Experimental Results for Generalized Spatial Modulation Scheme with Variable Active Transmit Antennas

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Abstract. This paper presents experimental results on the performance of generalized spatial modulation scheme with variable active transmit antennas (VA-GSM). In the VA-GSM scheme, one or more transmit antennas are activated simultaneously to transmit the same complex symbol. The indices of the set of activated transmit antennas at any time instant are then used to convey extra information in addition to the transmitted complex symbol. The average bit error rate performance of the proposed scheme is evaluated experimentally, and the results agree closely with simulation. We also compare the VA-GSM with existing SM and GSM schemes.

Keywords: Spatial Modulation (SM) · Generalized Spatial Modulation (GSM) · Variable active transmit antennas

1 Introduction

Spatial modulation (SM) is a new promising transmission technique that uses antenna indices, in a multiple antenna system, as avenues for data transmissions in addition to the transmitted modulated symbols. The principle of wireless transmissions in which the information is carried by both the indices of the active antennas and the symbol transmitted through these active antennas was first investigated by Mesleh et al. in [1, 2] where only one antenna was activated at each time instant thereby avoiding inter-carrier-interference (ICI) between the transmit antennas. Following that work, many variants of this idea were introduced such as the space shift keying (SSK) modulation that uses only the spatial modulation concept without transmitting any symbol. That scheme reduces the system complexity by cancelling the amplitude/phase modulation required at the transmitter and receiver sides, but at the expense of some degradation in the system's spectral efficiency [3]. The idea of Trellis coded modulation (TCM) was applied to the spatial points available in SM in [4, 6]. That scheme, named Trellis Coded SM (SM–TCM), achieves both coding and diversity gains, and has a significant performance enhancements over SM especially in the presence of realistic channel conditions such as Rician fading and spatial correlation. A combination of both SM and space-time block coding (STBC) that takes advantage of the benefits of both schemes was proposed in [6].

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In [7], SM system was generalized to multiple active transmitting antennas and low complexity detection MIMO system. In [8] receiver-side SM scheme for single user, called the Generalized Pre-Coding Aided SM (GPASM), was introduced. Generalized form of SSK (GSSK) was proposed in [9] where a set of transmit antennas were activated at a time, and all the active antennas transmit ones (i.e no symbols were transmitted). The scheme increases the spectrum efficiency compared to SSK. Generalized SM (GSM) in which a fixed set of transmit antennas were activated simultaneously, with all active antennas transmitting the same constellation symbol, was proposed in [10, 11]. Transmitting the same symbol from all active antennas keep the key advantages of SM which are: avoiding ICI, reducing complexity, and using only one radio frequency (RF) chain for hardware implementation. In [12], SSK with variable number of active transmit antennas (VA-SSK) was introduced.

In this paper, we propose GSM scheme in which a variable set of active transmit antennas are used. Unlike the GSM where a fixed number of transmit antennas are used at any time instant to transmit the same constellation symbol, the proposed scheme will vary the number of activated transmit antennas. Also unlike VA-SSK where no symbols are transmitted, the proposed scheme transmits symbols which increases the system's spectral efficiency.

2 System Model

2.1 VA-GSM Modulator

Consider a MIMO system equipped with N_t transmit and N_r receive antennas, where we assume $N_t \geq N_r$. In this system, one or more transmit antennas are activated simultaneously at any time instant and all the activated antennas transmit the same constellation symbol. If the maximum number of activated transmit antennas at a time is N_a (where $N_a \leq N_t$), then one or two, or three, up to N_a transmit antennas can be activated simultaneously. Then, the total number of possible active transmit antenna combinations in this scheme is $\sum_{n=1}^{N_a} \binom{N_t}{n}$, where $\binom{\cdot}{\cdot}$ denotes the binomial operation. These antenna combinations will be used to convey extra information. Because the number of active transmit antenna combinations that can be used for data transmission must be a power of two, only $g = 2^{k_l}$ active antenna combinations will be considered, where k_l *is* the number of bits transmitted per spatial symbol which is given by

$$k_l = \left\lfloor log_2 \left(\sum_{n=1}^{N_a} \binom{N_t}{n} \right) \right\rfloor, \tag{1}$$

where $\lfloor a \rfloor$ denotes the greatest integer less than or equal to a. For the case when $N_a = N_t$, Eq. (1) becomes

$$k_l = \left\lfloor log_2\left(\sum_{n=1}^{N_t}\binom{N_t}{n}\right)\right\rfloor$$

$$= \lfloor log_2(2^{N_t}-1)\rfloor = N_t - 1 \tag{2}$$

Equations (1) and (2) show that unlike SM in which the number of bits transmitted per spatial symbol increase logarithmically with increasing the number of transmit antennas N_t, the number of bits transmitted per spatial symbol in the proposed VA-GSM increases with increasing N_t and N_a. The total number of bits that can be transmitted using VA-GSM is given by

$$k_t = k_l + k_s, \tag{3}$$

where $k_s = log_2(M)$ and M is the constellation size.

Table 1. Transmitted vector $\boldsymbol{x}_{l,m}$ for different input bits in VA-GSM (assuming BPSK modulation).

Bits mapping	l	m	$\boldsymbol{x}_{l,m}$	Bits mapping	l	m	$\boldsymbol{x}_{l,m}$
000 0	1	1	$[s_1\ 0\ 0\ 0]^T$	100 0	5	1	$[s_1\ s_1\ 0\ 0]^T$
000 1	1	2	$[s_2\ 0\ 0\ 0]^T$	100 1	5	2	$[s_2\ s_2\ 0\ 0]^T$
001 0	2	1	$[0\ s_1\ 0\ 0]^T$	101 0	6	1	$[s_1\ 0\ s_1\ 0]^T$
001 1	2	2	$[0\ s_2\ 0\ 0]^T$	101 1	6	2	$[s_2\ 0\ s_2\ 0]^T$
010 0	3	1	$[0\ 0\ s_1\ 0]^T$	110 0	7	1	$[s_1\ 0\ 0\ s_1]^T$
010 1	3	2	$[0\ 0\ s_2\ 0]^T$	110 1	7	2	$[s_2\ 0\ 0\ s_2]^T$
011 0	4	1	$[0\ 0\ 0\ s_1]^T$	111 0	8	1	$[0\ s_1\ s_1\ 0]^T$
$\underbrace{011}_{k_l}\ \underbrace{1}_{k_s}$	4	2	$[0\ 0\ 0\ s_2]^T$	$\underbrace{111}_{k_l}\ \underbrace{1}_{k_s}$	8	2	$[0\ s_2\ s_2\ 0]^T$

The transmitter divides the incoming data into blocks of k_t bits. The first k_s bits are mapped to a symbol $s_m \in \{s_1, s_2 \dots, s_M\}$ in the constellation while the next k_l bits are used to select a set of active antenna combinations which is denoted here by the set $\Gamma_l, l \in \{1,2,\cdots g\}$. The set of active transmitting antennas Γ_l transmit the same complex symbol s_m while the other antennas transmit zeros. Then the received vector $\boldsymbol{y} \in \mathbb{C}^{N_r \times 1}$ is given by

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x}_{l,m} + \boldsymbol{w}, \tag{4}$$

Table 2. Comparing VA-GSM, GSM, and SM in term of number of available antenna combinations (assuming $\boldsymbol{N_r = 4}$).

N_t	Scheme	$N_a = 1$	$N_a = 2$	$N_a = 3$	$N_a = 4$
4	SM	$g = 2^2$			
	GSM	$g = 2^2$	$g = 2^2$	$g = 2^2$	
	VA-GSM	$g = 2^2$	$g = 2^3$	$g = 2^3$	$g = 2^3$
8	SM	$g = 2^3$			
	GSM	$g = 2^3$	$g = 2^4$	$g = 2^5$	$g = 2^6$
	VA-GSM	$g = 2^3$	$g = 2^5$	$g = 2^6$	$g = 2^7$
16	SM	$g = 2^4$			
	GSM	$g = 2^4$	$g = 2^6$	$g = 2^9$	$g = 2^{10}$
	VA-GSM	$g = 2^4$	$g = 2^7$	$g = 2^9$	$g = 2^{11}$
64	SM	$g = 2^6$			
	GSM	$g = 2^6$	$g = 2^{10}$	$g = 2^{15}$	$g = 2^{19}$
	VA-GSM	$g = 2^6$	$g = 2^{11}$	$g = 2^{15}$	$g = 2^{19}$

where $\boldsymbol{x}_{l,m} \in \mathbb{C}^{N_t \times 1}$ denotes the transmitted vector, $\boldsymbol{H} \in \mathbb{C}^{N_r \times N_t}$ is the channel response between the transmitter and receiver, and $\boldsymbol{w}$ is the zero-mean Gaussian noise vector with variance $\sigma^2 = N_0/2$. Table 1 shows the mapping process at the transmitter in the proposed scheme for the case of four transmit antennas ($N_t = 4$), one or two active antennas at a time ($N_a = 2$), and Binary Phase shift keying (BPSK) modulation ($M = 2$). As shown in the last highlighted row of the table, the first bit (k_s=1) is mapped to a symbol in the BPSK constellation $s_m \in \{s_1, s_2\}$, while the next three bits (since in this case, $k_l = \lfloor log_2(\sum_{n=1}^{2} \binom{4}{n}) \rfloor = 3$ which gives $g = 2^3 = 8$) are used to select active antenna combinations $\Gamma_l, l \in \{1,2,\cdots 8\}$. Therefore, the antenna selection in VA-GSM is based on the second part, k_l, of the incoming bit stream. For example, if we choose [0111] from Table 1, the first bit 1 is mapped to a symbol s_2 ($m = 2$) in the BPSK constellation while the next three bits 011 select the fourth transmit antenna combination ($l = 4$) which means the fourth antenna is activated to transmit the symbol s_2 while the other antennas transmit zeros as described by the transmitted vector $\boldsymbol{x}_{l,m} = \boldsymbol{x}_{4,2} = [0 \ \ 0 \ \ 0 \ \ s_2]^T$. If we choose 1111, the transmitted vector is $\boldsymbol{x}_{l,m} = \boldsymbol{x}_{8,2} = [0 \ \ s_2 \ \ s_2 \ \ 0]^T$ which means the second symbol is transmitted through the eighth transmit antenna combination where the first and fourth antennas are selected to transmit the same copy of the BPSK symbol s_2. The received signal at each receiving antenna can be described as

$$y_j = h_{j,l} s_m + w_j \, , j = 1, 2, \cdots, N_r, \tag{5}$$

where $h_{l,j} = \sum_{i \in \Gamma_l} h_{j,i}$ is the summation of channel responses from all active transmit antennas Γ_l used at the current transmission instant to the j-th receiving antenna, and w_j is the Gaussian noise at the j-th receiving antenna.

Table 2 compares VA-GSM method with the conventional SM and the GSM approach proposed in [10]. It is clear from the table that the proposed VA-GSM provides more active transmit antenna combinations except for $N_t = 64$ which is the same as GSM because we limit the number of activated transmit antennas N_a in this illustration to $N_a \leq N_r = 4$. If we increase N_a, VA-GSM will have more active antenna combinations than the GSM for this case as will.

2.2 Maximum Likelihood (ML) Detection

At the receiver, ML optimum detector computes the Frobenius distances between the received signal and the set of possible transmitted vectors. Then, the ML detection operation can be expressed as

$$[\hat{l}, \hat{m}] = \arg \min_{\substack{m \in \{1,2,..,M\} \\ l \in \{1,2,..,g\}}} \left\{ \left\| \mathbf{y} - \mathbf{H}\mathbf{x}_{l,m} \right\|_{\mathrm{F}}^{2} \right\}$$

$$= \arg \min_{\substack{m \in \{1,2,..,M\} \\ l \in \{1,2,..,g\}}} \left\{ \sum_{j=1}^{N_r} \left| y_j - h_{l,j} s_m \right|^2 \right\} \tag{6}$$

where $\|.\|_{\mathrm{F}}$ denotes the Frobenius norm while $\hat{l}, \hat{m}$ denote the indices of the estimated set of activated transmit antennas and the transmitted complex symbol respectively. If the complex symbol s_m is transmitted over the antenna combination Γ_l, then the correct decision is obtained when $\hat{l} = l$ and $\hat{m} = m$.

3 System Performance Analysis

3.1 Upper Bound on the Average Bit Error Rate

The average bit error rate (ABER) performance can be analytically estimated using the well-known union bounding technique [13]. The ABER in the proposed method can be upper bounded as

$$\mathrm{ABER} \leq \frac{1}{2^{k_t}} \sum_{\hat{l}} \sum_{\hat{m}} \sum_{l} \sum_{m} \frac{d_H\left(x_{l,m}, x_{\hat{l},\hat{m}}\right) E\left\{\Pr\left(x_{l,m} \rightarrow x_{\hat{l},\hat{m}}\right)\right\}}{k_t}, \tag{7}$$

where $d_H\left(x_{l,m}, x_{\hat{l},\hat{m}}\right)$ is the Hamming distance between the transmitted symbol $x_{l,m}$ and the estimated symbol $x_{\hat{l},\hat{m}}$ and Pr $(x_{l,m} \rightarrow x_{\hat{l},\hat{m}})$ denotes pairwise error probability when estimating $x_{\hat{l},\hat{m}}$ while $x_{l,m}$ is transmitted which is given by

$$\Pr\left(x_{l,m} \rightarrow x_{\hat{l},\hat{m}}\right) = \Pr\left[\left\| \mathbf{y} - \mathbf{H}\mathbf{x}_{l,m} \right\|_{\mathrm{F}}^{2} > \left\| \mathbf{y} - \mathbf{H}\mathbf{x}_{\hat{l},\hat{m}} \right\|_{\mathrm{F}}^{2}\right]$$

$$= Q\left(\sqrt{\frac{\gamma\|\mathbf{H}\boldsymbol{\delta}\|^2}{2}}\right) \quad (8)$$

where $\boldsymbol{\delta} = (\mathbf{x}_{\hat{l},\hat{m}} - \mathbf{x}_{l,m})$ and $\gamma = E_s/N_0 = 1/\sigma^2$ is the SNR between the transmitter and the receiver, and $E_s = E\left\{\left\|\mathbf{H}\mathbf{x}_{l,m}\right\|^2\right\} = 1$. Using the alternative integral expression for the Q-function we get

$$\Pr\left(x_{l,m} \to x_{\hat{l},\hat{m}}\right) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{\|\mathbf{H}\boldsymbol{\delta}\|^2}{4\sigma^2 \sin^2\theta}\right) d\theta. \quad (9)$$

3.2 Complexity Analysis

The receiver complexity is estimated in terms of the number of real multiplicative operations required by the ML detector. Note that computing the Euclidian distance $\left|y_j - h_{l,j}s_m\right|^2$ requires 2 complex multiplications, where each complex multiplication requires 4 real multiplications. Thus, from Eq. (6), the computational complexity of VA-GSM receiver is given by

$$C = 8N_r g 2^m, \quad (10)$$

which is the same as SM and GSM if we assume that the same number of bits are transmitted in these schemes at a time.

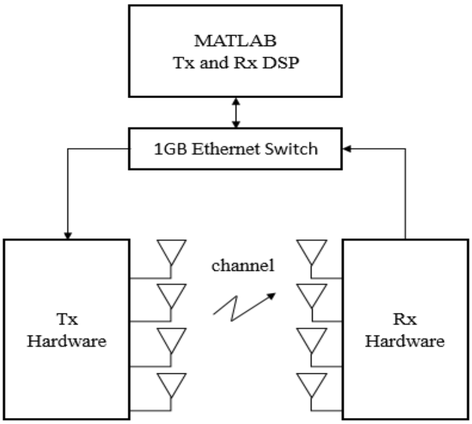

Fig. 1. Block diagram of test-bed setup for the experiment.

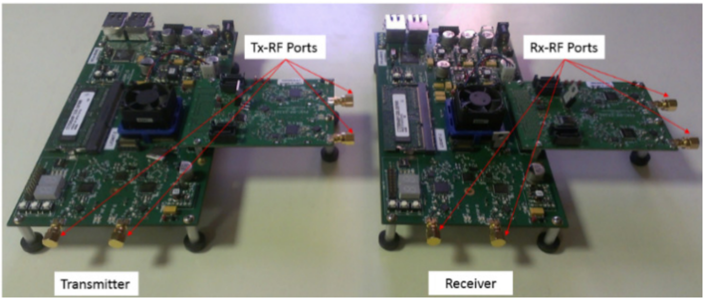

Fig. 2. WARP v3 Kits used in the hardware experiment.

4 Experimental Setup

Fig. 1 shows the block diagram of the software and hardware test-bed setup used in the experiment. As shown in this figure, the transmitted and received data are processed using MATLAB installed on a PC. The PC and the two hardware radio devices used are connected through a 1GB Ethernet Switch.

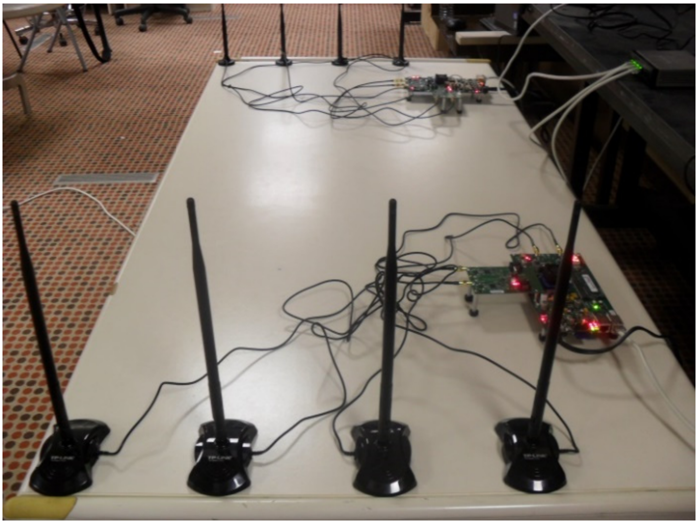

Fig. 3. Experimental setup for VA-GSM.

In our experimental work we used the WARP v3 Kit which is shown in Fig. 2.WARP v3 Kit is a software defined radio (SDR) platform developed by Rice University and Mango Communications. It is built on a Xilinx Virtex-6 LX240T FPGA with four programmable RF interfaces operating at 2.4 and 5 GHz with a 40 MHz bandwidth. The WARP v3 Kit was selected to be used with the platform due to its accessibility and ease of interface with MATLAB. The transmitted waveforms are sent directly to the transmit buffers and the received waveforms are extracted from the receive buffer using MATLAB. Synchronization, Modulation, coding, channel estimation, and equalization are performed in MATLAB. The physical layout of the experimental test-bed is shown in Fig. 3.

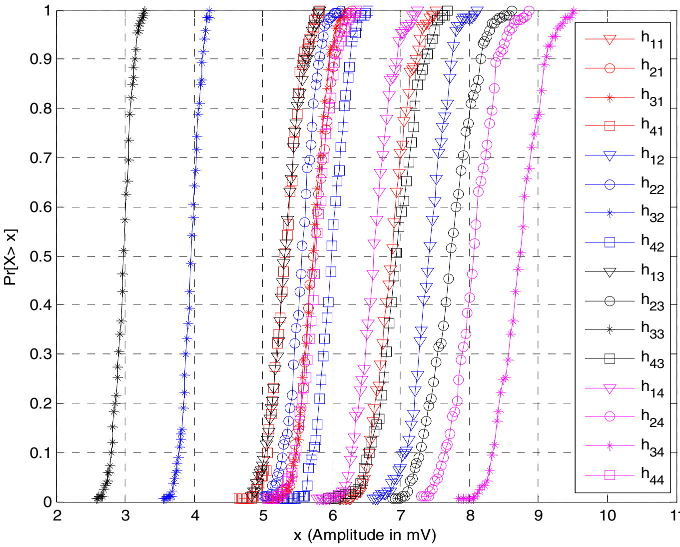

Fig. 4. CDFs for each of the fast-fading coefficients $\boldsymbol{h}_{ji}$ of all channel paths in the experiment.

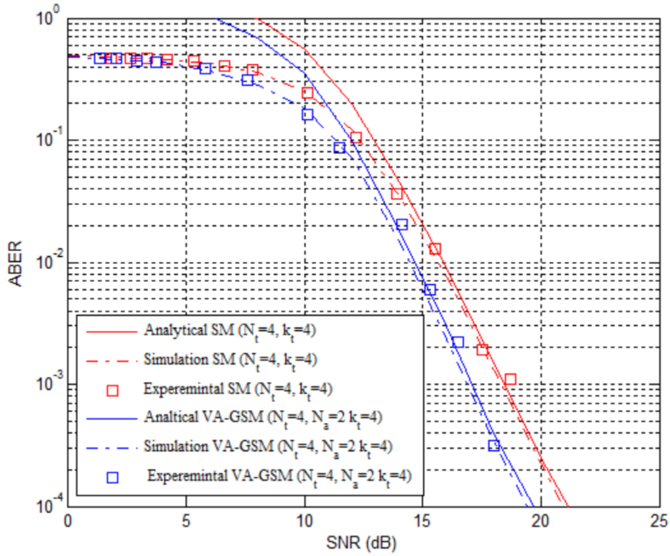

Fig. 5. ABER of VA-GSM compared with SM in the test-bed setup with $\boldsymbol{N_t = 4, N_a = 2}$ and $\boldsymbol{N_r = 4}$. BPSK modulation is used for VA-GSM while 4QAM modulation is used for SM. The simulation and analytical results are obtained with K=28dB to match the experimental Rician channel.

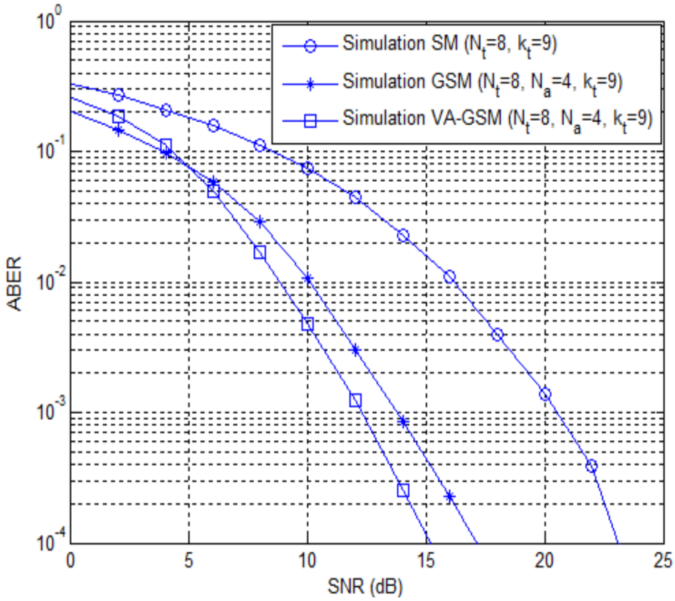

Fig. 6. ABER for the same $\boldsymbol{k_t} = \mathbf{9}$ in VA-GSM, GSM and SM employing the same transmit antennas $\boldsymbol{N_t} = \mathbf{8}$ in Rayleigh fading channel.

5 Validation Results from Hardware Setup

It is clear from the implementation layout in Fig. 3 that the fading between the transmitter and receiver is a Rician fading because the transmitter and receiver have clear line-of-sight (LoS). Rician fading is typically characterized by the K-factor, which denotes the ratio of the power of the LoS component to the power of the scattered components. We need to estimate the K-factor of the practical Rician channel between the transmitter and the receiver, in order to compare the experimental results with the analysis and simulations. Fig. 4 shows the CDFs of the channel fading coefficients h_{ji} for the sixteen paths between the transmitter and the receiver in the experiment. This figure demonstrates that the channels between the transmitter and the receiver follow fast fading, and that the fading are Rician distributed with different mean for each path. Hence different K-factor exist for each path. The Rician K-factors for all the paths are estimated separately for the collected data using a maximum-likelihood estimation. The K- factor obtained ranges between 27dB and 30 dB in this experiment.

Fig. 5 shows the ABER of VA-GSM compared with the conventional SM in 4x4 MIMO system. As shown in the figure, the experimental and simulation results agree closely, and are upper-bounded by the analytical expressions in Eqs. (7)-(9). Because we use 4 transmit antennas, the number of available antenna combinations for VA-GSM is $g = 2^{k_l} = 8$, and for SM is $g = 4$ as shown in Table 2. Therefore, the number of bits per spatial symbol $k_l = 3$ for VA-GSM while $k_l = 2$ for SM. To get the same transmitted bits at a time for both method, we used Binary Phase shift keying (BPSK) modulation for the proposed GSM ($k_s = 1$) and QPSK for SM ($k_s = 2$). It is clear from the figure that for the same transmitted bits $k_t = k_l + k_s = 4$, VA-GSM performs about 1.7 dB better than SM at ABER = 10^{-4}.

Fig. 6 compares the ABER of VA-GSM with GSM and SM in Rayleigh channels by simulation when using the same number of transmit antennas $N_t = 8$, and the same transmitted bits $k_t = 9$. To achieve $k_t = 9$ for each of these schemes, it was necessary to use QPSK for VA-GSM, 8PSK for GSM, and 64QAM for SM. The number of active antennas $N_a = 4$ which is fixed in GSM and variable (between 1 and 4) for the case of VA-GSM. As shown in the figure, for the same number of transmit antennas and the same transmitted bits at a time, VA-GSM has a better BER performance over both GSM and SM which can be attributed to the difference in the constellation size required to reach the same number of bits transmitted.

6 Conclusion

This work proposes generalized spatial modulation scheme using variable active transmit antennas (VA-GSM). The proposed scheme uses the variations in the active transmit antennas to increase the number of available spatial symbols and hence the number of transmitted spatial bits. The experimental results on the ABER performance of the system confirm the analytical bound as well as the computer simulations, for both the VA-GSM and Spatial modulation (SM) schemes. The simulation results shows that VA-GSM has better average bit error rate (ABER) performance over both the GSM and SM, when using the same number of transmit antennas and the same number of transmitted bits for the three schemes.

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