Turkish Journal of Science & Technology
19(1), 193-202, 2024

Research Paper
https://doi.org/10.55525/tjst.1334701

Improved Spatial Modulation with Mapping Diversity

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(Geliş/Received: 30/07/2023; Kabul/Accepted: 27/03/2024)

Abstract: In this work, the mapping diversity technique is exploited for generalized spatial modulation. In this context, multiple constellations, obtained as the solution of the optimization problem that maximizes Euclidean distance between the elements of the signal set, are employed in the active transmit antennas of the generalized spatial modulation scheme. Supported by analytical analysis and simulation results, the proposed scheme is shown to enhance the error rate performance of conventional generalized spatial modulation.

Key words: Spatial modulation, mapping diversity, constellation design, fading channel.

Eşlemleme Çeşitlemesi ile İyileştirilmiş Uzaysal Modülasyon

Öz: Bu çalışmada genelleştirilmiş uzaysal modülasyon için eşlemleme çeşitlemesi tekniğinden faydalanılmıştır. Bu kapsamda, genelleştirilmiş uzaysal modülasyon şemasındaki aktif iletim antenlerinde sinyal kümesindeki elemanlar arası Öklit mesafesini maksimize eden optimizasyon probleminin çözümü olarak elde edilen çoklu işaret kümeleri kullanılmıştır. Tasarlanan şemanın geleneksel uzaysal modülasyon tekniğinin hata oranı performansını iyileştirdiği analitik analiz ve benzetim sonuçları ile desteklenerek gösterilmiştir.

Anahtar kelimeler: Uzaysal modülasyon, eşlemleme çeşitlemesi, işaret kümesi tasarımı, sönümlemeli kanal.

1. Introduction

Using multiple antennas in both transmitter and receiver nodes of a wireless communication system [1] is a promising solution to improve capacity and throughput. In this context, there have been tremendous works in the literature in the first decade of this century that develop multiple input – multiple output (MIMO) transmission techniques. The two well-known approaches in MIMO systems are spatial multiplexing [2] and space-time block codes [3]. Although it is possible to achieve high bandwidth efficiency by employing spatial diversity, interference arises as an important drawback in detection at the receiver. On the other hand, space-time block codes have been shown to attain high diversity order with reasonable receiver complexity.

Spatial modulation is an enhanced MIMO technique that exploits the antenna index in addition to conventional modulation techniques to increase the number of information bits per symbol [4-10]. Specifically, for each channel use in a spatial modulated system, a certain number of the data bits are utilized to identify the active antennas used for transmission, while the remaining bits are used to select the corresponding symbol from the constellation diagram. Consequently, it is possible to improve the bandwidth efficiency by employing spatial modulation techniques. Spatial modulation is designed for quadrature amplitude modulation (QAM) and phase shift keying (PSK) modulation schemes and shown to outperform maximum ratio combining for different data rates in one of the pioneering works [4]. Space shift keying (SSK) [5] can be considered the simplest form of spatial modulation because it only uses antenna indices to transmit information without any specific modulation scheme. Specifically, SSK is a special case of spatial modulation in which the active antenna index is determined by data bits and the unmodulated carrier signal is transmitted from the corresponding active antenna/antennas. Spatial modulation is extended for OFDM in [6] and analytical performance results are supported with simulation results. In the general survey paper [7], transceiver design and link adaptation techniques are provided together with spatial constellation optimization. The results in [7] show that with proper spatial constellation design, it is possible to decrease the bit error ratio (BER) in spatial modulation systems.

In the spatial modulation technique, the overall system consists of a combination of two domains, namely space and signal domains. Increasing the constellation size of one of them requires decreasing the other, so it is critical to balance the constellation size of these two domains. Related to this issue, the optimal constellation sizes

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of signal and space domains in spatial modulation are found in [8] using the union bound of the bit error probability parameter. In the milestone work [9], spatial modulation is combined with the space-time block coding technique, and in addition to the increase in spectral efficiency provided by spatial modulation, the diversity and coding gains are attained due to the use of space-time block codes. In another related work [10], a spatial modulation multiple-input–multiple-output (SM-MIMO) system is proposed with spatial constellation diagrams and shaping filters being used as design parameters. It was shown in [10] that properly designed SM-MIMO systems achieve better performance than their counterpart MIMO systems, even with lower decoding complexity. Trellis-coding schemes are also considered in spatial modulation systems and like trellis-coded modulation, trellis coding is introduced in spatial modulation as well [11].

Generalized spatial modulation (GSM) [12-14] is an extension of spatial modulation in which the constraint of using only one transmit antenna for each message symbol is removed and multiple antennas are activated simultaneously for each group of information bits to be transmitted. By increasing the number of active transmit antennas, it is possible to improve spectral efficiency and error resilience. In GSM, an active set of transmit antennas is selected through a predetermined mapping table, and by using a maximum likelihood detector at the receiver, both the used antenna combinations and the transmitted symbols are detected [12]. The BER performance and capacity analysis of GSM is presented in [13]. In a concurrent work [14] the general framework of the GSM system is presented in which multiple active transmit antennas transmit the same information. Since multiple simultaneous transmission occurs in GSM, the performance may be enhanced with proper signal constellation design. In this context, there exist several works [15-18] in the literature that investigate the effect of constellation design on spatial modulation schemes. In [15], the rotated versions of the original constellation are used at several active transmit antennas carrying different information symbols. In the other related paper [16], it was shown that for the quadrature spatial modulation system, a remarkable increase in performance may be attained with optimized constellations compared with standard PSK and QAM constellations. A related paper [17] employs union bound to analyze the bit error probability of quadrature spatial modulation and reveals that in addition to Euclidean distance and energy, the in-phase and quadrature components of the symbols have an impact on the error performance. As an extension in [18], three constellation designs are suggested to improve the error performance of MIMO systems with spatial modulation.

The automatic repeat protocol (ARQ) is probably the simplest but the most effective solution for error-free transmission [19]. It has a simple signaling rule that forces the source to retransmit the packets detected erroneously by the receiver. Instead of simple repetition, Benelli proposed a method for automatic repeat request (ARQ) [20] which improves the Euclidean distance and consequently increases throughput by using two different mappings for transmitting the same symbol. In this context, employing different constellations for different retransmissions of the same information block is generally referred to as mapping diversity (MD) or mapping rearrangement in the literature. The motivation behind the idea of multiple transmissions of the same data block is the potential to improve the reliability of the link affected by channel conditions [21]. Symbol mapping diversity is applied for multiple packet transmissions in [21] using M different rotated versions of 8-PSK, 16-PSK, and 16-QAM. The uncoded BER upper bound is minimized by optimizing the mapping. In a related work, it was shown in [22] that by altering bit-to-symbol mappings, the increase rate of minimum squared Euclidean distance is larger than that of the number of transmissions. Constellation Rearrangement (CoRe) is a particular form of mapping diversity and is proposed [23] for equalizing the reliabilities of the individual bits in a single symbol. Such a need for equalization is necessary because the variations in bit reliabilities naturally increase if identical constellations and mappings are employed when identical symbols are retransmitted. It was shown in [23] that in the case of 16-QAM for the AWGN channel, the average log-likelihood ratios of bits can be equalized with a total of four different mappings. CoRe is also used to enhance the performance of the relay channel [24].

Since simultaneous transmission of the same symbol from all active antennas occurs in a MIMO system employing GSM, the constellation rearrangement technique is embedded in the system design to enhance the error correction capability in this work. Specifically, multiple different signal constellations obtained by the constellation rearrangement method are used individually at active transmit antennas at each time slot. The constellation optimization in mapping diversity is based on increasing the Euclidean distance of the successive constellations considered together. The overall effect can be regarded as an increase in BER performance like coding gain. Since embedding mapping diversity in the generalized spatial modulation system requires only using a second predetermined constellation obtained with optimization, no additional complexity arises compared to standard GSM. So, it can be stated that embedding mapping diversity in GSM system has the potential to enhance the BER without bringing any increase in the complexity of the system. Therefore, the main difference between the system structure of this paper and those of existing ones in the literature can be explained from the implementation aspect. In this work, multiple versions of the same symbol are transmitted using multiple constellations which are obtained by optimization. The organization of the paper is as follows: In the following second section, the system model is introduced together with transmission protocols. The analytical BER performance analysis is presented in the third section. Following the Monte Carlo simulation results in Section IV, the paper is concluded in Section V.

2. System Model and Transmission Protocols

The general framework of the GSM transceiver is given in Fig. 1. It is assumed that a total of $m = m_l + m_s$ information bits are grouped to message vector **b**. Next vector **b** is partitioned into two parts, while the first m_l bits are used for antenna mapping, the last m_s bits constitute the transmitted modulation symbol. There exists a total of N_T transmit antennas and N_R receive antennas. Among N_T transmit antennas, N_A of them are active at each time slot and they all transmit the same symbol. The number of possible combinations of active antennas out of all transmit antennas can be given as $\mathbb{C}\ N_T, N_A$ where $\mathbb{C}\ .$ stands for binomial coefficient.

Since the first m_l bits of data vector **b** is used for antenna selection, it is enough to use only $N = 2^{\lfloor \log_2 [\mathbb{C}\ N_T, N_A\ ]\rfloor}$ combinations among all these possible combinations and straightforward to define $m_l = \lfloor \log_2 [\mathbb{C}\ N_T, N_A\ ]\rfloor$ where $\lfloor k \rfloor$ is the largest integer less than or equal to k and $N = 2^{m_l}$. Let us define the set of all used combinations by **L**. Each combination, $l = \{l_1, l_2, ..., l_{N_A}\} \in \mathbf{L}$, is a set, elements of which gives indices of the N_A active antennas. As mentioned before, the last m_s bits are used to form the M-ary modulated symbol $s \in \mathbb{S}$ where $M = 2^{m_s}$ In each period, the same symbol, s, is transmitted simultaneously from all N_A active antennas, and the remaining N_T-N_A antennas remain silent. The overall spectral efficiency is $m = m_l + m_s$ bits per transmission.

The Rayleigh flat fading transmission channel H is a matrix whose individual elements are complex independent and identically distributed (i.i.d.) Gaussian random variables. Additionally, there exists an additive white Gaussian noise (AWGN) with zero mean and σ_n^2 variance in each transmission path. The transmitted signal is a $N_T \times 1$ sized vector **x**, whose elements are the same symbol, s, at indices $\{l_1, l_2, ..., l_{N_A}\}$ and the remaining elements are zeros. Following this definition, let **s** be a length $N_A \times 1$ vector with all elements s. In this context, the received signal can be expressed as given in equation (1),

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} = \sum_{n=1}^{N_A} \mathbf{h}_{l_n} s + \mathbf{n} = \mathbf{H}_l \mathbf{s} + \mathbf{n} \tag{1}$$

where $\mathbf{h}_l$ is the l^{th} column of the channel matrix **H** and $\mathbf{H}_l$ is a sized submatrix of **H** formed by extracting the $l = \{l_1, l_2, ..., l_{N_A}\}$ indexed columns of **H**. At the receiver, maximum likelihood detection is employed to jointly detect the active antenna set and transmitted symbol. Spatial modulation (SM) detector employs maximum likelihood algorithm and implements an exhaustive search over the sets **L** and $\mathbb{S}$ to find possible transmitted signal. It is assumed that perfect channel state information is available in respective receivers. The estimate of transmitted symbol and active antenna set can be found following the work [13] and is given in Eq (2).

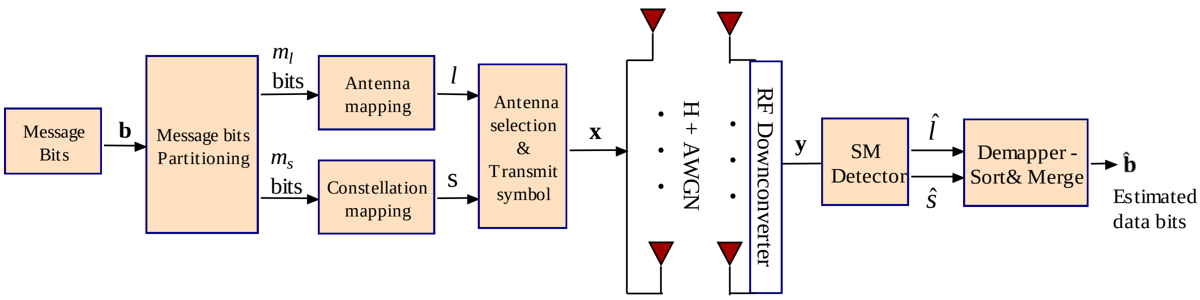

Figure 1. General block diagram of GSM system

$$\left[\hat{l},\hat{s}\right] = \underset{l\in\mathbf{L},\, s\in\mathbf{S}}{\arg\min} \left\|\mathbf{y}-\mathbf{H}_l\mathbf{s}\right\|_F^2 \tag{2}$$

In this work, a special case of the general spatial modulation is evaluated and specifically, it is assumed that there exists a total of four transmit antennas, two of which are active in each transmission at the transmitter node. In classical generalized spatial diversity scheme, as previously stated, the same symbol is transmitted from both two active antennas. Moreover, the same constellation is used for two simultaneous transmissions from two antennas. Additionally, to enhance the performance, mapping diversity is embedded in spatial modulation, and it is proposed to use two different constellations obtained by solving the optimization problem that aims to minimize the symbol error rate.

In this context, let the two different constellations used for mapping diversity be defined as $\mathbf{S}^{(1)}$ and $\mathbf{S}^{(2)}$ respectively. Since two active antennas are selected among all four transmit antennas, the set of antenna combination, $L = \ 1,4\ ,\ 2,3\ ,\ 2,4\ ,\ 3,4$, is selected and the corresponding four possible **x** vectors representing transmitted signals from four transmit antennas is given in Table 1. Without loss of generality, the while first active antenna uses the constellation $\mathbf{S}^{(1)}$ to determine the transmitted symbol, the second antenna employs the constellation diagram $\mathbf{S}^{(2)}$. In the spatial domain, m_l = 2 data bits are used to select one element of the set of antenna combinations.

Table 1. Transmit Antenna Mapping Table

bits used for antenna mapping	Transmitted vector
00	$\mathbf{x}=\left[s^{(1)}\ \ 0\ \ 0\ \ s^{(2)}\right]$
01	$\mathbf{x}=\left[0\ \ s^{(1)}\ \ s^{(2)}\ \ 0\right]$
10	$\mathbf{x}=\left[0\ \ s^{(1)}\ \ 0\ \ s^{(2)}\right]$
11	$\mathbf{x}=\left[0\ \ 0\ \ s^{(1)}\ \ s^{(2)}\right]$

3. Analytical Performance Analysis

In mapping diversity technique, the constellation diagrams can be found by solving the optimization problem that tries to minimize the BER. In this context, assuming a message out of M elements is transmitted through the N channel uses each with different constellation diagrams, the union bound for error probability [25] can be defined as given in Eq. (3),

$$P_b \leq \frac{1}{\log_2 M}\frac{1}{M}\sum_{i=1}^{M}\sum_{j=1,\, j\neq i}^{M} d_H\left(\mathbf{s}_i,\mathbf{s}_j\right)P\left(\mathbf{s}_i\to\mathbf{s}_j\right) \tag{3}$$

Here $\mathbf{s}_i=\left[s_i^{(1)},s_i^{(2)},...,s_i^{(N)}\right]$ is the i^{th} message vector formed by collecting all the ith indexed message symbols from a total of N different constellations and $s_i^{(k)}$ is the i^{th} element of the constellation $\mathbf{S}^{(k)}$. Additionally, $d_H\left(\mathbf{s}_i,\mathbf{s}_j\right)$ represents the Hamming distance between vectors $\mathbf{s}_i$ and $\mathbf{s}_j$ and $P\left(\mathbf{s}_i\to\mathbf{s}_j\right)$ is the pairwise error probability of detecting $\mathbf{s}_j$ although $\mathbf{s}_i$ is transmitted. Assuming that maximum ratio combining is employed at the receiver, the pairwise error probability, given in Eq.(4), can be expressed using the Chernoff bound as [26]

$$P\left(\mathbf{s}_i \rightarrow \mathbf{s}_j\right) \leq \frac{4\left(N_0\right)^N}{\prod_{k=1}^{N}\left|s_i^{(k)} - s_j^{(k)}\right|^2} \tag{4}$$

The pairwise error probability expression given in Eq. (4) shows that to minimize the symbol error rate, the term $\prod_{k=1}^{N}\left|s_i^{(k)} - s_j^{(k)}\right|^2$ should be maximized. For N=2 (single retransmission) we can express this optimization problem [24] mathematically as given in Eq.(5).

$$\begin{aligned} &\min_{\substack{s_i^{(1)}, s_i^{(2)} \\ i=1,2,..,M}} \sum_{i=1}^{M}\sum_{j=i+1}^{M} \frac{2C}{\left|s_i^{(1)} - s_j^{(1)}\right|^2 \left|s_i^{(2)} - s_j^{(2)}\right|^2} \\ &\text{such that } \ \frac{1}{M}\sum_{i=1}^{M}\left|s_i^{(k)}\right|^2 \leq 1 \quad \forall k \end{aligned} \tag{5}$$

In Eq. (5), $C=(4N_0)^2$ is a constant where $N_0/2$ is the noise variance. This optimization problem can be solved using an exhaustive search method. To obtain the optimum solution, the classical uniform constellations are chosen as the first constellation set, $\mathbf{S}^{(1)}$, as a baseline reference. Upon this selection, $\mathbf{S}^{(2)}$ is found by minimizing the metric given in Eq. (5). The constellations obtained by this search are given in Fig. 2 for 16-QAM.

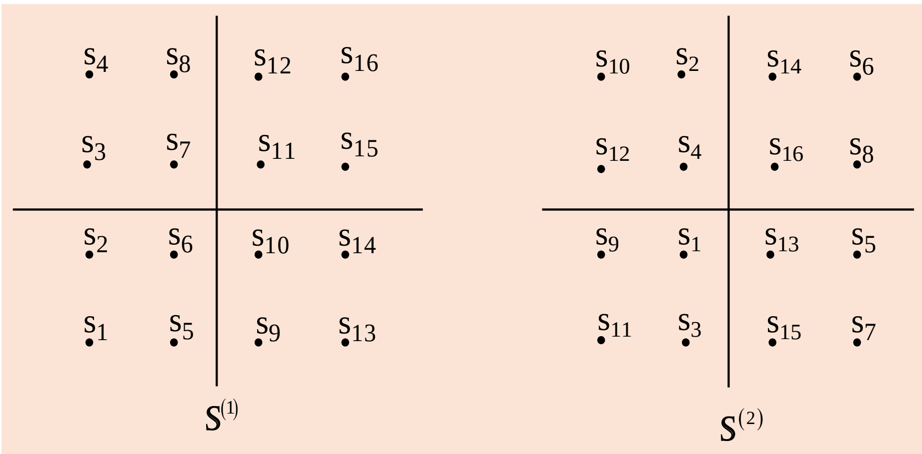

Figure 2. Mapping diversity constellations for 16-QAM

To derive the analytical average error probability of GSM the union bounding technique is applied [12,25]. Since the transmitted symbol in spatial modulation is the combination of spatial symbol and data symbol, a maximum likelihood joint detection of active antenna set, and transmitted data is realized at the receiver. Therefore, the pairwise error probability (PEP) can be defined as the probability that rather than deciding in favor of the actual transmitted spatial and data symbols (l,s) another set of symbols is detected. Following the analysis in [12,13] the PEP can be expressed mathematically as given in Eq.(6).

$$\begin{aligned} PEP\left(l, s \rightarrow \tilde{l}, \tilde{s}\right) &= \Pr\left(\left\|\mathbf{y} - \mathbf{H}_l\mathbf{s}\right\|_F^2 > \left\|\mathbf{y} - \mathbf{H}_{\tilde{l}}\tilde{\mathbf{s}}\right\|_F^2 \middle| \mathbf{H}\right) \\ &= Q\left(\frac{\left\|\mathbf{H}_l\mathbf{s} - \mathbf{H}_{\tilde{l}}\tilde{\mathbf{s}}\right\|_F^2}{2\sigma_n^2}\right) = Q\left(\sqrt{\sum_{r=1}^{N_R}\gamma_r}\right) \end{aligned} \tag{6}$$

where $Q(\alpha)=\frac{1}{2\pi}\int_{\alpha}^{\infty}e^{x^2/2}dx$ is the well-known Q function and $\gamma_r=\left|h_{l,r}s-h_{\tilde{l},r}\tilde{s}\right|^2$. Also $h_{l,r}$ is the r^{th} element of the vector $\mathbf{h}_l$. The random variable $\kappa=\sqrt{\sum_{r=1}^{N_R}\gamma_r}$ is chi-squared distributed and its probability distribution function [27] can be given as in Eq.(7),

$$f_{\mathrm{K}}(\kappa)=\frac{1}{\Gamma(N_R)\gamma^{N_R}}\kappa^{(N_R-1)}\exp\left(-\frac{\kappa}{\bar{\gamma}}\right) \tag{7}$$

where $\bar{\gamma}$ is the mean value of γ. Since two different constellations are applied for two simultaneous transmissions from two active antennas, $\bar{\gamma}$ can be defined as given in Eq.(8),

$$\bar{\gamma}=\begin{cases}\left|s^{(1)}-\tilde{s}^{(1)}\right|\left|s^{(2)}-\tilde{s}^{(2)}\right| & \text{if } \tilde{l}=l\\ \left|s^{(1)}s^{(2)}\right|+\left|\tilde{s}^{(1)}\tilde{s}^{(2)}\right| & \text{if } \tilde{l}\neq l\end{cases} \tag{8}$$

Following the works [28,29], the average value of PEP can be calculated as given in Eq. (9).

$$\begin{aligned}E\left[Q\left(\sqrt{\kappa}\right)\right]&=\int_{\kappa}f_{\mathrm{K}}(\kappa)Q\left(\sqrt{\kappa}\right)d\kappa\\&=\int_{\kappa}\frac{1}{\Gamma(N_R)\gamma^{N_R}}\kappa^{(N_R-1)}\exp\left(-\frac{\kappa}{\bar{\gamma}}\right)Q\left(\sqrt{\kappa}\right)d\kappa\\&=\beta^{N_R}\sum_{i=0}^{N_R-1}\mathbb{C}\left(\left(N_R-1+i\right),i\right)\left(1-\beta\right)^i\end{aligned} \tag{9}$$

where $\beta=\frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}/2}{1+\bar{\gamma}/2}}\right)$

Consequently, the analytical BER [25,28] can be obtained as given in Eq.(10) ,

$$\mathrm{BER}=\frac{1}{2^{\eta}}\sum_{\tilde{l},\tilde{s}}\sum_{l,s}\frac{e}{\eta}\beta^{N_R}\sum_{i=0}^{N_R-1}\mathbb{C}\left(\left(N_R-1+i\right),i\right)\left(1-\beta\right)^i \tag{10}$$

where e is the Hamming distance of the PEP event between (l,s) and $(\tilde{l},\tilde{s})$.

4. Simulation Results

The performance of the proposed scheme is evaluated for the Rayleigh fading channel. In all the simulations presented in this work, perfect channel state information is assumed at all the receivers. Additionally, the average signal energy is chosen as unity for all modulation schemes. The derived analytical BER performances are presented together with simulation results. Following the main framework with four transmit antennas among which two are active at each transmission and two receive antennas, the BER performances with respect to signal-to-noise ratio (SNR) value are obtained for both conventional GSM system and the proposed GSM system with mapping diversity. For a fair comparison between the conventional GSM system without mapping diversity and the proposed GSM system with mapping diversity, all common parameters (block size, transmit power) are chosen as the same.

In terms of modulation technique, uniform decomposable QAM schemes are applied initially. The two different constellations used in mapping diversity for 16-QAM are already given in Fig. 2. For the conventional GSM system in which mapping diversity is not employed, the conventional 16-QAM ($S^{(1)}$ in Fig. 2) constellation is used at both two active transmit antennas. The simulation results of the proposed mapping diversity embedded generalized spatial modulation for 16-QAM modulation are presented in Fig. 3. The main observation from simulation results is that a remarkable gain in terms of BER can be achieved by incorporating mapping diversity in spatial modulation. Defining the gain as the decrease in required SNR for a certain BER, it can be stated that this gain increases with increasing SNR and is almost constant in the high SNR regime. For instance, the gain is around 1,2 dB for a BER level of 10^{-3}. Also, the derived analytical BER bound is shown to align perfectly with simulation results for high SNR values. To determine its effect, the number of receive antennas is increased to four, and the results are given in Fig. 4. It can be easily stated that, since increasing the number of receive antennas increases the diversity as well, the BER performance increases with the number of receive antennas. Additionally, the proposed GSM system with mapping diversity still outperforms the conventional GSM system without mapping diversity.

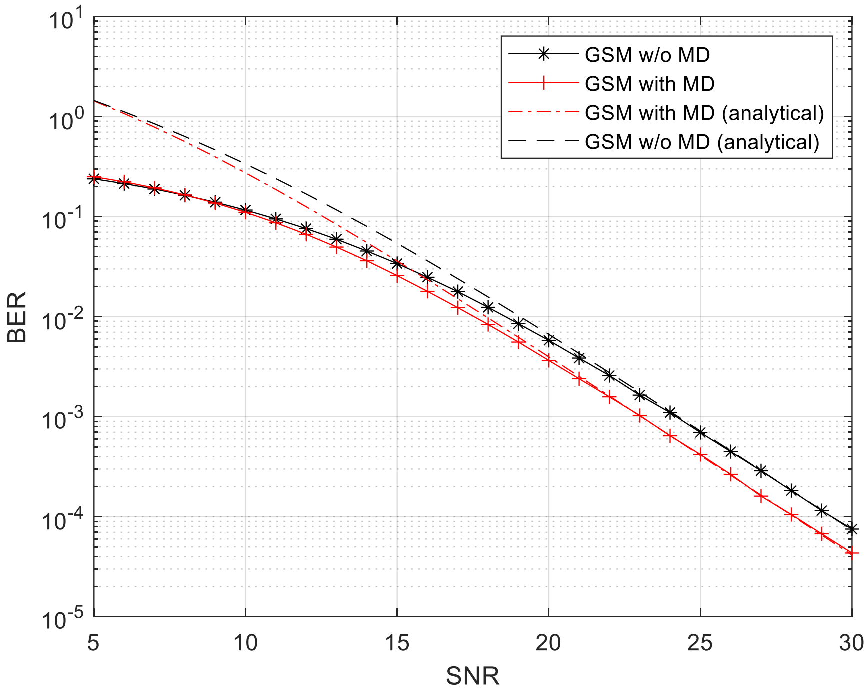

Figure 3. Analytical and simulation results for 16-QAM modulation

To determine the effect of constellation size, the M value is increased to 64 and another uniform, decomposable QAM scheme, namely 64-QAM is also considered. Following the optimization technique given in Section 3, two different constellations are obtained to be used in mapping diversity. The analytical and simulation results of the proposed system for 64-QAM modulation are presented in Fig. 5. Likewise, embedding mapping diversity in generalized spatial modulation achieves a larger gain in terms of BER than the 16-QAM case. To compare, the gain for the BER level of 10^{-3} is 2,1 dB which is 0,9 dB larger than 16-QAM modulation. The reason for this is that the potential of improvement with mapping diversity increases with modulation level, i.e., increasing modulation level value (M) from 4 (16-QAM) to 6 (64-QAM) results in a better improvement in average BER.

Lastly, two non-decomposable QAM schemes, 8-QAM and 32-QAM are used as the modulation technique, and the performances of the proposed systems are presented in Fig. 6 and Fig. 7 respectively. The analytical results still align with simulation results and embedding mapping diversity in the GSM system improves the BER performance. Numerically, while the gain for 8-QAM is 0,9 dB at a BER level of 10^{-3} (Fig. 6), which is 0,3 dB smaller than that of 16-QAM, it reaches a value of 1,4 dB for 32-QAM (Fig. 6) which is slightly larger (0,2 dB) than 16-QAM case.

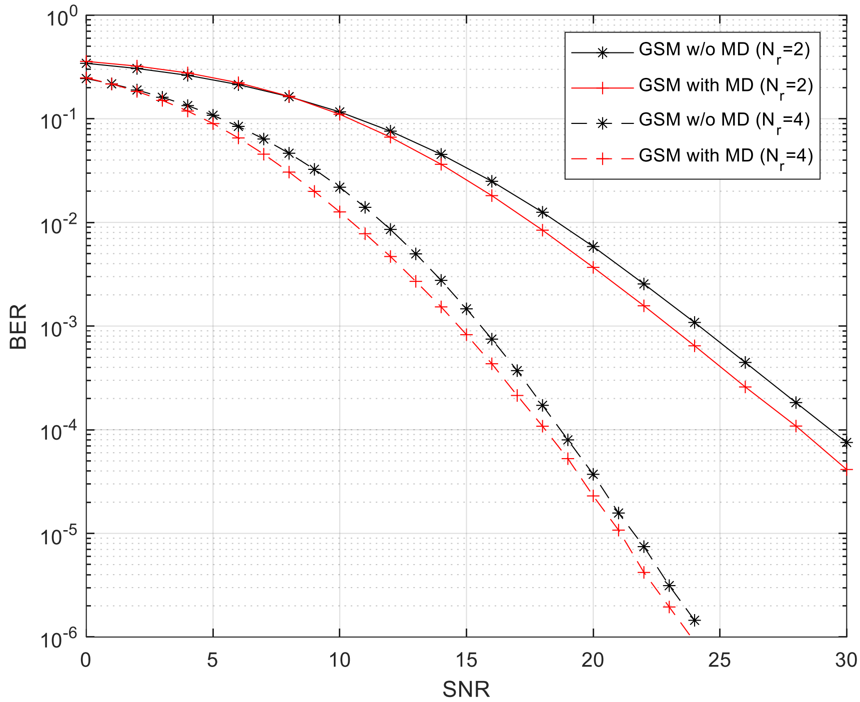

Figure 4. Simulation results for 16-QAM modulation for different number of receive antennas.

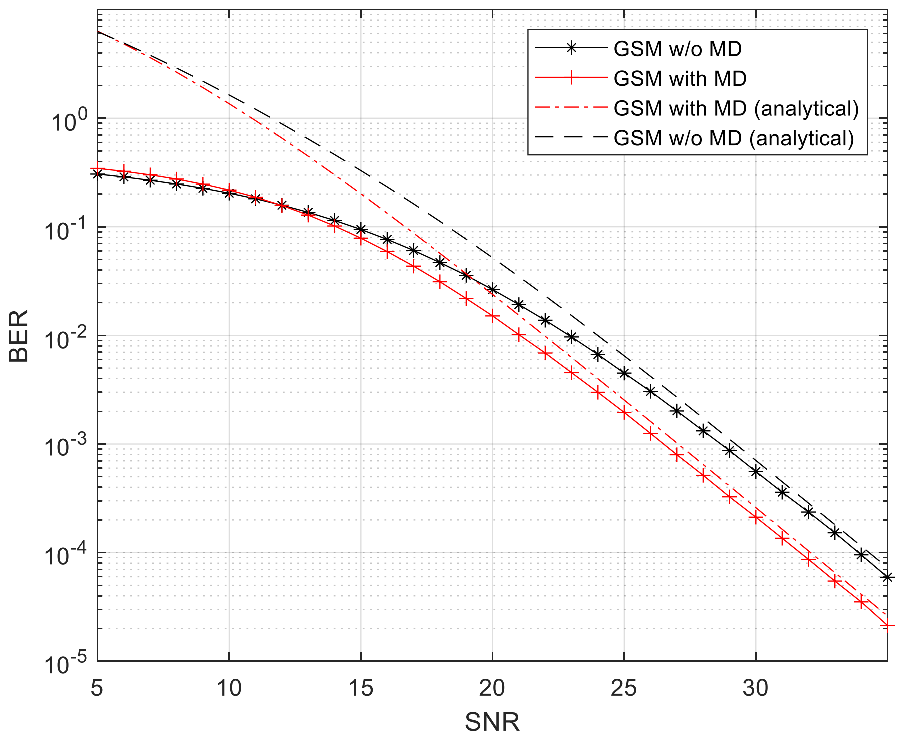

Figure 5. Analytical and simulation results for 64-QAM modulation.

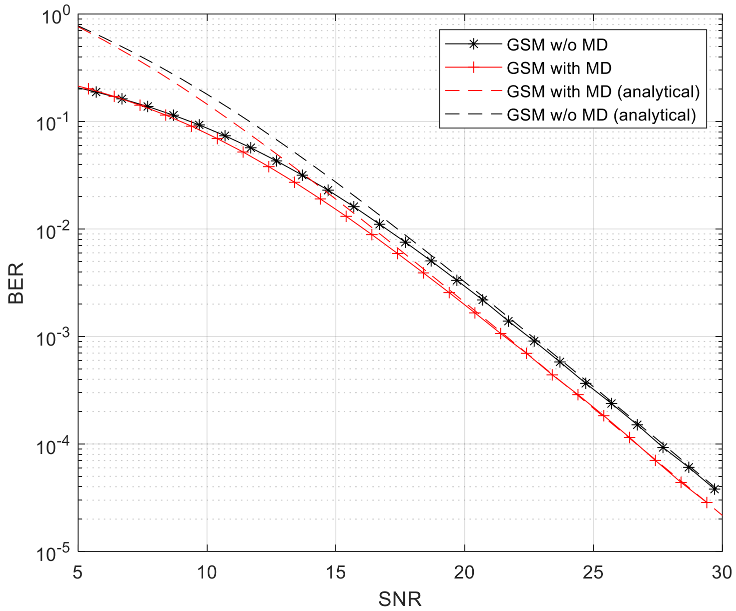

Figure 6. Analytical and simulation results for 8-QAM modulation.

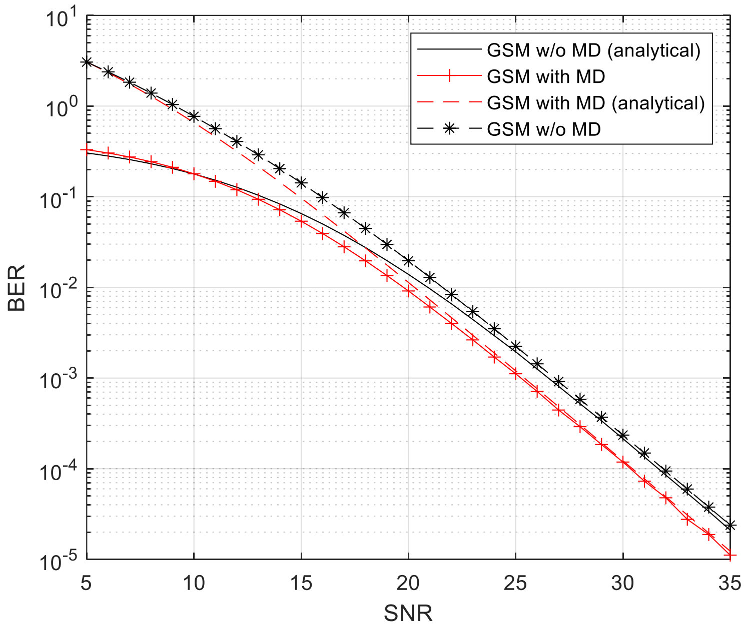

Figure 7. Analytical and simulation results for 32-QAM modulation.

5. Conclusion

In this work, mapping diversity is deployed in a MIMO system with generalized spatial modulation. Precisely, differently from conventional generalized spatial modulation in which the same constellation is applied in the transmission phase, multiple distinct constellations optimized for mapping diversity are used individually from all the active antennas in the setup. The potential of the proposed system is first evaluated analytically and then quantified with simulations. The results revealed that the performance of the generalized spatial modulation can be enhanced with the mapping diversity technique. Since perfect channel state information is assumed in this work, investigating the effect of channel estimation errors on overall performance is a future work of this paper.

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