Short Papers

Flexible Spatial Modulation With Transmit Antenna Selection for MIMO Systems

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***Abstract*—This article introduces flexible spatial modulation with transmit antenna selection (FSM-TAS) for future multiple-input multiple-output systems. In this scheme, the number of active antennas varies in each time interval depending on the incoming bits. After determining the number of active antennas, channel coefficients corresponding to each possible active antenna combination are added up. Then, a certain number of antenna combinations with largest gains is selected to apply spatial modulation (SM). For the proposed system, complexity and outage probability analyses are performed. In addition, it has been shown by Monte Carlo simulations that FSM-TAS provides better bit error rate performance than the benchmark enhanced SM with generalized antenna selection under the same spectral efficiency and the same number of transmitter and receiver antennas.**

***Index Terms*—Complexity analysis, multiple-input multiple-output (MIMO) systems, outage probability, transmit antenna selection (TAS).**

I. Introduction

INDEX modulation (IM) has been regarded as a novel approach for multiple-input multiple-output (MIMO) systems since a significant increase in spectral efficiency and energy efficiency can be achieved with a low complexity [1], [2]. In recent years, for the IM concept, two approaches, which are spatial modulation (SM) [3] and orthogonal frequency division multiplexing IM [4] have become popular. SM carries additional bits to activate one transmit antenna at each time interval. In this way, interchannel interference (ICI) is avoided with a low receiver complexity. Using only one transmit antenna at each time interval in SM decreases the efficiency of the use of multiple transmit antennas. To overcome this issue, generalized SM (GSM) is proposed [5]. GSM transmits an M-ary symbol with more than one active transmit antenna at each time interval. Thus, the transmit antennas are used in a more effective way without ICI since the same symbol is transmitted over the active antennas. Enhanced approaches, which are capacity optimized antenna selection (COAS) and Euclidian distance antenna selection (EDAS), are introduced in [6] and [7] for SM-based MIMO systems. Both COAS and EDAS schemes require channel state information (CSI) at both transmitter and receiver and need higher modulation orders with respect to SM under the same spectral efficiency. Despite their higher modulation order, these schemes have better bit error rate (BER) performance than SM since they select a subgroup of transmit antennas with higher channel gains and Euclidian distances, respectively, to apply SM. In [8], the advantages of transmit antenna selection (TAS) algorithms on SM are discussed. Then, QR decomposition based TAS and the error-vector magnitude-based TAS, which provide better BER performances with lower complexity, are proposed. An outage probability analysis for SM with TAS, which aims to maximize the power of the received signal over Rayleigh fading channel, is performed in [9], and a closed-form expression is shown. In [10], enhanced SM with generalized antenna selection (ESM-GAS) is introduced. ESM-GAS scheme sorts squared-norm values of all possible combinations of channel coefficients at each time interval and selects a subgroup of these combinations with higher norm to apply SM. In this way, ESM-GAS uses transmit antennas more efficiently to maximize the received signal power. However, sorting all possible combinations significantly increases the transmitter and receiver complexities.

In this short article, flexible SM with TAS (FSM-TAS) is proposed for MIMO systems. The contributions of this novel FSM-TAS scheme are stated as follows. The number of active antennas is not fixed and it is determined by incoming bits. In this way, additional bits can carry information and transmit antennas can be used in a flexible way. These advantages become more clear when the number of transmit antennas increases since the number of additional bits and the upper limit of active transmit antennas increases in this case. After the number of active antennas is decided, the active antennas are determined using norm-based sortation. In this way, all possible channel combinations do not need to be considered, and this decreases transmitter complexity. After the system model of FSM-TAS is introduced, complexity analysis and outage probability derivations are expressed. Then, Monte Carlo simulations are performed to compare FSM-TAS and ESM-GAS at the same spectral efficiency, to assess the potential of FSM-TAS with different number of selected channel combination values. Besides, theoretical expressions and Monte Carlo simulations for the outage probability are compared for validation.

II. System Model

In this article, we consider a MIMO system with N_T transmit antennas, N_R receive antennas, and M-ary constellation. The channel between transmitter and receiver follows Rayleigh fading and is denoted as $\mathbf{H} \in \mathbb{C}^{N_R \times N_T}$, where $h_{i,j}$ with $i \in \{1, 2, \ldots, N_R\}$ and $j \in \{1, 2, \ldots, N_T\}$ represents channel gain between ith receive and jth transmit antennas, which is assumed to be an independent and identically distributed complex Gaussian random variable with $\mathcal{CN}(0, 1)$ distribution. It is also assumed that both transmitter and receiver have perfect CSI (PCSI). The system model of the proposed FSM-TAS scheme can be seen in Fig. 1.

A. Transmitter Side

The vector of channel coefficients between the kth transmit and all receive antennas can be expressed as $\mathbf{h}_k = [h_{1,k}, h_{2,k}, \ldots, h_{N_R,k}]^T$.

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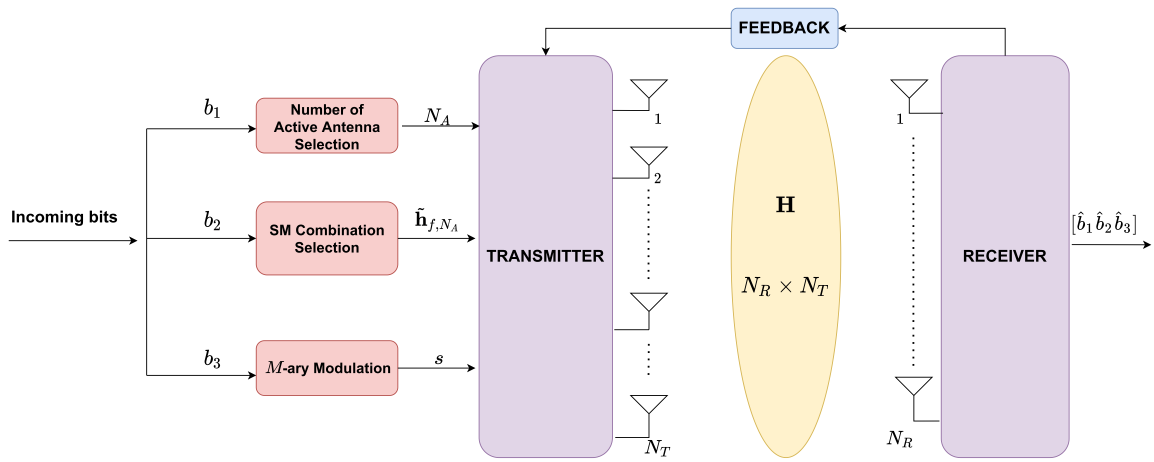

Fig. 1. FSM-TAS system model.

TABLE I
MAPPING FOR N_A WITH $N_T = 8$

b_1	N_A
{00}	1
{01}	2
{10}	3
{11}	4

TABLE II
MAPPING FOR SELECTED CHANNEL COMBINATIONS WITH $N_T = 8$, $N_A = 2$, AND $S = 4$

b_2	Selected combination	Channel coefficients
{00}	$\tilde{h}_{1,2}$	h_1,h_2
{01}	$\tilde{h}_{2,2}$	h_4,h_6
{10}	$\tilde{h}_{3,2}$	h_3,h_7
{11}	$\tilde{h}_{4,2}$	h_1,h_8

N_A is the number of active antennas out of N_T transmit antennas and varies as $1 \leq N_A \leq N_T/2$ with respect to incoming bits; the number of possible transmit antenna combinations can be shown as $K = \binom{N_T}{N_A}$, where $\binom{a}{b} = \frac{a!}{(a-b)!b!}$ is the binomial coefficient. The combination set, which includes all possible channel combinations with N_A active antennas, can be shown as $Q_{N_A} = \{\hat{\mathbf{h}}_{1,N_A}, \hat{\mathbf{h}}_{2,N_A}, \hat{\mathbf{h}}_{3,N_A}, \ldots, \hat{\mathbf{h}}_{K,N_A}\}$ and the construction of nth element of Q_{N_A} is shown as in (1), where $\mathbf{h}_{t_{n,m}}$ is the channel coefficient vector of $t_{n,m}$th transmit antenna and $t_{n,m}$ is the index of mth active antenna of nth element in Q_{N_A} for $t_{n,m} \in \{1, 2, \ldots, N_T\}$, $n \in \{1, 2, .., K\}$, and $m \in \{1, 2, .., N_A\}$

$$\hat{\mathbf{h}}_{n,N_A} = \frac{1}{\sqrt{N_A}} \sum_{m=1}^{N_A} \mathbf{h}_{t_{n,m}}. \quad (1)$$

In the FSM-TAS system model, the incoming bits that are accepted by the transmitter are divided into three main subgroups such as b_1, b_2, and b_3. Using b_1 bit group, N_A is determined and a sample mapping for N_A with $N_T = 8$ can be seen in Table I. After N_A is determined, Q_{N_A} is constructed by following (1) and the combinations of channel coefficients are sorted with respect to their gains as in (2), where $\tilde{\mathbf{h}}_{r,N_A}$ has the rth largest gain

$$\left\|\hat{\mathbf{h}}_{1,N_A}\right\|^2 > \left\|\tilde{\mathbf{h}}_{2,N_A}\right\|^2 > \left\|\tilde{\mathbf{h}}_{3,N_A}\right\|^2 > \cdots > \left\|\tilde{\mathbf{h}}_{K,N_A}\right\|^2. \quad (2)$$

Then, S out of K transmit antenna combinations with largest gains from (2) are selected to apply SM, where S is assumed to be an integer power of two. The selected combinations are mapped into b_2 and one combination for the transmission of the data symbol is determined. A sample mapping of the selected combinations over b_2 with $N_T = 8$, $S = 4$, and $N_A = 2$ can be seen in Table II. The determined combination of channel coefficients is shown as $\tilde{\mathbf{h}}_{f,N_A}$, where f is the index of determined combination $f \in \{1, 2, \ldots, S\}$. Besides, $\tilde{t}_{f,g}$ represents the index of the gth active transmit antenna of determined combination, where $g \in \{1, 2, \ldots, N_A\}$. The last bit group b_3 determines the data symbol s, and the same symbol is transmitted over all active antennas in each time slot. In this way, FSM-TAS requires just a single RF chain independent from N_A since all activated antennas transmit the same data symbol. The lengths of b_1, b_2, and b_3 are $\log_2(N_T/2)$, $\log_2 S$, and $\log_2 M$, respectively, and the spectral efficiency (in b/s/Hz) of the FSM-TAS can be expressed as

$$\eta = \log_2(N_T/2) + \log_2 S + \log_2 M. \quad (3)$$

After the number of active antennas, their indices and the data symbol are determined, and the transmit vector $\mathbf{x} \in \mathbb{C}^{N_T x1}$ is created as $\mathbf{x} = \frac{1}{\sqrt{N_A}}\left[0, 0, \underbrace{s}_{\tilde{t}_{f,1}}, 0, \underbrace{s}_{\tilde{t}_{f,2}}, \ldots, \underbrace{s}_{\tilde{t}_{f,N_A}}, 0, 0\right]^T$, where $E[\mathbf{x}^H\mathbf{x}] = 1$.

An example is shown below for transmission process of the proposed FSM-TAS scheme with $N_T = 8$ and $S = 4$.

Example: Assume that $N_T = 8$ and N_A changes as $1 \leq N_A \leq 4$ with respect to incoming bits. Then, $S = 4$ of K possible combinations are selected to apply SM. In case of quadrature amplitude modulation (4-QAM), the spectral efficiency is obtained as 6 b/s/Hz. Assume that incoming bits are {011011}, and these are separated into subgroups as $b_1 = \{01\}$, $b_2 = \{10\}$, and $b_3 = \{11\}$. By looking at Table I, it can be seen that $b_1 = \{01\}$ determines the number of active antennas as $N_A = 2$. $b_2 = \{10\}$ determines $\tilde{\mathbf{h}}_{f,N_A} = \tilde{\mathbf{h}}_{3,2}$ which can be seen from Table II and it is clear that the indices of activated antennas will be $\tilde{t}_{3,1} = 3$ and $\tilde{t}_{3,2} = 7$. The last bit group $b_3 = \{11\}$ decides the data symbol as $s = 0.7 - 0.7i$. After the indices of activated antennas and data symbol are determined, the transmit vector is obtained as $\mathbf{x} = \frac{1}{\sqrt{2}}\left[0, 0, \underbrace{0.7 - 0.7i}_{\tilde{t}_{3,1}=3}, 0, 0, 0, \underbrace{0.7 - 0.7i}_{\tilde{t}_{3,2}=7}, 0\right]^T$.

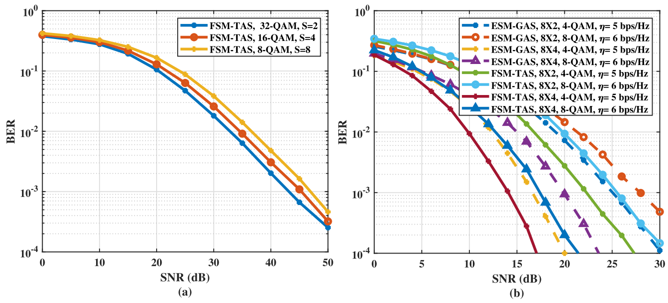

Fig. 2. BER performances of (a) FSM-TAS for $S = 2$, $S = 4$, and $S = 8$ at $\eta = 8$ b/s/Hz with 8×1 MIMO system and (b) FSM-TAS for $S = 2$ and ESM-GAS under $\eta = 5$ and 6 b/s/Hz with 8×2 and 8×4 MIMO systems.

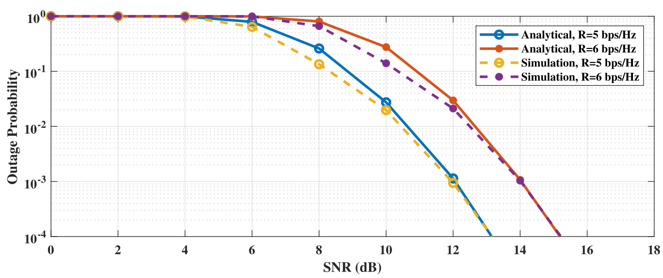

Fig. 3. Theoretical expression and Monte Carlo simulation results for outage probability of FSM-TAS at $\eta = 5$ and 6 b/s/Hz with $N_T = 8$ and $N_R = 1$.

B. Receiver Side

The received signal $\mathbf{y} \in \mathbb{C}^{N_R \text{x} 1}$ at the receiver side is given in

$$\mathbf{y} = \sqrt{\rho}\tilde{\mathbf{h}}_{f,N_A} s + \mathbf{n} \tag{4}$$

where $\mathbf{n} \in \mathbb{C}^{N_R \text{x} 1}$ is additive white Gaussian noise vector with $\mathcal{CN}(0, 1)$, and ρ is average signal-to-noise ratio (SNR) at each receiver antenna. N_A, the selected combination, and data symbol are determined using a maximum likelihood detector at the receiver. This detector works as follows:

$$[\hat{N}_A, \hat{f}, \hat{s}] = \arg\min_{N_A, f, s} ||\mathbf{y} - \sqrt{\rho}\tilde{\mathbf{h}}_{f,N_A} s||^2. \tag{5}$$

In (5), $\hat{N}_A$, $\hat{f}$, and $\hat{s}$ stand for the detected number of active antennas, the index of channel combination, and data symbol, respectively.

III. Complexity Analysis

In this section, the average transmitter and receiver complexities of the proposed FSM-TAS scheme are calculated separately. In [6], the transmitter complexity of COAS scheme is defined as the required number of complex multiplications (CMs) and complex additions (CAs) to order the norm squares of channel vectors. By following the same procedure, the transmitter complexity of FSM-TAS scheme, which is the required number of CAs and CMs to order the norm squares of the combinations of channel coefficients as in (2) for determined N_A, is calculated. As mentioned before, N_A varies between 1 and $N_T/2$ with equal probability, and the average transmitter complexity of FSM-TAS scheme can be calculated as

$$C_{\text{Tx,FSM-TAS}} = \frac{\sum_{N_A=1}^{N_T/2} \binom{N_T}{N_A} [(N_A + 2)N_R - 1]}{N_T/2}. \tag{6}$$

On the other hand, the benchmark ESM-GAS scheme sorts all possible combinations of channel coefficients. Then, transmitter complexity of ESM-GAS is given as

$$C_{\text{Tx,ESM-GAS}} = \sum_{N_A=1}^{N_T} \binom{N_T}{N_A} [(N_A + 2)N_R - 1]. \tag{7}$$

Since ESM-GAS compares all possible combinations of channel coefficients in each time slot, the proposed FSM-TAS scheme has lower average transmitter complexity than ESM-GAS as can be seen from (6) and (7).

In the next step, the average receiver complexity of FSM-TAS scheme is calculated. The average receiver complexity is measured by the total number of CAs and CMs that is required to make the detection in (5). Then, the average of required number of complex calculations for FSM-TAS is

$$C_{\text{Rx,FSM-TAS}} = \left(\left(3 \frac{\left(\frac{N_T}{2} + 1\right)}{2} + 2 \right) N_R - 1 \right) 2^{\eta} \tag{8}$$

where $\left(\frac{\frac{N_T}{2}+1}{2}\right)$ is the expected value of N_A in FSM-TAS. Different from the FSM-TAS scheme, N_A changes between 1 and N_T in ESM-GAS and the expected value of N_A in ESM-GAS is $\left(\frac{N_T+1}{2}\right)$. The average receiver complexity for ESM-GAS can be calculated as

$$C_{\text{Rx,ESM-GAS}} = \left(\left(3 \left(\frac{N_T + 1}{2} \right) + 2 \right) N_R - 1 \right) 2^{\eta'} \tag{9}$$

where η' is the spectral efficiency of the ESM-GAS scheme. For a fair comparison, under the same spectral efficiency (i.e., $\eta = \eta'$), (8) and (9) show that FSM-TAS scheme has lower average receiver complexity than ESM-GAS. This is caused by the difference in possible values of N_A in these schemes. For instance, for $N_T = 8$ and $N_R = 2$, FSM-TAS has 86% lower transmitter and 41% lower receiver complexity, respectively.

IV. Outage Probability

In this section, the outage probability analysis of FSM-TAS is performed. In [11], $||\mathbf{h}_k||^2$ is given as a chi-squared random variable with $2N_R$ degrees of freedom. Adding the channel vectors linearly as in (1) to get the combinations does not affect the degrees of freedom and $||\hat{\mathbf{h}}_{n,N_A}||^2$ is also a chi-squared random variable with $2N_R$ degrees of freedom. The probability density function (pdf) and cumulative distribution function (cdf) of $||\hat{\mathbf{h}}_{n,N_A}||^2$ are shown in (10) and (11), respectively.

$$f_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x) = \frac{x^{N_R - 1} e^{-x}}{\Gamma(N_R)} \tag{10}$$

$$F_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x) = 1 - e^{-x} \sum_{i=0}^{N_R - 1} \frac{x^i}{i!} = \frac{\gamma(N_R, x)}{\Gamma(N_R)} \tag{11}$$

Here, $\Gamma(.)$, $\gamma(.,.)$, and $\beta(.,.)$ are the upper incomplete gamma function, the lower incomplete gamma function, and beta function, respectively. As mentioned above, S out of K combinations of channel coefficients with maximum norm squares are selected to apply SM in FSM-TAS scheme. After sorting the combinations as in (2), in [12], the pdf of $||\tilde{\mathbf{h}}_{S,N_A}||^2$ is given as

$$f_{||\tilde{\mathbf{h}}_{S,N_A}||^2}(x) = \frac{1}{\beta(K - S + 1, S)} \left\{ F_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x) \right\}^{(K-S)} \times \left\{ 1 - F_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x) \right\}^{(S-1)} f_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x). \tag{12}$$

Then, the pdf of instantaneous received SNR (γ_i) for the determined N_A can be expressed as in the following equation:

$$f_{\gamma_i}^{N_A}(x) = \frac{1}{S}\sum_{l=1}^{S}\frac{1}{\beta(K-l+1,l)}\left\{F_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x)\right\}^{(K-l)} \times \left\{1 - F_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x)\right\}^{(l-1)} f_{||\hat{\mathbf{h}}_{n,N_A}||^2}(x). \quad (13)$$

For the determined N_A, the outage probability of FSM-TAS scheme is defined as $P_{\text{out},N_A}(\gamma, R) = P\{\gamma_i < \gamma_{\text{th}}\} = \int_0^{\gamma_{\text{th}}} f_{\gamma_i}^{N_A}(x)\,dx$, where R is the predetermined spectral efficiency, γ is the average SNR, and $\gamma_{\text{th}} = \frac{2^R-1}{\gamma}$ is the threshold SNR value.

After inserting (10)–(13) into the outage probability expression, the outage probability of FSM-TAS can be expressed as

$$P_{\text{out},N_A}(\gamma, R) = \frac{1}{\Gamma(N_R)S}\sum_{l=1}^{S}\frac{1}{\beta(K-l+1,l)} \times \int_0^{\gamma_{\text{th}}} x^{N_R-1}e^{-x}\left\{\frac{\gamma(N_R,x)}{\Gamma(N_R)}\right\}^{(K-l)} \times \left\{1 - \frac{\gamma(N_R,x)}{\Gamma(N_R)}\right\}^{(l-1)} dx. \quad (14)$$

Since N_A changes with respect to incoming bits, the average outage probability is calculated and expressed as

$$P_{\text{out,avg}}(\gamma, R) = \frac{1}{N_T/2}\sum_{N_A=1}^{N_T/2} P_{\text{out},N_A}(\gamma, R). \quad (15)$$

V. Simulation Results

In this section, Monte Carlo simulations are performed to test the BER performance of FSM-TAS for different S values and to compare the BER performances of FSM-TAS and ESM-GAS [10] under the same spectral efficiency for a fair comparison. In addition, a comparison is performed between the theoretical outage probability expression in Section IV and Monte Carlo simulations. Simulations are performed for a MIMO system with $N_T = 8$ and different N_R values.

Fig. 2(a) shows BER performances of FSM-TAS for $S = 2$, $S = 4$, and $S = 8$ at $\eta = 8$ b/s/Hz spectral efficiency. BER performance decreases when S increases despite the modulation order also decreasing. The reason is that decreasing S means to have less but more powerful combinations of channel coefficients and it enhances the BER performance of the system despite using a higher modulation order. A BER comparison between the proposed FSM-TAS scheme and ESM-GAS is shown in Fig. 2(b) under $\eta = 5$ and 6 b/s/Hz. As seen from Fig. 2(b), FSM-TAS with $S = 2$ has approximately 3 dB gain at 10^{-4} with respect to ESM-GAS under the same spectral efficiency since FSM-TAS carries additional bits to determine N_A and selects less and more powerful combinations with respect to ESM-GAS. In Fig. 3, the theoretical outage probability results derived in Section IV is compared with simulation results. We see that theoretical derivations and simulation results are in agreement at high SNR values and they are close to each other at low SNR values.

VI. Conclusion

In this article, a novel SM-IM based MIMO scheme called FSM-TAS has been introduced. The proposed scheme determines N_A by means of IM to convey additional information bits and uses transmit antennas flexibly. Transmitter and receiver complexities have been analyzed and compared with the benchmark scheme. It has been shown that a varying N_A provides lower complexity. In addition, the theoretical expression of outage probability has been derived and compared with Monte Carlo simulation for validation. The BER superiority of FSM-TAS is also shown. Finally, we conclude that FSM-TAS can be a candidate for future MIMO systems due to its improved BER performance and flexibility in the number of active antennas. The proposed idea is described for ordinary SM; however, it can also be applied for ESM techniques in the future.

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