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Spectrally Efficient Adaptive Generalized Spatial Modulation MIMO Systems

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***Abstract*—We propose a spectrally efficient and low complexity spatial modulation (SM) transmission scheme for a multiple-input multiple-output (MIMO) system. As compared to conventional generalized spatial modulation (GSM), which can achieve fixed data rates, the proposed adaptive generalized spatial modulation (AGSM) uses adaptive modulation in combination with the GSM. The AGSM MIMO scheme improves the spectral efficiency (SE) of GSM by increasing the modulation order of transmission in better channel conditions. GSM maps information into a spatial symbol and a constellation symbol of constant modulation order but in proposed AGSM, the constellation size increases as the channel conditions improves keeping the bit-error-rate (BER) below a certain threshold value. The proposed technique is compared with the adaptive spatial modulation (ASM). It is shown that for the same SE, the proposed AGSM requires less number of antennas than ASM. The performance of AGSM MIMO is validated through Monte-Carlo simulations. The results show that AGSM reduces the number of transmit antennas compared to ASM without any BER degradation.**

***Index Terms*—Generalized spatial modulation, spatial modulation, spectral efficiency and adaptive modulation.**

I. INTRODUCTION

The next-generation cellular networks are proposed to be $green$ implying that energy efficiency will be an important design parameter. Until recently, the majority of the research has focused on the improvement of spectral efficiency (SE) because of the demand of high data rates and wideband communication [3]. Multiple-input multiple-output (MIMO) systems such as vertical Bell Laboratories layered space-time (V-BLAST), transmit data through multiple antennas simultaneously, thus improving the SE enormously [2]. However, such techniques are not energy efficient because they consume high power due to multiple active radio-frequency (RF) chains [2]. Also all the antennas transmit at same time and at the same frequency, which increases the system complexity and causes significant amount of inter-channel interference (ICI) [6].

A relatively new technique known as spatial modulation (SM) MIMO is rather energy efficient and has low complexity compared to conventional MIMO because it has only one active antenna at an instance to transmit [4]. SM MIMO has two types of constellation (i.e., the spatial constellation) that decide the active antenna index and the signal constellation through which the data is modulated into a symbol such as quadrature amplitude modulation (QAM). The active antenna index and the symbol to be transmitted depends on random data bits at the transmitter. At the receiver, the index of active antenna is detected first, followed by symbol detection. SM MIMO increases the SE by appending some portion of data in the active antenna index and also avoids the ICI due to single active antenna for a transmission. However a limitation with SM MIMO is that the number of transmit antennas must be a power of two, i.e., 2, 4, 8, and so on.

In generalized spatial modulation (GSM) MIMO, more than one antennas are active for a transmission instance. Data is transmitted in antenna combination indices in addition to symbol modulation over QAM. The spectral gain of GSM MIMO for N_t transmit and N_a active antennas is $\lfloor log_2\binom{N_t}{N_a} \rfloor$, where $\lfloor . \rfloor$ is the floor operator. As $\lfloor log_2\binom{N_t}{N_a} \rfloor$ is greater than the spectral gain of SM MIMO, i.e., $log_2(N_t)$, that is why the GSM MIMO is spectrally more efficient than SM MIMO. GSM MIMO requires $N_t = 5$ and $N_a = 2$ to transmit three bits because $\lfloor log_2\binom{5}{2} \rfloor = 3$ while SM MIMO needs $N_t = 8$. GSM MIMO is more reliable than SM MIMO because the receiver in GSM MIMO receives more than one copy of same symbol. GSM MIMO performance is very close to SM MIMO in terms of BER with less number of required transmit antannas [6]. While the SM MIMO and GSM MIMO are energy efficient than conventional MIMO but their SE still needs to be improved as it is low compared to a conventional MIMO.

The SE of GSM MIMO can be further improved by adaptive modulation (AM) technique [1], [2], where the constellation size increases with the increase in received signal-to-noise ratio (SNR) for a given average bit error rate (ABER). In [2], ASM was introduced to improve SE of conventional SM MIMO holding the ABER below a pre-defined threshold. In order to further improve the SE, this paper presents adaptive generalized spatial modulation (AGSM) MIMO, which achieves high SE by increasing the modulation order of QAM according to channel conditions while keeping the ABER under a pre-defined threshold value. Simulation results are matched with the analytical results for ABER and SE of AGSM and are compared with ASM MIMO in [2]. Also the GSM MIMO and AGSM MIMO are compared in terms of SE.

The rest of the paper is organized as follows. Section II presents system and channel model, Section III presents the numerical results for the proposed scheme and Section IV concludes the paper.

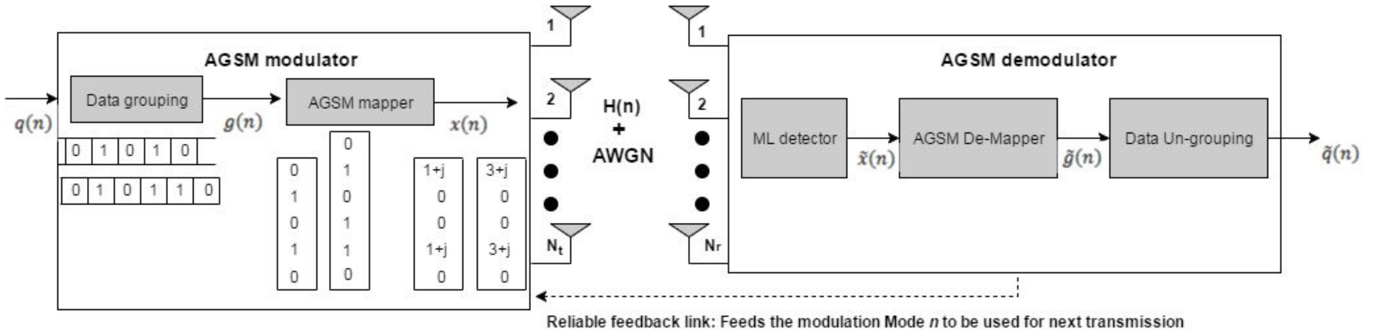

Fig. 1. AGSM system model

TABLE I
AGSM MAPPING TABLE FOR $N_t = 5$, $N_a = 2$, $4-QAM$,$8-QAM$

m_a *bits*	*Antenna Combination*	*4-QAM, n=2*	*Symbol x*	*8-QAM, n=3*	*Symbol x*
000	(1,2)	00	-1+j	000	-3+j
001	(1,3)	01	-1-j	001	-3-j
010	(1,4)	10	1+j	010	-1+j
011	(1,5)	11	1-j	011	-1-j
100	(2,3)			100	1+j
101	(2,4)			101	1-j
110	(2,5)			110	3+j
111	(3,4)			111	3-j

II. AGSM SYSTEM MODEL

A. System and Channel Model

The proposed AGSM MIMO model has N_t transmit and N_r receive antennas as shown in Fig. 1. AM is used in AGSM to increase the QAM constellation size in better channel conditions to send more data. The first m_a=$\lfloor\ log_2\binom{N_t}{N_a}\ \rfloor$bits of the random incoming information bits $q(n)$ are spatially modulated over the antennas in the combination. The transmitter transmits a symbol of order M-ary QAM (M-QAM) through the selected antennas, where $M = 2^n$ is the number of bits transmitted using the signal constellation. The receiver feeds back the modulation mode n for next transmission to the transmitter based on the received SNR threshold according to a pre-determined ABER level. The total number of bits transmitted by AGSM MIMO during a single transmission instance are $m = m_a + M = \lfloor log_2\binom{N_t}{N_a}\rfloor + log_2 m_n$, where $n = \{0, 1, 2..., N\}$ is the rate adaptive modulation mode.

The incoming bits are grouped, then mapped into spatial symbol and QAM symbol as shown in Table I. The concept of mapping data can be further elaborated with the help of an example. Let $N_t = 5$ and $N_a = 2$ then $m_a = 3$ as shown in Table I. The data to be transmitted in the first transmission **g** =[0 1 0 1 0]^T is mapped into **x** =[1+j 0 0 1+j 0]^T starting with 4-QAM where $n = 2$ as shown in Table I. The data is received at the receiver and the modulation mode n is fed back to the transmitter for next transmission. According to the example in Fig. 1, **g** =[0 1 0 1 1 0]^T for the next transmission is mapped into **x** =[3+j 0 0 3+j 0]^T. The receiver has fed back modulation mode $n = 3$ because the value of received SNR is greater than the least value to maintain the pre-determined ABER at the receiver. The symbol constellation size has increased from 4-QAM to 8-QAM and this is how the AGSM improves the SE.

The AGSM modulated signal x is transmitted through a wireless MIMO channel denoted by **H** with an order of $N_r \times N_t$ and experiences an additive white Gaussian noise (AWGN) $\mathbf{w} = [w_1, w_2, w_3, ..., w_{N_r}]^T$. The elements of **H** and **w** are independent and identically distributed (i.i.d) complex Gaussian random variables with zero mean and unit variance σ_n^2. The received signal at a given transmission instance is given as

$$\mathbf{y} = \sqrt{\rho}\mathbf{h}_{\alpha}^{'}x + \mathbf{w}, \tag{1}$$

where ρ is the average SNR at each receive antenna, $x\ \epsilon$ M-QAM is the transmitted symbol by antenna combination $\alpha = (\alpha_1, \alpha_2, ..., \alpha_{N_a})$, α_k is the k-th antenna in the antenna combination used in a transmission instance among all the possible combinations of antennas. For example, $\alpha = (1, 4)$ for the transmission shown in Fig. 1. The channel vector $\mathbf{h}_{\alpha}^{'}$=$\sum_{k=1}^{N_a}\mathbf{h}_{\alpha_k}^{'}$, where $\mathbf{h}_{\alpha_k}^{'}$ is the channel vector from active transmit antenna α_n to all the receive antennas, so $\mathbf{h}_{\alpha}^{'}$ is the summation of active antennas channels vectors. For the first transmission given in Fig. 1, $\alpha = (1, 4)$, $\mathbf{h}_{\alpha_1}^{'}$=$[h_{11} \quad h_{21}]^T$ and $\mathbf{h}_{\alpha_4}^{'}$=$[h_{14} \quad h_{24}]^T$. Thus $\mathbf{h}_{\alpha}^{'}$=$[h_{11} + h_{14} \quad h_{21} + h_{24}]^T$ is the sum of $\mathbf{h}_{\alpha_1}^{'}$ and $\mathbf{h}_{\alpha_4}^{'}$. The receiver of GSM MIMO is based upon the ML principle proposed in [2] i.e. $[\tilde{\alpha}, \tilde{x}] = \underset{\alpha,x}{\text{argmax}} p_y(\mathbf{y}|\mathbf{x}, \mathbf{H}) = \underset{\alpha,x}{\text{argmin}} \sum_{i=1}^{N_r} |y_i - h_{\alpha,i}^{'}x|^2$, which estimates the combination of active antenna and the transmitted M-QAM, where $|y_i - h_{\alpha,i}^{'}x|^2$ is the Euclidian distance between the received signal and actual constellation points. Similarly $p_y(\mathbf{y}|x, \alpha, \mathbf{H})$ is the probability density function (PDF) of received signal y conditioned over the transmit signal x, the antenna combination used α and the channel **H** given as

$$p_y(\mathbf{y}|x, \alpha, \mathbf{H}) = \frac{1}{(\pi\sigma_n^2)^{N_t}} exp(-\frac{\|\mathbf{y} - \mathbf{h}_{\alpha}^{'}x\|_F^2}{\sigma_n^2}), \tag{2}$$

where $\|.\|_F^2$ denotes the frobenius norm. The detector in AGSM MIMO has to detect symbols of different sizes because of the varying constellation size according to the fed back modulation mode n.

B. Adaptive Transmission

The adaptive transmission system modeled for the proposed AGSM MIMO is constant-power variable-rate M-QAM. The

SNR is divided into $N+1$ regions and nth region ($n = 0,1,....,N$) is assigned a constellation size $M = 2^n$ in the proposed adaptive modulator. Modulation mode n is selected when the received SNR γ_r is above the switching threshold γ_n and below γ_{n+1}. The modulation mode n increments to $n+1$ in the next transmission if the received SNR falls between γ_{n+1} and γ_{n+2}. The switching threshold SNR can be represented as $\gamma_n = -\frac{2}{3}\ln(5P_{b_0})(2^{n-1})$ for modulation mode $n = \{0, 1, ..., N\}$ at a target BER of P_{b_0} [1].

C. Performance Analysis

1) Received SNR: The statistics of received SNR, γ_r gives a Chi-squared random variable (RV) with degree of freedom equal to ($2{\times}N_t{\times}N_r$) [2]. In proposed AGSM MIMO, N_a active antennas are transmitting thus its γ_r is a Chi-squared RV with $2{\times}N_a{\times}N_r$ degrees of freedom having a PDF and CDF given respectively as

$$f_{\gamma_r}(\gamma) = \frac{\gamma^{(N_a N_r)-1}}{[(N_a N_r)-1]!\rho^{(N_a N_r)}} e^{-\frac{\gamma}{\rho}}. \tag{3}$$

$$F_{\gamma_r}(x) = 1 - e^{-\frac{\gamma}{\rho}} \sum_{k=0}^{(N_a N_r)-1} \frac{1}{k!}\left(\frac{\gamma}{\rho}\right)^k. \tag{4}$$

2) Average SE: The proposed AGSM MIMO has a throughput equal to the sum of throughputs obtained by the signal dimension $\eta_{AM} = log_2 m_n$ and the spatial dimension η_c=$log_2\lfloor log_2\binom{N_t}{N_a}\rfloor$, i.e., $\eta_{avg} = \eta_{AM} + \eta_c = log_2 m_n + log_2\lfloor log_2\binom{N_t}{N_a}\rfloor$, where $m_n = 2^n$ for a modulation mode n and η_{avg} is the total average SE. The average SE of signal dimension for proposed AGSM MIMO link is equal to the weighted sum of data rates of each $N+1$ threshold regions because the modulation mode n changes when the received SNR falls in the next threshold region. These data rates are the weighted functions of the probability that a received SNR has a value in the nth threshold region [1], hence $\eta_{AM} = \sum_{k=0}^{N} n p_n$ for proposed AGSM MIMO, where $p_n = Pr[\gamma_n \leq \gamma_r < \gamma_{n+1}] = F_{\gamma_r}(\gamma_{n+1}) - F_{\gamma_r}(\gamma_n)$ is the probability to transmit with nth modulation mode. Thus average SE of the signal dimension for AGSM MIMO becomes $\eta_{AM} = N - \sum_{k=2}^{N} F_{\gamma_r}(\gamma_n)$.

3) Average BER: An asymptotic performance bound for M-QAM in AGSM MIMO is derived for i.i.d Rayleigh flat fading channel. An AGSM detector has to detect both: QAM constellation symbol and the active antennas indices. Following the approach as in [4], where estimation of antenna index and the transmit symbol are considered to be mutually independent processes, the assumption presents an ideal scenario where antenna indices are estimated given that the transmit symbol is estimated perfectly and vice versa. It is an inconsistent approach in general because AGSM MIMO detector jointly detects the QAM symbol and indices of antenna combination. But it is shown in [4] that despite this ideal assumption of independent estimation processes, the lower bound given is very tight as $P_{be} \geq 1 - P_{corr} = P_a + P_x - P_a P_x$, where P_{be} denotes the average probability of bit error and $P_{corr} = (1-P_a)(1-P_x)$ is the probability of correctly detected bits. $P_a = \sum_{n=2}^{N} p_n P_{a|n}$ is the probability of bit error due to antenna indices estimation for an active antenna combination when the transmit symbol is detected correctly, where p_n is the probability of using n modulation mode and $P_{a|n} \leq \sum_{\alpha,s} N(x_{\alpha,s}, x_{\tilde{\alpha},\tilde{s}}) P(x_{\alpha,s} \rightarrow x_{\tilde{\alpha},\tilde{s}})$ is the error probability of antenna index detection for a given modulation mode n [2], [5]. $P(x_{\alpha,s} \rightarrow x_{\tilde{\alpha},\tilde{s}})$ is pairwise probability of error (PEP) of detecting signal vector $x_{\hat{\alpha},\hat{s}}$ while $x_{\alpha,s}$ was transmitted [6], where $\hat{\alpha}$ is the estimated antenna combination and $\hat{s}$ is the estimated QAM symbol. $P_x = \frac{1}{\eta_{AM}} \sum_{n=2}^{N} n\bar{P}_{b_n}$ is the probability of bit error of proposed AM system due to symbol estimation when the antennas indices are perfectly estimated, where $\bar{P}_{b_n} = \int_0^{\gamma_2} P_{b_1}(x) f_{\gamma_r}(x) dx$ for modulation mode $n = 1$ and $\bar{P}_{b_n} = \int_{\gamma_k}^{\gamma_{n+1}} P_{b_n}(x) f_{\gamma_r}(x) dx$ for $n > 1$ with $f_{\gamma_r}(.)$ given in Eq. (3) [1].

III. SIMULATION RESULTS

This section illustrates performance analysis of proposed AGSM MIMO for different values of N_t, N_a and $P_{b_0} = 10^{-3}$.

A. Average Bit Error Rates

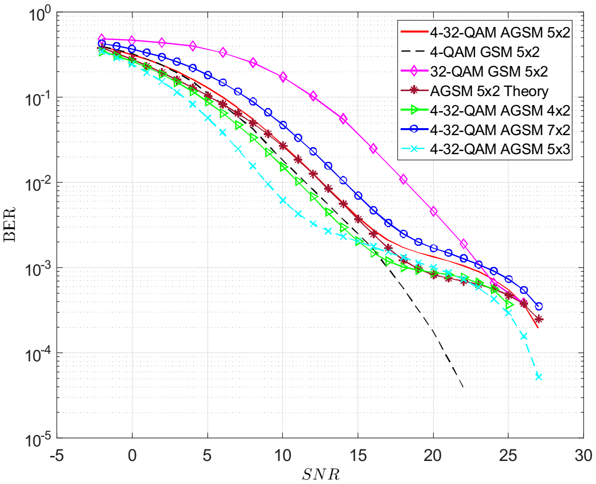

Fig. 2. ABER for the AGSM and GSM MIMO schemes versus ρ(dB)

The ABERs for proposed AGSM MIMO and GSM MIMO are shown in Fig. 2, which is a function of ρ(dB) for $N_t = 5$, $N_r = 2$ and $N_a = 2$. Fig. 2 depicts that for the same number of transmit and receive antennas, the ABER curve of AGSM MIMO is similar to that of GSM MIMO for 4-QAM in low SNR ranges (i.e., $0 < \rho \leq 17$dB). Then there is a gradual variation in ABER slope of the proposed AGSM MIMO because of the increase in the modulation mode n at higher SNR values. Due to adaptive modulation, the modulation order increases from 4-QAM to 8-QAM and so on to 32-QAM. The ABER of proposed AGSM MIMO finally converges to the same performance as GSM MIMO for 32-QAM at high SNR values, which shows that the ABER of the GSM MIMO for the lowest and highest modulation mode n bounds the ABER performance of proposed AGSM MIMO. The ABER of 5x3 AGSM MIMO is better than 5x2 AGSM MIMO as shown in Fig. 2, which shows the receiver diversity in terms of number of receive antennas for proposed AGSM MIMO.

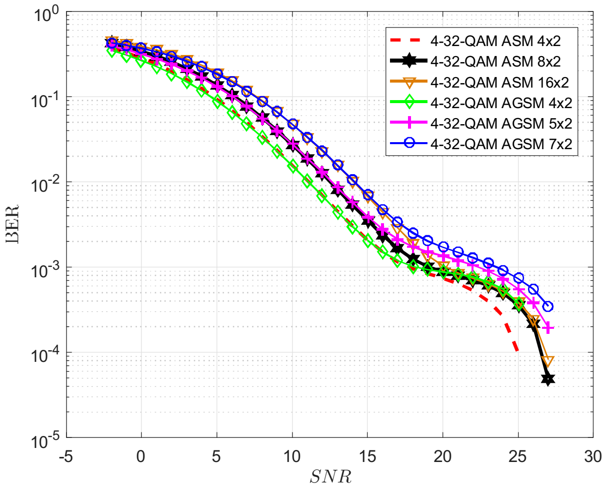

Fig. 3. ABER for the AGSM and ASM MIMO schemes versus ρ(dB) for different values of N_t

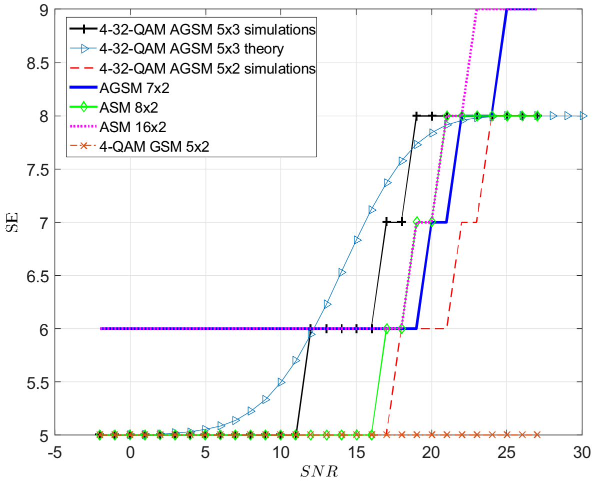

Fig. 4. Average SE of AGSM, ASM and GSM MIMO schemes versus ρ(dB) for different values of N_t and N_r

Fig. 3 shows that the diversity of the system does not depend on the number of transmit antennas because the ABER of 4x2 AGSM MIMO is better than ABER of 5x2 and 7x2 AGSM MIMO. Higher number of transmit antennas increases the SE of the system but it also degrades the ABER of proposed AGSM MIMO because higher number of N_t means that the constellation points of proposed scheme becomes less separated. Also greater number of transmit antennas means greater number of spatially modulated bits m_a, which implies higher the bit error rate when an incorrect antenna combination is detected. Fig. 3 shows that ABER of AGSM MIMO with $N_t = 5$ and $N_t = 7$ is almost the same as that of ASM MIMO in [2] with $N_t = 8$ and $N_t = 16$, respectively. Thus the proposed scheme can achieve same ABER as ASM MIMO with less number of transmit antennas.

B. Average Spectral Efficiency

It is clear from Fig. 4 that the average spectral efficiency (i.e., η_{AM}+η_c) of AGSM MIMO is higher with $N_r = 3$ than with $N_r = 2$ at any value of SNR. For example, average spectral efficiency of AGSM MIMO is 8 bits per channel use (bpcu) with $N_r = 3$ and 6 bpcu with $N_r = 2$ at 20dB. Thus the proposed AGSM MIMO achieves greater SE with higher number of receive antennas. This figure also shows that the simulation results match the analytical results for the proposed scheme.

Fig. 4 shows that the proposed AGSM MIMO can achieve high data rates for high SNR values as compared to conventional GSM MIMO which has fixed data rates. For example, the GSM MIMO has 5 bpcu with $N_t = 5$ and 4-QAM symbol modulation with any number of receive antennas and for all values of SNR while AGSM MIMO with $N_t = 5$ and $N_a = 2$ can achieve 6 bpcu for $17 < \rho \leq 21$dB, 7 bpcu for $21 < \rho \leq 24$dB and 8 bpcu for 24dB$< \rho$. Conventional GSM MIMO can achieve 7 bpcu with $N_t = 7$. Thus AGSM MIMO can achieve same SE as GSM MIMO but with less number of antennas.

Fig. 4 shows that AGSM MIMO achieves same SE with $N_t = 5$ and $N_a = 2$ as the ASM MIMO with $N_t = 8$ for $0 < \rho \leq 16$dB, $17 < \rho \leq 19$dB and $24 < \rho \leq 27$dB (i.e., 5 bpcu, 6 bpcu and 8 bpcu), respectively, and 1 bpcu less than ASM MIMO for $16 < \rho \leq 17$dB and $17 < \rho \leq 19$dB. While AGSM MIMO with $N_t = 7$ and $N_a = 2$ outperforms ASM MIMO with $N_t = 8$, which implies that AGSM MIMO can achieve even greater spectral efficiency than ASM MIMO with lesser number of antennas.

IV. CONCLUSION

This paper proposed a low complexity AGSM MIMO scheme that takes advantage of adaptive modulation to enhance the spectral efficiency of the conventional GSM MIMO having fixed data rates. Simulation results show that the proposed scheme outperforms both GSM MIMO and ASM MIMO schemes because of its high spectral efficiency and reduced number of transmit antennas. AGSM MIMO also addresses the issue that the number of transmit antennas must be a power of two for ASM MIMO without any significant ABER degradation.

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