($K < N_R$, the number of receive antennas, or RAs) active TAs out of the N_T available TAs to transmit different signal symbols simultaneously. As a result, the spectral efficiency (SE) can be much higher than SM MIMO at the cost of increase in active RF links, yet reduces the number of TAs needed and eliminates the limitation on the number of TAs. The SE can even be higher than that of

V-BLAST, as long as large active and available antennas are used, even with low order modulation method like BPSK.

The rest of the paper is organized as follows: The mapper and system model of the new GSM MIMO transmission scheme are presented in part II. Part III presents the optimal and sub-optimal MMSE detecting algorithms proposed by the author. Computation complexity analysis, simulation results and conclusion are provided in part IV, V and VI, respectively.

Notations: Throughout the paper, the following notations are used. Bold lowercase and bold uppercase letters denote vectors and matrices respectively. $[\cdot]^T$, $\text{Tr}[\cdot]$, $[\cdot]^*$, $[\cdot]^H$, and $[\cdot]^+$ are used to denote transpose, trace, conjugate, Hermitian and pseudo-inverse of a matrix or a vector, respectively. Furthermore, $\|\cdot\|^F$ are used to denote Frobenius norm of a matrix or a vector, and $E[\cdot]$ to denote the statistical expectation. We use $n!$, $C(n, k)$ to denote factorial, binomial coefficient, respectively. Other notations will be explained in its first use.

II. SYSTEM MODEL

The system block diagram is given in Fig.1, where 2 out of 8 TAs are active(right column) to transfer 6 bits(2 8PSK symbols) on each active TA at one time.

In the proposed scheme, the random transmitted information bits are grouped into equal-length bit blocks. Each block contains $p + K \log_2(M)$, where the combination of the K active TAs conveys the first p bits, M is the modulation order of signal symbols. In order to relax the requirement of linearity of amplifier, and to improve EE, MPSK are preferred. For example, consider a system with $N_T=10$, $K=5$, $M=2$ (BPSK), there are $C(10,5)=250$ combinations available, in which we choose $2^7=128$ combinations to convey $p=7$ bits using 5 active TAs. The other $K \log_2(M) = 5$ bits are transmitted on the 5 active TAs simultaneously using BPSK symbols. Here total 12 bits pcu can be got, as compared to 4 bits pcu for the original SM with 8 antennas, and 10 bits pcu for V-BLAST with the same configuration. With the $N_T=20$, $K=10$, $M=2$, the proposed scheme offers 27 bits pcu, while V-BLAST can provide only 20 bits pcu. Thus the proposed scheme are more energy efficient as well as spectral efficient than the V-BLAST. Also to notice, when $K=1$, it is the original SM. When $K=N_T$, it is a pure spatial multiplexing (SMX) scheme.

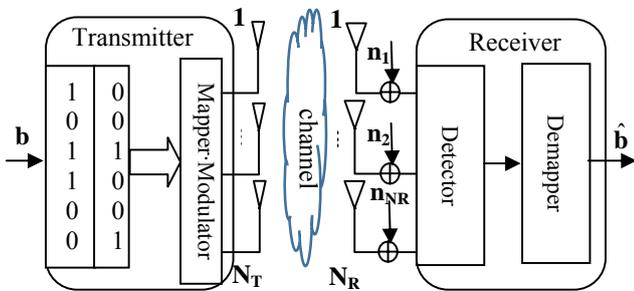


Figure 1. Block diagram of the proposed GSM MIMO system

A. Antenna Mapping

Different than the original SM scheme, where one of the 2^p TAs is used to send a modulated symbol, the proposed GSM scheme uses multiple active TAs to transmit different symbols simultaneously. The first problem for GSM is to choose a way to map numeric numbers ranging from 0 to $N=2^p-1$ to distinct antenna combinations. Fortunately, combinatorial mathematics provides a one-to-one mapping between natural numbers and k -combinations, for all n and k [12, 13]. For each n and k , $C(n, k)$ can be presented by a sequence J of length k , which takes elements from the set $\{0, 1, \dots, n-1\}$, according to the following equation:

$$Z = C(n_k, k) + L + C(n_2, 2) + C(n_1, 1) \quad (1)$$

Where $n_1, \dots, n_k \in \{0, 1, \dots, n-1\}$, and $n_i > n_{i-1}$ for all $i \geq 2$ and $i \leq k$ and $J = \{n_k, \dots, n_2, n_1\}$.

For example, when $n=8$, $k=4$, $C(8,4)=70$. The following J sequences can be calculated:

$$\begin{aligned} 69 &= C(7,4) + C(6,3) + C(5,2) + C(4,1) ? J \quad \{7,6,5,4\} \\ 68 &= C(7,4) + C(6,3) + C(5,2) + C(3,1) ? J \quad \{7,6,5,3\} \\ &\dots \\ 32 &= C(6,4) + C(5,3) + C(4,2) + C(1,1) ? J \quad \{6,5,4,1\} \\ 31 &= C(6,4) + C(5,3) + C(4,2) + C(0,1) ? J \quad \{6,5,4,0\} \\ &\dots \\ 1 &= C(4,4) + C(2,3) + C(1,2) + C(0,1) ? J \quad \{4,2,1,0\} \\ 0 &= C(3,4) + C(2,3) + C(1,2) + C(0,1) ? J \quad \{3,2,1,0\} \end{aligned}$$

In this way, a one-to-one correspondence of natural numbers to the k antenna indexes are established. Yet in this proposed scheme, only 2^p out of all $C(N_T, K)$ active TA combinations are used. For the example above, $p=6$, $N=2^p=64$ combinations are used. That is,

$$N = \lfloor C(N_T, K) \rfloor_{2^p} \quad (2)$$

where p is the largest integer that satisfies

$$2^p \leq C(N_T, K) < 2^{p+1} \quad (3)$$

And $N = 2^p$.

In the proposed scheme, the number of bits per symbol that can be transmitted by using the SM and the new scheme are calculated, respectively, as

$$h_{SM} = \log_2(N_T) + \log_2(M) \text{ bpcu} \quad (4)$$

$$h_{GSM} = \log_2(N) + K \log_2(M) \text{ bpcu} \quad (5)$$

, where bpcu means bit per channel use.

B. System Model

The transmitter groups the incoming bits, \mathbf{b} , into blocks of $\log_2(NM^K)$ bits, the first $p(=\log_2(N))$ bits are used to select the combination pattern of active TAs based on the combinatory method described previously, and the remaining $K \log_2(M)$ are mapped into a complex signal constellation vector $\mathbf{x} = [x_1, x_2, \dots, x_K]^T$ to be transmitted on the selected K active TAs, where $x_k(1 \leq k \leq K)$ is selected uniformly from an M -ary complex constellation such as MPSK etc., and is assumed to be independently identically distributed (i.i.d.) complex variables with covariance matrix $\mathbf{R}_{xx} = E[\mathbf{x}^H \mathbf{x}]$. The average energy per transmission is limited as $E_x = \text{Tr}[\mathbf{R}_{xx}]$,

which is the power constraint at the transmitter side. And the average symbol energy per timeslot is $s_s^2 = Es/K$.

As with the traditional MIMO, the system model can be written as

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n} \quad (6)$$

where $\mathbf{y} = [y_1, y_2, \dots, y_{N_R}]^T$ is $N_R \times 1$ received sample vector, and \mathbf{s} is an $N_T \times 1$ vector whose non-zero elements represent symbols transmitted on the antenna according to the index of the elements

$$\mathbf{s} = [0, x_1, \dots, 0, \dots, x_K, \dots, 0]^T$$

\mathbf{H} is an $N_R \times N_T$ channel matrix between the transmit antennas and the receive antennas

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N_T} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R,1} & h_{N_R,2} & \dots & h_{N_R,N_T} \end{bmatrix} \quad (7)$$

where h_{ij} is a complex fading coefficient between the i^{th} transmit TA and the j^{th} RA and is modeled as an i.i.d. zero mean complex Gaussian (ZMCG) variable with unit variance. We assume the channel is flat faded. \mathbf{n} is the additive noise vector of size $N_R \times 1$, with i.i.d. elements each of which is also ZMCG with variance s_n^2 .

Equation (6) can also be written as

$$\mathbf{y} = \mathbf{G}_m \mathbf{x} + \mathbf{n} \quad (8)$$

where \mathbf{G}_m is an $N_R \times K$ matrix whose columns are from those of (7) with the column indexes corresponding to active antennas.

III. DETECTION ALGORITHMS

A. Optimal Detector

The optimal detector is the Maximum Likelihood (ML) detector as in [5], which estimate the combination index \hat{m} and the transmitted symbol vector \mathbf{x} jointly using the ML criterion

$$\begin{aligned} [\hat{m}, \hat{\mathbf{x}}] &= \underset{m, \mathbf{x}}{\operatorname{argmax}} \{ p(\mathbf{y} | \mathbf{G}_m, \mathbf{x}) \} \\ &= \underset{m, \mathbf{x}}{\operatorname{argmin}} \{ \|\mathbf{y} - \mathbf{G}_m \mathbf{x}\|^2 \} \end{aligned} \quad (9)$$

and $p(\mathbf{y} | \mathbf{G}_m, \mathbf{x})$ is the likelihood function of \mathbf{y} given \mathbf{G}_m, \mathbf{x}

$$p(\mathbf{y} | \mathbf{G}_m, \mathbf{x}) = \left(\frac{1}{\pi \sigma_n^2} \right)^{N_R} \exp \left(-\frac{\|\mathbf{y} - \mathbf{G}_m \mathbf{x}\|^2}{\sigma_n^2} \right) \quad (10)$$

By iterating every $m=1, 2, \dots, N$, and every possible symbol vector \mathbf{x} (totally M^K possibilities), the largest pair corresponding to the likelihood value is jointly detected as \hat{m} and $\hat{\mathbf{x}}$. However, this detector requires computations of exponential complexity in proportion to NM^K .

B. Suboptimal Detector

In this paper, a sub-optimal detector based on the MMSE algorithm is proposed, where the MMSE detector \mathbf{W}_m is first applied on each combinatorial channel matrix \mathbf{G}_m ,

$$\mathbf{W}_m = \mathbf{G}_m \left[\mathbf{G}_m^H \mathbf{G}_m + \frac{\sigma_n^2}{\sigma_s^2} \mathbf{I} \right]^{-1} \quad (11)$$

Then give an estimation of the transmitted symbols vector $\hat{\mathbf{x}}_m$ using quantization

$$\hat{\mathbf{x}}_m = \mathbf{W}_m^H \mathbf{y} = \left[\mathbf{G}_m \left(\mathbf{G}_m^H \mathbf{G}_m + \frac{\sigma_n^2}{\sigma_s^2} \mathbf{I} \right)^{-1} \right]^H \mathbf{y} \quad (12)$$

Later apply these two to (9) to calculate a ML metric L_m (the second equation). Among all these L_m values, \hat{m} and $\hat{\mathbf{x}}$ are detected according to the largest L_m value.

The algorithm is described as follows:

Algorithm: MMSE-based suboptimal detector

($\hat{m}, \hat{\mathbf{x}}$) = Detection(\mathbf{y}, \mathbf{H})

a) Initiate $L_0 = +\infty, m=1$

b) use (11) to get the m^{th} MMSE detector \mathbf{W}_m ,

c) use (12) and signal modulation constellation to get an estimated signal vector $\hat{\mathbf{x}}_m$

d) calculate a likelihood value L_m according to (9)

e) compare L_m to L_0 , keep the smaller m and $\hat{\mathbf{x}}_m$, and let L_0 equal this larger L_m value, saving the according m and $\hat{\mathbf{x}}_m$

f) $m=m+1$, repeat b)-e) for all $m=1, 2, \dots, N$ until $m>N$

g) Done. The last m and $\hat{\mathbf{x}}_m$ saved is what we want.

Unlike the ML detector described in A. which searches over all possible symbol vectors and N channel matrices, the proposed detector uses ML function to search only over the vectors obtained from MMSE detector, so as to reduce the computational complexity of the optimal ML detector.

IV. COMPUTATIONAL COMPLEXITY ANALYSIS

In this section, we use the so-called flops (float point operations) to evaluate the computation complexity of the detection algorithms described above. Each complex addition and multiplication accounts for one flop. Computation for Real operations (addition, multiplication, comparison) and transposes are ignored for the matter of simplicity.

For the optimal ML detector in (9), each likelihood value computation requires $N_r(2K-1)+N_r+1$ flops, and there are NM^K such operation. Thus in all the computation has $NM^K(N_r(2K-1)+N_r+1)$ flops, that is $\sim O(N_rKNM^K)$.

While for the MMSE-based sub-optimal detector, $\mathbf{G}_m^H \mathbf{G}_m$ needs $(2N_r-1)K^2$ flops, the addition inside the bracket needs K flops, and the matrix inversion needs about K^3 flops, then the inverted matrix multiplying the outer \mathbf{G}_m needs $N_r(2K-1)K$ flops. Then computation for \mathbf{W}_m needs $K^3+4K^2N_r-K^2-KN_r+K$ flops. Each likelihood computation

needs $2KN_r+1$ flops. These above computations are repeated N times, leading to a total computation complexity of $N(K^3+4K^2N_r-K^2+KN_r+K+1)$ flops, which is $\sim O(NN_r^3)$ when K is comparable to N_r .

From the analysis above we can see, the main advantage of the proposed MMSE-based sub-optimal is that the computational complexity is independent of M . And it can reduce the exponential complexity of the ML optimal detector.

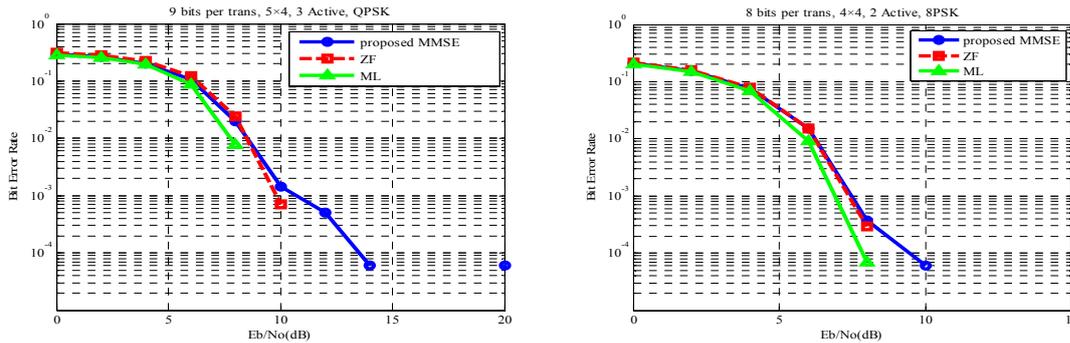


Figure 2. BER Performance of GSM MIMO for 9 bps/Hz(Left) and 8 bps/Hz(Right).

VI. CONCLUSION

In this paper, a new transmission scheme based on GSM aiming for exploiting high spectral efficiency in MIMO is proposed. The combination of indexes of the active antennas are used to convey information bits while different symbols are transmitted on each of the active TAs during one symbol interval. At the receiver, an optimal detector is used to estimate the transmitted symbols and the index of active antennas combination. This detector suffers from a high computational complexity, so the author also proposed a sub-optimal MMSE-based detector to lessen the stringent requirement for ML detector. Simulations show that the proposed scheme using suboptimal detector outperforms the optimal SM at high spectral efficiency with very low complexity and less number of transmit antennas and makes it a good candidate for high data rate transmission for LTE-A.

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V. SIMULATION RESULTS

Simulations are done under the assumption of uncorrelated Rayleigh fading with two different configurations: 9 bps/Hz(left) and 8 bps/Hz(right). MPSK modulations are used in both simulations. Bit error rate(BER) performance of them are plotted in Fig.2, from which we can see that the proposed MMSE-based detector shows sub-optimal performance with only a little degradation compared to the ML detector algorithm yet with less computation time.