Block Coded Modulation for Enhancing the BER Performance of MIMO Systems

DECLARATION

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Block Coded Modulation for Enhancing the BER Performance of MIMO Systems

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering
نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث محمد كامل صبري أبو فؤود ليل درجة الماجستير في كلية الهندسة قسم الهندسة الكهربائية - أنظمة الاتصالات وموضوعها:

Block Coded Modulation for Enhancing the BER Performance of MIMO Systems

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أ.د. فؤاد علي العاجز
DEDICATIONS

Kamel

He lived sowing good deeds where ever he went….

His implant matured into stars that followed his footsteps….

To that soul that left us ,, that still resides in every breath I take ,, I feel he is around me ,, I swear to him that I am keeping my pledge to keep doing good.

To my father, may Allah bless his soul

To the beacon of kindness, to who was able to be patient and her tongue always prays for me to promote in position and succeed in life.

To my precious mother

To the hearts that made my life meaningful that deserves living for

To my dear sisters

To my soul mate, friend and companion

To my precious brother; Dr Omar

To Muneer who was be a reflection of his name “lighting”

And to everyone who knows me

I dedicate this work
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First and foremost, my thanks are wholly devoted to ALLAH for blessings and for guiding me all the way to finish this work successfully.

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Mohammed Kamel AbuFoul
November, 2014
ABSTRACT

Block Coded Modulation for Enhancing the BER Performance of MIMO systems

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The next-generation wireless systems are required to have good techniques to ensure high throughput, good interference suppression, several different diversity modes and increasing spectral efficiency for a given total transmit power. In order to investigate all of these requirements, multiple-input-multiple-output (MIMO) technique in addition of using channel coding have been investigated and implemented. Most of the existing researches are combining the MIMO system with Trellis coded modulation (TCM) to have good performance of probability of bit error. TCM achieves high coding gain by integrating coding and modulation but needs a complex decoding algorithm. In contrast, block coded modulation (BCM) performs an accepted work compared to TCM but easier in construction and can be decoded simply by using multi-stage decoding algorithm.

To overcome the constraints in STC, this thesis uses Spatial Modulation (SM) as a transmission technique for increasing the capacity of the system with a low receiver complexity and single radio frequency for transmission to eliminate the Inter-Antenna synchronization (IAS).
For these reasons, designing a new low decoding complexity block coded spatial modulation is considered. To achieve this goal, the ideas of MIMO communication systems, block coded modulation, set partitioning, multi stage decoding and spatial modulation are combined. Spatial modulation is used for higher spectral efficiency than space time coding and lower decoding complexity compared to Multiplexing MIMO. BCM is used to enhance the BER performance as a compensation for no transmit diversity gain associated with SM. Matrix Laboratory (MATLAB) is used for the simulation and Bit Error Rate (BER) is obtained and verified.

The simulation results for the combination of BCM with SM show significant improvement in BER performance compared to the classical SM techniques. It gives an approximately 6 dB enhancing of BER performance over using SM only, and about 3 dB enhancing over coded information bits with SM.
Using Block Coded Modulation for Enhancing the performance of MIMO systems

الملخص

التعديل الرمزي الكتلي لتحسين معامل نسبة الخطأ في أنظمة الاتصالات متعددة المداخل والخارج

إعداد: محمد كامل أبوغول

باشر: د. محمد رمضان

يدخل الجيل القادم من الاتصالات اللاسلكية إلى تقنيات ذات كفاءة عالية وقادرة على مواجهة المؤثرات الخارجية، ولديها القدرة على العمل في بيئات مختلفة ومتنوعة وذلك لزيادة كفاءة الطيف التردد، مع ثبات الطاقة المنبعثة من المرسل. لضمان الحصول على جميع ما سيق، أصبح بالإمكان استخدام أنظمة الاتصالات متعددة المداخل والمخرج (MIMO) مضافًا إليها بعض أنواع الترميز.

إن أغلب الأبحاث العلمية الحالية في مجال الاتصالات اللاسلكية تهدف وبشكل أساسي إلى الجمع بين أنظمة الاتصالات متعددة المداخل والمخرج وبين التعديل الرمزي التشغيلي (TCM) للحصول على أداء جيد

لكن، ومع كل الميزات التي يعطيها التعديل الرمزي التشغيلي والتي من ضمنها الحصول على كسب عالي (High coding gain)، إلا أنه يحتاج إلى عمليات متعددة في فك الترميز (Decoding) في المستقبل. في المقابل، فإن التعديل الرمزي الكتلي (BCM) يعطي ويشكل تقريب نفس المزايا التي يمكن أن يعطيها التعديل الرمزي التشغيلي وذلك باستخدام بعض التقنيات التي تعتمد على الحصول على نتائج جيدة وبطريقة أسهل من TCM باستخدام الترميز متعدد المستويات (Multi-level coding)، وفك الترميز متعدد المراحل (stagedecoding).
Using Block Coded Modulation for Enhancing the performance of MIMO systems

Spatial Modulation (SM) is one of the modern topics that is currently attracting the attention of researchers and engineers in the field of wireless communications. The current trend is using SM to improve the performance of wireless communication systems by increasing the system capacity and reducing the complexity in the reception process. Therefore, this research aims to develop a low-complexity design and decoding system, and it gives a significant improvement in the error rate in wireless communication systems called Block Coded Spatial Modulation (BCM), which relies on the use of multiple input and output systems, multi-level modulation, and multi-stage decoding.

MATLAB has been used to perform the necessary simulations and obtain the expected results for improving the error rate. The results obtained indicate that using BCM with SM can achieve a significant improvement in the error rate compared to using SM alone, with an improvement of up to 6 dB compared to the results obtained when using SM alone. Using multi-level modulation and SM can also achieve an improvement of up to 3 dB.
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<td>Additive White Gaussian Noise</td>
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<td>BC</td>
<td>Block Codes</td>
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<td>BCM</td>
<td>Block Coded Modulation</td>
</tr>
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<td>BER</td>
<td>Bit Error Rate</td>
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<td>BCSM</td>
<td>Block Coded Spatial Modulation</td>
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<td>CSIT</td>
<td>Channel State Information at the Transmitter</td>
</tr>
<tr>
<td>CSIR</td>
<td>Channel State Information at the Receiver</td>
</tr>
<tr>
<td>IAS</td>
<td>Inter Antenna Synchronization</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter–Channel Interference</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
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<td>MIMO</td>
<td>Multi-Input Multi-Output</td>
</tr>
<tr>
<td>ML</td>
<td>Maximum Likelihood</td>
</tr>
<tr>
<td>MRC</td>
<td>Maximal Ratio Combining</td>
</tr>
<tr>
<td>MSE</td>
<td>Minimum Squared Euclidean Distance</td>
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<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing</td>
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<td>PSK</td>
<td>Phase Shift Keying</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>SDM</td>
<td>Spatial Division Multiplexing</td>
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<td>SISO</td>
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<td>STTC</td>
<td>Space-Time Trills Codes</td>
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<tr>
<td>TA</td>
<td>Transmit Antenna</td>
</tr>
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<td>TAS</td>
<td>Transmit Antenna Selection</td>
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<td>TC</td>
<td>Trills Codes</td>
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<td>TCM</td>
<td>Trills Coded Modulation</td>
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<td>4G</td>
<td>Fourth Generation of the Mobile Communication</td>
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Chapter 1

Introduction

1.1 Introduction

Radios, televisions, computer terminals, cellular systems, access points, satellites, accessing internet, and etc. are different applications of the use of communications which dominate our daily lives today [1]. Two different types of communication systems are available; the first one is the wire communication such as telephone, LANs and fibers which need a cable to communicate between transmitter and receiver. The other one is the wireless communications which are the main scope of researches nowadays.
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Wireless communications are the fastest growing segment of the communication applications. They enter all parts of our days, and have the attention of the researchers and the industry. Indeed, wireless systems have become a critical business tool and part of everyday life like cellular and wireless networks which replace wired networks in many homes, businesses, and campuses [2].

Although there is growing use of wireless systems, there are many challenges in designing robust wireless networks that deliver the performance necessary such as increasing data rate, and minimizing the error probability. This thesis aims to enhance the BER performance of the MIMO system by using Block Coded Modulation (BCM). Thus, BCM when using it as a coding technique with the presence of MIMO system is studied. Spatial Modulation (SM) as a transmission technique using in the recent years is studied and simulated. The simulation in this thesis is started with the comparison between SM and SISO systems, and between SM and STBC. The simulation is continued by comparing the use of one and two receive antennas in SM systems. All results obtained in this thesis show that SM increases the capacity of the system with the use of simple receiver demodulation complexity. The use of BCM constructed by set partitioning with SM shows that the BER performance is enhanced. Simulation results are introduced in chapter 4.

This chapter shows some background concepts that are used in this thesis such as AWGN, channel propagation and the importance of using channel coding. The motivations of choosing the thesis topics are then introduced and the reasons behind choosing study BCM with the presence of SM and MIMO systems are illustrated. Moreover, this chapter shows some literature review, and illustrates the problem statement. At the end, the contribution and organization of this thesis are presented.
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1.2 Wireless communications

The main goal of any wireless communication system (figure 1.1) is to receive the transmitted information in a suitable method and in less BER especially in the modern wireless applications.

Three basic issues should be studied and to be into consideration when designing and analyzing any wireless systems. One of them is the noise added to the transmitted signal (AWGN), and the second one is the channel characteristics, and finally the suitable channel code to be used in order to utilize the bandwidth efficiently.

1.2.1 Additive White Gaussian Noise (AWGN)

To mimic the effect of many random processes that occur in any wireless system, the AWGN is a basic noise model used. The AWGN name denotes that it is added to the transmitted information, and has the idea that it has uniform power across the frequency band for the information system, and has a normal distribution in the time domain with an average time domain value of zero.
Figure 1.2 shows that the AWGN is one of the effects that the transmitted information $x(t)$ faced, the resulting received information $y(t)$ will be as in equation 1.1:

$$y(t) = x(t) + n(t) \ldots \ldots \ldots \ldots 1.1$$

This noise comes from many natural sources, such as the thermal noise in conductors, the natural factors such as the weather and the sun. AWGN is often used as a channel model in which the only factors affects the transmitted information is a linear addition of white noise with a constant spectral density and a Gaussian distribution of amplitude. But, in wireless communications, the transmitted information is usually affected by other phenomena like fading, frequency selectivity, interference, nonlinearity and/or dispersion which will be discussed in the next section.
1.2.2 Channel characteristics:

In modern communication systems, which are usually high-speed wireless communication systems, the channel plays the main rule in the system. Transmitted information is not only susceptible to noise, but it is also susceptible to channel characteristics which are the variation in received signal power over distance due to path loss, shadowing and multipath. These factors restrict the range, data rate, and the reliability of the wireless transmission.

Path loss and shadowing classified as a large-scale propagation effects. Path loss is caused by dissipation of the power radiated by the transmitter and expressed as the ratio of the power of the transmitted signal to the power of the same signal received by the receiver on a given path. Shadowing is caused by obstacles between the transmitter and receiver that attenuate signal power through absorption, reflection, scattering, and diffraction. When the attenuation is very strong, the signal is blocked. The effect of large-scale propagation is proportional to the distance; it means that the attenuation increases exponentially as the signal propagates from the transmitter to the receiver for hundreds of meters.

Variation over very short distances is called small-scale propagation effects, and it is due to multipath that the transmitted information faces and Doppler frequency effect due to moving objects. Multipath is caused by various signal components come from reflections. These replicas can be received in phase which leads to strong reception or out of phase which leads to a weak signal.

Figure 1.3 illustrates the ratio of the received-to-transmit power in dB versus log-distance for the combined effects of path loss, shadowing, and multipath.
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Two ways of classifying the multipath are used, one of them is according to its effect over the time (Slow and Fast Fading) and the other one is over the frequency (Frequency-Flat and Frequency Selective Fading).

When dealing with time, the channel coherence time $T_c$ of the channel is a measure of the period of time over which the fading process has the same effect. If the transmitted symbol time duration $T_s$ is smaller than $T_c$, the fading is called slow, otherwise it is fast. Slow fading means that each one symbol time or more have the same multipath channel effect whereas fast fading means that one symbol will have different effect over the time.

On the other hand, when dealing with Doppler frequency, the channel coherence bandwidth $B_c$ is the measure. Frequency-flat fading occurs when the transmitted signal bandwidth $B_s$ is smaller than $B_c$, otherwise it is frequency-selective channel.

1.2.3 Channel coding:

In previous sections, it has been illustrated that the transmitted information is affected by the channel characteristics and noise, so that, the communication systems should have techniques to minimize data corruption caused during transmission which are called error-correcting codes.
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Modern communication systems depend on transmit and receive massive amount of data reliably and without error. The advantage of these systems is that high data rates can be reliably transmitted while keeping the transmitted power and spectral bandwidth small. This advantage needs algebraic codes in the transmitter and needs sophisticated computations in the receiver. The modern communication system must transmit its data with very high reliability in the presence of these channel effects.

Another advantage of using channel codes is that the channel codes provide an excellent tool to reduce the required power because in many communication systems there are limitations on transmitted power because it may be very expensive in communication, for example in satellite communication. So with the aid of the code, the messages received weakly at their destinations can be recovered correctly.

Block codes and Trellis codes are the two basic classes of codes which are illustrated in figure 1.4. A trellis code is more complicated than a Block code. It takes a non-ending sequence of data symbols arranged in $k$-symbol segments and puts out a continuous sequence of code symbols arranged in $n$-symbol segments. The distinction with block codes is that in a trellis code, $k$-symbol segments can affect all succeeding codewords, whereas in a block code, a $k$-symbol data block determines only the next $n$-symbol codeblock, but no others [4].

A block code represents a block of $k$-data symbols by an $n$-symbol codeword. The rate $R$ of a block code is defined as $R = k/n$. There are many different types of block codes, as an example: Hamming codes, parity check codes, repetition codes and Reed-Muller code [14].
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Figure 1.4: Two types of channel coding [4].

As mentioned above, the trellis code is a complex code and needs a complex computations in the receiver, so that, our scope in this thesis is how to use block codes with simple decoding algorithm with the presence of symbol modulation and SM as studied in next chapters.

1.3 Motivation

In the last decade, the increase of the demand on wireless applications with good performance and suitable data rate is appeared on the surface. Most of researches interested in transmission rate and/or bit error rate which are considered the most important issues in the modern communication systems. Because of that, significant increasing of transmission rate or a minimization of bit error rate can be achieved by using MIMO digital transmission system which is shown in figure 1.5. MIMO systems are currently retaining more and more attention due to the very high spectral efficiencies they can achieve [5] and constitutes a breakthrough in the design of modern wireless communication systems like 4G Mobile communication. They deliver significant
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performance enhancements in terms of data transmission rate and reliability with respect to conventional single-antenna wireless systems [6].

![MIMO wireless system](image_url)

Figure 1.5: MIMO wireless system [7].

In order to utilize the benefits of MIMO technologies, channel coding is used to improve the transmission reliably and spectral efficiency. Two kinds of channel coding have been available; one of them is convolutional (Trellis) codes (TC) and the other one is block codes (BC). In TC, a trellis code is transmitted over time via the source, but BC act on a block of data at once like a block coding and then transmit over time. BC has proved to be a very effective technique to achieve a transmit diversity, mainly due to its low decoding complexity compared to TC [8]. For this reason, we will focus on BC on this research.

Also, in order to let BC has a suitable coding gain, block coded modulation (BCM) technique will be used which it is a combination of block coding and channel signal sets to construct bandwidth-efficient codes [9]. A lot of researches have been done to increase coding gain using BCM but with SISO systems. Because of that; the main focus of this thesis will be on designing an efficient BCM codes for MIMO systems with presence of SM with low decoding complexity.
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1.4 Statement of the problem

Most of research that design MIMO systems depends on using Space-Time Codes (STC) as a transmission technique. This technique suffers from IAS which causes some errors in detection. In addition, MIMO needs more than one RF to transmit symbols that means more frequencies used. Because of that, this thesis presents a new approach for enhancing the performance of MIMO systems depending on the principle of multi-level coding and multi-stage decoding algorithms which are used in BCM construction in SISO systems in an accepted manner. In order to let this concept available in MIMO systems, SM is used.

1.5 Literature review

- Mohammad Janani and Aria Nosratinia (2009), [11], proposed an space-time codes that are derived by pruning codewords from an expanded set of orthogonal space-time codewords by the selection of codewords from the expanded signal set. The resulting codes have attractive coding gains with simple decoding algorithm but with large amount of pruning symbols from the expanding code.

- Ertugrul Basar, Umit Aygolu and Erdal Panayirci (2011), [12], proposed technique for designing MIMO transmission scheme, called trellis coded spatial modulation (TC-SM) in which a trellis encoder and a SM mapper are jointly designed similar to the conventional trellis coded modulation (TCM). This technique still used TCM which means difficult decoding complexity.
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- Ertugrul Basar, Umit Aygolu, Erdal Panayirci and Vincent Poor (2011), [13], proposed space-time block coded spatial modulation (STBC-SM) which is a combination between SM and STBC in MIMO transmission.

1.6 Thesis contribution

The main contributions of this thesis can be summarized as follows:

- Having a good performance of BCM with simple decoding algorithm when applying it to the MIMO systems with the use of spatial modulation.
- Brief study of spatial modulation which is considered as a hot topic in researches nowadays. This means, this thesis may be considered as a good reference for whom want to study SM and its uses.

1.7 Thesis organization

In this thesis, a brief study of Block coded modulation design for spatial modulation using in MIMO systems (BCSM) is introduced. Therefore, BCM builds using multi stage encodes and multi-level decode, Block codes, MIMO systems, and Spatial Modulation are the main pillars of this thesis, and they will be explained in the following three chapters:

- Chapter 2: gives a theoretical background of block codes and BCM, and how to construct the multi stage encoder and multi-level decoder to enhance the BER performance of a wireless communication. MIMO systems in brief discussion are explained. Diversity types specially space diversity are explained in the last section of this chapter.
- Chapter 3: introduces the concept of SM which is recently developed as a transmission technique that uses multiple antennas. The basic idea is to map a block of information bits to two information carrying units; one of them a symbol that was chosen from a
Chapter 1: Introduction

constellation diagram and the other one a unique transmit antenna number that was chosen from a set of transmit antennas.

- **Chapter 4**: represents the Block Coded Modulation application for Spatial Modulation (BCSM) MIMO systems. The effects on BER performance of using this approach are derived from simulations and analyzed.

- **Chapter 5**: the conclusion of this thesis is proposed, and some suggestions for future work are also presented.
Chapter 2
Block Coded Modulation and MIMO Systems

2.1 Introduction

The increasing demand for efficient and reliable digital data has appeared in the last few years. This demand needs a high speed data rate to fulfill the needs of users who exchange, process, and deal with digital information in different fields. [1]. According to this, the major task of the communication designers is the control of errors so that the data can be reliably reproduced. To obtain this goal, reliability and quality of the transmission system should be in the considerations of the communication designer.
Chapter 2: Block coded modulation and MIMO systems

Logically, communication designer concerns in the design of wireless communication systems can be classified into two important parameters which are: the transmitted signal power and channel bandwidth [1]. The importance of these two parameters is that to determine the signal to noise ratio $E_b/N_0$. This ratio in general determines the bit error rate for a particular modulation scheme under certain channel conditions. However if the signal power is limited to a certain value, the modulation scheme may provide unacceptable performance. The solution of this problem is using controlled channel coding.

Encoding of the transmitted information reduce the error rate without sacrificing the rate of the information as long as the information rate is less than the capacity of the channel as Shannon theorem stated. In the last years, and with recent developments in wireless communications which need high data rate and speed digital systems, many contributions in channel coding toward achieving the desired data rate have been produced. Moreover, the use of channel coding has become an integral part in the design of modern wireless communications.

![Figure 2.1: Block diagram of the coded system.](image)
Chapter 2: Block coded modulation and MIMO systems

As shown in figure 2.1, any coded wireless communication system has two main coding process. One of them is in the transmitter side called channel encoder which transforms the information sequence $u$ into a discrete encoded sequence $v$ called a code-word. The other one is in the receiver side called channel decoder which transforms the received sequence $r$ into a binary sequence $\hat{u}$ called the estimated information sequence.

Ideally, $\hat{u}$ will be the same as the information sequence $u$, but practically, the noise and channel characteristics may cause some decoding errors. Because of that, the decoding strategy is based on the rules of channel encoding and the noise characteristics of the channel that leads to design and implement the channel decoders in order to minimize the probability of decoding error. Designing the channel encoder/decoder pair has some constraints like [1]:

1) The information can be transmitted in a noisy environment as fast as possible.
2) The information can be received in free errors as possible.
3) The cost of implementing the encoder and decoder falls within acceptable limits.

As mentioned in chapter 1, there are two types of channel coding which are block codes and trilles codes or convolutional codes, that means absence or presence of memory in the encoders, respectively [1].

Another method introduced in this chapter to increase the data rate without additional bandwidth or increasing transmit power is the MIMO technology. MIMO systems have attracted attention in modern wireless communication systems. MIMO technology works in spreading the same total transmit power over the antennas to improve the spectral efficiency and/or to achieve a diversity gain that improves the link reliability.
Chapter 2: Block coded modulation and MIMO systems

2.2 Block codes

In general, most of research and studies assume that the input and the output of the communication system are a sequence of binary digits "0" or "1". In block coding system shown in figure 2.2, the binary information sequence is segmented into the input sequence of fixed length called “message blocks”; each message block, denoted by $u$, consists of $k$ information bits [1].

At the input of the encoder, there are a total of $2^k$ distinct messages, where according to certain rules, the encoder transforms each input message $u$ into a binary $n$ sequence denoted by $v$ and called “code word or code vector” of the message $u$. The relation between $n$ and $k$ is that $n$ must be greater than $k$ ($n > k$). Because of all $2^k$ possible messages have corresponding $2^k$ code word, the accumulation of all code words construct the block code, and the $2^k$ code words must be distinct in order to let a block code useful to be used.

![Block coding diagram](image)

Figure 2.2: Block coding diagram.

Most known block codes that are widely used and have good performance are called linear codes [4]. This class of codes is defined by imposing a strong structural property on the codes and also helps to make the encoders and decoders practical. A code is said to be linear if the addition of any two code-words produce a valid code-word in the code.
Chapter 2: Block coded modulation and MIMO systems

In order to construct a linear block code, consider an \((n,k)\) linear block code, in which \(k\) bits of the \(n\) code bits are always identical to the message bits to be transmitted and the \(n-k\) bits in the remaining \(n\) bits are computed from the mathematical structure of the code and called generalized parity check bits or simply parity bits.

Figure 2.3 shows that the \(n\) code bits in any systematic linear block codes can be constructed by letting the parity bits in usual in the right-most bits of a code word, and the message bits in left-most bits of the code word. Note that in some notations, the order of bits is not restricted as said, that means; parity bits and message bits can be changed their positions in \(n\).

![Systematic code-word sequence.](image)

Some concepts in block codes should always be taken into consideration. One of them is the rate \(R\) of the code, and it is defined as the ratio between the message length \(k\) and the block length \(n\):

\[
R = \frac{k}{n} \quad \text{........................................2.1}
\]

The rate of a code measures the transmission speed, that is a large rate means that the message per transmitted block is high, and the quantity \(1-R\) measures the overhead during the encoding process. Note that, in usual, the rate of a block codes can not exceed 1.
Chapter 2: Block coded modulation and MIMO systems

The another concept is the distance or the minimum distance $d$, which indicate the minimum number of positions in which any two distinct codewords differ, and the fraction between $d$ and $n$ denoted by $\delta$ is the relative between number of different bits between two code words in the code.

Consider that we have two different code words $c_1$ and $c_2$, and let $\Delta(c_1,c_2)$ denote the number of positions in which $c_1$ and $c_2$ differ. Then the minimum distance $d$ of the code $C$ is defined as:

$$d = \min_{c_i, c_j \in C; i \neq j} \Delta(c_i, c_j) \quad \text{for all pair of } i \text{ and } j \quad \text{...............2.2}$$

Note that, in linear block codes, any two codewords will differ from each other in at least one position, so the distance of any code is at least 1. If $d$ increases, this allows for more errors correction and detection. A code with distance $d$ allows the receiver to detect up to $d-1$ errors and corrects $(d-1)/2$ of the detected errors. If more than $(d-1)/2$ transmission errors occur, the receiver cannot uniquely decode the received word in general as there might be several possible codewords. In this case, the designer must use list-decoding in the reciever, in which the decoder outputs a list of all codewords in a certain radius [14]. The weight $wt(c_i)$ of a vector $c_i \in C$ is the number of nonzero bits in $c_i$, and the minimum distance $d$ is the same as the minimum weight of the nonzero codewords of $C$ if $C$ is a linear code.

Most popular coding books used the notation $(n,k,d)_q$ to identify the block code under the consideration of block length $n$, message length $k$, and distance $d$, and $q$ which refers to the field that the code use. In genarl, for binary codes, the index $q$ is dropped and sometimes $d$ is also dropped. In order to find the minimum distance $d$ from $n$ and $k$, $d$ is always equal to $d = n - k + 1$. 
Chapter 2: Block coded modulation and MIMO systems

As mentioned before, block codes are widly used in wireless communication systems because they give a simple coding and decoding algorithms, and have a theorists and mathematical model to construct. Becouse of that, block codes comprise the large and important family of error-correcting codes that encode data in blocks. All parameters that discussed before are taken into consideration espacially the rate of the code and its ability to detect and correct errors.

Some examples of block codes are Hamming codes, parity check codes, repetition codes, Hadamard codes, and Reed–Muller codes [14]. Some of these codes are discussed in next subsections.

2.2.1 Parity check codes

Parity check codes are an elementary linear block code. It is considerd as a high rate code with poor error performance and used as the simplest form of only error detecting code [4]. It dependes on the parity bit which it is a bit added to the end of the information bits to build the code word. This parity bit indicates whether the number of ones in the information bits are even or odd. In other words, there are two types of parity bits, even parity and odd parity [17].

If there are \( k \) information bits, then \( n \) has \( k + 1 \) bits so that the total number of ones in each codeword is even for even parity check codes or odd for odd parity check codes. This code is a \((k + 1, k)\) or an \((n, n - 1)\) code, its minimum distance is 2, no errors can be corrected, and its used for just detecting one error occurred during transmission.
Chapter 2: Block coded modulation and MIMO systems

2.2.2 Repetition codes

An \((n, 1)\) code with minimum distance \(n\), and \(\frac{1}{2} (n - 1)\) errors can be corrected [4] by using Majority logic detection. In contrast of parity check codes, the repetition code is a low rate code with good error performance and it is considered as one of the basic error correcting codes [4]. The chief attraction of the repetition code is the ease of implementation because of the constructing idea depends on repeating the information bits \(n\) times in order to construct the code word in which \(n\) is usually odd. There is only two codewords as an example if \(n\) equals 5, then the two codewords are:

\[
0 \leftrightarrow 0\ 0\ 0\ 0\ 0 \\
1 \leftrightarrow 1\ 1\ 1\ 1\ 1
\]

In the receiver, the decoder can recover the original information bits by looking at the received code in the data stream and find the ones and zeros which occurs most often.

The Majority logic detection that is usually used in decoding depends on the hamming weight of the code [16]. If the code is \((n, 1)\) repetition code, and \(n\) can be written as \(n=2t+1\), then the Hamming weight \(d_H\) is calculated and the code words can be decoded by the following conditions:

- If \(d_H \leq t\), the decoded code word is all 0’s and then the information bit is 0.
- If \(d_H \geq t+1\), the decoded code word is all 1’s and then the information bit is 1.

2.2.3 Hamming codes

It is one of a linear block codes that invented in 1950 [15]. In general, Hamming codes are an important family of codes which are easy to encode and decode, they can detect up to two bit
Chapter 2: Block coded modulation and MIMO systems

errors and correct one bit error. Hamming codes can be generalized in any field, but in common, it is used in binary field [14], so that this section discussed only binary Hamming codes.

The previous section presented that there are some concepts in linear codes defined the code, in Hamming codes, if the integer \( m \geq 2 \), then the block length \( n = 2^m - 1 \), the message length \( k = 2^m - m - 1 \) and the rate \( R = k/n = 1 - m/(2^m - 1) \). As a note, when \( m \) is large, the code rate is close to 1.

The common used Hamming code is when \( m = 3 \), then the code is (7,4) Hamming code, which can be constructed according to figure 2.4 which shows how to generate parity bits.

The parity bits \( (p_0, p_1, p_2) \) defined by:

\[
\begin{align*}
p_0 &= a_0 + a_1 + a_2 \\
p_1 &= a_1 + a_2 + a_3 \\
p_2 &= a_0 + a_1 + a_3
\end{align*}
\]

Figure 2.4: Simple encoder for a (7, 4) Hamming code [4].
Because the Hamming code is a linear code, it can be written in terms of matrices [16], that is after defined the parity bits, a generator matrix $G$ can be constructed. The generator matrix $G$ for an $(n,k)$ linear code $C$ is a $k$-by-$n$ matrix, and $C$ can be found by $C=xG$ where $x$ is the encoding bits. The standard form for a generator matrix is:

$$G = (I_k | P) \quad \text{........................................2.3}$$

where $I_k$ is the $k \times k$ identity matrix and $P$ is a $k \times m$ matrix from the parity check equations. The another matrix is the parity check matrix $H$, and it is constructed as:

$$H = (-P^T | I_{n-k}) \quad \text{........................................2.4}$$

obviously changing the order of the columns doesn't affect the number of errors a code can correct or its error probability [15], and the relation between $H$ and $G$ is $HG^T=0$.

The generator matrix $G$ is used to encode information at the transmitter as shown in figure 2.5. On the other hand, the parity check matrix $H$ is used in the decoding operation at the reciever.

![Figure 2.5: Generator matrix to construct the code vectors.](image)

If $c$ is transmitted over a noisy channel, the received vector $r$ can be expressed as the sum of the original code vector $c$ and an error vector or error pattern $e$ as:

$$r=c+e \quad \text{........................................2.5}$$
Chapter 2: Block coded modulation and MIMO systems

From table 2.1 for the error pattern of (7,4) Hamming code, the $i^{th}$ element of $e$ equals 0 if the corresponding element of $r$ is received correctly. On the other hand, the $i^{th}$ element of $e$ equals 1 if the corresponding element of $r$ is received in error. That is $e$ can be expressed as:

$$e_i = \begin{cases} 1 & \text{If an error has occurred in the } i^{th} \text{ location} \\ 0 & \text{Otherwise} \end{cases}$$

The receiver has the task of decoding the code vector $c$ from the received vector $r$ by computing the corresponding syndrome of $r$ as shown in figure 2.6 by:

$$S = rH^T$$

which has the following important properties [15]:

- The syndrome depends only on the error pattern, and not on the transmitted code word.
- All error patterns that differ by a code word have the same syndrome.

After computing $S$, and from the syndrome table 2.1, the error pattern $e_0$ is identified and the decoded vector $c$ is computed.
2.2.4 Reed–Muller codes

Another type of linear block codes is introduced here, this is the Reed–Muller code over GF(2) which is considered one of the easy described code and have an elegant structure [4]. It was discovered and proposed by D. E. Muller and I. S. Reed in 1954 [18], and has the properties and advantages of forming an infinite family of codes, larger Reed-Muller code can be constructed from smaller ones, and it is simple in encoding process and in the decoding [18].

There are several ways to construct the Reed-Muller codes [19], one of them by using the indicator vectors and the product between them to generate the other vectors in the generator matrix $G$. If there are $x$ and $y$ vectors, the product between them is:

$$xy = (x_1y_1, x_2y_2, \ldots, x_ny_n)$$

This type of codes is denoted by RM$(r,m)$ where $r$ and $m$ are defined as:

$$m = \log_2 n$$

and,

$$r = m - \log_2 d_{\text{min}}$$
Chapter 2: Block coded modulation and MIMO systems

The Hamming distance of this code, \(d_{\text{min}}\) is defined as:

\[ d_{\text{min}} = 2^{m-r} \]

Note that, \(n\) is considered the vector length and it is the number of the columns of the generator matrix, where \(k\) which is the number of rows in \(G\) is:

\[ k = 1 + \binom{m}{1} + \binom{m}{2} + \ldots + \binom{m}{r} \]

Using equation 2.7, the generator matrix of the RM(1,3) as an example is generated by the set of \(\{v_0; v_1; v_2; v_3\}\) where these vectors have a pattern of \(2^{m-i}\) ones followed by \(2^{m-i}\) zeros repeated until \(n\) is completed:

\[ v_0 = (1,1,1,1,1,1,1,1) \quad v_1 = (1,1,1,1,0,0,0,0) \]

\[ v_2 = (1,1,0,0,1,1,0,0) \quad v_3 = (1,0,1,0,1,0,1,0) \]

and then, the \(G(1,3)\) matrix will be:

\[ G(1,3) = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & v_0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & v_1 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & v_2 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & v_3 \end{pmatrix} \]

where the column on the right hand side is the corresponding generator vector.

Another example is the RM(2,3) code which can be generated by adding the rows \(v_1v_2, v_1v_3\) and \(v_2v_3\) to the generator matrix \(G(1,3)\) as follows:

\[ G(2,3) = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & v_0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & v_1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & v_1v_2 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & v_1v_3 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & v_2v_3 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]
Chapter 2: Block coded modulation and MIMO systems

From $G(1,3)$ and $G(2,3)$, It must be noted that the $G(r,m)$ can be achieved by adding $\binom{m}{r}$ rows to the $G(r-1,m)$. The message must sent to the generator matrix in bloks of length $k$, so the encoded message is found by multiplying the message bits by the generator matrix $G$.

Table 2.2 shows different types of reed-muller codes of length up to 32:

<table>
<thead>
<tr>
<th>$G(r,m)$</th>
<th>$G(1,m,2^m,1)$</th>
<th>$G(4,5,2^m,2^m-1,2)$</th>
<th>$G(4,5,2^m,2^m-m-1,4)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G(1,1)$</td>
<td>$G(1,2,4,4,1)$</td>
<td>$G(1,3,4,8,1)$</td>
<td>$G(1,3,5,8,1)$</td>
</tr>
<tr>
<td>$G(0,0)$</td>
<td>$G(0,1,2,1,2)$</td>
<td>$G(0,1,3,16,11,4)$</td>
<td>$G(0,2,3,8,7,2)$</td>
</tr>
<tr>
<td>$G(-1,0)$</td>
<td>$G(-1,1,2,0,\infty)$</td>
<td>$G(-1,1,3,16,5,8)$</td>
<td>$G(-1,2,4,0,\infty)$</td>
</tr>
<tr>
<td>$G(1,1)$</td>
<td>$G(1,2,4,4,1)$</td>
<td>$G(1,3,4,8,1)$</td>
<td>$G(1,3,5,8,1)$</td>
</tr>
<tr>
<td>$G(0,0)$</td>
<td>$G(0,1,2,1,2)$</td>
<td>$G(0,1,3,16,11,4)$</td>
<td>$G(0,2,3,8,7,2)$</td>
</tr>
<tr>
<td>$G(-1,0)$</td>
<td>$G(-1,1,2,0,\infty)$</td>
<td>$G(-1,1,3,16,5,8)$</td>
<td>$G(-1,2,4,0,\infty)$</td>
</tr>
</tbody>
</table>

Table 2.2: List of different types of RM codes [20].
Chapter 2: Block coded modulation and MIMO systems

The decoding algorithm is based on majority logic techniques [19] which is fast and easy to implement. It depends on the distance between two codes which it is the number of different values at the corresponding places between two code words. If the distance is greater than $2e$ where $e$ is number of errors in the RM(r,m) code, then the code can corrects up to $e$ errors [19].

2.3 Block Coded Modulation

Block Coded Modulation is one of the techniques that combines block codes with the signal sets (Modulation) to construct bandwidth-efficient codes [8]. BCM is the same as TCM but easier in construction and decoding using multi-level coding and multi-stage decoding [8]. It is designed to achieve large coding gain and high spectral efficiencies with simple decoding process [8]. The common core of this technique is to optimize the code in Euclidean space rather than dealing with Hamming distance as in classical coding schemes [21].

In two dimensional Euclidean space $R^2$ with $x$ and $y$ coordinates, any point in this space $s$ is defined by its components on $x$ and $y$ $(X(s),Y(s))$, then the squared Euclidean distance $d_E^2$ between $s$ and $s'$ is defined as:

$$d_E^2(s,s') = (x(s) - x(s'))^2 + (y(s) - y(s'))^2 \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots 2.8$$

But, if there is a vector $v$ in the space $R^2$, then the squared Euclidean distance $d_E^2$ between $v$ and $v'$ is defined as:

$$d_E^2(v,v') = \sum_{i=0}^{n-1} [(x(s_i) - x(s'_i))^2 + (y(s_i) - y(s'_i))^2] \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots 2.9$$
Chapter 2: Block coded modulation and MIMO systems

If the signal space is a two dimensional space, then the BCM code $C$ of length $n$ has a minimum squared Euclidean (MSE) distance denoted by $d_E^2[C]$ and defined as:

$$d_E^2[C] = \min\{d_E(v, v') : v, v' \in C \text{ and } v \neq v'\} \quad \text{........................2.10}$$

which the error performance of $C$ depends on the MSE distance.

2.3.1 Multi-level block modulation codes

In digital communication, there are two main parts of digital transmission technology that are used to enhance the performance of transmission over channel effects as described in chapter one. One of them is the digital modulation technology that converts a digital signal into a transmission signal, and the other one is the error correction technology that overcomes errors during the transmission path. These two parts have traditionally been researched independently [21]. Block coded modulation is a technique which allows a complicated code to be created by combining simple block codes and modulation [23].

In order to construct the BCM code, multilevel coding process can be used, it is a very powerful technique for constructing bandwidth-efficient modulation codes to enhance the performance for a given channel by providing the flexibility to coordinate the distance parameters of a code [5].

Equations 2.8 to 2.10 show that the distance parameter is depended on the Euclidean distance, it means that the error can be reduced if the separation of the transmitted symbols is as large as possible [25]. In general, the separation between symbols only without using of multilevel coding may vary depending on the symbol position on the constellation [25].
Chapter 2: Block coded modulation and MIMO systems

Figure 2.7 shows different M-ary PSK modulation scheme and the corresponding distance between symbols. In QPSK, the transmission of symbol \( S_0 \) may be received as \( S_1 \) or \( S_3 \) than \( S_2 \) because the distance between them is less than the distance between \( S_0 \) and \( S_2 \). In 8PSK, diagonally placed symbols can maintain a distance of at least 2.6 times that of adjacent symbols.

\[
\begin{align*}
\text{S1} & \quad d_{\text{S1}}=2d \\
\text{S0} & \quad d_{\text{S0}}=2d
\end{align*}
\]

\[
\begin{align*}
\text{S2} & \quad d_{\text{S2}}=1.414d \\
\text{S1} & \quad d_{\text{S1}}=1.414d
\end{align*}
\]

\[
\begin{align*}
\text{S3} & \quad d_{\text{S3}}=0.765d \\
\text{S0} & \quad d_{\text{S0}}=1.414d
\end{align*}
\]

\[
\begin{align*}
\text{S4} & \quad d_{\text{S4}}=2d \\
\text{S5} & \quad d_{\text{S5}}=2d
\end{align*}
\]

\[
\begin{align*}
\text{S6} & \quad d_{\text{S6}}=2d \\
\text{S7} & \quad d_{\text{S7}}=2d
\end{align*}
\]

\[
\begin{align*}
\text{d is the signal amplitude}
\end{align*}
\]

Figure 2.7: Symbol distance for different types of PSK [25].

As a modulation scheme of symbols without error correcting may not meet the transmission purpose in high rate digital communication, the multilevel coding is used [24] to maximizes the Minimum Squared Euclidean Distance between symbols by using set partitioning in which different encoders are used to encode the data bits at different levels of the partitioning tree [22].

Set partitioning is simply explained by using 3-level codes over 8-PSK modulation as shown in figure 2.8. Each signal \( s \) in the 8-PSK signal set is labeled by 3 bits \( a_3a_2a_1 \). For the first level the signal points in \( S \) whose have \( a_1 \) (0 or 1) as a prefix have been used and form QPSK (four symbols in each branch). For the second level, the signal points in \( S \) whose have \( a_2a_1 \) as a
Chapter 2: Block coded modulation and MIMO systems

Prifex have been used and form BPSK (two symbols in each branch). The last level have the signal points whose have \(a_3a_2a_1\) as a prifex. The product distance is a main issue in set partitioning, it is defined as:

\[
d_p^2(v, v') = \prod_{i=0, s_i \neq s_i'}^{n-1} d_E^2(s_i, s'_i)
\]

And the minimum product distance of the code \(d_p^2[C]\) is defined as:

\[
d_p^2[C] = \min\{ d_p^2(v, v') : v, v' \in C \text{ and } d_H(v, v') = d_H[C] \}
\]

For the set partitioning of 8-PSK in figure 2.8, the product distances \(d_0^2, d_1^2, d_2^2\) and \(d_3^2\) of \(S\) equal 0.586, 2, 4, and \(\infty\) respectively.

Figure 2.8: Set partitioning of 8PSK [25]
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From this technique, it is clear that if \( a_1 \) and \( a_2 \) can be guaranteed to be corrected using robust error-correcting code, the characteristics of BPSK can be obtained and \( a_3 \) can be obtained. This means that the error probability is decreased. Figure 2.9 shows the modulator of the \( l \)-level coding.

Because of this technique uses several number of codes, each of them has its rate, then rate of the overall code is the sum of the rates of the individual codes at different levels [22], that is:

\[
R = \frac{k_1 + k_2 + \ldots + k_l}{n}, \quad \text{where } l \text{ is number of levels} \quad \text{.........................2.12}
\]

Since decoding the overall multilevel code can be prohibitively complex, this technique are usually decoded in a sequential manner using a multistage decoder which is discussed in the next sub-section.
2.3.2 Multi stage decoding

Multi-stage decoding is considered an optimal decoding technique of multilevel codes to achieve an efficient trade-off between error performance and decoding complexity [26]. It can be performed by a maximum likelihood decoder that finds the best input vector in each stage that maximizes the probability of receiving sequence [25]. This multistage decoding technique allows the receiver to decode the first level code and then use the output decoded sequence in decoding the second level code and so on [22]. In order to perform this technique, a multilevel code should be constructed and entered to the multistage decoder. The component codes are decoded in stages, one at a time, stage by stage from the first level component code to the ends as in figure 2.10. In general, this technique is optimal for the small and medium length block codes and number of decoding stages [26].

The entire decoding complexity depends on the complexity of each stage. It is considered as a sum of the stages decoding complexity. Thus, the entire decoding complexity is not optimum unless each stage of decoding is optimum [26].
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For simplicity, the decoding process was discussed by using 3-level stage of 8-PSK signal modulation, and the process of decoding is generalized. Let \( r = (r_1, r_2, \ldots, r_n) \) be the received signal entered to the decoding process, and each element in this sequence will be defined as \( r_i = (x_i, y_i) \in \mathbb{R}^2 \) where \( 0 < i \leq n \) on the constellation diagram.

For a 3-level stage decoding, let \( v_1 = (v_{10}, v_{11}, \ldots, v_{1n}) \), \( v_2 = (v_{20}, v_{21}, \ldots, v_{2n}) \), and \( v_3 = (v_{30}, v_{31}, \ldots, v_{3n}) \) be a code words in \( C_1, C_2 \) and \( C_3 \), respectively. The decoding process as shown in figure 2.10 is started from the first stage as follows:

For the **first stage decoding**, the MSE distance \( d_E^2[r_i, Q(v_{ii})] \) \((Q(.) \) is the symbol’s location on the constellation diagram) between \( r \) and \( v_{ii} \) is calculated and defined as:

\[
 d_E^2(r, v_1) = \sum_{i=1}^{n} d_E^2[r_i, Q(v_{1i})] \quad \text{...............2.13}
\]

For every codeword \( v_1 \in C_1 \), the distance \( d_E^2(r, v_1) \) is calculated, and \( r \) is decoded into the code word \( \hat{v}_1 = (\hat{v}_{11}, \hat{v}_{12}, \ldots, \hat{v}_{1n}) \) for which \( d_E^2(r, \hat{v}_1) \) is minimum.

The decoding process is continued, so for the **second stage decoding**, the decoded information \( \hat{v}_1 \) is passed to the second stage, then \( d_E^2[r_i, Q(\hat{v}_{1i}, v_{2i})] \) is calculated by:

\[
 d_E^2(r, \hat{v}_1 v_2) = \sum_{i=1}^{n} d_E^2[r_i, Q(\hat{v}_{1i}, v_{2i})] \quad \text{...............2.14}
\]

then \( r \) is decoded into the codeword \( \hat{v}_2 \) for which \( d_E^2(r, \hat{v}_1 \hat{v}_2) \) is minimum.
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The last stage of the 3-level 8-PSK modulation is the third stage decoding, where the decoded information at the first and second stages is made available to the third one. For every codeword \( v_3 \in C_3 \), the distance \( d_E^2[r_i, Q(\tilde{v}_1, \tilde{v}_2, v_3)] \) is calculated by:

\[
d_E^2(r, \tilde{v}_1, \tilde{v}_2, v_3) = \sum_{i=1}^{n} d_E^2[r_i, Q(\tilde{v}_1, \tilde{v}_2, v_3)]
\]

Then \( r \) is decoded into the codeword \( \tilde{v}_3 \) for which \( d_E^2(r, \tilde{v}_1, \tilde{v}_2, \tilde{v}_3) \) is minimum. This completes the entire decoding process and \( \{\tilde{v}_1, \tilde{v}_2, \tilde{v}_3\} \) forms the decoded set.

2.4 MIMO systems

High data rate wireless communication systems in modern applications is the main focus of researches nowadays [2]. This is needed to be done without using conventional methods like increasing bandwidth which is a limited resource or using higher order modulation types which increases the probability of symbol errors rate. Multiple Input, Multiple Output (MIMO) systems give a significant enhancement to data rate and channel capacity without increasing bandwidth [5].

In MIMO systems, multiple antennas can be mounted at both transmitter and receiver as shown in figure 2.11. The multiple paths between any pair of transmit-receive antenna can be used to transmit the same data to achieve diversity gain which results in decreasing the probability of bit error rate (BER) [5]. On other hand, it can be used to transmit independent data through independent channel paths, achieving multiplexing gain and increasing the transmitted data rate. If the MIMO system used multiplexing or diversity gains, the question is when each of them is used? Simply the answer is that there should be a tradeoff between multiplexing and diversity to enhance the performance [5].
Several different diversity modes are used to make radio communications more robust such as time diversity, frequency diversity, and spatial diversity. Spatial diversity requires the use of multiple antennas at the transmitter or the receiver [3]. The fundamental analysis of MIMO systems is based on the assumption of independent flat fading channel which is known at the receiver through the transmission but not necessarily at the transmitter and constrained total power [5].

2.4.1 Modeling of MIMO system

Suppose that a MIMO wireless communication system is used. The transmitter has $M$ transmit antennas and the receiver has $N$ receive antennas as shown in figure 2.11. The channel between $m^{th}$ antenna and $n^{th}$ antenna denotes as $h_{mn}$, whose statistical model is Rayleigh as an example. To transmit information $S= [s_1, s_2, s_3, \ldots, s_L]$, where $L$ is number of symbols. Number of symbols is entered to the transmitter which all transmit antennas transmit their symbol at the same time. Every $N$ antenna receives this set; each symbol pass through different channel path,
the received signal is affected by AWGN. If we denote the noise at $N$ antenna as $n_N$, then the received signal at $n^{th}$ antenna can be written as:

$$y_n = \sqrt{\rho} \sum_{i=1}^{M} h_{iN} s_i + n_N \quad \text{...............2.16}$$

where $\rho$ is expected signal to noise ratio (SNR) at receiver. Also the system can be rewritten in matrix form as:

$$Y = HS + N_N \quad \text{......................2.17}$$

Equation 2.17 can be written in details as:

$$\begin{bmatrix} y_1 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1M} \\ \vdots & \ddots & \vdots \\ h_{N1} & \cdots & h_{NM} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_M \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_N \end{bmatrix} \quad \text{...............2.18}$$

Recovering process of the transmitted symbol $S$ needs acknowledgment of the channel gain matrix $H$, which is known as the channel state information at the transmitter (CSIT) and the channel state information at the receiver (CSIR).

### 2.4.2 Space diversity

The diversity techniques are widely used to overcome the problem that the transmission over a single path has a large probability to face a deep fading which will cause a large amount of errors in data. These diversity techniques aim to provide a multiple replicas of the transmitted signals at the receiver and the receiver use a proper combination technique of these replicas. As a result, that the multipath fading effects will be reduced and the reliability of the transmission will improved without increasing the transmitted power or sacrificing the bandwidth.
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Space diversity which also known as antenna diversity is one of the diversity techniques. It is implemented using multiple antennas arranged together at transmitter and/or at the receiver separated physically by distance. The value of this physical separation depends on many factors such as antenna height, propagation environment and frequency. In space diversity, there is no loss in bandwidth, data rate and transmitting power, since it is not use the time or frequency to provide a replica of signal.

2.5 Summary

This chapter introduced the basic concepts used in this thesis. The channel coding types that introduced here played a role as a channel coding for constructing a 3-level BCM code by using set partitioning. After that, in order to recover the transmitted symbols, the multi-stage decoding algorithm introduced. At the end of this chapter, space diversity as one of the diversity types in MIMO systems is introduced because SM used the same concept that is there are multiple antennas at the transmitter spaced from each other to give space diversity which means multiple channel response at each transmission time which is more studied in chapter 3.
Chapter 3

Spatial Modulation

3.1 Introduction

The need for high data rate and high spectral efficiency are the key elements of our modern life. To satisfy these demands for high data rate; most of research in modern wireless communication systems aims to develop some techniques [27]. The researchers used different technologies and approaches such as; adaptive coding and modulation, space–time coding (STC), MIMO systems, OFDM, and ultra wideband radio [27].

MIMO systems can be exploited in different ways; one of them is multiplexing which requires synchronizing all of the antennas to transmit at the same time, and introduces interference from all antennas during reception which results in complex detection schemes.
Chapter 3: Spatial Modulation

The other one is diversity. Thus, in this case, antennas are used to increase the reliability of
the message which exploits the spatial domain as a coding mechanism to increase diversity. The
third ways is the hybrid transmission, which means that both spatial multiplexing and diversity
concepts are integrated together to have a trade-off between diversity and multiplexing gains.

But the main drawback of any MIMO scheme is an increase in the complexity and cost due
to Inter–Channel Interference (ICI) caused by coupling multiple symbols in time and space, Inter–
Antenna Synchronization (IAS) which represents the baseline assumption for space–time and
encoded methods, and multiple Radio Frequency (RF) chains which are needed to transmit all the
signals simultaneously [28]. These issues make the practical implementation of MIMO schemes
difficult, especially in mobile stations because the economical limit in mobile stations which
states that this station should be not complex and not has a large number of receive antennas that
require increase in the energy used [28]. However, due to the important advantages of MIMO,
techniques ought to be found for multiple antenna transmission in order to mitigate the practical
limitations while retaining the key advantages like using STC, orthogonal transmission of
symbols, and multiplexing.

Spatial modulation (SM) is one of these techniques; it is a recently developed transmission
 technique that uses multiple antennas [27]. The basic idea behind SM is that symbols are chosen
from a constellation diagram and a unique transmit antenna number that is chosen from a set of
transmit antennas.

Spatial modulation has been proposed as a new modulation concept for MIMO systems,
which aims to reduce the complexity and cost and still guarantee good data rates [31] by:
Chapter 3: Spatial Modulation

1. One transmit antenna is activated for data transmission at each time instance. This allows SM to avoid the ICI, to require no synchronization among the transmit antennas, and to need only one RF chain for data transmission. This allows SM to exploit a low–complexity single stream receiver design for optimal Maximum Likelihood (ML) decoding [31].

2. The spatial position of each transmit antenna in the antenna array is used as a source of information which results in a coding mechanism that allows SM to achieve a spatial multiplexing gain with respect to conventional single antenna systems. Accordingly, even though just one antenna is active each time, SM can also achieve high data throughput [31].

The two distinguishable features above show that SM depends on a constellation point in the signal domain and a constellation point in the spatial domain. This makes the SM a technique which combines digital modulation, coding, and spatial domain to achieve high data rates and low–complexity implementations. In particular, these characteristics make a difference between SM and Transmit Antenna Selection (TAS) or Spatial Division Multiplexing (SDM) schemes [31] which are discussed later in this chapter.

Figure 3.1 shows the block diagram of the SM system. It is clear that a block of any number of information bits is mapped into two domain that SM depends on (signal domain and spatial domain) as cleared in table 3.1. In order to let only one transmit antenna of the set to be active at each time instant; the other antennas will transmit zero power. The results of that, ICI at the
receiver and the need to synchronize the transmit antennas are completely avoided [27]. In the receiver, SM allows to design a low–complexity optimal ML decoder [30].

Figure 3.1: Block diagram of SM.

Table 3.1: SM mapping table: 3 bit/symbol/subchannel.
Chapter 3: Spatial Modulation

Instead of the normal two dimensional modulation schemes such as PSK and QAM, the SM introduces a third dimension which is the index of the transmitter antenna where the symbol is emitted from among the $M_t$ antennas where number of bits that determine the antenna is $\log_2(M_t)$. The receiver must determine which of the $M_t$ antennas was selected for transmission [29]. More details of the SM system design are introduced in the next section.

3.2 SM system model

If there are $N_t$ transmit antennas, and $N_r$ receive antennas as shown in figure 3.1, the net result of the information to be transmitted into the position of the transmit antenna is a hybrid modulation and MIMO technique in which the modulated signals belong to the signal sets. If the modulation used is QPSK as an example to introduce the mechanism of SM as in figure 3.2, and the number of antennas is four at the transmitter and one at the receiver. The system will be as follows:

At the transmitter, the number of binary bits that are transmitted at each time is equal to $\log_2(N_t) + \log_2(M)$ bits, where $\log_2(N_t)$ is the number of bits needed to identify the transmit antenna in the antenna array. Apart from the transmitting antenna, all other transmit antennas are kept silent in the current signaling time interval. $\log_2(M)$ is the number if bits in each symbol in the signal constellation diagram as shown in table 3.1. In the example, if $N_t$ is equal 4 and QPSK is used, the binary bits that are transmitted at each time is equal to 4. That is; if the transmitted bits are [1110], then Tx3 will be activated for data transmission by the two bits {11} and a $-1+0j$ signal will be sent from it out corresponding to the other two bits {10}. 
Chapter 3: Spatial Modulation

Two main highlights should be taken into consideration when using SM. The first one is that the activated TA may change at each transmit time according to the input bits. The other one is that the information bits are modulated onto a 3D constellation diagram, which generalizes the known 2D constellation diagram, where the third dimension is provided by the antenna array and termed as "spatial constellation diagram" [32].

![Spatial Modulation Diagram](image-url)

Figure 3.2: spatial modulation for QPSK and $N_t = 4$ [32].

It is apparent from this transmitting mechanism that the transmitted bits emitted by the active antenna go through a generic wireless channel $h(i,t)$ which is different from the other channels according to the different position of the transmit antennas. The signal transmitted by each antenna will experience different propagation conditions due to the different interacting environmental objects. This represents the fundamental working principle of SM as shown in...
In addition, only one signal will be actually received because the other antennas will radiate no power [31].

The Receiver in general used ML detection [30] in order to detect the transmitted signal from the noisy received signal $y$, and the receiver must know the channel state information of all the wireless links. In general, since there are $N_t$ and $N_r$ then there are $N_tN_r$ channel coefficients need to be estimated. According to the ML principle, the receiver computes the Euclidean distance between the received signal and the set of all possible signals modulated by the wireless channel and chooses the closest one. Thus there are $MN_tN_r$ Euclidean distances needed to be computed.

If multiple antenna are available at the receiver, they are exploited under the assumption of ML optimum detection to get receive diversity gains via Maximal Ratio Combining (MRC) [31].

### 3.3 Advantages and some constraints on SM

With respect to conventional MIMO systems, the advantages of SM system are:

- Due to the working mechanism of SM that depends on using a single transmit antenna for data transmission while all the other antennas are kept silent. The Spatial modulation systems entirely avoid ICI and IAS and only require a single RF chain at the transmitter.

- The 3D constellation diagram in SM introduces a multiplexing gain in the spatial domain which yields an increase by a factor of $\log_2(N_t)$ [31] and without any bandwidth expansion.
Chapter 3: Spatial Modulation

- Lower transmit power supply due to the using of single RF source at each time.

- SM attains ML decoding as in simple single antenna receiver which make the design of the receiver is simple.

- Suitable for downlink settings with low complexity mobile units due to the use of single antenna for receiving that gives a diversity gain. In practice, SM can efficiently work if \( N_r < N_t \).

- SM provides a larger capacity than conventional low complexity coding methods for MIMO systems [30] due to the multiplexing gain that SM provides.

Despite all the advantages of SM, there are some constraints when designing the SM systems such that:

- Still using at least two transmit antennas to exploit the SM concept with STC.

- The wireless links should be different from each other, because the SM paradigm might not be used or might not yield adequate performance if the wireless links are might similar to each other.

- The receiver requires perfect channel knowledge for data detection to attain the simple design of the receiver.

- SM offers a logarithmic increase of the data rate with the number of transmit antennas. This might limit SM to achieve very high spectral efficiencies for practical numbers of antennas at the transmitter [30].
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The above list of advantages and disadvantages clearly indicates that SM appears to be a promising candidate for low complexity MIMO implementations.

3.4 SM vs. SSK, and other MIMO techniques

Both Spatial modulation and Space shift keying (SSK) used multiple antennas at the transmitter where only one antenna is active at each transmission time. SSK can be thought of as the special case of SM [33]. In SM, the spatial domain is an additional dimension to the 2D signal dimension which allows the encoder to establish a one-to-one mapping between the information bits and the wireless links [34].

Unlike SM, the modulation in SSK is only the spatial constellation diagram where it is used for data modulation. For this, SSK modulation works in general as SM where the transmitter encodes blocks of \( \log_2(N_t) \) data bits into the index of a single transmit antenna which is switched on for data transmission while all the other antennas are kept silent. The receiver decoded the transmitted information by estimates the transmit antenna that is not idle. Amplitude/phase modulation (APM) is eliminated when using SSK and only antenna indices are used to transmit information. However, SSK modulation does not provide any performance advantage compared to SM [13].

In summary, figure 3.3 shows the difference between spatial modulation and special multiplexing and space time coding.
Chapter 3: Spatial Modulation

In **spatial multiplexing**:

- Multiple antennas are used for transmission in parallel streams of symbols.
- The spectral efficiency increased with the number of $N_t$ antennas.
- The BER performance decreases due to ICI, and there is an Inter-antenna synchronization (IAS) problem.

For **space-time coding**:

- Parallel transmission of orthogonal symbol streams is used.
- Diversity in the system improved the BER performance.
- There is no ICI and the IAS problem is still occurred.

Figure 3.3: Difference between SM, STC, and spatial multiplexing
Chapter 3: Spatial Modulation

And finally for the **spatial modulation**:

- Single antenna is used for each transmission time.
- Information bits is transmitted by the antenna selected from the antenna index bits.
- SM increases the spectral efficiency of the system.
- ICI is eliminated, and no IAS appears.
- Single RF reduces the energy consumption in the system.
Chapter 4

Block Coded Spatial Modulation

4.1 Introduction

The basic principle of SM as explained in chapter 3, is to use the indices of multiple antennas to convey information in addition to the conventional two dimensional signal constellations such as $M$-ary Quadrature amplitude modulation ($M$-QAM). The information is conveyed by not only the amplitude/phase modulation techniques, but also by the antenna indices. Since only one transmit antenna is active during each symbol transmission, ICI is completely eliminated in SM and this results in much lower (linear) decoding complexity [12].
Chapter 4: Block Coded Spatial Modulation

In this chapter, many simulation results are obtained to study the spatial modulation technique in MIMO systems. Some results obtained to make some comparison with other transmission coding techniques used in MIMO. At the end of this chapter; thesis contributions of combining coded modulation with SM are illustrated and verified.

4.2 Simulation of Spatial Modulation

In this section, a study of the SM performance is illustrated:

4.2.1 Spatial Modulation as a transmission technique

Figure 4.1 shows the basic block diagram of using SM as a transmission technique in MIMO systems. There are four transmit antennas ($N_t = 4$) and one receive antenna ($N_r = 1$). The information bits to be transmitted ($m$) are separated into two groups. One group determines the transmit antenna index on which transmission will take place ($i$), and the second group determines the symbol to be transmitted from the chosen antenna ($s$). The symbol transmitted on the chosen antenna can be from a regular modulation alphabet $M$-QAM. Therefore, the number of bits that belong to the first and second group, respectively, are $\log_2(N_t)$ and $\log_2(M)$. This gives a spectral efficiency of $\log_2(N_t) + \log_2(M)$ bits/s/Hz.

In this simulation, and for illustration purpose, there are 2 bits to determine the transmit antenna index, and the other 2 bits are used to form the transmitting symbol. Thus the information rate of the system is 4 bits/s/Hz. As a result, this system can be compared with 16-QAM modulation technique in a SISO system which has a 4 bits/s as a spectral efficiency. This comparison is demonstrated in figure 4.2.
Chapter 4: Block Coded Spatial Modulation

\[ y(i, t) = \sqrt{\frac{\rho}{\mu}} x(i, t) h(i, t) + n(i, t) \]  
\[ \text{................................. 4.1} \]

Equation 4.1 and as shown in figure 4.1, shows that \( y(i, t) \) in the receiver is considered the received vector at one transmission time where \( x(i, t) \) represents the transmitting stream. It contains the antenna index and the symbol transmitted at each time. That is, \( x(i, t) \) has a form as an example as \( x(i, t) = [0, s, 0, 0] \), where the symbol \( s \) is transmitted from the second antenna. \( h(i, t) \) in figure 4.1 represents the channel response from the transmit antenna at one transmission times and \( \mu \) is a normalization factor to ensure that \( \rho \) is the average SNR at each receive antenna.

The decoding process of \( y(i, t) \) aims to estimate the antenna index \( i(t) \) and to detect the symbol transmitted \( \hat{x}(t) \) by using a full search of all possibilities that achieves:

\[ m' = \arg \min_{x \in \text{all possible}} \left\| y - \sqrt{\frac{\rho}{\mu}} x(i, t) h(i, t) \right\|^2 \]  
\[ \text{................................. 4.2} \]

Figure 4.1: SM as a transmission technique in 4 x 1MIMO system.
Chapter 4: Block Coded Spatial Modulation

Figure 4.2 shows the simulation results of the comparison between the SISO system used 16-QAM to modulate symbols and the 4 x 1 SM system with the same spectral efficiency rate, which is 4 bits/s/Hz at each transmission. The figure shows that there is enhancing in the performance of more than 3 dB in the low SNR. It is due to the property that SM needs less power in transmitting symbols because some of information bits are used as an antenna index. The second reason for this enhancement is the lower modulation order used in SM compared with SISO for the same data rate. For 4 bps in this simulation, SISO system needs 16-QAM to modulate symbols, while the SM needs only 4-QAM as 2 bps are achieved by utilizing the antenna index.

Figure 4.2: Comparison between SISO and SM with the same rate 4 bit/s.

Figure 4.3 shows a simulation results of comparing 2 x 1 STBC with a spectral efficiency rate 4 bits/s with a 4 x 1 SM with the same spectral efficiency. This simulation confirms the
Chapter 4: Block Coded Spatial Modulation

property that with no appears of IAS in SM enhance the BER performance of the system by nearly 1.5 dB from STBC.

![Graph showing comparison between 2×1 STBC and 4×1 SM with the same rate 4 bit/s.](image)

**Figure 4.3:** Comparison between 2×1 STBC with 4×1 SM with the same rate 4 bit/s.

### 4.2.2 Different number of receive antennas in Spatial Modulation

For simplicity, all simulations in this chapter are performed with one receive antenna. However, to make sure that SM is also used in \( N_r \) receive antennas, and the procedure used in simulations is acceptable in MIMO systems of different types of transmit and receive antennas. Two receive antennas are used to receive the transmitted sequence of the SM system and ML detection is used in the receiver in this section.

The channel matrix \( H \) contains eight independent channel characteristics from the \( j^{th} \) receive antenna to the \( i^{th} \) transmit antenna.
Chapter 4: Block Coded Spatial Modulation

\[ H = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \\ h_{13} & h_{23} \\ h_{14} & h_{24} \end{bmatrix} \]

In order to let the simulation represents the effects of using two receive antennas only; the transmitting sequence \([0,s,0,0]\) is transmitted, and the symbol \(s\) is convolved with \(h_{11}\) and received in \(Rx_1\) and then the same \(s\) is convolved with \(h_{21}\) and received in \(Rx_2\). The received vector is a combining of the two images, and then a full search of all possible is performed to obtain the transmitted sequence. BPSK is used for the symbol modulation, and RM(2,5) is used as a block code.

Figure 4.4 shows the simulation results of this section, and the results are compared with the results obtained when one receive antenna is used. The results indicates that there is an remarkable enhancement when using multi receive antennas than using one, as it is expected because of the increase in the receiving diversity by one.

![Figure 4.4: Comparison between using one or two receive antennas in SM.](image-url)
Chapter 4: Block Coded Spatial Modulation

4.2.3 Coding Antenna indices

As known that only single antenna is used at each transmission time, the question is what is the role of the other antennas in the receiving process? To ask this question, it should be remembered that antenna index in SM convoys information bits. That is, at each transmission time, there is a symbol transmitted according to the information bits that the antenna index has, which allows the receiver to find the suitable detection of the received vector.

After decoding, if the decoded symbol is incorrect, there is two reasons for this, the first one is that the error is occurred at the symbol itself but the antenna index is correct, this yields to an incorrect symbol receiving. The second reason occurs when the antenna index received incorrectly, that means the transmitting information transmits from one antenna and detected as from another one. In this reason, the other antenna indices may correct the symbol and as a result the antenna index also.

Figure 4.5: Block diagram of using indices to correct symbols.

Figure 4.5 and 4.7 shows the block diagram of using indices to correct symbols and the procedure of doing this, respectively.
Chapter 4: Block Coded Spatial Modulation

The procedure starts when the vector \( y(i,t) \) is received and from equation 4.2 the antenna index and the symbol transmitted is estimated. After the estimated bit stream is decoded, the resulting bits are tested to know if the antenna index is decoded correctly or not. If it is decoded correctly, the procedure is repeated and another transmission time is allowed. But if it is decoded incorrectly, the antenna index is corrected and the associated modulated symbol is redetected with ML detector with fixed antenna index as clearly described in the flow chart of figure 4.7.

Figure 4.6 shows the simulation result and it is clear that there is an enhancement in the BER performance when antenna indices correct some symbols. The enhancement is about 0.5 dB because not all error modulated symbols occur from a wrongly detected antenna index.

![Figure 4.6](image_url)

**Figure 4.6**: The effect of using indices to correct symbols.
Chapter 4: Block Coded Spatial Modulation

Figure 4.7: Flow chart of testing indices errors
4.2.4 Increasing the number of transmit antennas

One of the most important issues in SM is the number of transmit antennas, which is one of the complexity criteria of the system. Increasing the number of transmit antennas makes an extension of the transmission possibility which means an increasing in channel paths that leads to an enhancement in BER performance. But, increasing $N_t$ leads to use more bits as an antenna index which makes the system more complex in the receiver because ML detection makes a full search of all possibilities. This sub-section introduces the effect of increasing number of transmit antennas without any addition process in the coding stage (like using set partitioning as discussed in the following section).

Figure 4.8 shows a comparison between using 4 transmit antennas to transmit 4 bits/s/Hz with using 8 transmit antennas at the same spectral efficiency by using one code has a rate 2/3. The figure shows that using $N_t=8$ with the same spectral efficiency with $N_t = 4$ makes an enhancement of nearly 2 dB of the BER performance.
4.3 Block Coded Spatial Modulation (BCSM)

In this section, a MIMO transmission scheme, called Block Coded Spatial Modulation (BCSM), which directly combines block coding and SM, is proposed. Set partitioning used in conventional BCM and the SM mapper are jointly designed. At the receiver, the ML decoding is used to estimate the antenna index and symbol and decoded by using multi stage decoding. The BCSM mechanism, which switches between transmit antennas of a MIMO link, provides a type of virtual interleaving and offers an additional diversity gain, known as time diversity [12]. Time diversity implies that the same data is transmitted multiple times, or a redundant error correcting code is added. By means of bit-interleaving, the error bursts may be spread in time. System model and simulation result are obtained in the following subsections.

4.3.1 System model of BCSM

The considered BCSM system model is given in figure 4.9. The independent and identically distributed binary information sequence $u$ is entered to a separation block to separate the antennas indices bits from the symbol bits. The antenna index bits are not encoded and still as generated. However, symbols bits were encoded by a 3-level BCM coding as shown in figure 2.8 with rate $R=2/3$ whose output sequence $v$ enters the SM mapper. The 3-level BCM codes used in this system are $C_0$ is the (8,1,8) repetition code that consists of the all-zero and all-one vectors, $C_1$ is the (8,7,2) even-parity check code that consists of all the even-weight 8-tuples over GF(2), and $C_2$ is the (8,8,1) universal code that consists of all the 8-tuples over GF(2).

The three bits of the symbols are from the previous three linear codes, where each bit comes from one code as shown in figure 2.9.
Chapter 4: Block Coded Spatial Modulation

The spatial modulator is designed in conjunction with the block encoder to transmit $n$ coded bits in a transmission interval by means of the symbols selected from a 8-PSK constellation, and of the antenna selected from a set of $N_t$ transmit antennas such that $n = \log_2(MN_t)$. The SM mapper first specifies the identity of the transmit antenna determined by the first $\log_2 N_t$ bits of the transmitting sequence. It then maps the remaining $\log_2 M$ bits of the coded sequence into the signal constellation employed for transmission of the data symbols. Due to BCM coding, the overall spectral efficiency of the BCSM would be the spectral efficiency of BCM plus the antenna index bits (bits/s/Hz). The new signal generated by the SM is denoted by $x = (i, s)$ where $s \in x$ is the data symbol transmitted over the antenna labeled by $i \in \{1, 2, \ldots, N_t\}$. That is, the spatial modulator generates an $1 \times N_t$ signal vector $[0, 0, s, \ldots, 0]$ whose $i^{th}$ entry is $s$ at the output of the $N_t$ transmit antennas for transmission.

Figure 4.9: BCSM system model.
The MIMO channel, over which the spatially modulated symbols are transmitted, is characterized by an $N_t \times N_r$ matrix $H$, whose entries are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero means and unit variances. $H$ remains constant during the transmission of a frame (antenna index and symbol like $x = [0,0,s,0]$) and takes independent values from one frame to another, and is perfectly known at the receiver, but is not known at the transmitter. The transmitted signal is corrupted by an $N_r$-dimensional additive complex Gaussian noise vector with (i.i.d.) complex Gaussian random variables with zero means and unit variances.

At the receiver, a ML decoder is employed to provide an estimation of the antenna index bits and symbol bits. The estimated symbol bits are entered to the 3-stage decoding to provide the decoded $\hat{v}$ as in figure 2.10 and then combined to the estimated indices bits to have $\hat{u}$ output bits.

To introduce the concept of BCSM by an example, let $N_t = 4$ and a single receive antenna. Consider the overall rate of the 3-level BCM code is 2/3 which leads to a 2 bits/s/Hz for BCM and 2 bits for choosing the transmission antenna at each time. That is, the overall spectral efficiency of this BCSM system is 4 bits/s/Hz. At each coding step, the first two coded bits determine the active transmit antenna over which the 8-PSK symbol determined by the last three BCM coded bits.

The signal matrix $Y$ which is described as:

$$Y = \sqrt{\frac{\rho}{\mu}} XH + N \tag{4.3}$$
where $X$ is the $1 \times N_t$ BCSM transmission matrix, transmitted over the channel, and $\mu$ is a normalization factor to ensure that $\rho$ is the average SNR at each receive antenna. $H$ is assumed to remain constant during the transmission and takes independent values from one transmission time to another. An ML decoder must make an exhaustive search over all possible $MN_t$ transmission matrices, and decides in favor of the matrix that minimizes the equation 4.2. The estimated 3 bits of symbol decoded by using a 3-stage decoding algorithm as in figure 2.10 to have a decoded vector at each stage by using equations 2.13 to 2.15.

### 4.3.2 Simulation result of BCSM

In figure 4.10, the simulation results for 4 bits/s/Hz transmission with four transmit antennas and one receive antenna using set partitioning in the transmitter and multi stage decoding at the receiver is obtained. The results are compared to the case of using SM only as a transmission technique without any linear coding of the information bits. They are also compared to the case of using linear code RM(1,3) as a coding of the information bits because this code corrects one errors only and has a rate of 1/2. As seen from this figure, BCSM scheme offers a significant improvement in the BER performance compared to the classical SM techniques. It gives an approximately 6 dB enhancing of BER performance from the use of SM only, and about 3 dB enhancing from the use of coded information bits.
Repeating the same process with using Q-PSK as a symbol modulation transmitted at one of the 8 transmit antennas used, and compared the result with the those obtained when using 4 transmit antennas as in figure 4.11 shows an enhancement of BER performance by 1 dB, and verify the concept illustrated in section 4.2.4.
Chapter 4: Block Coded Spatial Modulation

As a conclusion, SM in general gives an enhancement in the BER performance of MIMO systems, it gives an improvements due to the properties of it that are introduced in section 3.4. In addition to that, figures 4.10 and 4.11 show that using set partitioning to construct BCM as a coding with SM gives a coding gain enhancement in MIMO systems. Figure 4.11 shows that increasing number of transmit antenna will enhance the BER performance but with a complex construction in the transmitter due to a large number of transmit antennas used. To overcome this, it can use block codes in the transmitter that detect and correct more than one error to construct BCM.
Chapter 5

Conclusion and Future works

5.1 Conclusion

The goal of this thesis is to enhance the BER performance of MIMO systems by using Block Coded Modulation as a transmission coding. BCM is firstly developed to work with SISO systems, and it gives a good enhancement of BER performance. This thesis generalized this concept of using it in MIMO systems taking the advantages of SM that depends on one transmit antenna at each transmission time like SISO systems. In addition, this thesis takes the advantages of having multi paths of transmission according to the active antenna which makes advantages of spatial and time diversity.

To achieve the goal of enhancing the BER performance of MIMO systems, the effect of using SM as a transmission technique in MIMO has been studied, then the main concepts of SM
Chapter 5: Conclusion and Future works

and its properties has been evaluated. The effect of using multi receive and transmit antennas also has been studied. The result shows that when increasing transmit antenna numbers, the BER performance is enhanced but with increasing complexity. Finally, the use of transmit antennas to correct some error received symbols has been simulated and a flow chart of the process is showed. All simulations have the assumption that the channel gains are known at the receiver.

The performances of using BCSM based on set partitioning with three level coding gives a 4 bits/s/Hz as spectral efficiency is compared with using SM only as a transmission technique and also compared with using SM to transmit a coded data. Simulations show that the new BCSM code enhance the BER performance by approximately 6 dB over the use of SM only, and about 3 dB enhancing over coded information bits.

5.2 Future works

There are several possible future works on this as follows:

- Using a sphere decoding in the receiver instead of ML detection, which means searching over the noiseless possible received signals that lie around the actual received signal which can reduces the search possibility.

- Modify the method of BCSM to let the antenna indices play a role of detecting some errors-received symbols in BCSM according to know the exact transmit antenna used.

- It can use the same approach of constructing BCSM to construct trellis coded modulation transmitted via a spatial modulation technique.
References


