Performance Enhancement of Generalized Spatial Modulation (GSM) Multiple Input Multiple Output (MIMO) Systems

By

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A thesis submitted in partial fulfillment of the requirements for the degree

of Masters of Science in Electrical Engineering (MS EE)

In

School of Electrical Engineering and Computer Science,

National University of Sciences and Technology (NUST),

Islamabad, Pakistan.

(22nd september 2016)

Approval

It is certified that the contents and form of the thesis entitled "**Performance Enhancement of Generalized Spatial Modulation (GSM) Multiple Input Multiple Output (MIMO) Systems**" submitted by **Sikandar Afridi** have been found satisfactory for the requirement of the degree.

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Abstract

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

Dedication

I dedicate this thesis to my parents, teachers and colleagues who helped me throughout my research phase.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at National University of Sciences & Technology (NUST) School of Electrical Engineering & Computer Science (SEECS) or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Acknowledgment

I am thankful to Allah Almighty for His blessings, which allowed me to accomplish this mile stone.

I would especially like to thank my supervisor, Dr. Syed Ali Hassan, whose guidance had been a constant companion throughout the course of this dissertation.

I would also like to thank my parents for their encouragement and moral support, which helped me get through the trying spots during this journey.

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Chapter 1

Introduction

Till now most of the proposed solutions for advanced transmission technologies to maximize the spectral efficiency (SE) are the most conventional responses to the surge in mobile data communication. That is why SE is the main performance metric for designing and optimizing wireless communication systems in general and cellular networks in particular. As a result, most of the transmission technologies are designed for the operation of mobile and cellular networks taking into account factors such as data rates, QoS, scalability, throughput etc. ignoring the energy consumption [20], [5]. Hence it is very crucial to develop such energy efficient (EE) and low-complexity solutions which can satisfy the target QoS and data rate requirements because the operational cellular systems can achieve EE at the cost of some SE degradation. So there is a need of more appropriate performance metrics to design transmission technologies and protocols for next generation cellular networks which takes EE into account [7].

When we look at the physical layer perspective of 5G future cellular networks multiple-input multiple-output (MIMO) communication is one of the most promising wireless communication techniques. The capacity of MIMO systems is proportional to $min\{N_t, N_r\}$ under some agreeable propagation conditions [14], where Nt is the number of transmit antennas and Nr is the number of receive antennas. Consequently the throughput may be increased linearly with the number of antennas if the SNR is sufficiently high, the links are independent and channel side information is available at both the transmitter and the receiver. As a result the MIMO techniques are capable to provide high data rates without increasing the spectrum utilization and the transmit power. However MIMO systems need power amplifiers, filters, multiple RF chains, synchronizers etc., which increases its power consumption significantly. The SE advantages of MIMO communication are widely recognized, but the EE potentials are yet to be explored. According to recent results presented by [26] for the power amplifier under power consumption constraint the transmit antenna having the weakest channel gain should be turned off, which turns off the related RF chain and mixers thus saves power consumption. That is why the design of an EE MIMO systems for cellular networks is a fairly open research problem. Hence there is a need to develop new air-interface transmission techniques that has a fair tradeoff between the SE and the EE [7].

As compared to single antenna transmission, all the antennas are active in conventional MIMO systems at any time instant to simultaneously transmitting multiple data streams and achieve SE at the cost of

- Increased signal processing complexity at the receiver in order to counteract the inter channel interference because of simultaneously transmitting multiple antennas.

- More perfect synchronization is required among the transmit antennas in order to exploit the multi-user (MU)-MIMO or space-time block coding (STBC) MIMO configuration.

- Multiple RF chains at the transmitter need independent power amplifiers each of which causes high power consumption at the transmitter and it also makes the transmitter bulky.

According to these considerations designing a multi-antenna transmission scheme with a limited number of RF chains is a major challenge for next generation MIMO based cellular networks, which can reduce the required inter antenna synchronization, signal processing and receiver complexity while aiming to improve the EE. In this context, single-RF MIMO design is an emerging research area currently. The basic idea behind single-RF MIMO is to utilize the spatial gain and the transmit diversity gain of many antennas, but with a few, possibly single activated antenna elements at transmitter at a transmit instant [18]. The motive behind the paradigm shift from multi-RF to single-RF in MIMO design is because of the idea that a large number of transmit antenna can be installed at the base station (BS) (large-scale MIMO or massive MIMO) in emerging millimeter-wave band [21], [29] given that the power consumption and complexity of the system is determined by the number of active antennas (active RF chains) simultaneously [18], [27]. Spatial modulation (SM) has proven to be one of the novel and most promising transmission techniques belonging to the single-RF large-scale or massive MIMO wireless transmission family, which exploits the multiple antennas as compared to the state-of-the-art power-hungry and more complex conventional MIMO systems [8]. SM-MIMO uses a limited number of RF chains while taking the advantage of all the transmit antenna array. The basic working principle of SM-MIMO is that it maps some of the information bits into the SM constellation diagram which consists of one or a subset of antenna as a constellation element. This novel approach helps SM-MIMO to achieve high data rate with low complexity and less signal processing as well as an improved EE [31]. According to some recent results presented in [6] SM-MIMO has the potential to outperform many state-of-the-art MIMO schemes with a few numbers of active antennas provided that a sufficient large number antenna is available at the transmitter side. In short the main reason behind SM-MIMO communication design to achieve SE and EE in cellular networks is based upon two main concepts as follows

- Minimizing the number of active antennas in order to increase the EE by reducing the power consumption for a given performance constraint (single-RF principle).

- Maximizing the number of transmit antennas in order to increase the SE (large-scale or massive MIMO principle) which is achieved by utilizing the spatial gain introduced by mapping the information bits onto the SM constellation.

The working principle of SM-MIMO and its various variants will be presented in the sections below.

1.1 Background

Since the begging of the 20th century the growth in the cellular market has been remarkable because the number of cellular subscribers and wireless services demand has escalated. Mobile communication, mobile data and video as well as television services are becoming an important component of our daily life. Some of the most significant reasons for cellular data traffic growth in recent years are the introduction of Android phones, iPhone and social networking such as Facebook. Hence satisfying the data traffic demands with a minimum cost and to maintain portability in wireless communication networks is a challenge for the mobile operators. This unpredictable surge in data traffic in cellular industry has led the telecommunication operators and the researchers develop such transmission technologies which are spectral efficient and has high throughput. On the other hand a little or no attention has been paid to the energy consumption and complexity issues of such transmission technologies. That is why information and communication technology (ICT) sector already contributes 2% of the global carbon emission [7] while mobile networks contributes 0.2%,which is comparable to that of airplanes and almost a quarter of global carbon emission of cars. This amount is expected to increase in future due to the huge increase in mobile data traffic. Up to 80% of an operators total energy is consumed by the radio networks. Hence there is a need of clean-slate wireless communication technologies which can fulfill the growing needs for future mobile data traffic while reducing the carbon footprint. That is why next-generation cellular networks are proposed to be *green* implying that energy efficiency will be an important design parameter. Until recently, the majority of the research has focused on the improvement of spectral efficiency (SE) while there has been a very little attention devoted to the energy efficiency (EE) of wireless systems [7]. The demand of high data rates and wideband communication are the key motivations that led to design and implementation of several transmission technologies and techniques to improve the SE and throughput of wireless communication systems. MIMO systems such as vertical Bell Laboratories layered space-time (V-BLAST) architecture is one of these transmission technologies which offers high SE [9, 33]. V-BLAST MIMO transmits data through multiple antennas simultaneously, thus improves the SE enormously. However, such techniques are not energy efficient as they consume much power [3] because of multiple active radio-frequency (RF) chains simultaneously. Also all the antennas transmit at same time at the same frequency, which increases the system complexity and causes significant amount of inter-channel interference (ICI) [36]. Designing a system that can balance the tradeoff between the SE and EE for next generation wireless networks is an active research area.

1.2 SM MIMO

SM MIMO was introduced as a modified version of MIMO in [22, 24]. SM MIMO is energy efficient and has low complexity as compared to conventional MIMO because it has only one active antenna at an instance to transmit. SM MIMO increases the SE by appending some portion of data in the active antenna index and also avoids the ICI due to single active antenna for a transmission. The spectral gain of SM MIMO is $log_2(N_t)$, where N_t denotes the total number of transmit antennas. The rate of SM MIMO is $log_2(N_t)+log_2(M)$, where M is the modulation order of QAM. The SM-MIMO transmit symbol S_1 out of the two symbols explicitly and the other symbol S_2 is transmitted by determining the index of active antenna implicitly in each channel use. To illustrate the working principle of SM MIMO its difference with the working principle of spatial multiplexing (SMX) MIMO and orthogonal space-time block coding (OSTBC) MIMO is presented in Fig. 1.1.

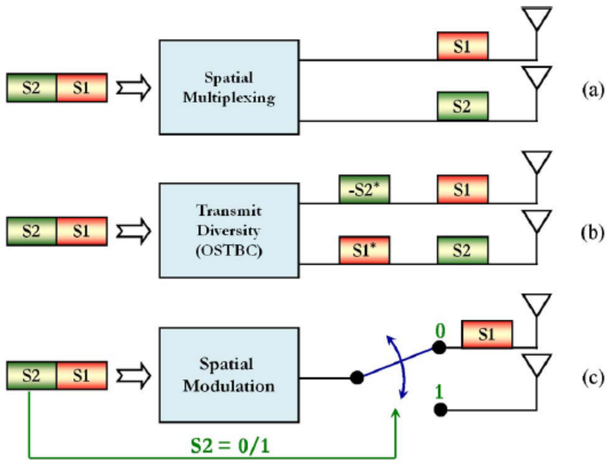

Figure 1.1: Illustration of three different MIMO concepts: (a) spatial multiplexing; (b) transmit diversity; and (c) SM.[1]

According to Fig. 1.1 SMX MIMO transmit both the QAM symbols S_1 and S_2 from a pair of antenna in a a single channel use with a rate of $N_t log_2(M)$ while in OSTB MIMO both the QAM symbols S_1 and S_2 are

[1]M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized mimo: Challenges, opportunities, and implementation," Proceedings of the IEEE, vol. 102, no. 1, pp. 56 103, 2014.

encoded before transmitting simultaneously from a pair of transmit antennas in two channel use with a rate of $R_c log_2(M)$ with $R_c = N_m/N_{cu}$, where N_m is is the number of transmitted symbols in N_{cu} channel uses.

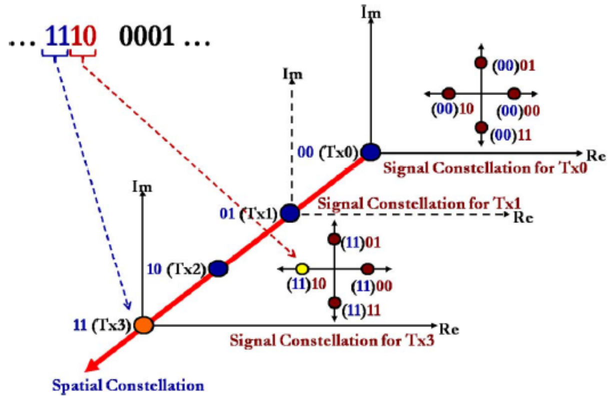

Figure 1.2: Illustration of the 3-D encoding of SM (first channel use).[2]

SM MIMO uses the amplitude and phase modulation (APM) as well as antenna indices to modulate data. SM MIMO has two types of constellation (i.e., the spatial constellation) which decides the active antenna index and the signal constellation through which the data is modulated into a symbol such as quadrature amplitude modulation (QAM). The active antenna index and symbol to be transmitted depends on random data bits at the transmitter.

The encoding mechanism of SM MIMO is shown Fig. 1.2 and 1.3 illustrating the concept of spatial constellation, where $Nt = 4$ and $M = 4$ with a data rate of $log_2(N_t)+log_2(M) = 4$bpcu. In the first channel use a four bit long block of information 1100 is encoded, where the first $log_2(N_t) = 2$ bits, 11, determine the single active antenna TX_3 while the last $log_2(M) = 2$

[2]M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized mimo: Challenges, opportunities, and implementation," Proceedings of the IEEE, vol. 102, no. 1, pp. 56 103, 2014.

bits, 00, determines the QAM symbol shown in Fig. 1.2. Like wise the information 0001 determines TX_1 and the QAM symbol for second channel use shown in Fig. 1.3. At the receiver, the index of active antenna is detected

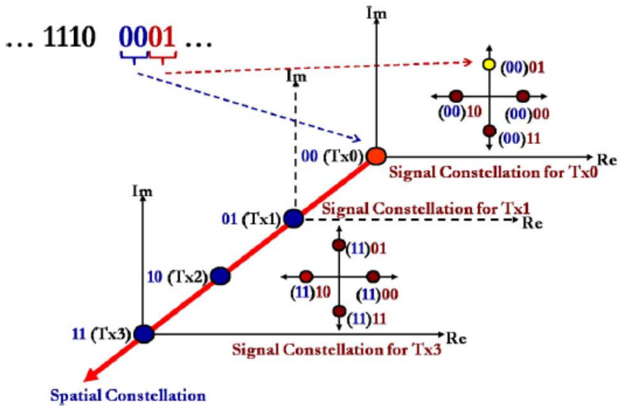

Figure 1.3: Illustration of the 3-D encoding of SM (second channel use).[3]

first, followed by symbol detection.

Following are some of the most significant advantages of SM MIMO

- **Higher throughput.** Due to introduction of spatial dimension results in a 3-D constellation the SE of SM MIMO is higher than that of the OSTBC MIMO and single antenna transmission with reduced RF output power.

- **Simpler receiver design.** Due to a single active transmit antenna per channel used ICI is avoided by SM MIMO, which results in an optimal ML receiver design with a single-stream decoding complexity.

- **Simpler transmitter design.** The deployment of the SM MIMO

[3]M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized mimo: Challenges, opportunities, and implementation," Proceedings of the IEEE, vol. 102, no. 1, pp. 56 103, 2014.

transmitter is easy and inexpensive because of the fact that SM MIMO needs a single RF chain with many inactive transmit antennas.

- **Lower transmit power supply.** SM MIMO reduces the total consumed power for required same RF output power since it utilizes the spatial gain with single RF chain. The power consumed independent of the number of transmit antennas which results in an EE system.

An issue with SM MIMO is that N_t must be a power of two (i.e., 2, 4, 8, 16 ,.... which becomes very large) for the scheme to work.

1.3 GSM MIMO

In generalized spatial modulation (GSM) MIMO, more than one antennas are active for a transmission instance. It was proposed as an alternative to SM MIMO, where the spatial constellation is the indices of combination of active antennas. Whereas in SM MIMO, it is the index of single active antenna. Data is transmitted in combinations of antenna indices in addition to symbol modulation over QAM.

The spectral gain of GSM MIMO for N_t transmit and N_a active antennas is $\lfloor\ log_2\binom{N_t}{N_a}\ \rfloor$, where $\lfloor\ .\ \rfloor$ is the floor operator. As $\lfloor\ log_2\binom{N_t}{N_a}\ \rfloor$ is greater than $log_2(N_t)$ with same number of N_t and $N_a > 1$, that is why the GSM MIMO is more spectrally efficient than SM MIMO. SM MIMO needs $N_t = 8$ to spatially modulate three bits because $log_2(8) = 3$, while GSM MIMO needs $N_t = 5$ and $N_a = 2$ to transmit the same three bits because $\lfloor\ log_2\binom{5}{2}\ \rfloor = 8$. The receiver in GSM MIMO receives more than one copy of same symbol. Hence GSM MIMO is more reliable than SM MIMO. GSM MIMO performance is very close to SM MIMO in terms of BER with less number of required transmit antannas [36]. While the SM MIMO and GSM MIMO are energy efficient than conventional MIMO but their SE still needs to be improved because it is very low as compared to conventional MIMO.

1.4 ASM MIMO

The SE of GSM MIMO can be further improved by adaptive modulation (AM) technique [1, 13]. While maintaining a certain average bit error rate (ABER), the constellation size is adopted according to the channel conditions in AM systems. The constellation size increases with the increase in received signal-to-noise ratio (SNR) than the pre-defined threshold for a given ABER. To improve the ABER of conventional SM MIMO with fixed SE or data rates, an adaptive scheme was proposed known as adaptive spatial modulation (ASM) [34]. In [3], ASM was introduced to improve SE of conventional SM MIMO holding the ABER below a pre-defined threshold. In order to further improve the SE, this paper presents adaptive generalized spatial modulation (AGSM) MIMO, which achieves high SE by increasing the modulation order of QAM according to channel conditions while keeping the ABER under a pre-defined threshold value. Simulation results are matched with the analytical results for ABER and SE of AGSM and are compared with ASM MIMO in [3]. Also the GSM MIMO and AGSM MIMO are compared in terms of SE.

1.5 ESM MIMO

In extended spatial modulation (ESM) MIMO, one or more than one antennas are active for a transmission instance. It was proposed as an extended version of GSM MIMO, where the spatial constellation is the indices of combination of active antennas but unlike GSM MIMO the number of active antennas is not fixed in ESM. Data is transmitted in antenna combination indices in addition to symbol modulation over QAM.

The spectral gain of ESM MIMO for N_t transmit and N_a active antennas, where N_a varies from 1 up to N_t is $\lfloor\ log_2(2^{N_t} - 2)\ \rfloor$. As $\lfloor\ log_2(2^{N_t} - 2)\ \rfloor$ is greater than $\lfloor\ log_2\binom{N_t}{N_a}\ \rfloor$ with same number of N_t, that is why the ESM MIMO is more spectrally efficient than GSM MIMO. GSM MIMO needs $N_t = 5$ and $N_a = 2$ to spatially modulate three bits because $\lfloor\ log_2\binom{5}{2}\ \rfloor = 3$, while ESM MIMO needs $N_t = 4$ to transmit the same three bits because $\lfloor\ log_2 2^4 - 2\ \rfloor = 3$. The receiver in ESM MIMO receives more than one copy of same symbol for $N_a > 1$. Hence ESM MIMO is more reliable than SM MIMO.

1.6 SM for Massive MIMO

Massive MIMO is an evolution of MU-MIMO, which scales up the MIMO to a massive magnitude. In massive MIMO hundred of base station antennas are available to serve tens of terminals using same time frequency resources [19, 37].

Massive MIMO provides all the benefits provided by conventional MU-

MIMO at a very large scale with more efficient use of spectrum, more energy efficiency, robustness and network security for future broadband networks. Different antenna configurations and deployment are shown in Fig. 1.4 for the massive MIMO base station.

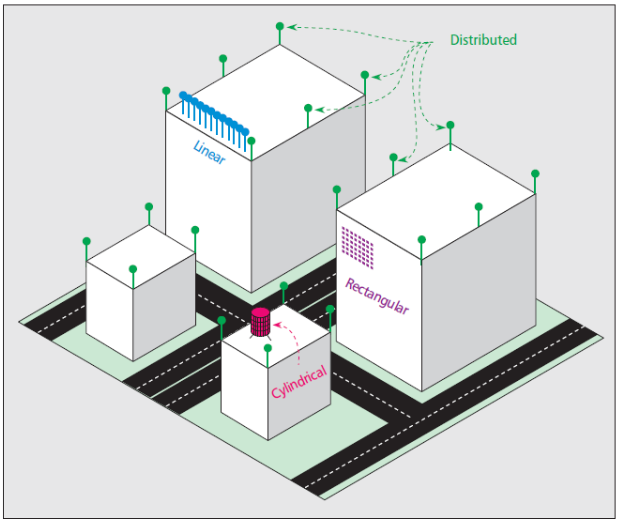

Figure 1.4: Some possible antenna configurations and deployment scenarios for a massive MIMO base station.[4]

Massive MIMO has gained a clear edge over other existing technologies because it is currently in practice by using time-division duplexing (TDD) operations in a very large number and large number of service antennas on the terminals. The throughput and the radiated energy efficiency can be improved at a large scale by massive MIMO with the help of extra antennas [32]. When the orthogonal channels are assigned to the terminals the throughput depends on the propagation environment mainly. Reduction in the latency, cheap and low power components and MAC layer simplification

[4]E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive mimo for next generation wireless systems," IEEE Communications Magazine, vol. 52, no. 2, pp. 186-195, 2014.

are some of the other benefits of massive MIMO [19].

SM can be combined with massive MIMO to further improve the energy efficiency of MIMO for future communication networks by activating a subset of transmit antennas for each channel use instead of all the transmit antennas [2]. Some portion of the information is spatially modulated into the indices of the subset of active antenna thus achieves a spatial spectral gain with limited number of active RF chains.

Chapter 2

Literature Review

The pioneer work in the area of SM MIMO dates back to 2001 when the principle of space modulation was introduced by [4]. This scheme was termed as space shift keying (SSK). SSK works on the principle of distinct multiple channel characteristics of different antennas in a wireless fading channel which results in distinct received signal from different antennas. This helps the receiver to discriminate the transmitted information from multiple antennas. The work in [4] presents a SSK scheme for MIMO with two transmit antennas which provide a data rate of 1-bpcu. In this scheme only one antenna is active to encode one information bit, while both the transmit antennas are active to encode the other information bit. To increase the data rates up to 2-bpcu another MIMO scheme was proposed with two transmit antennas, where SSK was combined with 2-PSK modulation. In [4] it was concluded that SSK can also be used with other higher order modulation schemes such as QPSK and also more number of transmit antennas can be used to increase the data rates of the proposed scheme.

Another multi-antenna modulation scheme, where the number of transmitted bits is equal to number of transmit antenna was proposed by [11] in 2002. The information bits are multiplexed in an orthogonal fashion using Walsh-Hadamard codes and antenna array. The main feature of the multiplexing scheme is that only one antenna transmits data using BPSK out of the antenna array in each symbol duration. The receiver detects the transmit antenna assuming un-correlated fading between each antenna and perfect channel information is considered at the receiver. The scheme is evaluated for four transmit antenna with 2-PSK modulation and gives a SE equal to 8-PSK because one bit is used for parity check in each transmission with an SNR improvement of 2.5 dB [11]. In addition the interference between the antennas is avoided because of the fact that only a single antenna transmit at a time.

A more similar approach to SM-MIMO was presented in 2004 by [30], where the binary bits are mapped into both the information symbol such as QPSK and the active antenna number which transmit this symbol. This scheme was originally proposed for code division multiple access (CDMA) that is why it is termed as channel hopping technique and the bits modulated spatially over antenna were known as channel bits. Hence the total number bits transmitted over a channel at a time is the sum of bits per transmit symbols such as QPSK and the channel bits. The proposed scheme in [30] can achieve a SE of 3-bpcu with two transmit antenna i.e. one channel bit implicitly transmitted by activating a single antenna and QPSK modulated symbol i.e. QPSK symbol with two bits per symbol explicitly transmitted through the activated antenna. The channels are considered to be independent, so that the receiver can detect the specified channel bit value.

In 2005 an approach similar to the one presented in [11] was proposed by [23] to design a scheme that avoids ICI in multi-antenna modulation scheme while maintaining high SE. The proposed scheme considerably reduces the signal processing complexity as compared to numerous ICI reducing techniques proposed in literature and in addition it avoids the need of synchronization between the antennas. In this scheme QPSK modulation is used instead of BPSK which results in a Fourier encoded matrix instead of the Hadamard matrix to design orthogonal codes. The SE of proposed scheme can be compared to 16-PSK. The proposed scheme outperforms V-BLAST algorithm by a 6.5 dB reduction in SNR to achieve a given symbol-error-ratio (SER) with 35-42% reduction in receiver complexity at a cost of a slight reduction in SE [23]. It also outperforms the minimum mean squared error (MMSE) and zero-forcing (ZF) symbol detection techniques by 12 dB.

In 2006, the same authors proposed further variants of the scheme presented by [23] and they started using the term spatial modulation (SM) for this encoding scheme in [22] and [10]. A novel multi-antenna orthogonal frequency division multiplexing (OFDM) transmission approach was proposed by [22] called SM-OFDM, which entirely avoids the ICI and needs no inter-antenna synchronization. According to this approach a block of data is mapped into the two dimensional signal plane as well as into the spatial dimension forming a three dimensional constellation plane. The proposed scheme has a BER performance gain of 3 dB for six bits per subcarrier and 4 dB for four bits per subcarrier over V-BLAST OFDM.

The work in [22] was further investigated in the presence of Rician fading, spatial coupling and mutual coupling by the same authors in [10]. According to the results SM-OFDM outperforms the V-BLAST OFDM by 2 dB while achieving the same SE, which means that SM-OFDM has the highest improvements over V-BLAST OFDM in the presence of all the channel and antenna imperfections.

The SM scheme proposed in [22] was evaluated with iterative-maximum ratio combining (i-MRC) which estimates the transmit signal as well as the transmit antenna numbers. The BER performance achieved by the proposed technique is same as ideal V-BLAST and MRC for same SE with a significant reduction in the receiver complexity.

SM-OFDM is compared with the V-BLAST OFDM for both the coded and uncoded systems in [22]. It shows that SM outperforms the V-BLAST by 7dB SNR in case of both coded and uncoded systems for at target BER of 2×10^{-3} and 10^{-3} respectively in the presence of all channel imperfections i.e. Rician fading, SC and MC.

After a couple of years in 2008, the SM-MIMO concepts were improved by further investigation in a number of publications. The authors in article [35] studied the channel capacity of an advanced version of the channel hopping technique in [30] known as information guided channel hopping (IGCH) technique with the maximum likelihood algorithm. The results suggested that IGCH has the larger channel capacity than the STBC for more than two antennas because with the increase in the number of transmit antennas the equivalent code rate increases for IGCH system and decreases for STBC systems.

A detailed study of SM-MIMO concept introduced in [23], [22] and [10] is presented by [24] in 2008, where a block of information is mapped into two information units i.e. a symbol from a constellation diagram and a unique transmit antenna number. The use of transmit antenna index gives a SE gain equal to the base-two logarithm of number of transmit antennas. A low-complexity two-step demodulator with a maximum receive ratio combining (MMRC) algorithm used to detect both the active antenna number and the transmitted symbol. The closed-form analytical results for SM-MIMO are derived which matches the simulation results for independent identically distributed (i.i.d) Rayleigh flat-fading channels. The results show that SM-MIMO is better than the V-BLAST- MIMO scheme in terms of BER but the SE of SM increases by the base-two logarithm of the total number of transmit antennas as compared to the linear increase in the case of V-BLAST. According to [24] an adaptive algorithm is needed in future that the SE of SM increases by incrementing signal modulation order on the bases of the received signal to noise ratio (SNR). As compared to V-BLAST scheme SM-MIMO results in a 90% reduction in the receiver complexity and almost the same receiver complexity as the Alamouti scheme. Another advantage of SM-MIMO is that it provides the freedom to work with any configuration of antennas, even if the number of receive antennas are less than the number of transmit antennas.

An optimal maximum likelihood (ML) detector was developed in 2008 for SM-MIMO by [16] which performed significantly better than i-MRC detector in [24] with a gain of 4dB. Due to ICI caused by the coupling of multiple symbols in V-BLAST the complexity of ML detector increases exponentially, but that is not the case for SM-MIMO where only one antenna transmit a symbol at a time and avoids the ICI. The authors in [16] also derived the closed form expression for average bit error probability of the proposed system.

In 2009, the concept of SSK scheme was simplified in [17] by restricting the information transmission to the antenna index only rather than transmitting symbols and generalized the concept proposed in [4] to an arbitrary number of transmit antennas. The authors showed that the absence of symbol information avoids the need of APM transceiver and coherent detectors which makes it better than APM transmission with a performance gain of 3dB at a BER of 10^{-5} while the simplicity of the modulation technique reduces its detection complexity as compared to SM with same performance gain.

A new SM detection scheme was introduced by [25] known as multi-stage (MS) detection in 2011, which gives near optimal BER performance and reduction in receiver complexity up to 35% as compared to the optimal ML detector. In order to increase the SE [25] proposed a scheme to combine SM with more spectral efficient techniques such as M-QAM for the first time. The complexity of proposed sub-optimal MS detector is compared to the ML detector whose complexity increase up to 125% for $M >= 16$ SM configuration. The proposed MS detector is a combination of both the sub-optimal MRRC SM detector and the optimal ML SM detector. That is why the MS detector inherits the property of low complexity of sub-optimal detector as well as the property of high performance of optimal detector and can be applied for any SM configuration. The SM detector has to detect the transmit antenna index as well as the transmitted symbol that is why the performance of SM-MIMO depends upon two process i.e. the transmit antenna index and the transmit symbol estimation. The optimal detector has to apply a very complex operation to find amongst all the possible pairs of transmit antenna index and modulated symbol as a result the complexity of SM optimal detector rapidly increases with the increase in number of transmit antennas and modulation order. In order to reduce the receiver complexity the MS detector reduces the number of inputs to the detector by splitting the SM detection process into two stages. The MS detector uses the sub-optimal MRRC detector to estimate the most probable transmit antenna index in the first stage, therefore reducing the number of input set to the optimal ML SM detector in the second stage where the final estimation of antenna index and the transmit symbol are performed. The high performance of the SM optimal detector is maintained because the input to the optimal detector in the second stage are the most probable estimates of transmit antenna index and transmit symbols [25].

The concept presented in [17] is extended by the work proposed in [15] which tends to increase its SE by allowing more than one antenna to be active in every channel use and encoding data into various combinations of active transmit antennas instead of a single active transmit antenna. The data rates can be improved for the same number of transmit antenna at the cost of increasing the number of active RF chains. Results show that the proposed scheme known as generalized space shift keying (GSSK) out performs multiple antenna system such as V-BLAST by a gain of 1.5-3dB making it a most appealing candidate for future wireless communication systems.

The concept of SM-MIMO presented in [24] was extended to a novel scheme known as GSM by [36] in the similar fashion as the concept of SSK in [17] by [15]. In the proposed scheme a block of information bits is mapped into a constellation symbol and spatial symbols. The spatial symbols are the indices of combination of active transmit antennas because more than one antenna is active in every channel use. The constellation symbols and the spatial symbols are jointly detected at the receiver using the ML principle [15]. Unlike SM, where only one transmit antenna is active and has spatial spectral efficiency of base-two logarithm of number of transmit antenna the GSM has a spatial spectral gain of base-two logarithm of number of transmit antenna combination. GSM also overcomes the constraint in SM that the number of transmit antennas has to be a power of two [15]. Simulations results show that GSM performs nearly the same as SM with less number of transmit antennas for same SE. The number of transmit antennas is reduced for the same SE for the proposed scheme as compared to SM.

Another variant of SM-MIMO is presented to improve its spectral efficiency known as ESM by [12] in 2014. ESM is a SM based modulation scheme, where the number of active antenna is not fixed in an antenna combination. It is rather variable as compared to GSM-MIMO scheme where number of active antennas is fixed. Hence more spatial symbols are available in spatial constellation and more information bits could be spatially modulated so the data rate can be improved. As the number of active antenna could be various in ESM therefore how many antennas with the largest magnitude should be identified as the active antennas is unknown that is why a detection scheme similar to GSM could not be applied to ESM. A low complexity detection scheme consisting of threshold method and iterative validation is proposed for ESM in [12]. Analytical expression is derived for symbol error probability (SEP) in [12] along with the complexity analysis and numerical simulations are performed to validate the theoretical analysis for proposed detection scheme.

A new scheme proposed in 2014, where the SM MIMO was combined with AM was introduced by [3] to improve its spectral efficiency known as ASM MIMO. ASM MIMO optimizes the throughput by increasing the spectral efficiency with variations in a wireless channel. The basic idea behind AM is to adopt the symbol constellation size according to the fading conditions of the channel while maintaining a certain ABER. The simulation results are matched with the analytical results derived in this paper which shows a considerable spectral gain of the proposed technique to SM MIMO with the requirement of only a limited feedback from the receiver to the transmitter to change its constellation size for the next transmission if the received SNR is better.

In 2015 SM was proposed for large scale MIMO or massive MIMO by [2], where a subset of transmit antennas is active per channel use in order to make the transmission energy efficient without any requirement of channel state information at the transmitter (CSIT). Massive MIMO with SM achieves capacity comparable to open loop MIMO capacity because SM compensates the loss of information capacity due to activating a subset of antennas by appending some information in the active antenna index besides the original symbol transmission.

Chapter 3

Adaptive Generalized Spatial Modulation

3.1 System Model

The proposed AGSM MIMO model has N_t transmit and N_r receive antennas as shown in Fig. 3.1.

AM is used in AGSM to increase the QAM constellation size in better channel conditions to send more data. The first m_a=$\lfloor$ $log_2\binom{N_t}{N_a}$ $\rfloor$bits of the random incoming information bits $q(n)$ determine the antenna combination with N_a active antennas for transmission and are spatially modulated over the antennas in the combination. The transmitter transmits a symbol of order M-ary QAM (M-QAM) through the selected antennas, where $M = 2^n$ is the number of bits transmitted using the signal constellation and $n = \{0, 1, 2..., N\}$ is the rate adaptive modulation mode. The receiver feeds back the modulation mode n for next transmission to the transmitter based on the

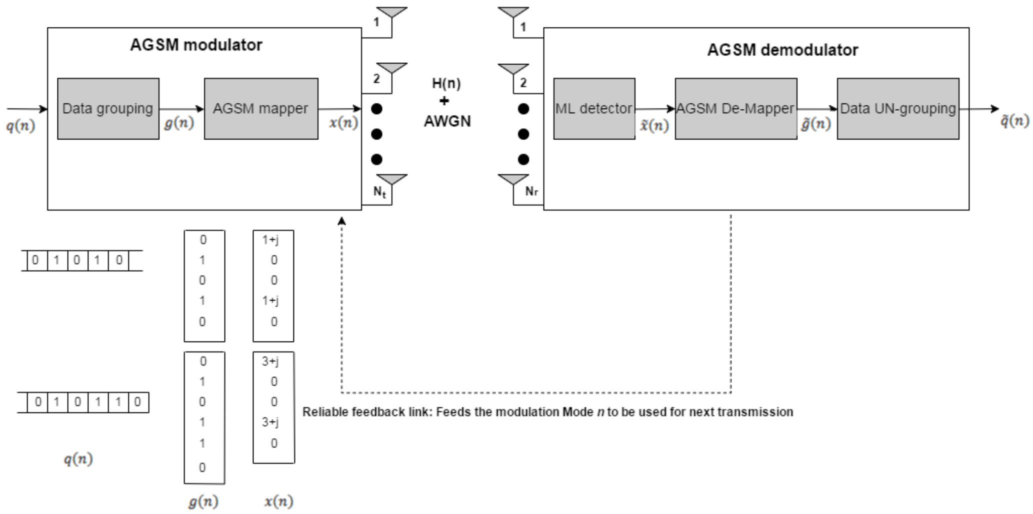

Figure 3.1: AGSM system model

received SNR threshold according to a pre-determined ABER level. The total number of bits transmitted by AGSM MIMO during a single transmission instance is given by

$$m = m_a + M = \lfloor log_2 \binom{N_t}{N_a} \rfloor + log_2 m_n, \tag{3.1}$$

for $n = \{1, 2, 3..., N\}$.

The incoming bits are grouped, then mapped into spatial symbol and QAM symbol as shown in Table. 3.1. The concept of mapping data can be further elaborated with the help of an example. Let $N_t = 5$ and $N_a = 2$ then $m_a = 3$ as shown in Table. 3.1. As shown in Fig. 3.1, the data to be transmitted in the first transmission $\mathbf{g}$ =[0 1 0 1 0]^T is mapped into $\mathbf{x}$ =[1+j 0 0 1+j 0]^T starting with 4-QAM where $n = 2$ as shown in Table. 3.1. The data is received at the receiver and the modulation mode n is fed back to the transmitter for next transmission. According to the example in Fig. 3.1,

Table 3.1: AGSM mapping table for $N_t = 5$, $N_a = 2$, $4-QAM$,$8-QAM$

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

$\mathbf{g}$ =[0 1 0 1 1 0]^T for the next transmission is mapped into $\mathbf{x}$ =[3+j 0 0 3+j 0]^T. The receiver has fed back modulation mode $n = 3$ because the value of received SNR is greater than the least value to maintain the pre-determined ABER at the receiver. The symbol constellation size has increased from 4-QAM to 8-QAM and this is how the AGSM improves the SE. It increases the modulation order when the channel gets better.

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

$$\mathbf{y} = \sqrt{\rho}\mathbf{h}_{\alpha}^{'}x + \mathbf{w}, \tag{3.2}$$

where ρ is the average SNR at transmit antennas, $x \,\epsilon$ M-QAM is the transmitted symbol by antenna combination $\alpha = (\alpha_1, \alpha_2, ..., \alpha_{N_a})$, α_k is the k-th antenna in the antenna combination used in a transmission instance among all the possible combinations of antennas. For example, $\alpha = (1, 4)$ for the transmission shown in Fig. 3.1. The channel vector $\mathbf{h}'_{\alpha}$=$\sum_{k=1}^{N_a} \mathbf{h}'_{\alpha_k}$, where $\mathbf{h}'_{\alpha_k}$ is the channel vector from active transmit antenna α_n to all the receive antennas, so $\mathbf{h}'_{\alpha}$ is the summation of active antennas channels vectors. For the first transmission given in Fig. 3.1, $\alpha = (1, 4)$, $\mathbf{h}'_{\alpha_1}$=$[h_{11} \quad h_{21}]^T$ and $\mathbf{h}'_{\alpha_4}$=$[h_{14} \quad h_{24}]$. Thus $\mathbf{h}'_{\alpha}$= $[h_{11} + h_{14} \quad h_{21} + h_{24}]$ is the sum of $\mathbf{h}'_{\alpha_1}$ and $\mathbf{h}'_{\alpha_4}$.

The receiver of GSM MIMO is based upon the ML principle proposed in [16] assuming that the perfect channel state information (CSI) is known at the receiver, which estimates the combination of active antenna and the transmitted M-QAM symbol as

$$\begin{aligned}
[\tilde{\alpha}, \tilde{x}] &= \underset{\alpha,x}{\operatorname{argmax}} p_y(\mathbf{y}|\mathbf{x}, \mathbf{H}) \\
&= \underset{\alpha,x}{\operatorname{argmin}} \sum_{i=1}^{N_r} |y_i - h'_{\alpha,i}x|^2, \qquad (3.3)
\end{aligned}$$

where $|y_i - h'_{\alpha,i}x|^2$ is the Euclidian distance between the received signal and actual constellation points. Similarly $p_y(\mathbf{y}|x, \alpha, \mathbf{H})$ is the probability density function (PDF) of received signal y conditioned over the transmit signal x, the antenna combination used α and the channel $\mathbf{H}$ given as

$$p_y(\mathbf{y}|x, \alpha, \mathbf{H}) = \frac{1}{(\pi\sigma_n^2)^{N_t}} exp(-\frac{\|\mathbf{y} - \mathbf{h}'_{\alpha}x\|_F^2}{\sigma_n^2}), \qquad (3.4)$$

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

3.1.1 Adaptive Transmission

The adaptive transmission system modeled for the proposed AGSM MIMO is constant-power variable-rate M-QAM. The SNR is divided into $N+1$ regions and nth region ($n =$ 0,1,....,N) is assigned a constellation size $M = 2^n$ in the proposed adaptive modulator. Modulation mode n is selected when the received SNR (γ) is above the switching threshold γ_n and below γ_{n+1}. The modulation mode n increments to $n+1$ in the next transmission if the received SNR falls between γ_{n+1} and γ_{n+2}. The adaptive modulator switching threshold SNR (γ_n) for modulation mode $n = \{0, 1, ..., N\}$ at a target BER (P_{b_0}) [1] can be calculated as

$$\gamma_n = -\frac{2}{3}\ln(5P_{b_0})(2^{n-1}), \tag{3.5}$$

where BER (P_{b_n}) for 2^n-QAM modulation for AWGN channel with γ is given as

$$P_{b_n}(\gamma) \simeq \frac{1}{5}exp\left(\frac{-3\gamma}{2(2^{n-1})}\right). \tag{3.6}$$

3.1.2 Performance Analysis

Received SNR

The statistics of received SNR (γ_r) gives a Chi-squared random variable (RV) with degree of freedom equal to ($2\times N_t\times N_r$) [28]. In proposed AGSM MIMO, only a combination with N_a number of active antenna is transmitting thus its γ_r is a Chi-squared RV with $2{\times}N_a{\times}N_r$ degrees of freedom having a PDF given as

$$f_{\gamma_r}(\gamma) = \frac{\gamma^{(N_a N_r)-1}}{[(N_a N_r)-1]!\rho^{(N_a N_r)}} e^{-\frac{\gamma}{\rho}}. \tag{3.7}$$

The cumulative distribution function (CDF) for γ_r can be derived from [28] as

$$F_{\gamma_r}(x) = 1 - e^{-\frac{\gamma}{\rho}} \sum_{k=0}^{(N_a N_r)-1} \frac{1}{k!}\left(\frac{\gamma}{\rho}\right)^k. \tag{3.8}$$

Average SE

The proposed AGSM MIMO has a throughput equal to the sum of throughputs obtained by the signal dimension $\eta_{AM} = log_2 m_n$ where $m_n = 2^n$ for a modulation mode n and the spatial dimension $\eta_c{=}log_2\lfloor\, log_2\binom{N_t}{N_a}\rfloor$. The total average SE, η_{avg}, is as follow

$$\begin{aligned} \eta_{avg} &= \eta_{AM} + \eta_c \\ &= log_2 m_n + log_2\lfloor log_2\binom{N_t}{N_a}\rfloor. \end{aligned} \tag{3.9}$$

The modulation order of M-QAM modulation changes with modulation mode n as the received SNR falls between γ_n and γ_{n+1}. Thus the average SE of signal dimension for proposed AGSM MIMO link is equal to the weighted sum of data rates of each $N+1$ threshold regions. These data rates are the weighted functions of the probability that a received SNR has a value in the *nth* threshold region [1], so the η_{AM} of proposed AGSM MIMO is given as

$$\eta_{AM} = \sum_{k=0}^{N} n p_n, \tag{3.10}$$

where p_n is the probability to transmit with *nth* modulation mode and is given as

$$\begin{aligned} p_n &= Pr[\gamma_n \leq \gamma_r < \gamma_{n+1}] \\ &= F_{\gamma_r}(\gamma_{n+1}) - F_{\gamma_r}(\gamma_n). \end{aligned} \tag{3.11}$$

The average SE of the signal dimension for AGSM MIMO is then given as

$$\eta_{AM} = N - \sum_{k=2}^{N} F_{\gamma_r}(\gamma_n). \tag{3.12}$$

Average BER

An asymptotic performance bound for M-QAM in AGSM MIMO is derived for i.i.d Rayleigh flat fading channel. An AGSM detector has to detect both: QAM constellation symbol and the active antennas indices. Following the approach as in [24], where estimation of antenna index and the transmit symbol are considered to be mutually independent processes, the assumption presents an ideal scenario where antennas indices are estimated given that the transmit symbol is estimated perfectly and the transmit symbol is estimated given that the antennas indices are perfectly estimated. It is an inconsistent approach in general because AGSM MIMO detector jointly detects the QAM symbol and indices of antenna combination. But it is shown in [24] that despite this ideal assumption of independent estimation processes, the lower bound given is very tight as

$$P_{be} \geq 1 - P_{corr} = P_a + P_x - P_a P_x, \tag{3.13}$$

where P_{be} denotes the average probability of bit error, $P_{corr} = (1-P_a)(1-P_x)$ is the probability of correctly detected bits, P_a is the probability of bit error due to antennas indices estimation for an active antenna combination when the transmit symbol is detected correctly and P_x is the probability of bit error due to symbol estimation when the antennas indices are perfectly estimated.

BER due to symbol estimation

The ABER of proposed AM system, P_x, when the channel is Rayleigh fading is given as in [1]

$$P_x = \frac{1}{\eta_{AM}} \sum_{n=2}^{N} n\bar{P}_{b_n}. \tag{3.14}$$

For a modulation mode $n = 1$, $\bar{P}_{b_n}$ is the ABER given as

$$\bar{P}_{b_n} = \int_0^{\gamma_2} P_{b_1}(x) f_{\gamma_s}(x) dx, \tag{3.15}$$

and for n is greater than one

$$\bar{P}_{b_n} = \int_{\gamma_k}^{\gamma_{n+1}} P_{b_n}(x) f_{\gamma_s}(x) dx, \tag{3.16}$$

where $f_{\gamma_s}(.)$ is given in Eq. (3.7).

BER due to antenna index estimation

By averaging all possible used modulations, the BER due to antenna index estimation can be determined as

$$P_x = \sum_{n=2}^{N} p_n P_{x|n}, \tag{3.17}$$

where p_n is the probability of using n modulation mode and $P_{a|n}$ is the error probability of antenna index detection for a given modulation mode n. With an optimal detector, we can obtain an asymptotic performance bound [3], [25] of $P_{a|n}$ as follow

$$P_{a|n} \leq \sum_{\alpha,s}^{1} N(x_{\alpha,s}, x_{\tilde{\alpha},\tilde{s}}) P(x_{\alpha,s} \rightarrow x_{\tilde{\alpha},\tilde{s}}), \tag{3.18}$$

where $P(x_{\alpha,s} \rightarrow x_{\tilde{\alpha},\tilde{s}})$ is pairwise probability of error (PEP) of detecting signal vector $x_{\hat{\alpha},\hat{s}}$ while $x_{\alpha,s}$ was transmitted [36], where $\hat{\alpha}$ is the estimated antenna combination and $\hat{s}$ is the estimated QAM symbol.

3.2 Results

This section illustrates performance analysis of proposed AGSM MIMO for different values of N_t, N_a and $P_{b_0} = 10^{-3}$. Analytical results derived in previous section for ABER and SE matched with the simulation results.

3.2.1 Average Bit Error Rates

The ABERs for proposed AGSM MIMO and GSM MIMO are shown in Fig. 3.2, which is a function of ρ(dBs) for $N_t = 5$, $N_r = 2$ and $N_a = 2$. Fig. 3.2 depicts that for the same number of transmit and receive antennas, the ABER curve of AGSM MIMO is similar to that of GSM MIMO for 4-QAM in low SNR ranges (i.e., $0 < \rho \leq 17$dB). Then there is a gradual variation in ABER slope of the proposed AGSM MIMO. This variation in the ABER

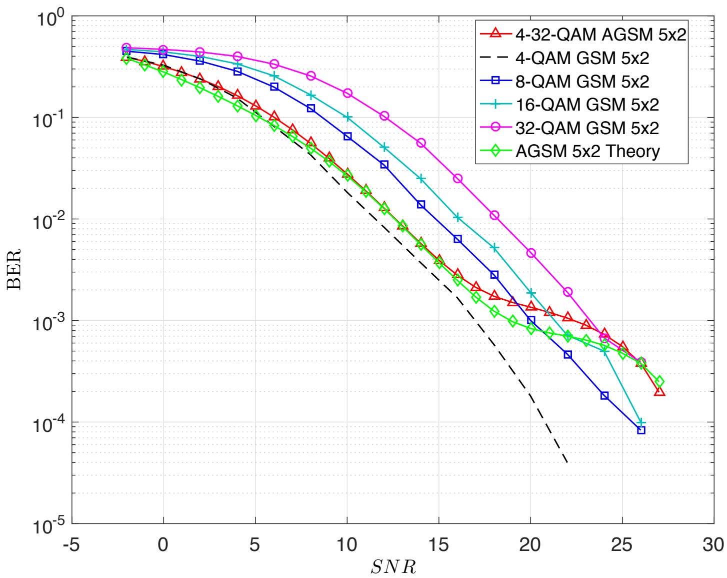

Figure 3.2: ABER for the AGSM and GSM MIMO schemes versus ρ(dB)

curve is due to increase in the modulation mode n at higher SNR values while the modulation mode of GSM MIMO is not adaptive to channel conditions. Due to adaptive modulation, the modulation order increases from 4-QAM to 8-QAM and so on to 32-QAM. The ABER of proposed AGSM MIMO finally converges to the same performance as GSM MIMO for 32-QAM at high SNR values. Thus it is clear from Fig. 3.2 that the ABER of the GSM MIMO for the lowest and highest modulation mode n bounds the ABER performance of proposed AGSM MIMO.

The ABER for 5x2 AGSM MIMO and 5x3 AGSM MIMO with $N_a = 2$ is shown as a function of ρ(dBs) in Fig. 3.3. It shows that the number of receive antennas determines the diversity of the system. The ABER of 5x3 AGSM MIMO is better than 5x2 AGSM MIMO, which shows the receiver diversity of proposed AGSM MIMO. Fig. 3.3 also shows the ABER of proposed AGSM

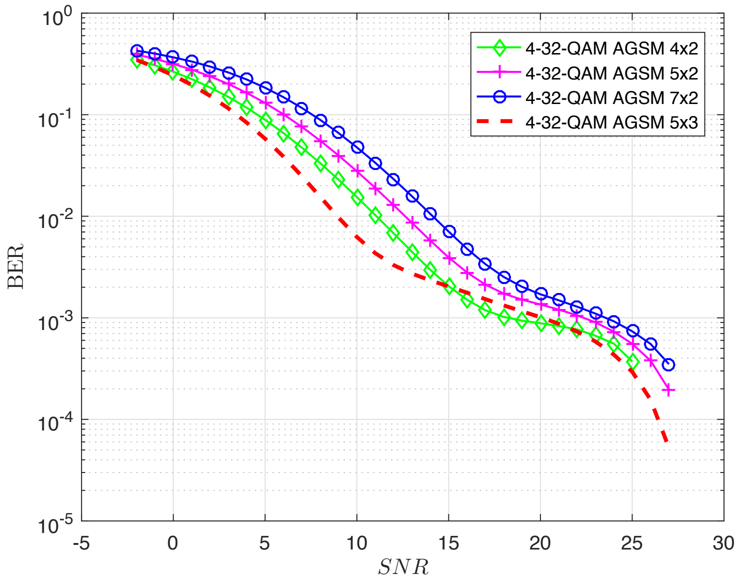

Figure 3.3: ABER for the AGSM MIMO scheme versus ρ(dB) for different values of N_t and N_r

MIMO for different number of transmit antenna with $N_a = 2$ as a function of ρ(dBs). It can be verified from the figure that the diversity of the system does not depend on the number of transmit antennas because the ABER of 4x2 AGSM MIMO is better than ABER of 5x2 and 7x2 AGSM MIMO. Higher number of transmit antennas increases the SE of the system but it also degrades the ABER of proposed AGSM MIMO. The error probability performance degrades because higher number of N_t means the constellation points of proposed scheme becomes less separated which is a function of $\mathbf{H}$. Also greater number of transmit antennas means greater number of spatially modulated bits m_a, which implies higher the bit error rate when an incorrect antenna combination is detected.

Fig. 3.4 shows the ABER comparison of proposed scheme and ASM MIMO in [3]. It shows that ABER of AGSM MIMO with $N_t = 5$ and

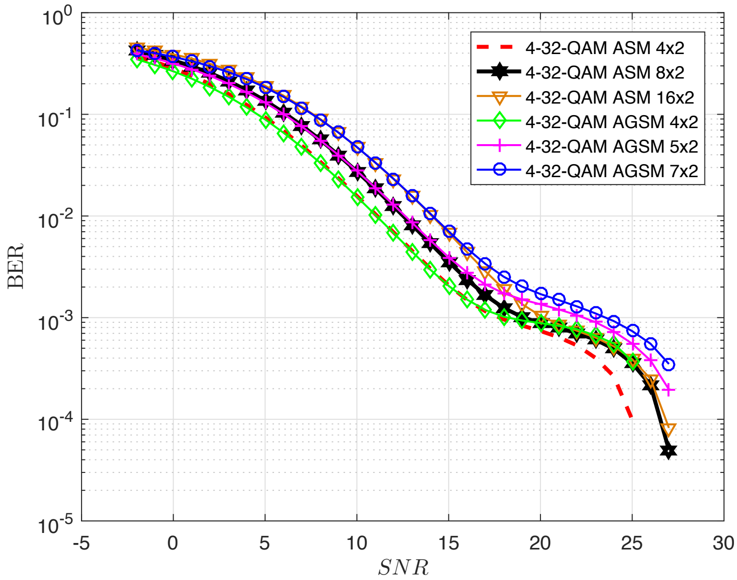

Figure 3.4: ABER for the AGSM and ASM MIMO schemes versus ρ(dB) for different values of N_t

$N_t = 7$ is almost the same as that of ASM MIMO with $N_t = 8$ and $N_t = 16$, respectively. Thus the proposed scheme can achieve same ABER as ASM MIMO with less number of transmit antennas.

3.2.2 Average Spectral Efficiency

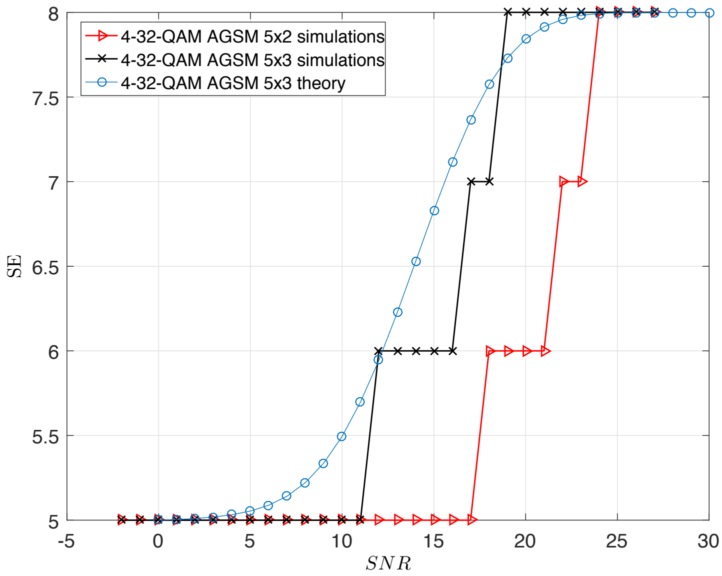

Figure 3.5: Average SE of AGSM MIMO scheme for different values of N_r

Fig. 3.5 shows the average spectral efficiency (i.e., $\eta_{AM}+\eta_c$) for two different numbers of receive antennas N_r (i.e., 2 and 3) as a function of SNR per antenna ρ(dBs). It is clear from the figure that the average spectral efficiency of AGSM MIMO is higher with $N_r = 3$ than with $N_r = 2$ at any value of SNR. For example, average spectral efficiency of AGSM MIMO is 8 bits per channel use (bpcu) with $N_r = 2$ and 6 bpcu with $N_r = 2$ at 20(dB). Thus the proposed AGSM MIMO achieves greater SE with higher number of receive antennas. This figure also shows that the simulation results match the analytical results for the proposed scheme. The total spectral efficiency is a function of transmit antennas N_t (i.e., η_c=$\lfloor\, log_2\binom{N_t}{N_a}\,\rfloor$).

Fig. 3.6 shows that the proposed AGSM MIMO can achieve high data rates for high SNR values as compared to conventional GSM MIMO which

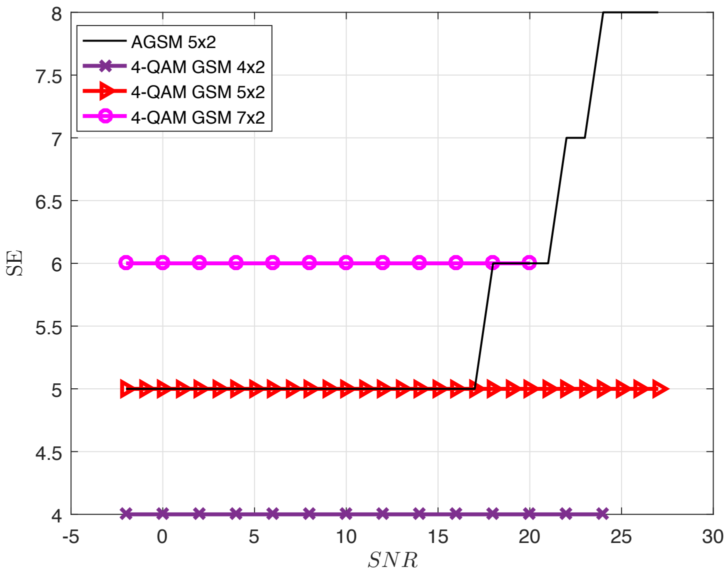

Figure 3.6: Average SE of AGSM and GSM MIMO scheme for different values of N_t

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

The SE of ASM MIMO and AGSM MIMO is shown in Fig. 3.7. AGSM MIMO achieves same SE with $N_t = 5$ and $N_a = 2$ as the ASM MIMO with $N_t = 8$ for $0 < \rho \leq 16$dB, $17 < \rho \leq 19$dB and $24 < \rho \leq 27$dB (i.e., 5 bpcu, 6 bpcu and 8 bpcu) respectively and 1 bpcu less than ASM MIMO for $16 < \rho \leq 17$dB and $17 < \rho \leq 19$dB. While AGSM MIMO with $N_t = 7$ and $N_a = 2$ outperforms ASM MIMO with $N_t = 8$ as shown in Fig. 3.7, which

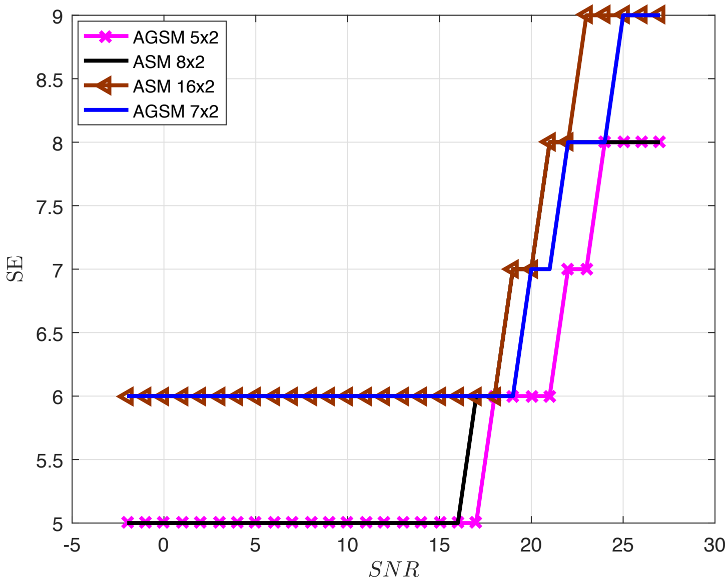

Figure 3.7: Average SE of AGSM and ASM MIMO scheme for different values of N_t

implies that AGSM MIMO can achieve even greater spectral efficiency than ASM MIMO with lesser number of antennas. Thus the proposed scheme outperforms previously proposed schemes, (i.e., GSM MIMO and ASM MIMO). Due to this increase in spectral efficiency and low overall complexity, the proposed AGSM MIMO has a high potential to be an attractive scheme for higher data rate and energy efficient wireless systems.

Chapter 4

Conclusions and Future Work

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

We suggest some possible directions for the future work of this thesis as following

- To evaluate the proposed scheme in terms of BER and SE for partial CSI instead of perfect CSI known to the receiver.

- Extending the proposed AM for SM MIMO to the ESM MIMO.

- To evaluate the proposed scheme in terms of BER and SE for a channel other than Rayleigh flat fading such as Rician fading channel.

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