Generalised Spatial Modulation with LR-aided K-best Decoder for MIMO Systems

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Abstract

This paper presents a generalised spatial modulation (GSM) with lattice reduction (LR) aided K-best decoder for multiple-input multiple-output (MIMO) systems, achieving near optimal performance with low complexity. GSM is one of the current feasible solutions alleviating the requirement of high number of transmit RF chains in large scale MIMO systems. It conveys information by activating a subset of transmit antennas to reduce the transmit power and design complexity. In our proposed system, either the same or multiple information bits can be transmitted through multiple antennas achieving diversity gain and spatial multiplexing (SMx) respectively. In addition, as a MIMO decoder at the receiver side, a LR-aided K-best decoder for both real and complex domain is incorporated in order to obtain near optimal performance with less complexity, compared to a maximum likelihood (ML) decoder. Following IEEE 802.11 standard, we develop the decoder for 4×4 MIMO for different modulation schemes, with 2 active antennas at the transmitter side. The simulation results show comparable bit error rate (BER) performance between GSM with ML and the proposed scheme using both SMx and diversity gain. However, GSM with SMx utilises lower modulation order to achieve same spectral efficiency and thereby reduces the computational complexity.

Keywords: Generalized Spatial Modulation, K-best Decoder, Lattice Reduction, MIMO.

1. INTRODUCTION

Large scale MIMO technology has been considered as a potential candidate for next generation wireless system by advanced wireless standards (i.e., IEEE 802.11, LTE etc.) due to its advantage of high spectral efficiencies, increased reliabilities and throughput with power efficiencies. However, the main challenges in realization of large MIMO systems include design and placement of antennas and multiple RF chains, maintaining the performance of the receiver with complex signal processing, etc.

Several algorithms have been proposed so far to address these issues, offering different trade-offs between power and performance. The maximum likelihood (ML) detector minimizes bit error rate (BER) performance through exhaustive search, but complexity grows exponentially with the number of antennas [1]. In contrast, linear detectors (LDs) (such as Zero Frequency (ZF), Minimum Mean Square Error (MMSE), etc.) and successive interference cancellation (SIC) detectors requiring polynomial complexity suffer from significant performance loss. In the past few years, lattice reduction (LR) has been proposed in order to achieve high performance, yielding much less complexity than the conventional K-best decoder [2]. It can also achieve the same diversity as ML at the cost of some performance loss. Later, it has been implemented in the complex domain [3-4].

A conventional MIMO system offers two characteristics. First, there will be a transmit radio frequency (RF) chain for each transmit antenna. Hence, if N_t is the number of transmit antennas, then the number of transmit RF chains, N_{RF}, will also be equal to N_t. Secondly, information bits are carried only on the modulation symbols. Therefore, the number of required RF chain increases significantly in a large scale MIMO system.

Lately, spatial modulation (SM) is a MIMO transmission technology alleviating the requirement of high number of transmit RF chains for MIMO systems with large number of antennas. It also increases spectral efficiency (SE) by transmitting extra information using antenna index compared to single input multiple output (SIMO) systems, increasing bits per symbol [5]. SM mitigates inter-channel interference (ICI) [5], reduces implementation complexity [6] and energy consumption [7] by activating only a single antenna to convey information in each symbol period, i.e. $N_{RF} = 1$. In SM, the input data bits are divided into two groups, one of which is used to select active antenna and the other determines the transmitted symbol. Therefore, a total SE of $\log_2(N_t) + \log_2(M)$ is achieved, where N_t and M are the number of transmit antennas and modulation order, respectively.

Nevertheless, SM has its limitations. The number of transmit antennas N_t has to be a power of two and the logarithm increase in spectral efficiency requires a large number of transmit antennas due to its sub-optimality in SE [5]. Therefore, generalised spatial modulation (GSM) [6] is introduced to overcome the limitation in N_t and continues to offer higher SE by utilising more than one antenna at each symbol period to simultaneously transmit data symbols, i.e., $1 < N_{RF} < N_t$. GSM is the combined concept of spatial multiplexing and phase shift keying (PSK). It increases the achievable SE while maintaining all the advantages of SM. Therefore, GSM is considered as a promising solution for future MIMO systems [8-10].

Several detection schemes have been studied for both Spatial Modulation (SM) and GSM. Low-complexity linear decoders can be used to detect GSM, but their performances are not comparable to that of the ML decoder. However, ML offers higher complexity with the number of transmit antenna [10-11]. Considering that a linear equaliser is optimal for an orthogonal channel matrix, lattice reduction (LR) technique [12-15] is utilised to improve the channel orthogonality. LR in combination with linear decoders such as ZF and MMSE have demonstrated to achieve comparable performance in comparison with the ML but with lower complexity.

This paper presents a novel transmission technique based on GSM systems in combination with LR-aided K-best decoder for different MIMO system which can achieve near optimal performance with low computational complexity. Firstly, the proposed one can transmit both same and different information through the active transmitters by exploiting diversity gain and spatial multiplexing (SMx) respectively, which increases the SE of the system. In addition, the K-best decoder can achieve near-optimal BER performance with lower complexity in systems based on GSM schemes. It enables the utility of LR and employs the strategy of Schnorr-Euchner (SE) enumeration in order to perform on-demand child expansion, which inherently reduces the computational complexity significantly.

The decoder has been developed for 4x4 MIMO with 2 active transmit RF chains and for different modulation schemes. It has been employed for real domain and complex domain MIMO decoder [2, 4]. However, it can be scalable to any MIMO configuration including massive MIMO (for both hard and soft decision based iterative MIMO decoder). The simulation results show comparable BER performance between GSM with ML and the proposed scheme using both SMx and diversity gain. It is also observed that GSM with SMx utilises lower modulation order compared to diversity one in order to achieve same spectral efficiency and thus, inherently reduces the computational complexity. While comparing the simulations between real and complex K-best decoder, the later one provides slightly better result for both of the transmission schemes. Hence, complex K-best decoder with re-configurability offers a trade-off between performance and complexity by adapting the computation of on demand child expansion for choosing the list candidates.

The rest of this paper is organized as follows. Section 2 describes the GSM with LR-aided K-best decoder. It includes both of two transmission designs along with real and complex domain K-best decoder. Then, simulation results and comparisons follow in Section 3. Lastly, Section 4 concludes the paper with a brief overview.

Notation

Italicised symbols denote scalar values, whereas bold lowercase symbols denote vectors, and uppercase symbols denote matrices. $(\cdot)^T$ and $(\cdot)^H$ are the transpose and the conjugate transpose, respectively. $\|\cdot\|$ is the 2-norm of a vector/matrix used, and $det(\cdot)$ indicates the matrix determinant. More notations used are as follows: $CN(n, \sigma^2)$ is the complex Gaussian distribution of a random variable, with mean n and variance σ^2. I_N denotes the $N\times N$ identity matrix, and $\mathbb{Z}$ as the integer set. $\mathcal{O}(\cdot)$ indicates the computational complexity in terms of the number of arithmetic operations.

2. SYSTEM MODEL

The general GSM system model consists of an MIMO wireless link between N_t transmit and N_r receive antennas. Figure 1 shows the block diagram of GSM.

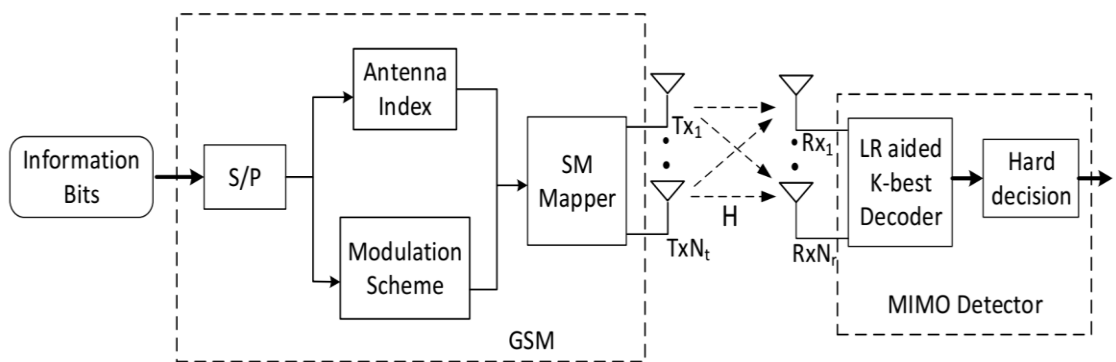

FIGURE 1: GSM Block Diagram.

As shown in the Figure 1, a random sequence of independent bits $\boldsymbol{b} = [b_1 \;\; b_2 \;\; \cdots \;\; b_k]^T$ enters the serial-to-parallel converter. The first *m* bits select an antenna pattern, and *k−m* bits choose the conventional amplitude/phase modulation (APM) symbols. The output is mapped to a vector $\boldsymbol{x} = \left[x_1 \;\; x_2 \;\; \cdots \;\; x_{N_t}\right]^T$. The number of transmit RF chains, n_{RF}, is parameterized such that $1 \le N_{RF} \le N_t$. Hence, in a given channel use, n_{RF} out of N_t transmit antennas are chosen and activated, where the remaining $(N_t - N_{RF})$ antennas remain silent. Then, through each selected antenna, modulation symbols are transmitted over an $N_r \times N_t$ wireless channel, $\boldsymbol{H}$.

Hence, the received signal is given by

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{v}, \tag{1}$$

where $\boldsymbol{v} = \left[v_1 \;\; v_2 \;\; \cdots \;\; v_{N_t}\right]^T$ represents the additive white Gaussian noise (AWGN) vector observed at the receive antennas with zero mean and covariance matrix $E[vv^H] = \sigma_v^2 \boldsymbol{I}_{N_r}$, where

σ_v^2 is the noise variance. The channel matrix $\boldsymbol{H}$ has $i.i.d.$ entries with $CN(0,1)$. The channel is assumed to be flat fading, time invariant, and independently changing from symbol to symbol.

In the MIMO system, it is assumed that channel state information (CSI) is available at the transmitter (CSIT), such as in massive MIMO, which is only feasible in reciprocal propagation channels as in time-division duplex systems [16]. At the receiver, the antenna patterns and the APM symbol of the signals are estimated by the LR-aided K-best detector [2] and demapped to the transmitted bits with the help of hard decision.

2.1 GSM with Diversity Transmission Design

The transmission process begins with the bit stream being mapped into symbols, which are divided into two blocks. The first block contains $\log_2\binom{N_t}{N_{RF}}$ bits and the second block is $\log_2(M)$, where M is the total number of APM symbols, and N_{RF} is the number of active antennas. Hence, the length of the GSM symbol is $\left\lfloor log_2\binom{N_t}{N_{RF}}\right\rfloor + \log_2(M)$. It can be assumed that the same information is going to be transmitted by all the active transmitters, exploiting transmit diversity. Thus, the receiver solves the $N_t \times M$ hypothesis detection problem to estimate both blocks jointly to properly decode the transmitted symbol.

At the receiver, a LR-aided real domain K-best decoder is included in order to lessen the complexity than that of a ML decoder [2]. The ML-optimum decoder calculates the Euclidean distance between the received signal and the set of the total GSM symbols. It performs an exhaustive tree search for finding all the possible candidates. Hence, the complexity of this decoder increases exponentially with higher number of transmitters or high APM constellations. The brief description of K-best decoder of our proposed system is included later in section 2.4.

The symbol vector $\boldsymbol{b}$ is divided into two blocks in GSM:

- The first l bits are used to determine the indices of the N_{RF} active antennas (i.e., RF chains), where

$$l \leq \lfloor \log_2 M' \rfloor, \tag{2}$$

$$M' = \binom{N_t}{N_{RF}}. \tag{3}$$

  Clearly, 2^l must be smaller than or equal to M', Hence the maximum number of bits which can be conveyed by N_{RF} antenna indices is $\lfloor \log_2 M' \rfloor$. Assuming the CSI is only available at the receiver, $c = 2^l$ antenna combinations are randomly selected from the overall M' possibilities.

- The remaining $m - l$ bits indicate the M different APM symbols.

Table 1 shows the proposal transmission design using diversity. Here, the active transmitters convey the same information, which impacts in the spectral efficiency. For the sake of illustration, the following parameters are selected to generate the mapping of Table 1. Let us consider, $N_t = 4, N_{RF} = 2, N_r = 4$ and a MIMO system transmitting BPSK modulation. Thus, the symbol length is 3 bits per symbol, where the first two bits (b_1, b_2) determine the active antenna combinations, $c = 4$ and b_3 corresponds to the BPSK modulation.

$\boldsymbol{b} = [b_1\ b_2\ b_3]$	N_{RF} indices	$\boldsymbol{x} = [x_1\ x_2\ x_3\ x_4]$
0 0 0	1, 2	[-1 -1 0 0]
0 0 1	1, 2	[+1 +1 0 0]
0 1 0	1, 3	[-1 0 -1 0]
0 1 1	1, 3	[+1 0 +1 0]

1 0 0	1, 4	[-1 0 0 -1]
1 0 1	1, 4	[+1 0 0 +1]
1 1 0	2, 4	[0 -1 0 -1]
1 1 1	2, 4	[0 +1 0 +1]

TABLE 1: GSM Table Mapping using Transmit Diversity.

2.2 GSM with SMx Transmission Design

The main drawback of GSM using transmit diversity is its suboptimal SE. Hence, GSM with spatial multiplexing (SMx) is adopted to solve this issue. Although the transmission design is similar to that of GSM with diversity, it transmits different APM symbol through all the N_{RF} increasing the throughput and efficiency. Therefore, the length of the GSM symbol is $\left\lfloor log_2 \binom{N_t}{N_{RF}} \right\rfloor + N_{RF} \log_2(M)$, since $\log_2(M)$ bits are different for each of N_{RF} active antennas.

To illustrate the main difference between GSM with diversity and GSM with SMx, the following example is provided. Let us consider, $N_t = 4, N_{RF} = 2, N_r = 4$ and the system is transmitting a symbol length of 6 bits per symbol. Then, the first two bits of both systems correspond to the antenna indices. However, GSM with diversity transmits a 16-QAM symbol and GSM with SMx conveys QPSK symbols through its N_{RF} in order to carry 6 bits per symbol. Table 2 presents a comparison of several symbols for both systems. Here, we consider grey mapping for modulation indices.

$\boldsymbol{b} = [b_1\ b_2\ b_3\ b_4\ b_5\ b_6]$	N_{RF} indices	GSM w/diversity $\boldsymbol{x} = [x_1\ x_2\ x_3\ x_4]$	GSM w/SMx $\boldsymbol{x} = [x_1\ x_2\ x_3\ x_4]$
0 0 0 0 0 0	1, 2	[-3-3j -3-3j 0 0]	[-1-1j -1-1j 0 0]
0 0 0 0 0 1	1, 2	[-3-1j -3-1j 0 0]	[-1-1j -1+1j 0 0]
1 1 0 0 1 0	2, 4	[-3+3j 0 -3+3j 0]	[-1-1j 0 +1-1j 0]
0 1 1 0 0 0	1, 3	[+3-3j 0 +3-3j 0]	[+1-1j 0 -1-1j 0]
1 0 0 1 1 1	1, 4	[-3+1j 0 0 -3+1j]	[-1+1j 0 0 +1+1j]
0 1 1 0 0 1	2, 3	[0 +3-1j 0 +3-1j]	[0 +1-1j 0 -1+1j]
1 1 1 1 1 1	2, 4	[0 +1+1j 0 +1+1j]	[0 +1+1j 0 +1+1j]

TABLE 2: Mapping design comparison between GSM with diversity and GSM with SMx.

2.3 Lattice Reduction

It is well established that using the ML algorithm as a sequence estimator is the optimal way to remove the effect of ISI for digital transmission communication systems. However, the implementation of this algorithm may be infeasible for practical implementation, since the decoding complexity exponentially increases with the number of antennas and/or constellation size. For high-rate transmission systems, the performance of symbol-to-symbol estimation becomes inaccurate since the ISI cannot be solved by simply raising the transmitted power. Linear detectors are alternative possible solutions [17] for lower complexity detection schemes, but show an inferior performance compared to the ML detector for ill-conditioned channel.

The concept of basis reduction was proposed more than a century ago [18] to find simultaneous rational approximations to real numbers and to solve the integer linear programming problem in fixed dimensions. The main purpose of lattice basis reduction is to find a good basis for a given lattice. A basis is considered to be good when the basis vectors are close to orthogonal. The concept of LR is to find a reduced set of basis vectors for a given lattice to obtain certain properties such as short and nearly orthogonal vectors [18]. A lattice can be represented by many different bases. It is a set of discrete points representing integer linear combinations of linearly independent vectors, which are called basis.

Taking the received signal in a MIMO system as:

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{v}, \tag{4}$$

where $\boldsymbol{H}$, $\boldsymbol{x}$ and $\boldsymbol{v}$ are the channel matrix, the transmit signal and the noise vector respectively. $\boldsymbol{Hx}, \boldsymbol{x} \in \mathbb{Z}$ forms a lattice spanned by the columns of $\boldsymbol{H}$ [19].

To quantify the orthogonality of a matrix, the orthogonality deficiency (od) [20] for a matrix $\boldsymbol{H}$ is defined as:

$$od(\boldsymbol{H}) = 1 - \frac{\det(\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})}{\prod_{n=1}^{N_t}\|\boldsymbol{h}_n\|}, \tag{5}$$

where $\boldsymbol{h}_n$ is the n-th column of the channel matrix H. It is important to note that $0 \leq od(H) \leq 1$. If $od(\boldsymbol{H}) = 1$, $\boldsymbol{H}$ is singular and when $od(\boldsymbol{H}) = 0$ all the columns of $\boldsymbol{H}$ are orthogonal. Generally, it is not possible to achieve $od(\boldsymbol{H}) = 0$. If $od(\boldsymbol{H})$ is close to "0", it is said that $\boldsymbol{H}$ is near to being orthogonal.

2.4 LR-aided K-best Decoder

The K-Best search with lattice reduction belongs to a particular subset of the family of breadth-first tree search algorithms. The search is performed sequentially, solving for the symbol at each antenna. The block diagram of the K-best decoder in our proposed system is presented in Fig. 3.

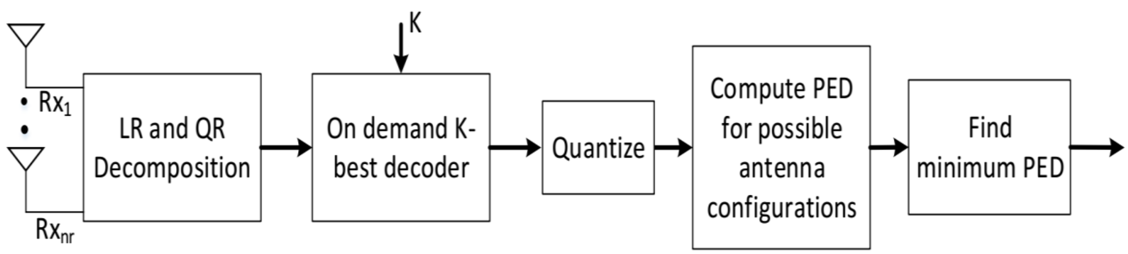

FIGURE 3: A model diagram of proposed LR aided K-best decoder.

As shown in Figure 3, first LR is applied in order to eliminate some effects of noise over the channel matrix and to make the co-ordinates more orthonormal to each other. Then, QR decomposition is performed to obtain an upper triangular matrix, *R* and henceforth, on-demand K-best algorithm is applied on modified receiver symbols. In a conventional K-best algorithm, at any level of the tree, *K* nodes are selected and passed to the next level for future consideration. Finally, at the last level, all the K-paths with minimum overall error are selected as the most likely solutions.

Our proposed K-best method exploits on-demand child expansion to find the *K* possible solutions [4, 15]. It is based on the SE strategy to enumerate the children of a given node in a strictly non-decreasing error order. On demand child expansion employs expanding of a child if and only if all of its better siblings have already been expanded and chosen as the partial candidates of the particular layer. Hence, for both real and complex domain K-best decoder, it ensures the minimum number of calculation for a given node. However, complex one includes an additional parameter, *Rlimit* besides list size, *K* which offers a better trade-off between complexity and performance [4, 21].

After calculating the *K* probable solutions, symbol wise quantization is applied based on the modulation scheme. While working with GSM with diversity gain, the same information bits are transmitted by each antennas. Hence, partial Euclidean distances (PED) are calculated for each node of *K* solutions of all the possible antenna combinations of Tx. Then, the one with minimum PED is chosen as hard decision. The main idea behind this is, if any node decoded from any antenna has the lowest PED, then that will be the final solution.

However, GSM with SMx transmits different information bits. First, PEDs for all *K* solutions considering every possible antenna configurations are calculated. Then, the one with minimum PED is chosen and that represents the final solution. Therefore, GSM with diversity gain provides better reliability, whereas GSM with SMx offers higher spectral efficiency with lower modulation scheme for a MIMO system.

The complexity analysis of the on-demand child expansion proceeds as follows. For the real domain K-best decoder, it requires maximum $2K-1$ nodes to be expanded at any level of the tree as the worst case scenario. Hence, for a MIMO system of N_t transmit antennas, the total number of nodes calculated is equal to $\sum_{i=2}^{N_t}(2K-1)+K$. For a conventional K-best algorithm, this number increases to $\sum_{i=2}^{N_t} KM + M$, where M is the number of APM symbols.

On the other hand, for complex domain K-best decoder, at any level of tree search, first *KRlimit* nodes need to be expanded along the real axis. After that, only imaginary domain SE enumeration will be performed [4, 21]. Hence, considering the worst case, the total number of nodes calculated at each level is $KRlimit + (K-1)$. For N_t transmit antennas, the complexity becomes $\sum_{i=2}^{N_t} K(Rlimit+1) - N_t$. Therefore, complexity order of both real and complex domain K-best decoder does not depend on the modulation scheme. While comparing with ML, it performs an exhaustive search through all the possible candidates and will require $\sum_{i=1}^{N_t} M^i$ node calculation in total.

For example, with an MIMO system of 3 transmit antennas and QPSK modulation scheme, ML requires 84 node calculations, where the number of nodes required for a conventional K-best decoder is 28 with K equal to 3. On the other hand, on demand real K-best decoder requires maximum 13 node calculations to get the near optimal performance with *K* equal to 3. For complex K-best decoder, minimum node calculation can be 9 considering *Rlimit* as 1 and *K* equal to 3, which results 1.4x less computational complexity than that of a real decoder. When *Rlimit* is 2, then complexity increases to 15. Therefore, compared to the ML, our proposed real domain and complex domain decoder require 6.4x and maximum 9.3x less calculation respectively for 3x3 MIMO with QPSK modulation scheme.

3. SIMULATION RESULTS

This section demonstrates the performance of the proposed GSM with LR-aided K-best decoder for both real and complex domain. The test and simulation environment has been implemented using IEEE 802.11 standard. All the simulations are for 4×4 MIMO with different modulation schemes, where there are 2 active antennas on the transmitter side. Hence, $N_t = 4, N_{RF} = 2, N_r = 4$. The ratio of the signal and noise power is considered as signal to noise ratio (SNR). A flat Rayleigh fading channel with AWGN is used and CSIT and CSIR are assumed for simulation purposes. All the results are achieved with a simulation of 10^5 packets.

We first analyse the performance of GSM with diversity transmission design for different list size. *K* and compare it with that of ML. Then, the similar performance curves are obtained for GSM with SMx. Finally, we compare the results of GSM between the two transmission designs for proposed MIMO system. The parameters of the system model are considered in such a way that a symbol lengths of 6 bits and 4 bits are transmitted for 16QAM and QPSK modulation scheme.

3.1 GSM with Diversity Transmission Scheme

The transmission process includes sending same data through all the active antennas in order to achieve diversity gain. The simulation includes both real and complex domain K-best decoder for different MIMO configurations and modulation schemes.

3.1.1 Using Real Domain LR-aided K-best Decoder

The BER versus SNR curves of the above specified MIMO system using real domain K-best decoder for 16-QAM modulation scheme are shown in Fig. 4.

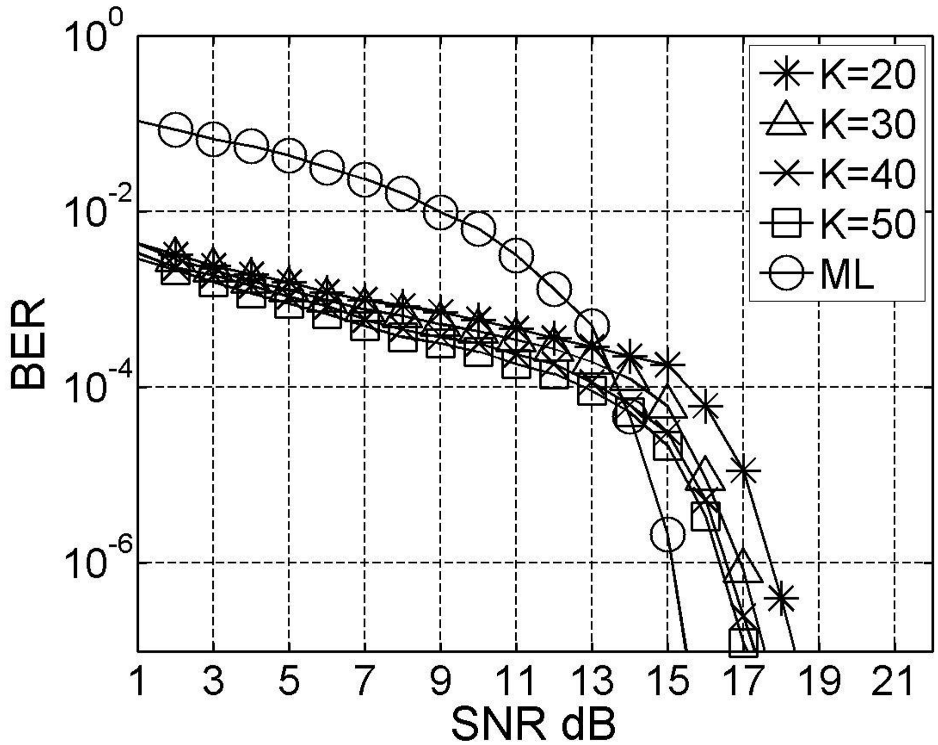

FIGURE 4: BER vs SNR curve for 4x4 MIMO and different list size, *K*. 2 active antennas are considered at the transmit side. Hence, using diversity scheme, 6 bits per symbols are attained with 16QAM modulation scheme.

As demonstrated in Figure 4, ML gives the minimum BER, although for low SNR dB, the proposed one provides better performance. It is because of the rearrangement of channel matrix while converting it from complex to the real domain, where ML is performed with complex channel matrix [21, 22]. With increasing *K*, the performance also improves and gradually approaches closer to ML. Then, it gets saturated (i.e., the performance does not improve with increasing list size). If we compare the performance of proposed K-best one with that of ML, *K* equal to 20 lags around 3.5 dB from ML. With *K* equal to 30, the gap reduces to 2.5 dB, where use of *K* as 40 results to 2.0 dB gap reduction compared to ML. If the list size *K* is further increased to 50, the performance almost gets saturated and lags behind 1.9 dB against ML. On the other hand, if the list size is reduced less than 20, it provides poor performance. The simulation results for QPSK modulation scheme for list size increasing from 1 to 4 are shown in Figure 5.

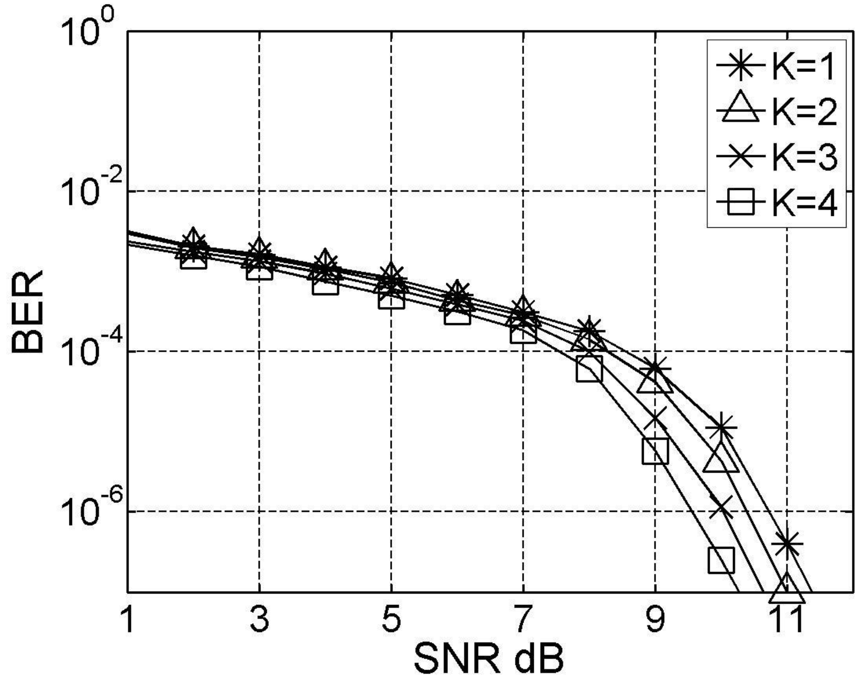

FIGURE 5: BER vs SNR curve for 4x4 MIMO and list size, *K* from 1 to 4. 2 active antennas are considered at the transmit side. Hence, using diversity scheme, 4 bits per symbols are attained with QPSK modulation scheme.

As observed in Figure 5, the performance improves with increasing list size for QPSK modulation scheme. When *K* is equal to 2, it provides 0.7 dB better performance than that of K as 1. For K equal to 3 and 4, the improvements became 1.0 dB and 1.5 dB respectively. The result demonstrates only hard decision based MIMO detection, however, it can also be implemented for soft decision MIMO decoding and any MIMO configuration with different modulation schemes. All the list sizes that are used as the maximum effective list sizes in this analysis are derived through extensive simulations. Next, the simulation results for GSM with diversity gain using complex domain K-best decoder are analysed.

3.1.2 Using Complex Domain LR-aided K-best Decoder

Complex domain MIMO decoder includes two reconfigurable parameters: list size, *K* and *Rlimit* [4] in order increase the adaptability between complexity and performance. As showed in Figure 4, maximum performance is achieved with *K* as 50 for 16 QAM and real domain MIMO decoder. Hence, for complex decoder, all simulations for 16QAM modulation scheme are performed with list size fixed to 50 and variant *Rlimit*. The BER versus SNR curves of the above specified MIMO system using complex domain K-best decoder for 16-QAM modulation scheme are shown in Fig. 6.

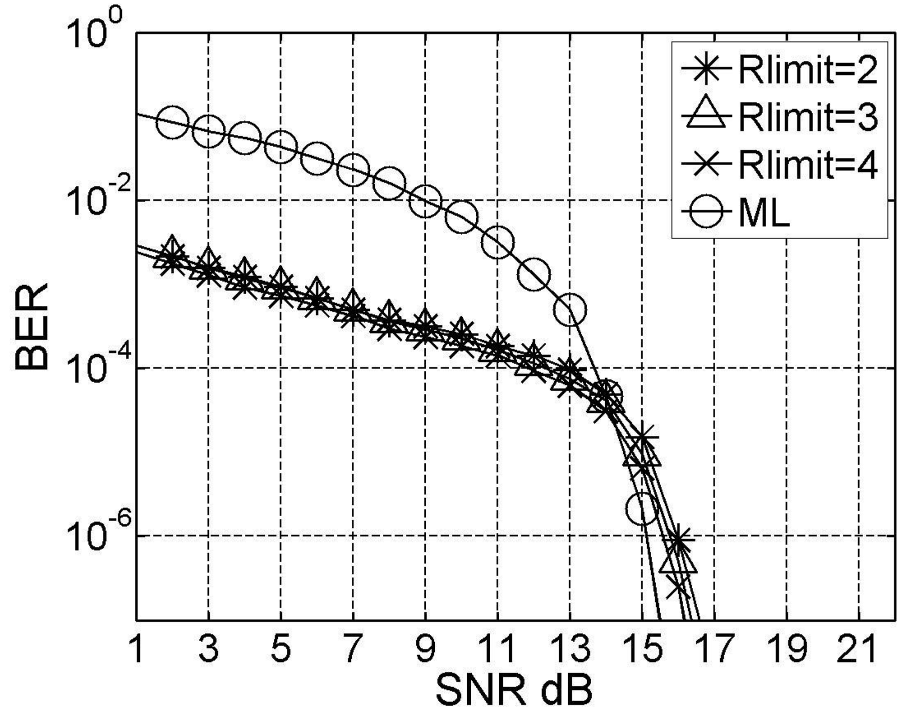

FIGURE 6: BER vs SNR curve for 4x4 MIMO and different *Rlimit* and *K* as 50. 2 active antennas are considered at the transmit side. Hence, using diversity scheme, 6 bits per symbols are attained with 16QAM modulation scheme.

As demonstrated in Figure 6, ML gives the minimum BER, although for low SNR dB, the proposed one provides better performance due to the rearrangement of the channel matrix [22]. With *K* as 50 and increasing *Rlimit*, the performance improves and gradually approaches closer to ML. When comparing the performance of proposed K-best one with that of ML, *Rlimit* equal to 2 lags around 1.0 dB from ML. With *K* equal to 3, the gap reduces to 0.7 dB, where use of *K* as 4 results to around 0.5 dB gap reduction compared to ML. On the other hand, if *Rlimit* is reduced less than 2, it provides poor performance.

The simulation results for QPSK modulation scheme for different list size and *Rlimit* are shown in Figure 7 in order to demonstrate the effect of *Rlimit* on BER performance. *K* is chosen as 1 and 4 where *Rlimit* is considered to be 2 and 3 for each chosen list size.

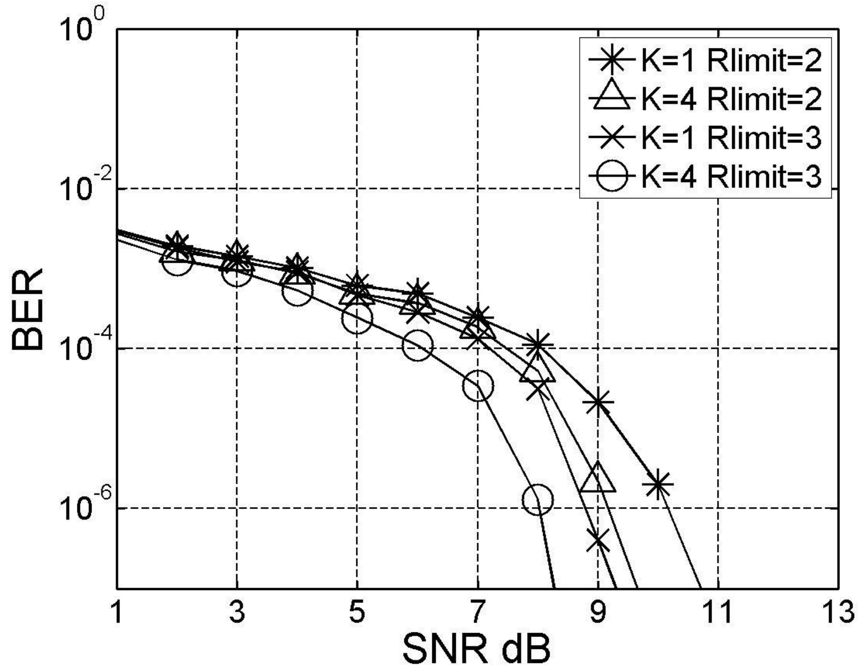

FIGURE 7: BER vs SNR curve for 4x4 MIMO and QPSK modulation scheme. *K* is chosen to be 1 and 4, while *Rlimit* is considered 2 and 3. 2 active antennas out of 4 available ones are considered at the transmit side. Hence, using diversity scheme, 4 bits per symbols are attained with QPSK modulation scheme.

As demonstrated in Figure 7, the performance improves with increasing *K* and *Rlimit* for QPSK modulation scheme. When *K* is equal to 4 and *Rlimit* as 2, it provides 1.2 dB better performance than that of *K* and *Rlimit* as 1. If we increase the *Rlimit* to 3 and limit *K* to 1, around 1.5 dB improvement can be attained. When *K* and *Rlimit* are 4 and 3 respectively, it results to around 2.6 dB improvement. Next, the simulation results for GSM with spatial multiplexing using real and complex domain K-best decoder are analysed.

3.2 GSM with Spatial Multiplexing

While considering the SMx, different information bits are transmitted by active antennas, which increases the throughput and spectral efficiency. The simulation includes both real and complex domain K-best decoder for different MIMO configurations and modulation schemes.

3.2.1 Using Real Domain LR-aided K-best Decoder

The BER versus SNR curves of the above specified MIMO system using real domain K-best decoder are shown in Fig. 8. In order to achieve 6 bits per symbol length, QPSK modulation scheme is applied for our proposed MIMO system with $N_t = 4, N_{RF} = 2, N_r = 4$

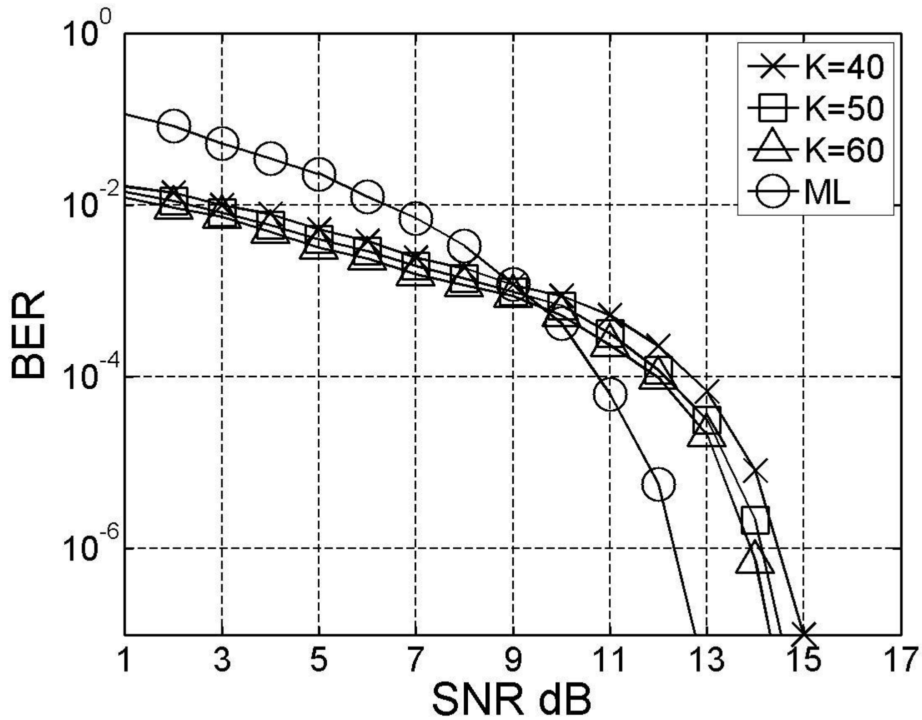

FIGURE 8: BER vs SNR curve for 4x4 MIMO and different list size, *K*. 2 active antennas are considered at the transmit side. Hence, using SMx, 6 bits per symbols are observed with QPSK modulation scheme.

As observed in Figure 8, the proposed one gives lower BER for low SNR. With the increase of SNR, ML outperforms the proposed one. The ML detector provides the best BER performance at high SNR values. However, for low SNR values, the proposed detection scheme provides better performance. LR enhances the orthogonality condition of the channel, thus, at low SNR values, the channel is extremely contaminated. Therefore, as LR improves, the orthogonality of $\boldsymbol{H}$ and additionally the performance gradually improves with higher *K*, and approaches closer to ML. Then, it gets saturated, which means that the performance does not improve with increasing list size.

If we compare the performance of proposed K-best one with that of ML, *K* equal to 40 lags around 2.3 dB from ML. With *K* equal to 50, the gap reduces to 1.9 dB. If the list size, *K* is further increased to 60, the performance almost gets saturated and lags behind 1.6 dB against ML. On the other hand, if the list size is reduced less than 40, it provides poor performance.

The result demonstrates only hard decision based MIMO detection, however, it can also be implemented for soft decision MIMO decoding and any MIMO configuration with different modulation schemes. All the list sizes that are used as the maximum effective list sizes in this analysis are derived through extensive simulations. Next, the simulation results for GSM with spatial multiplexing using complex domain K-best decoder are analysed.

3.2.2 Using Complex Domain LR-aided K-best Decoder

Complex domain MIMO decoder has the re-configurability between complexity and performance by including *Rlimit* as parameter with list size, *K* [4, 21]. As showed in Figure 8, maximum performance is achieved with *K* as 60 for QPSK and real domain MIMO decoder while transmitting using spatial multiplexing. Hence, for complex decoder, all simulations for QPSK modulation scheme are performed with list size fixed to 60 and variant *Rlimit*. The BER versus

SNR curves of the above specified MIMO system using complex domain K-best decoder for QPSK modulation scheme are shown in Fig. 9.

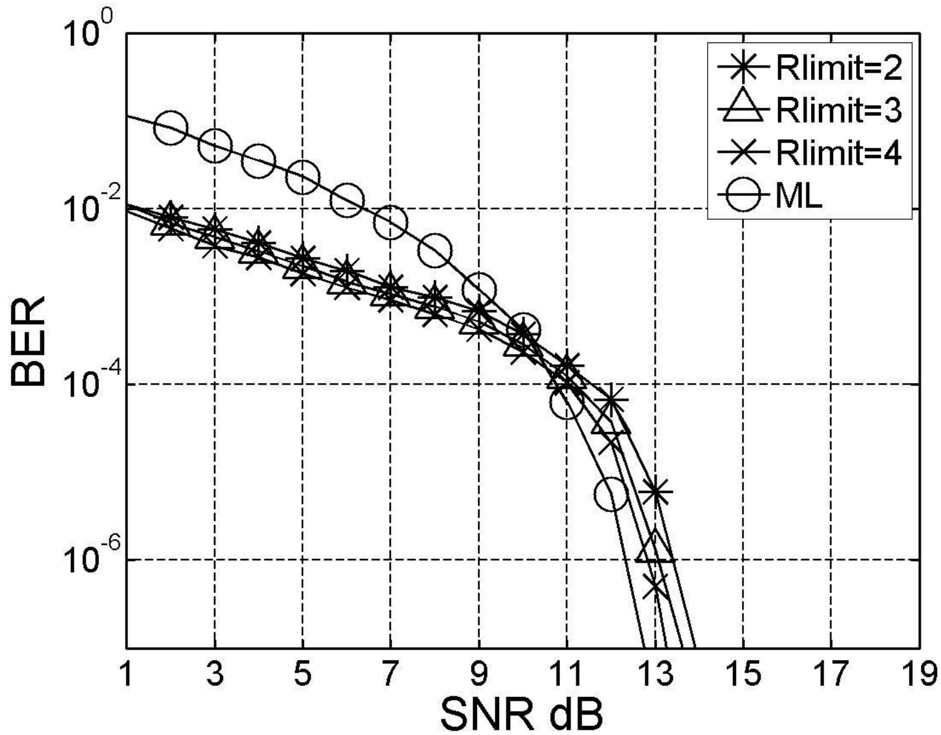

FIGURE 9: BER vs SNR curve for 4x4 MIMO and different *Rlimit* and *K* as 60. 2 active antennas are considered at the transmit side. Hence, using diversity scheme, 4 bits per symbols are attained with QPSK modulation scheme.

As demonstrated in Figure 9, ML gives the minimum BER, although for low SNR dB, the proposed one provides better performance because of the rearrangement of the channel matrix [22]. With *K* as 60 and increasing *Rlimit*, the performance improves and gradually approaches closer to ML. When comparing the performance of complex one with that of ML, *Rlimit* equal to 2 lags around 1.3 dB from ML. With *K* equal to 3, the gap reduces to 0.9 dB, where use of *K* as 4 results to around 0.5 dB gap reduction compared to ML. On the other hand, *Rlimit* when reduced to 1, it provides poor performance.

The result demonstrates only hard decision based MIMO detection, however, it can also be implemented for soft decision MIMO decoding and any MIMO configuration with different modulation schemes. All the list sizes that are used as the maximum effective list sizes in this analysis are derived through extensive simulations. In the following section, the comparison of performances for GSM with diversity gain and spatial multiplexing using both real and complex domain K-best decoder are analysed.

3.3 Comparison of Performances

This section represents the complexity analysis and comparison of performances between two above proposed transmission schemes and also both real and complex domain MIMO decoder. First, the comparison is done between real and complex decoder for diversity gain transmission scheme. Then similar analysis is presented for spatial multiplexing. After that, comparison between 2 transmission schemes are demonstrated.

The number of the nodes calculated for a given condition is considered as a parameter of complexity analysis. As explained before in section 2.4, ML require $\sum_{i=1}^{N_t} M^i$ node calculation to perform an exhaustive search, where M is the number of APM symbols and N_t represents the number of transmit antenna. For real and complex domain decoder, it is equal to $\sum_{i=2}^{N_t}(2K-1)+K$ and $\sum_{i=2}^{N_t}K(Rlimit+1)-N_t$ respectively. Therefore, complexity order of both real and complex domain K-best decoder does not depend on the modulation scheme.

3.3.1 Comparison between real and complex domain K-best decoder using GSM with diversity gain

This subsection includes the comparison of performances between real and complex domain MIMO decoder using diversity transmission scheme. Since real one achieved maximum performance using *K* as 50 for 16QAM modulation scheme, therefore, for the complex decoder same list size is used for different *Rlimit*. Complexity analysis of the above 2 decoders with that of ML for 4x4 MIMO and 16QAM modulation scheme is shown in Table 3.1.

TABLE 3.1: Complexity analysis of real and complex domain 4x4 MIMO with that of ML for 16QAM modulation. Diversity gain is achieved transmitting same information bits through 2 antennas.

K	Real	Complex		ML vs Real (in dB)	ML vs Complex (in dB)	Complex vs Real (in dB)
	Node	Rlimit	Node			
50	743	2	446	1.9	1.0	0.9
50	743	3	596	1.9	0.7	1.2
50	743	4	746	1.9	0.5	1.4

As shown in Table 3.1, for real domain 4x4 MIMO decoder with 16QAM modulation scheme, the node calculation is equal to 743 for choosing *K* as 50. However, it lags in the performance compared to ML for 1.9 dB. Considering complex MIMO decoder, the node calculation became 446, 596 and 746 for Rlimit 2, 3 and 4 respectively; although the gap between complex and ML reduces to 1.7, 0.7, and 0.5 dB accordingly. Hence, allowing more node calculation and complexity, we can get performance close to ML.

Next, we compare the performances between real and complex decoder, as shown in Table 3.1. With less node calculation, complex one achieved 0.9 dB to 1.2 better performance. Allowing more complexity for complex decoder can lead to 1.4 dB better performance than that of real one.

3.3.2 Comparison between real and complex domain K-best decoder using GSM with spatial multiplexing

This subsection includes the similar comparison of performances between real and complex domain MIMO decoder with spatial multiplexing transmission scheme. However, real one achieved maximum performance using *K* as 60 for QPSK modulation scheme. Hence, for the complex decoder same list size is used for different *Rlimit*. Complexity analysis of the above 2 decoders with that of ML for 4x4 MIMO and QPSK modulation scheme is shown in Table 3.2.

TABLE 3.2: Complexity analysis of real and complex domain 4x4 MIMO with that of ML for QPSK modulation scheme. Spatial multiplexing is performed by transmitting different information bits using 2 active antenna.

K	Real	Complex		ML vs Real (in dB)	ML vs Complex (in dB)	Complex vs Real (in dB)
	Node	Rlimit	Node			
60	893	2	536	1.6	1.3	0.3
60	893	3	716	1.6	0.9	0.7
60	893	4	896	1.6	0.5	1.1

As shown in Table 3.2, real domain MIMO decoder requires 743 node calculation for 4x4 MIMO and QPSK modulation scheme with *K* as 60. However, it lags in the performance compared to ML for 1.6 dB. Considering complex MIMO decoder, the node calculation became 536, 716 and 896 for Rlimit 2, 3 and 4 respectively; although the gap between complex and ML reduces to 1.3, 0.9, and 0.5 dB accordingly. Hence, allowing more node calculation and complexity, we can get performance close to ML.

Next, we compare the performances between real and complex decoder, as indicated in Table 3.2. Even with less node calculation, complex one achieved 0.3 dB to 0.7 better performance. Hence, attaining increased complexity for complex decoder can lead to 1.1 dB better performance than that of real one. In the following subsection, comparison results of GSM between the two transmission designs are presented.

3.3.3 Comparison Between 2 Transmission Schemes

This subsection includes the comparison of performances between two above mentioned schemes. Figure 10 represents the BER versus SNR curves for both GSM with ML and LR-aided K-best decoder as MIMO decoder. For GSM with diversity gain, list size as 50 is considered in order to attend the maximum performance. However. GSM with SMx requires *K* as 60 for attaining the maximum performance. For complex decoder, *Rlimit* from 2 to 4 are considered for performance evaluation.

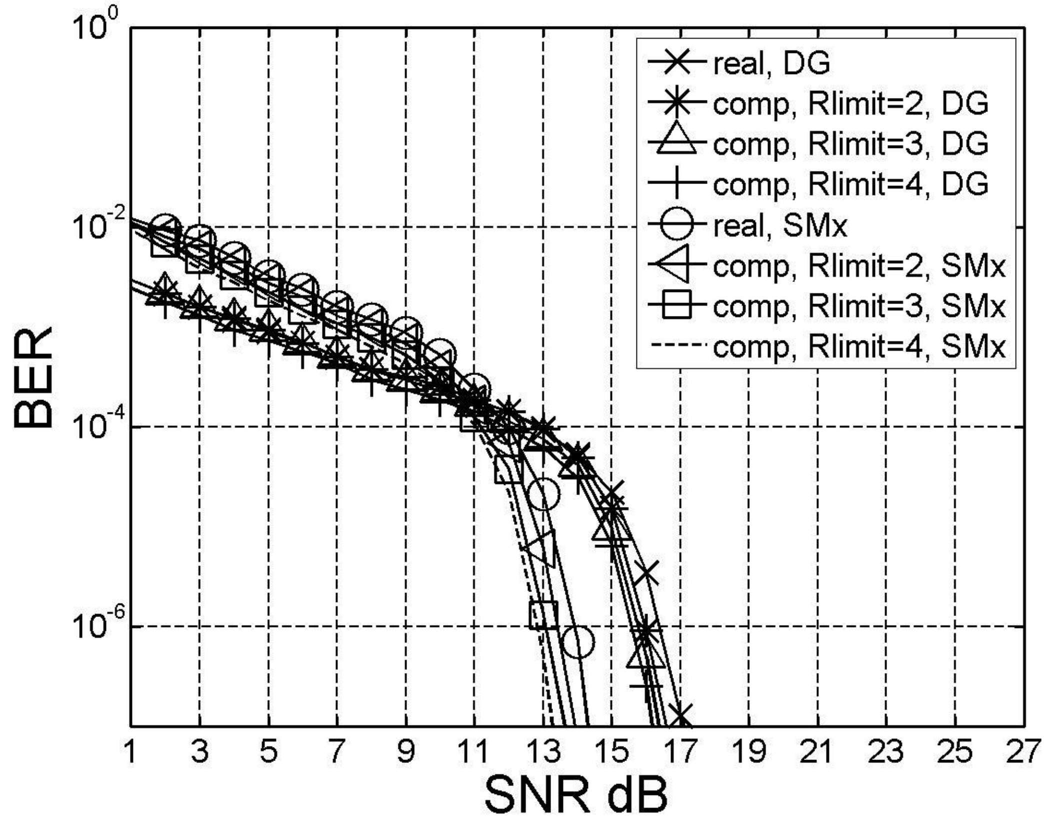

FIGURE 10: BER vs SNR curve of maximum performances between GSM with diversity gain (DG) and spatial multiplexing for 4x4 MIMO system with 2 active transmit antennas. Using diversity gain, 6 bits per symbols are observed with 16QAM modulation scheme, where GSM with SMx uses QPSK for the similar configuration. For ML, 16QAM is considered.

Figure 10 demonstrates the BER versus SNR curves for both GSM transmission designs. The parameters set for this plot are as follows. $N_t = 4, N_{RF} = 2, N_r = 4$ and system is transmitting a symbol length of 6 bits per symbol. Therefore, GSM with diversity requires 16-QAM modulation scheme, where GSM with SMx attains the same spectral efficiency with QPSK modulation scheme. It is observed that, GSM with diversity provides better performance at extremely noisy channel conditions (i.e., low SNR) due to the fact that having redundancy of the information helps to the detection. On the other hand, at high SNR values, the GSM with SMx outperforms diversity because low modulation order is being transmitted and the distances between constellation points is larger.

As shown in Figure 10, GSM with LR-aided real K-best decoder lags behind around 3.0 dB considering diversity gain, when compared with that of GSM with SMx for real MIMO decoder. When comparing the real of GSM with SMx with complex decoder of diversity gain, Rlimit equal to 2 lags behind 2.1 dB. If we increase Rlimit to 3 and 4, the gap reduces to 1.8 dB and 1.6 dB respectively. If we compare the result of complex decoder for diversity gain with that of GSM with SMx, we obtain 2.4 dB, 2.2 dB and 2,0 dB better performance for GSM with SMx and using Rlimit 2, 3 and 4 respectively. The performance analysis is demonstrated in Table 3.3.

TABLE 3.3: Comparison of performances of GSM between spatial multiplexing and diversity gain for 4x4 MIMO with 2 active antennas. Using diversity gain, 6 bits per symbols are observed with 16QAM modulation scheme, where spatial multiplexing uses QPSK for the similar configuration.

GSM with SMx vs Diversity gain transmission scheme				
Real vs Real (in dB)	Complex vs Real		Complex vs Complex	
	Rlimit	in dB	Rlimit	in dB
3.0	2	2.1	2	2.4
3.0	3	1.8	3	2.2
3.0	4	1.6	4	2.0

As shown in Table 3.3, it is observed that GSM with SMx provides better performance than GSM with diversity gain. Theoretically, GSM with SMx uses lower modulation scheme compared to GSM with diversity gain in order to maintain the same bits per symbol. Hence, the larger distance between lower modulation symbols benefits and improves the BER performance over GSM with diversity gain using higher modulation scheme.

4. CONCLUSION

In this paper, generalised spatial modulation (GSM) with LR-aided K-best decoder is proposed. It conveys information by activating a subset of transmit antennas reducing the transmit power and design complexity. At the transmission side, both MIMO transmission schemes, diversity gain and spatial multiplexing (SMx) are being utilised based on the spatial modulation (SM) principle. Additionally, an LR-aided real and complex domain K-best decoder is incorporated as a MIMO decoder in order to obtain near optimal performance with less complexity, compared to the maximum likelihood (ML) decoder.

Following the IEEE 802.11 standard, we develop the decoder for a 4×4 MIMO system with 2 active antennas at the transmitter side. Although current system model presents hard decision based MIMO detection, it can also be implemented for soft decision iterative MIMO decoding and any MIMO configuration with different modulation schemes. The simulation results show that the proposed scheme with SMx provides better performance utilising lower modulation than that of GSM with diversity gain for high SNR. However with bad channel conditions, the diversity scheme outperforms GSM with SMx.

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