GENERALIZED SPATIAL MODULATION WITH CORRELATED ANTENNAS IN RAYLEIGH FADING CHANNELS

Yafei Sun and **Deva K. Borah**
Advising Professor: Dr. Deva K. Borah, Professor
Klipsch School of Electrical & Computer Engineering
New Mexico State University
Las Cruces, NM 88003, USA
email: yafeisun@nmsu.edu, dborah@nmsu.edu
Graduate Category

ABSTRACT

Spatial modulation (SM) is a transmission scheme where only one transmit antenna is active at any time instant. It thus reduces interchannel interference (ICI) and receiver complexity over traditional multi-antenna systems. However, the spectral efficiency of SM is low. To improve the spectral efficiency, generalized spatial modulation (GSM) can be used. In this paper, we propose to apply the Alamouti technique with GSM for correlated antennas, and show that the proposed approach provides significant improvement over conventional SM and GSM. Our study also shows the importance of bit-to-antenna mappings and their roles on the selection of appropriate correlated antennas.

KEY WORDS

MIMO, spatial modulation, Rayleigh fading, correlated antennas, Alamouti technique.

INTRODUCTION

In wireless communication, multiple antennas can be used at the transmitter and the receiver to increase the data rate and system's capacity [1]. Vertical Bell Labs Layered Space-Time (V-BLAST) [2] architecture is one of the most well-known techniques for a multiple-input multiple-output (MIMO) system. It allows data to be transmitted through different transmit antennas at the same frequency simultaneously in order to achieve a very high spectral efficiency. However, V-BLAST system's channel capacity highly depends on the channel characteristics and the antenna's features [3]. Besides, since all antennas transmit information at the same frequency and time, there is interchannel interference (ICI) which degrades the system performance at the receiver [4]. Finally, the use of multiple RF chains increases the system complexity.

To avoid ICI and to eliminate multiple radio frequency (RF) chains, spatial modulation (SM) [5] and generalized spatial modulation (GSM) [6] are proposed. Unlike V-BLAST, in SM and GSM, not all of the antennas transmit data. While in SM only one antenna transmits data at a given time, GSM allows more than one antenna to transmit data simultaneously. In this way, the RF chains at the transmitter are reduced and ICI is thus decreased. SM can also be considered as a special case of GSM, since only one transmit antenna is active at each time instant [5], [7]. Therefore, SM highly decreases the system complexity and entirely eliminates the ICI. In SM/GSM, at any given time, which antenna(s) is/are used can be represented by transmit binary bits. The transmit bits in SM/GSM can therefore be divided into two parts: the bits that identify the active antenna(s) and the bits to be transmitted by the active antenna(s). In this way, SM/GSM system transmits more bits than a single-input single-output (SISO) system at each time instant, thus enhancing the spectral efficiency over a SISO system.

There are two types of GSM techniques considered in the literature: (1) All active antennas transmit the same data [6], and (2) different antennas transmit different information [8]. In this paper, we consider the second approach which can improve the spectral efficiency even more without increasing the bandwidth or data rate or changing modulation schemes, since more bits are transmitted in parallel at transmitter. Alamouti algorithm [9] is a well-known approach to increase diversity. In Alamouti, there are two transmit antennas and multiple receive antennas. Due to the diversity increase, the bit error rate (BER) performance of the system is enhanced.

In this paper, we propose to improve the performance of GSM by combining it with the Alamouti modulation technique. To our best knowledge, there have been no studies that use Alamouti technique with GSM for correlated antennas. Our study shows that the new Alamouti-GSM scheme presents a significant BER performance improvement for both independent as well as correlated antennas. Further improvement is obtained by selecting appropriate bit-to-antenna selection and bit-to-symbol mappings. We have compared the performance of GSM and SM for the same spectral efficiency and found that GSM behaves better than SM with four transmit antennas, but its performance becomes worse when the number of antennas is greater than four in case of independent transmit antennas. For correlated antennas, SM has better BER performance in all cases (with different numbers of antennas).

SPATIAL MODULATION

In SM, the transmit data bits are split into two parts. The first part represents the selected active antenna. To see this, let N_t denote the total number of available transmit antennas. So the number of bits needed to represent any of the available antennas is $m_a = \log_2 N_t$. For instance, we need 2 bits to select a single antenna in a 4-transmit-antenna system, and so 00, 01, 10, and 11 represent antenna 1, 2, 3 and 4 respectively. Similarly, 3 bits are needed for selecting one antenna in an 8 antenna transmit system.

The second part of the transmit data is mapped to symbols of a given modulation alphabet, such as MPSK and MQAM. For an M-ary system, the number of bits per symbol is $k = \log_2 M$. Thus, the total bits for each transmission is $m = m_a + k$.

Fig. 1 presents an example SM transmission, where 4 transmit antennas are used and 8PSK symbols are transmitted. For this example, 5 bits are transmitted at each time instant. These bits are divided into two parts. The first two bits are used to select the active antenna and the remaining three bits are mapped to 8PSK symbols to be transmitted by the chosen antenna. At time t_1, the first two bits 01 of the transmitted bits 01010 indicate that the second antenna is selected as the active antenna. The remaining three bits 010 correspond to the 8PSK symbol $\frac{1}{\sqrt{2}}(-1-j)$ which is transmitted by the active antenna. Thus, the whole symbol to be transmitted by the 4 antennas can be represented as $[0, \frac{1}{\sqrt{2}}(-1-j), 0, 0]^T$, where $[\cdot]^T$ denotes vector transpose.

ALAMOUTI-GENERALIZED SPATIAL MODULATION

In SM, only one transmit antenna is selected at a given time. In contrast, GSM allows selection of more than one antennas for each transmission. Let N_a denote the number of active transmit

Data Transmission Example:

Transmission Time	t_1	t_2	t_3	...
Data to transmit	01010	11001	00110	...
Antenna selection bits	01	11	00	...
Bits transmitted by the active antenna	010	001	110	...
Symbol transmitted by antenna #1	0	0	-1	...
Symbol transmitted by antenna #2	$\frac{1}{\sqrt{2}}(-1-j)$	0	0	...
Symbol transmitted by antenna #3	0	0	0	...
Symbol transmitted by antenna #4	0	$\frac{1}{\sqrt{2}}(1+j)$	0	...

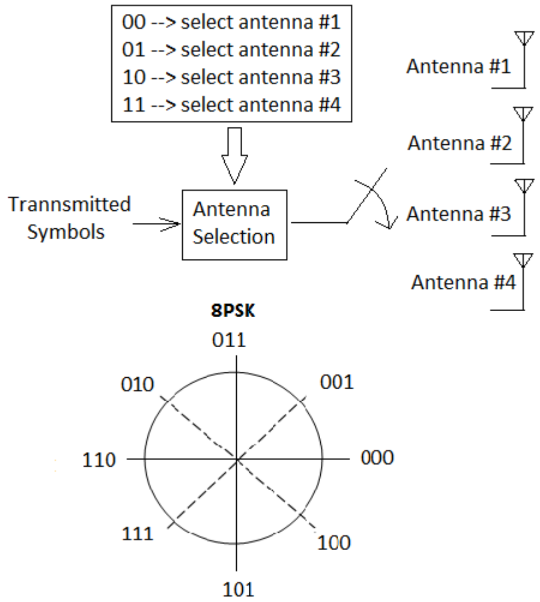


Fig. 1. Spatial modulation for a N_t=4 system with 8PSK

antennas. Based on [8], there are $\binom{N_t}{N_a}$ possible combinations, and hence the corresponding number of bits, m_a, is given by

$$m_a = \lfloor log_2 \binom{N_t}{N_a} \rfloor \tag{1}$$

where $\lfloor \cdot \rfloor$ is the floor function. The total number of bits transmitted during each transmission period is $m = m_a + N_a k$, where $k = \log_2 M$ for a system with M-ary modulation. As an example, if $N_a = 2$ antennas are used out of $N_t = 4$ total transmit antennas, there are $\binom{4}{2} = 6$ combinations, i.e., (1,2), (1,3), (1,4), (2,3), (2,4) and (3,4), where (m, n) denotes that the Antenna $\#m$ and Antenna $\#n$ are the active antennas. Only 4 out of 6 combinations can be used since the available number of combinations has to be a power of two.

In this paper, we propose to combine Alamouti technique with GSM. In Alamouti-GSM, two antennas are active for each transmission. Define T as the transmission duration. At each even time slot (time 0, time $2T$, time $4T$, etc.), the symbols transmitted by two antennas are determined from the transmit data. At the odd time slots (time T, time $3T$, time $5T$, etc.), the same active antennas are used, but the symbols that will be transmitted by them are determined according to the Alamouti scheme.

Fig. 2 shows an example of the Alamouti-GSM transmission when 2 antennas are activated out of a total of 4 transmit antennas. At time 0, assume Antenna 1 and 3 are activated, and they transmit signals s_1 and s_2 respectively. Next, at time T, the active antennas remain the same. However, Antenna 1 transmits $-s_2{}^*$, and Antenna 3 transmits s_1^*, where $*$ denotes complex conjugation. Next, at time $3T$, the active antennas are changed to Antenna 2 and 3, and they transmit symbols s_3 and s_4 respectively. At time $4T$, the antenna selection remains the same as at time $3T$, and the symbols are $-s_4^*$ and s_3^*. The process then repeats with different data for the next time instants.

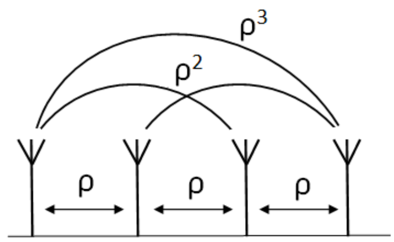
Transmission time	$t_1=0$	$t_2=T$	$t_3=2T$	$t_4=3T$
Antenna #1	s_1	$-s_2^*$	0	0
Antenna #2	0	0	s_3	$-s_4^*$
Antenna #3	s_2	s_1^*	s_4	s_3^*
Antenna #4	0	0	0	0

* denotes complex conjugate

Fig. 2. Alamouti Generalized Spatial Modulation ($N_t = 4$ $N_a = 2$)

CORRELATED ANTENNAS AND BIT MAPPINGS TO ANTENNAS

If the antennas are correlated, the selection of the specific antennas affects performance. Fig. 3 shows one approach of transmit antenna placement [10]. It assumes that the antennas are placed along a straight line. The correlation coefficient between two neighboring antennas is ρ $(-1 < \rho < 1)$. The correlation coefficient between the first and the third antenna is ρ^2, and between the first and the fourth is ρ^3.



Antenna:	#1	#2	#3	#4
Case 1:	00	01	10	11
Case 2 (best):	00	01	11	10
Case 3 (worst):	00	11	10	01

Fig. 3. Correlation among the transmit antennas and bit mappings for spatial modulation

For SM with $N_t = 4$, two bits are needed to identify the active transmit antenna's number. The best bit-to-antenna mapping should be selected so that the antennas with higher correlations have smaller Hamming distances. Gray code mapping can be used as shown in Fig. 3.

Mapping Case 1		Mapping Case 2		Mapping Case 3	
Antenna selection bits	Combination Case 1	Antenna selection bits	Combination Case 2 (best)	Antenna selection bits	Combination Case 3 (worst)
00	(1, 2)	00	(1, 2)	00	(1, 2)
01	(1, 3)	01	(1, 3)	11	(1, 3)
10	(1, 4)	11	(1, 4)	10	(2, 3)
11	(2, 3)	10	(2, 4)	01	(2, 4)

Fig. 4. Transmit antennas selection for generalized spatial modulation

For GSM, Fig. 4 lists three example selections of the active transmit antennas. The best antenna selection combination for GSM is to choose two antennas which are as far way from each other as possible, since the correlation decreases with the increase in the distance between two antennas.

To minimize the correlation effect for a given selection case, we also need to choose appropriate bit mappings. The bit patterns need to be assigned in such a way that any two antenna combinations that are less similar will have a higher Hamming distance. For instance, in Case 1, the combinations $(1,2)$ and $(1,3)$ differ due to Antennas 2 and 3 that are neighbors. Therefore, we use 00 and 01 mapped to the combinations $(1,2)$ and $(1,3)$ respectively. In contrast, the combinations $(1,2)$ and $(1,4)$ differ due to Antennas 2 and 4 that are separated more than the previous case of $(1,2)$ and $(1,3)$. Therefore, bit patterns 00 and 11 (with a Hamming distance of 2) are assigned to $(1,2)$ and $(1,4)$ respectively.

Let $\boldsymbol{y} = [y_1, y_2, ..., y_{N_r}]^T$ be the received signal, where N_r is the number of receive antennas and y_i is the received sample at the i-th receive antenna. Then $\boldsymbol{y}$ is given by

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{2}$$

where $\boldsymbol{x} = [x_1, x_2, ..., x_{N_t}]^T$ is the transmit signal vector, x_i is the symbol transmitted by the i-th transmit antenna, $\boldsymbol{n}$ is the additive white Gaussian noise (AWGN) vector containing noise samples of zero mean and variance σ^2, and the channel matrix $\boldsymbol{H}$ is defined as

$$\boldsymbol{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix} \tag{3}$$

where h_{ij} is the channel coefficient between the i-th receive antenna and the j-th transmit antenna. According to [10], we can write the channel matrix $\boldsymbol{H}$ as $\boldsymbol{H} = \boldsymbol{H_r}\boldsymbol{C_t}$, where $\boldsymbol{H_r}$ is the $N_r \times N_t$ frequency-flat channel matrix with all elements in $\boldsymbol{H_r}$ distributed as i.i.d. Rayleigh. Matrix $\boldsymbol{C_t}$ identifies the transmit antenna correlation. The $N_t \times N_t$ transmit antennas correlation matrix is $\boldsymbol{R_t} = \boldsymbol{C_t}^H\boldsymbol{C_t}$, where $[\cdot]^H$ denotes the matrix Hermitian. Therefore $\boldsymbol{C_t} = \boldsymbol{R_t}^{\frac{1}{2}}$, and $\boldsymbol{R_t}$ is determined by the correlation coefficient, ρ, of the transmit antennas, so that the (i,j)-th element of $\boldsymbol{R_t}$ is $\rho^{|i-j|}$. For a $N_t = 4$ system,

$$\boldsymbol{R_t} = \begin{bmatrix} 1 & \rho & \rho^2 & \rho^3 \\ \rho & 1 & \rho & \rho^2 \\ \rho^2 & \rho & 1 & \rho \\ \rho^3 & \rho^2 & \rho & 1 \end{bmatrix} \tag{4}$$

For SM and GSM, the maximum likelihood (ML) detection [10] is applied as

$$\hat{\boldsymbol{x}} = \arg\ \min_{\tilde{\boldsymbol{x}}} \parallel \boldsymbol{y} - \boldsymbol{H}\tilde{\boldsymbol{x}} \parallel^2 \tag{5}$$

where $\hat{\boldsymbol{x}}$ is the detected transmit signal vector. For an M-ary modulated system, there are $2^{m_a}M^{N_a}$ possible signal vectors to transmit. For example, for a 2×2 SM system with QPSK modulation, $m_a = N_a = 1$, and thus there are $2 \times 4 = 8$ possible vectors for transmit signal, and they are given as $[1,0]$, $[j,0]$, $[-1,0]$, $[-j,0]$, $[0,1]$, $[0,j]$, $[0,-1]$ and $[0,-j]$.

For Alamouti-GSM, the ML detection is modified. Since the transmitted bits are actually the same but modulated differently at time $(2i-2)T$ and $(2i-1)T$, where i represents the i-th transmission, $i = 1,2,3,...$, the detection needs to combine the two time slots together. Therefore, in (5), $\hat{\boldsymbol{x}}$

becomes $[\hat{\boldsymbol{x}}(2i-2),\ \hat{\boldsymbol{x}}(2i-1)]^T$, where $\hat{\boldsymbol{x}}(2i-2)$ is the transmit signal vector at time $(2i-2)T$ and $\hat{\boldsymbol{x}}(2i-1)$ is the signal transmitted at time $(2i-1)T$. Similarly, $\boldsymbol{y}$ is changed to $[\boldsymbol{y}(2i-2),\ \boldsymbol{y}(2i-1)]^T$, and $\tilde{\boldsymbol{x}}$ becomes $[\tilde{\boldsymbol{x}}(2i-2),\ \tilde{\boldsymbol{x}}(2i-1)]^T$.

NUMERICAL RESULTS

In this paper, we define SNR as $\frac{P}{\sigma^2}$, where P is the transmit signal power. We use $N_t = 4$ and 8. For GSM and Alamouti-GSM, we use $N_a = 2$. In all cases, the number of receive antennas is kept as $N_r = 4$. Modulation schemes are selected in such a way that the spectral efficiency is the same for all the curves in each figure.

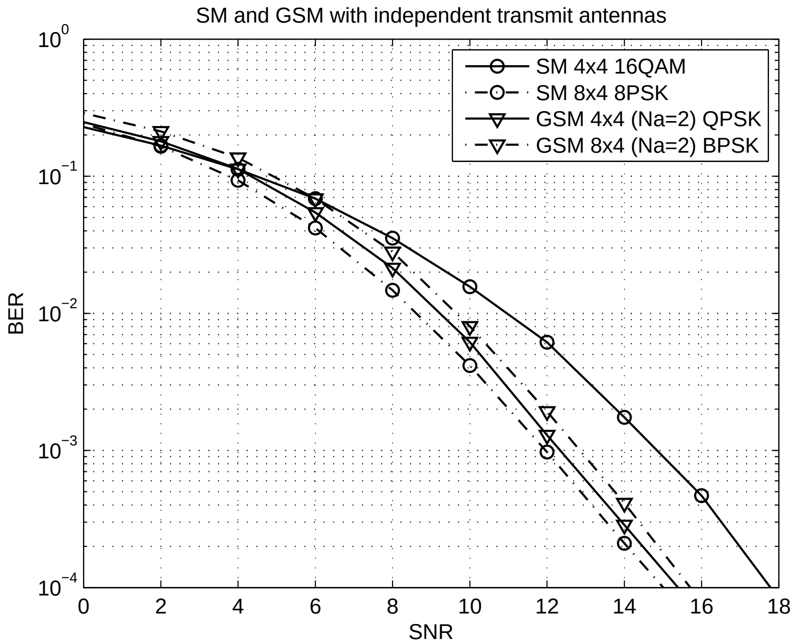


Fig. 5. SM and GSM with independent transmit antennas ($\rho = 0$) with a spectral efficiency of 6 bits/transmission

1) Comparison of SM and GSM: Fig. 5 presents the BER performance of SM and GSM with independent transmit antennas when 6 bits are transmitted at each time instant. For the 4 transmit antenna system, GSM has a better BER performance than SM by about 2 dB. For this case, the probabilities of incorrectly detecting the active antenna or antennas is similar for both SM and GSM, but GSM uses lower level modulation, thus resulting in better performance for GSM. GSM's BER performance is worse than SM when $N_t = 8$. In this case, there are 4 bits used to select the combinations of antennas in GSM, and so GSM is more prone to errors in the active antenna detection than SM where 3 bits are used for antenna selection. When active antennas are wrongly detected, it is likely that the symbols transmitted by the antennas are detected wrongly as well. When transmit antennas are correlated, Fig. 6 shows that both SM's and GSM's BERs degrade compared with the BER results obtained with independent antennas considered in Fig. 5. In this case, since two transmit antennas are active for each transmission in GSM, GSM is more sensitive to the antenna correlation than SM. Thus, SM does better than GSM with correlated antennas generally. At high SNR, the benefit of using lower modulation helps GSM.

2) GSM vs. Alamouti-GSM: Fig. 7 presents the BER results for GSM and Alamouti-GSM. Since

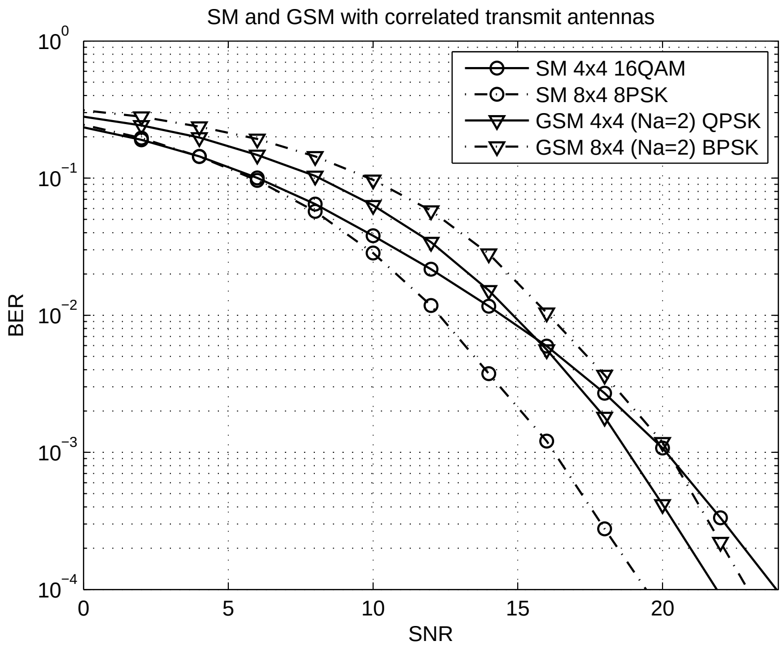


Fig. 6. SM and GSM with correlated transmit antennas (ρ=0.9) for all cases, with a spectral efficiency of 6 bits/transmission

Alamouti scheme increases diversity, it improves BER performance for both independent transmit antennas and correlated antennas. For correlated antennas, our proposed Alamouti-GSM provides more than 4 dB gain over conventional GSM. The effect of antenna correlations is investigated in detail in Fig. 8. Over the whole range of correlations shown, Alamouti-GSM's BER performance remains the best compared to SM and GSM.

3) Bit-to-antenna and bit-to-symbol mappings: Fig. 9 presents the BER performance of SM for different bit-to-antenna mappings. The mappings correspond to the 3 cases shown in Fig. 3. We can see that the antenna mapping with Gray code (Case 2) provides the best performance and Case 3 gives the worst result as expected.
Fig. 10 shows the BER curves of GSM for different bit-to-antenna mappings and the cases correspond to Fig. 4. We see that the differences among the three cases are slightly larger than the SM antenna mappings. Therefore, appropriate bit mapping is even more important for GSM.

CONCLUSION

We have proposed Alamouti-GSM technique for correlated transmit antennas. It is observed that Alamouti-GSM performs better than GSM by 4 dB in some cases even in the presence of antenna correlations. For independent transmit antennas, GSM is found to perform better than SM for a 4 transmit antenna system but its performance worsens when the number of transmit antennas is greater than 4. Antenna correlation affects GSM's performance more heavily than SM, so SM generally has a better performance with correlated antennas. In addition, antenna selection mapping affects both SM's and GSM's BER. We observe that the BER performance can be further improved by assigning bit patterns of large Hamming distances to antennas with lower correlations.

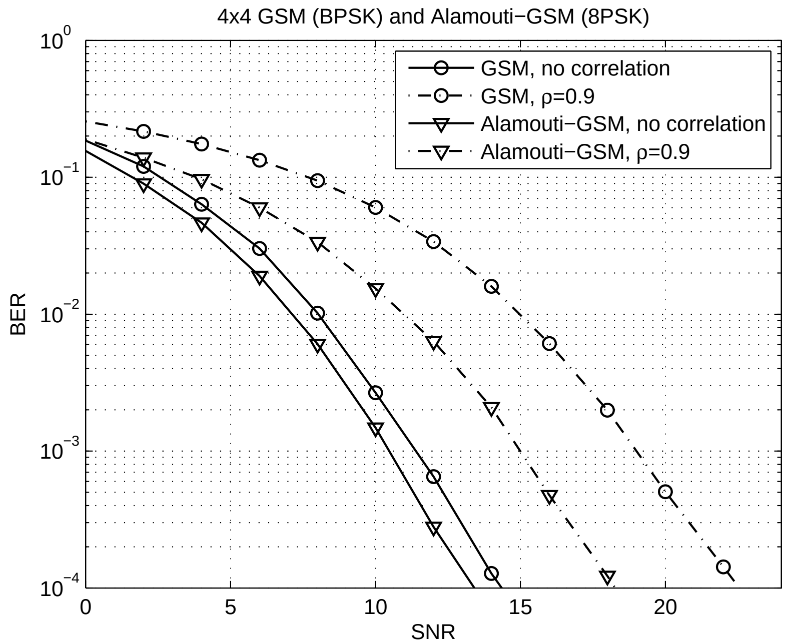


Fig. 7. GSM and Alamouti-GSM for a 4×4 MIMO system with N_a=2. The spectral efficiency is 4 bits/transmission and ρ=0.9

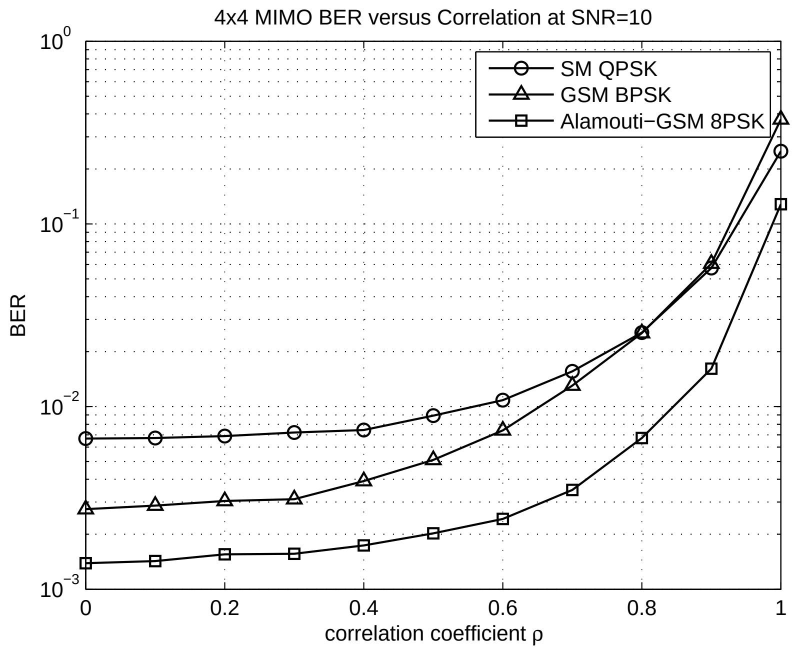


Fig. 8. BER vs. correlation coefficient ρ for SM, GSM and Alamouti-GSM for a 4×4 MIMO system. N_a=2 for GSM and Alamouti-GSM. The spectral efficiency is 4 bits/transmission

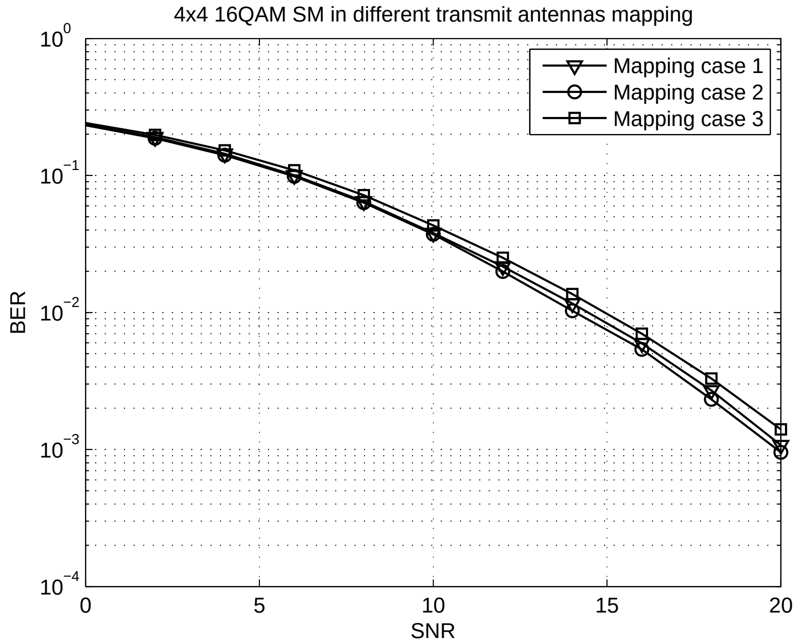


Fig. 9. SM for different bit-to-antenna mappings with 4×4 MIMO and $N_a = 2$. The modulation is 16QAM and ρ=0.9

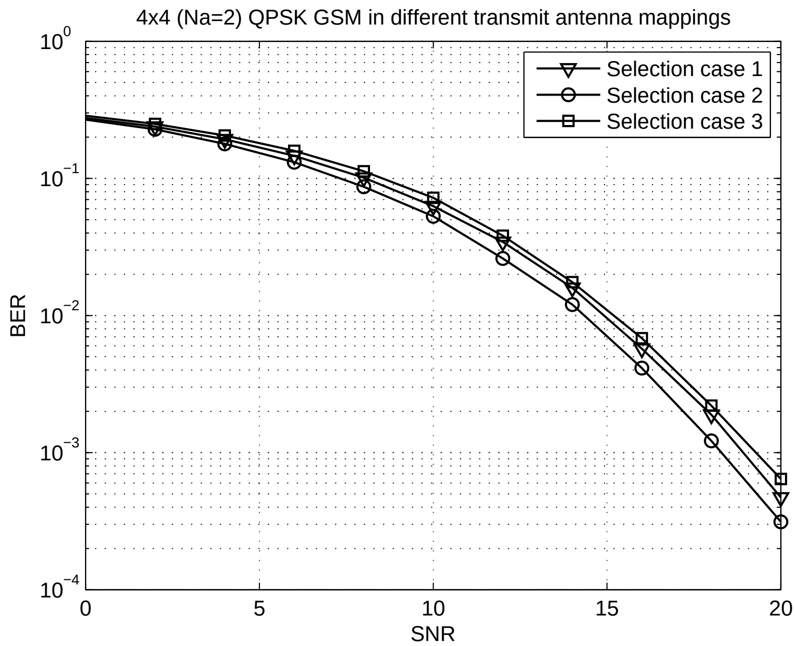


Fig. 10. GSM for different bit-to-antenna mappings with 4×4 MIMO and $N_a = 2$. The modulation is QPSK and ρ=0.9

REFERENCES

[1] E. Telatar, "Capacity of multi-antenna Gaussian channels," *Eur. Trans. Telecommun.*, vol. 10, no. 6, pp. 558–595, 1999.

[2] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *the IEEE International Symposium on Signals, Systems, and Electronics (ISSSE)*, no. 2, pp. 295–300, Sept. - Oct. 1998.

[3] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wirel. Pers. Commun.*, vol. 6, pp. 311–335, 1998.

[4] R. Mesleh, H. Haas, Y. Lee, and S. Yun, "Interchannel interference avoidance in MIMO transmission by exploiting spatial information," in *International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 141–145, Sept. 2005.

[5] R. Mesleh, H. Haas, C. Ahn, and S. Yun, "Spatial modulation - a new low complexity spectral efficiency enhancing technique," in *1st International Conference on Communications and Networking in China (ChinaCom)*, pp. 1–5, Oct. 2006.

[6] A. Younis, N. Serafimovski, R. Mesleh, and H. Haas, "Generalised spatial modulation," *Signals, Syst. Comput.*, pp. 1498–1502, 2010.

[7] R. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 57, pp. 2228–2241, 2008.

[8] J. T. Wang, S. Y. Jia, and J. Song, "Generalised spatial modulation system with multiple active transmit antennas and low complexity detection scheme," *IEEE Trans. Wireless Commun.*, vol. 11, pp. 1605–1615, Apr. 2012.

[9] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, pp. 1451–1458, Oct. 1998.

[10] T. Handte, A. Muller, and J. Speidel, "BER analysis and optimization of generalized spatial modulation in correlated fading channels," in *IEEE Veh. Technol. Conf.*, p. 15, Sept. 2009.