Space-time Block Coding for Wireless Communications

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Thesis

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Abstract

Wireless designers constantly seek to improve the spectrum efficiency/capacity, coverage of wireless networks, and link reliability. Space-time wireless technology that uses multiple antennas along with appropriate signalling and receiver techniques offers a powerful tool for improving wireless performance. Some aspects of this technology have already been incorporated into various wireless network and cellular mobile standards. More advanced MIMO techniques are planned for future mobile networks, wireless local area network (LANs) and wide area network (WANs).

Multiple antennas when used with appropriate space-time coding (STC) techniques can achieve huge performance gains in multipath fading wireless links. The fundamentals of space-time coding were established in the context of space-time Trellis coding by Tarokh, Seshadri and Calderbank. Alamouti then proposed a simple transmit diversity coding scheme and based on this scheme, general space-time block codes were further introduced by Tarokh, Jafarkhani and Calderbank. Since then space-time coding has soon evolved into a most vibrant research area in wireless communications. Recently, space-time block coding has been adopted in the third generation mobile communication standard which aims to deliver true multimedia capability. Space-time block codes have a most attractive feature of the linear decoding/detection algorithms and thus become the most popular among different STC techniques. The decoding of space-time block codes, however, requires knowledge of channels at the receiver and in most publications, channel parameters are assumed known, which is not practical due to the changing channel conditions in real communication systems.

This thesis is mainly concerned with space-time block codes and their performances. The focus is on signal detection and channel estimation for wireless communication systems using space-time block codes. We first present the required background materials, discuss different implementations of space-time block codes using different numbers of transmit and receive antennas, and evaluate the performances of space-time block codes using binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and quadrature amplitude modulation (QAM). Then, we investigate Tarokh's joint detection scheme with no channel state information thoroughly, and also propose a new general joint channel estimation and data detection scheme that works with QPSK and 16-QAM and different numbers of antennas. Next, we further study Yang's channel estimation scheme, and expand this channel estimation scheme to work with 16-QAM modulation. After dealing with complex signal constellations, we subsequently develop the equations and algorithms of both channel estimation schemes to further test their performances when real signals are used (BPSK modulation). Then, we simulate and compare the performances of the two new channel estimation schemes when employing different number of transmit and receive antennas and when employing different modulation methods. Finally, conclusions are drawn and further research areas are discussed.

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List of Abbreviations

3G	third generation
4G	fourth Generation
3GPP	3^{rd} Generation Partnership Project
AWGN	additive white Gaussian noise
BER	bit error rate.
BPSK	binary phase shift keying
CSI	channel state information
FER	frame-error rate
GSM	the global system for mobile communications
MAC	medium access control
MIMO	multiple-input multiple-output
MISO	multiple-input single-output
ML	maximum likelihood
MLSE	maximum likelihood sequence estimation
MMSE	minimum mean square error

MPSK	M-ary phase shift keying
MRC	maximum ration combining
MS	mobile station
MSE	mean square error
MU-MIMO	multi-user multiple-input multiple-output
OFDM	orthogonal frequency-division multiplexing
OSTBC	orthogonal space-time block code/codes/coding
PAM	pulse amplitude modulation
PSK	phase shift keying
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
SISO	single-input single-output
SNR	signal-to-noise ratio
STC	space-time code
STBC	space-time block code
STTC	space-time trellis code
STTuC	space-time turbo code
WLAN	wireless local area network
ZF	zero forcing

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Declaration

The following papers have been published and the parts of their materials are included in the thesis:

- J. Yang, E. Masoud and Y. Sun, "Performance of Space-time Block Coding Using Estimated Channel Parameters", London Communications Symposium Conference UCL, 2004.
- M. Ma, E. Masoud, Y. Sun, and J. M. Senior, "A Hybrid Space-time and Collaborative Coding Scheme for Wireless Communications", International Symposium on Circuits and Systems, ISCAS. 6, pp. 6102-6105, May 2005.
- E. Masoud and Y. Sun, "Joint Channel Estimation and Data Detection for Space-time Block Coding with no Channel State Information", Smart Antennas and Cooperative Communications Presentations, IET, Nov 2007.

Chapter 1

1 Introduction

1.1 Background

During the last decade, the demand for capacity in wireless local area networks and cellular mobile systems has grown in a literally explosive manner. In particular, compared to the data rates made available by today's technology, the need for wireless Internet access and multimedia applications require an increase in information throughput with order of magnitude. One major technological breakthrough that will make this increase in data rate possible is the use of multiple antennas at the transmitters and receivers in the system.

Most work on wireless communications had focused on having an antenna array at only one end of the wireless link, usually at the receiver. Seminal papers by Foschini and Gans [1], Foschini [2] and Telatar [3] enlarged the scope of wireless communication possibilities by showing that when antenna arrays are used at both ends of a link, substantial capacity gains are enabled by the highly-scattering environment. Many established communication systems use receive diversity at the base station. For example, Global System for Mobile communications (GSM) [4] base station typically has two receive antennas. This receive technology is used to improve the quality of the uplink from mobile to base station without adding any cost, size or power consumption to the mobile [5]. Reference [6] has generally discussed the use of receive diversity in cellular system and its impact on the system capacity. Receive diversity was largely studied and used until Foschini's 1998 paper [1].

In recent years, researchers have realized that many benefits as well as a substantial amount of performance gain of receive diversity can be reproduced by using multiple antennas at transmitter to achieve transmit diversity. In the early 1990's, development of transmit diversity techniques has started. Since then the interest in the topic has grown in a rapid fashion. In fact, we can expect multiple-input multiple-output (MIMO) technology to be a cornerstone of many wireless communication systems due to the potential increase in data rate and performance of wireless links offered by transmit diversity and MIMO technology.

MIMO is the current theme for the international wireless research [7] [8]. The feasibility of implementing MIMO system and the associated signal processing algorithms is enabled by the corresponding increase of the computational power of integrated circuits, which is generally believed to grow with time in an exponential fashion. Figure 1.1 shows a MIMO wireless communication system which contains multiple antennas at both the transmitter and receiver.

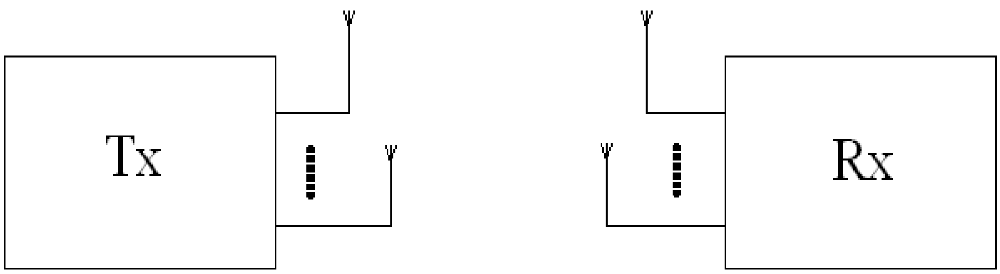

Figure 1.1: MIMO communication system

The predominant cellular network implementation is to have a single antenna on the mobile device and multiple antennas at the base station. This minimizes the cost of the mobile radio. A second antenna in mobile device may become more common when the costs for radio frequency components in mobile devices go down. Today, cellular phones, laptops and other communication devices have two or more antennas. The use of multiple antennas will become even more popular in the future.

In the commercial arena, Iospan Wireless Inc [9] developed the first commercial wireless system in 2001 that uses MIMO-OFDMA technology. The Iospan technology has supported both diversity coding and spatial multiplexing. In 2005, Airgo Networks [10] developed a IEEE 802.11n system based on their patents on MIMO. Following that, in 2006, several companies like Broadcom, Intel, and other proposed a MIMO-OFDM solution for the emerging IEEE 802.11e standard. MIMO is also planned to be used in mobile radio telephone standards such as recent 3G and 4G standards. In 3G, Long Term Evolution (LTE) standards and High-Speed Packet Access plus (HSPA+) take MIMO into account [11]. Moreover, to fully support cellular environments MIMO research consortia including IST-MASCOT propose to develop advanced MIMO techniques, i.e., multi-user MIMO (MU-MIMO) [12].

In 2006, several other companies like Beceem Communications, Samsung, Runcom Technologies, etc also developed MIMO-OFDMA based solutions for IEEE 802.16 WiMAX broadband fixed and mobile standards. WiMAX is the technology brand name for the implementation of the standard IEEE 802.16. IEEE 802.16 specifies the air interface at the Physical layer and at the Medium Access Control layer (MAC). WiMAX also specifies the support for MIMO antennas to provide good Non-line-of-sight (NLOS) characteristics.

In general MIMO gives WiMAX a significant increase in spectral efficiency [13], improves the reception and allows for a better reach and rate of transmission. All upcoming 4G systems will also employ MIMO technology [14]. Several research groups have demonstrated over 1 Gbit/s prototypes [15].

1.2 Space-time Codes

Space-time code (STC) is a method usually employed into wireless communication systems to improve the reliability of data transmission using multiple antennas [16, 17, 18]. STCs rely on transmitting multiple, redundant copies of a data stream to the receiver in the hope that at least some of them will survive the physical path between transmission and reception in a good state to allow reliable decoding.

Space time codes could be divided into three types. First, space–time trellis codes (STTCs) [16] distribute a Trellis code over multiple antennas and multiple time-slots. STTCs are always used to provide both coding gain and diversity gain. Space-time trellis code, proposed by Tarokh [19], is a scheme where symbols are encoded according to the antennas through which they are simultaneously transmitted and decoded using maximum likelihood detection. Trellis coding [19] is a very effective scheme that provides a considerable performance gain, as it combines the benefits of forward error correction (FEC) coding and diversity transmission. However, the scheme requires a good trade-off between constellation size, data rate, diversity advantage, and Trellis complexity.

The second type of STCs is space-time turbo codes (STTuC) a combination of space-time coding and turbo coding [20]. They are originally introduced as binary error-correcting codes built from the parallel concatenation of two recursive systematic convolution codes exploiting a sub-optimal but very powerful iterative decoding algorithm, which is called turbo decoding algorithm. The turbo principle has these days been successfully applied in many detection and decoding problems such as serial concatenation, equalization, coded modulation, multi-user detection, joint interference suppression and decoding.

The third type of STCs is space–time block codes (STBCs) [17] [18]. They act on a block of data. STBCs do provide diversity gain but they do not provide coding gain. This makes STBC less complex in implementation than STTCs and STTuCs. This thesis is mainly concerned with space-time block codes

1.3 Space-time Block Codes

Space-time block codes (STBC) are a generalized version of Alamouti scheme [18] [19] [21]. These schemes have the same key features. Therefore, these codes are orthogonal and can achieve full transmit diversity specified by the number of transmit antennas. In another word, space-time block codes are a complex version of Alamouti's space-time code in [17], where the encoding and decoding schemes are the same as there in the Alamouti space-time code in both the transmitter and receiver sides. The data are constructed as a matrix which has its rows equal to the number of the transmit antennas and its columns equal to the number of the time slots required to transmit the data. At the receiver side, when signals are received, they are first combined and then sent to the maximum likelihood detector where the decision rules are applied.

Space-time block codes were designed to achieve the maximum diversity order for the given number of transmit and receive antennas subject to the constraint of having a simple linear decoding algorithm. This has made space-time block codes a very poplar scheme and most widely used.

Space-time block codes and indeed many other space-time techniques including STTCs are designed for coherent detection where channel estimation is necessary. There is a substantial literature addressing the channel estimation issue for multiple-input multiple-output (MIMO) systems, ranging from standard training based techniques that rely on pilot symbols [22] [23] [24] in the data stream to blind [25] [26] which does not require pilot sequences and semi-blind [27] estimation where observations corresponding to data and pilot are used jointly. Other authors have considered non-coherent detection schemes based on differential encoding which do not require channel state information (CSI) [21] [28]. Although these methods avoid the need for channel estimation, they often suffer from problems such as error propagation.

Training-based methods seem to give very good results on the performance of channel estimation at the receiver. Pure training-based schemes can be considered as an advantage when an accurate and reliable MIMO channel needs to be obtained. However, this could also be a disadvantage when bandwidth efficiency is required. This is because pure training-based schemes reduce the bandwidth efficiency considerably due to the use of a long training sequence which is necessarily needed in order to obtain a reliable MIMO channel estimate.

Because of the computation complexity of blind and semi-blind methods, many wireless communication systems still use pilot sequences to estimate the channel parameters at the receiver side. These reasons motivated Tarokh to propose a new joint detection scheme for transmit diversity with no CSI [29]. These reasons also motivated Yang to propose a new channel estimation algorithm that uses pilot sequences and minimum square error (MSN) to estimate the channel parameters [30]. These two methods have the advantages of low computation, thus becoming the base of the research in this thesis.

1.4 Research Scope and Objectives

The aims of this research are to propose and investigate new coherent space-time block codes that use pilot sequences to estimate the channel coefficients. The two methods proposed by Tarokh and Yang are theoretically derived, studied and simulated. Generalized new schemes are proposed for different antenna combinations and modulation schemes. Chapter 2 started with reviewing Alamouti scheme in details. This includes Alamouti space-time encoding, combining and maximum likelihood decoding. After that the chapter describes Tarokh's generalization to Alamouti scheme by producing orthogonal space-time block codes that work with any transmit and receive antenna combinations. In addition, the chapter presents space-time block codes that work with real and complex signals that have different coding rates. In Chapter 3, Tarokh's joint channel estimation and data detection scheme is implemented and fully investigated. A new version of the scheme is proposed and tested using different numbers of transmit and receive antennas and higher order complex modulation methods (16-QAM). The performances of the proposed new joint channel estimation and data detection scheme are compared with space-time block codes that have a complete knowledge of the channel coefficients at the receiver. The channel coefficients are always assumed flat Rayleigh fading and constant while transmitting a frame that has a length of over 50 symbols and the real model used is the AWGN (additive white Gaussian noise). In Chapter 4, Yang's channel estimation scheme is implemented and fully investigated and a new channel estimation scheme that works with other modulation methods is proposed. The new channel estimation scheme is tested on different transmit and receive antenna combinations and with different modulation methods like QPSK and 16-QAM. The bit-error-rate performances are plotted and compared with the space-time block codes with known channel parameters at the receiver. All aspects of the channel estimation schemes described in Chapters 3 and 4 are then further investigated in Chapter 5 using real signal modulation methods, while Chapters 3 and 4 are concerned with complex signal consultations. In this thesis, all simulations are conducted in Matlab. To complete the research, in Chapter 6, a comparison of the two channel estimation schemes described in Chapters 3, 4 and 5 is carried out in terms of bandwidth efficiency and bit-error-rate performance.

1.5 Original Contributions

Several novel contributions have been described in this thesis:

- Implement Tarokh's joint channel estimation and data detection scheme in [28] using different BPSK real signals and QPSK and 16-QAM complex signals.
- A new joint channel estimation and data detection scheme based on the joint scheme proposed in [28] is fully investigated and tested with different combinations of transmit and receive antennas (two and four transmit antennas and one, two, three and four receive antennas).
- The new joint channel estimation and data detection scheme is also tested with different real and complex modulation methods (BPSK, QPSK, and 16-QAM).
- Implement Yang's channel estimation scheme in [29] with different combinations of transmit and receive antennas (two and four transmit antennas and one, two, three and four receive antennas).
- Implement Yang's channel estimation scheme with BPSK, QPSK and 16-QAM modulation methods.
- Computer simulations of the two channel estimation schemes for radio links using space-time block coding have been carried out and performance analyzed.
- The simulation results for the performance of STBC using the two estimated channel parameters are compared with particular details on their bit-error-rate performances.

1.6 Structure of the Thesis

This thesis is organized in the following way.

Chapter 2: presents the performance analysis and design criteria of space-time codes in general. Also, the chapter presents space-time block codes and evaluates their performance on MIMO fading channels. At first, the two-branch transmit diversity scheme referred as Alamouti space-time code is introduced and the key features and the performance of this scheme are explained. After that, space-time block codes with a number of transmit and receive antennas based on orthogonal designs are presented [17]. The decoding algorithms for space-time block codes with both complex and real signal constellations are explained. At last, the performance of space-time block codes with real signal constellation on MIMO fading channels using different modulation schemes is evaluated by simulations.

Chapter 3: is divided into three parts. In the first part, Taorkh's new channel estimation and data detection scheme for transmit diversity with no channel estimation [28] is completely investigated. All Tarokh assumptions are clearly explained, and the BER performance results are discussed. The second part of the chapter derives new joint channel estimation and data detection scheme that works with higher number of transmit and receive antennas. Adding to that, the new joint scheme is tested on 16-QAM modulation method. In the third part, the results are collected and the BER performance graphs are plotted for the purpose of comparisons with space-time block codes that have perfect knowledge of the channel coefficients at the receiver.

Chapter 4: gives an overview on Yang's channel estimation scheme. It further implements Yang's channel estimation scheme with higher order 16-QAM modulation method. The chapter collects simulation data and plots the results for the purpose of comparing the channel estimation scheme with space-time block codes that have perfect knowledge of the channel coefficients at the receiver.

Chapter 5: fully derives the joint channel estimation and data detection scheme proposed in Chapter 3 to work with real signal modulation. It also derives the channel estimation scheme proposed in Chapter 4 to work with space-time block codes that transmit real signals. Simulation results for both channel estimation schemes are produced.

Chapter 6: in the chapter, the two channel estimation schemes described in Chapters 3, 4, and 5 are compared from three points of view; similarities, differences, and bit-error-rate performance.

Chapter 7: provides a summarization of the thesis and conclusions of the work done. The chapter also presents some further research areas.

References

[1] G. J. Foschini and M. J. Gans, “Limits of Wireless Communications in a Fading Environment When using Multiple Antennas”, Wireless Personal Communications, Vol. 6, pp. 311-335, January 1998.

[2] G. J. Foschini, “Layered Space-time Architecture for Wireless Communications in a Fading Environment When using Multi-element Antennas”, Bell Labs Technical Journal, Vol. 1, pp. 41-59, Autumn 1996.

[3] E. Telatar, “Capacity of Multi-antenna Gaussian Channels”, European Transactions on Telecommunications, Vol. 10, no. 6, pp. 585-595, Nov/ Dec 1999.

[4] M. Mouly and M. B. Pautet,”The GSM Systems for Mobile Communications”, Telecommunications Publishing, Olympia, WA, 1992.

[5] Z. S. Asif, “Mobile Receive Diversity Technology Improves 3G Systems Capacity”, IEEE Communications, pp. 7803-8451, 2004.

[6] J. Winters, J. Salz and R. Gitlin, “The Impact of Antenna Diversity on the Capacity of Wireless Communications Systems”, IEEE Transactions on communications, Vol. 42, pp. 1740-1751, 1994.

[7] B. Allen, P. D. Edwards, W. Q. Malik and P. T. Brown, “Antenna System and Propagation Future Wireless Communications”, IET Microw Editorial, Vol. 1, No. 6, December 2007.

[8] A. Burg and H. Bolcskel, “Real-time MIMIO Testbed for Next Generation Wireless LANs”, ERCIM NEWS online edition, No. 59, October 2004.

[9] BNET Business Library, “Iospan Introduces Breakthrough Broadband Wireless Technology”, (http://findarticles.com/p/articles/mi_m0IGV/is_12_2/ai_71886882), Wireless Internet, December 2000.

[10] Airgo A qualcomm Company, “Is Airgo the Uncrowned King of 802.11n MIMO?”, Article on Airgo (http://www.airgonet.com/news/articles/2005.php) , June 20 2005.

[11] 3GPP organization, “Multiple Input Multiple Output (MIMO) Antennas”, 3GPP Work Item Description, (http://www.3gpp.org/specs/WorkItem-info/WI--2468.htm), 03 April, 2003.

[12] Mascot Information Society Technologies, “MASCOT - Multiple-Access Space-Time Coding Testbed”

[13] WiMax, “Throughput and Spectral Efficiency”, (wimax.com), Retrieved on: 03 march 2008.

[14] Nortel, “Key Technologies – The Future of 4G Mobility”, Corporate Information, (http://www.nortel.com/corporate/technology_new/technologies.html).

[15] Y. K. Kim and P. Ramjee, “4G Roadmap and Emerging Communication Technologies”, Artech House, pp. 12-13, 2006.

[16] V. Tarokh, N. Seshadri and A. R. Calderbank, “Space-time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction”, IEEE Transactions on Information Theory, Vol. 44, no. 2, pp. 744-765, March 1998.

[17] S.M Alamouti, “A simple Transmitter Diversity Scheme for Wireless Communications”, IEEE Journal on Selected Areas in Communications, Vol. 16, pp. 1451-1458, October 1998.

[18] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, “Space-time Block Codes from Orthogonal Designs”, IEEE Transactions on Information Theory, Vol . 45, No. 5, pp. 1456-1467, July 1999.

[19] S. M. Alamouti, V. Tarokh, P. Poon, "Trellis-Coded Modulation and Transmit Diversity: Design Criteria and Performance Evalution", in Proc. IEEE ICUPC 98, Oct. 1998, pp 703-707.

[20] Y. Liu, M. P. Fitz and O. Y. Takeshita, " Full Rate Space-Time Turbo Codes", IEEE Journal on Selected Areas in Communications, Publisher item Identifier: S 733-8716(01)03905-1, Vol. 19, No. 5, May 2001

[21] V. Tarokh and H. Jafarkhani, “A differential Detection Scheme for Transmit Diversity,” IEEE Journal on Selected Areas in Communications, Vol. 18, No. 7, pp. 1169-1174, July 2000.

[22] S. Ohno and G. B. Giannakis, “Optimal Training and Redundant Pre-coding for Block Transmissions with Application to Wireless OFDM”, IEEE Transactions on Communications, November 2000.

[23] H. Cheon and D. Hong, “Performance Analysis of Space-time Block Codes in Time-varying Rayleigh Fading Channels”, IEEE transactions, 2002.

[24] J. K. Cavers, “An Analysis of Pilot Symbol Assisted Modulation for Raleigh Faded Channels”, IEEE Transactions, Vol. 40, pp. 683-693, November 1991.

[25] M. Torlak and Guanghan Xu, “Blind Multiuser Channel Estimation in Asynchronous CDMA Systems”, IEEE Transactions on Signal Processing, Vol. 45, No. 1, January 1997.

[26] D. Boss, K. Kammeyer and T. Petermann, “Is Blind Channel Estimation Feasible in Mobile Communication Systems? A study Based on GSM”, IEEE Journal on Selected Area in Communications, Vol. 16, No. 8, October 1998.

[27] S. Zhou, B. Muquet and G. B. Giannakis, “Subspace-based (Semi-) blind Channel Estimation for Block Precoded Space-time OFDM”, IEEE Transactions on Signal Processing, Vol. 50, No. 5, May 2002.

[28] L. Song and A. G. Burr, “A simple Differential Modulation Scheme for Quasi-orthogonal Space-time Block Codes with Partial Transmit Diversity”, EURASIP Journal on Wireless Communications and Networking, 2007.

[29] V. Tarokh, S. M. Alamouti, and P. Poon, “New Detection Schemes for Transmit Diversity with no Channel Estimation,” IEEE International Conference on Universal Personal Communications, pp. 917-920, 1998.

[30] J. Yang, E. Masoud and Y. Sun, “Performance of Space-time Block Coding Using Estimated Channel Parameters”, London Communications Symposium Conference UCL, 2004.

Chapter 2

2 Space-time Block Codes

2.1 Introduction

In recent years, space-time coding techniques have received much interest. The concept of space-time coding has arisen from diversity techniques using smart antennas. By using data coding and signal processing at both sides of transmitter and receiver, space-time coding now is more effective than traditional diversity techniques [1], [2], [3], and [4]. Mostly, traditional diversity techniques are receive diversities. The problem with receive diversity for mobile communications is that the receive antennas had to be sufficiently apart so that the signals received at each antenna undergoes independent fade. Because of that, it is very costly to have more than one antenna in the mobile unit because they meant to be small in size and light in weight.

Therefore, the use of transmit diversity in base stations appears to be an attractive method, as more complex base stations can be allowed [5], [6], [7] and [8]. Base stations have the advantage of using both transmit and receive diversities when they communicate with each other, the case of multiple input multiple output (MIMO) channels. Moreover, transmit diversity could also be used when base stations need to transmit information to the mobile units which forms the channel of multiple input single output (MISO).

In this chapter, we present space-time block codes and evaluate their performance on MIMO fading channels. At first, the two-branch transmit diversity scheme referred to as Alamouti space-time code is introduced and its key features are explained. After that, space-time block codes with a large number of transmit and receive antennas based on orthogonal designs [9] are presented. The coding and decoding algorithms for space-time block codes with both complex and real signal constellations are explained in details. The performance of space-time block codes on MIMO fading channels using different modulation schemes is evaluated by simulations. At last, a conclusion on what has been presented and discussed in this chapter is given.

2.2 Alamouti Space-Time Code

Alamouti scheme is the first space-time block code scheme that provides full transmit diversity for systems with two transmit and one receive antennas [10]. It is a unique scheme in that it is the only space-time block code with an n_T x n_T complex transmission matrix to achieve the full rate of one [9]. In this section, we present Alamouti' transmit diversity technique in details, which includes the encoding and decoding algorithms. In addition to that, the performance of the scheme is discussed and analyzed using the simulations results.

2.2.1 Alamouti Encoding

At the transmitter side, a block of two symbols are taken from the source data and sent to the modulator. After that, Alamouti space-time encoder takes the two modulated symbols, in this case called s_1 and s_2 at a time and creates G_2 encoding matrix S where the symbols s_1 and s_2 are mapped to two transmit antennas in two transmit times as defined in the following:

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{2.1}$$

where the symbol * represents the complex conjugate. Therefore, s_1^* is the complex conjugate of s_1. The encoder outputs are transmitted in two consecutive transmission periods from the two transmit antennas. In the first transmission period, the signal s_1 is transmitted from antenna one and the signal s_2 is transmitted from antenna two, simultaneously. In the second transmission period, the signal $-s_2^*$ is transmitted from antenna one and the signal

s_1^* is transmitted from antenna two. The block diagram of the transmitter side using Alamouti space-time encoder is shown in Figure 2.1.

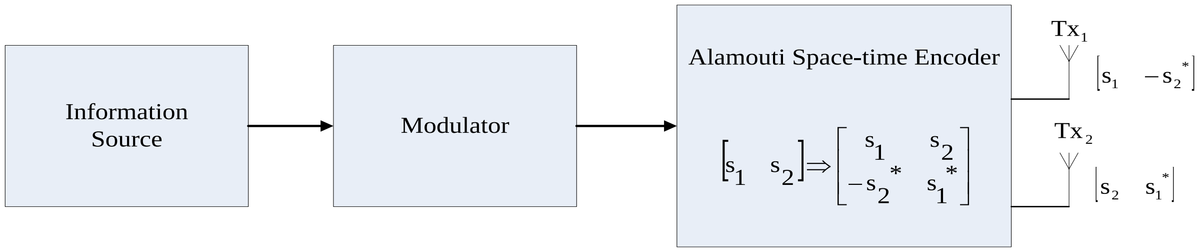

Figure 2.1: Alamouti space-time encoder diagram.

The encoding and mapping of this scheme can be summarized as in Table 2.1:

Table 2.1: Encoding and mapping for two transmit antennas using complex signals.

	Tx_1	Tx_2
t	s_1	s_2
$t+T$	$-s_2^*$	s_1^*

where t represents the transmission symbol period, Tx_1 and Tx_2 are the first and second transmit antennas. The transmit sequence from antennas one and two denoted by s^1 and s^2 are encoded in both space and time domains.

$$\begin{aligned} s^1 &= [s_1 \quad -s_2^*] \\ s^2 &= [s_2 \quad s_1^*] \end{aligned} \tag{2.2}$$

The inner product of s^1 and s^2 is equal to zero. This confirms the orthogonality of the Alamouti space-time scheme.

The block diagram of the Alamouti space-time system is shown in Figure 2.2. The fading coefficients denoted by $h_1(t)$ and $h_2(t)$ are assumed constant across the two consecutive symbol transmission periods and they can be defined as:

$$\begin{aligned} h_1(t) &= h_1(t+T) = h_1 = |h_1|e^{j\theta_1} \\ h_2(t) &= h_2(t+T) = h_2 = |h_2|e^{j\theta_2} \end{aligned} \tag{2.3}$$

where $h_1(t)$ and $h_2(t)$ are the fading coefficients from the first and the second transmit antennas to the receive antenna at time t. Where $|h_i|$ and θ_i, i = 1, 2, are the amplitude gain and the phase shift, respectively. T is the symbol period.

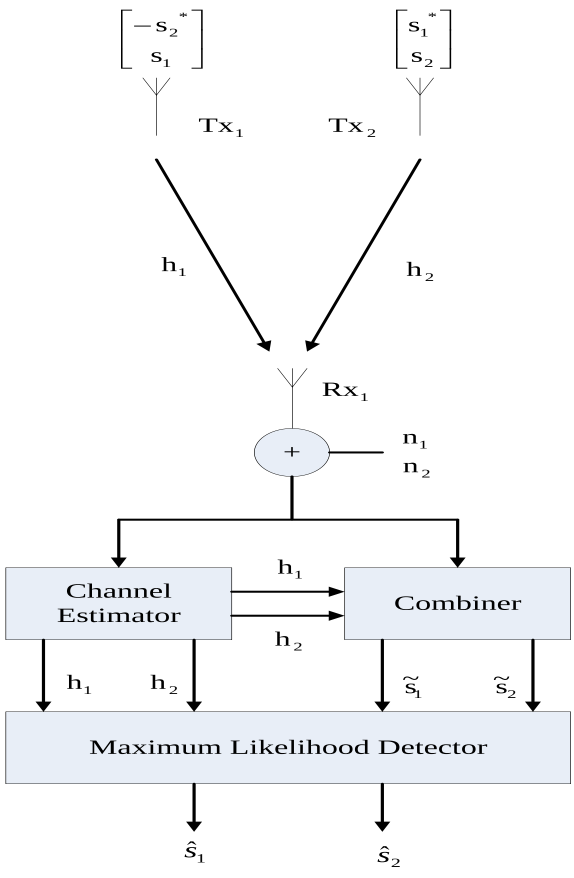

Figure 2.2: Alamouti space-time system with one receive antenna.

The channel coefficients for two transmit antennas and one receive antenna for Alamouti space-time code can be expressed as in Table 2.2.

Table 2.2: Two transmit and one receive antenna channel coefficients.

	Rx_1
Tx_1	h_1
Tx_2	h_2

where Tx_1 and Tx_2 are the first and second transmit antennas and Rx_1 is the receive antenna. The block diagram of the receiver side using Alamouti space-time decoder is shown in Figure 2.3.

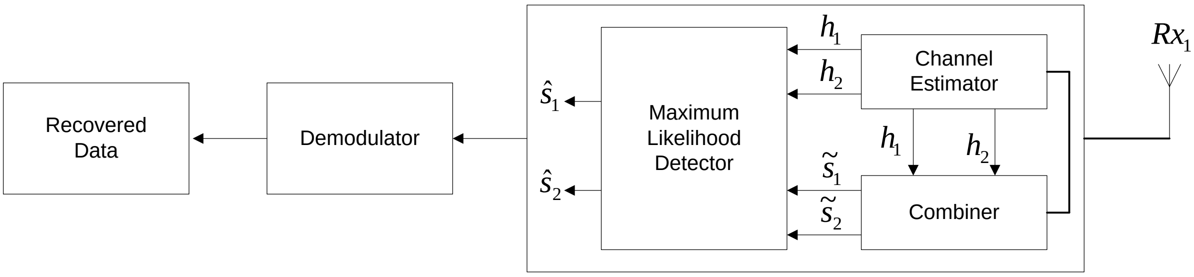

Figure 2.3: Alamouti space-time decoder diagram.

The receiver receives r_1 and r_2 denoting the two received signals over the two consecutive symbol periods for time t and $t+T$. The received signals can be expressed by:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \begin{bmatrix} h_1 s_1 + h_2 s_2 + n_1 \\ -h_1 s_2^* + h_2 s_1^* + n_2 \end{bmatrix} \tag{2.4}$$

where the additive white Gaussian noise samples at time t and $t+T$ are represented by the independent complex variables n_1 and n_2 with zero mean and power spectral density No/2 per dimension.

2.2.2 Combining and ML Detection

In most space-time codes, it is always assumed that the receiver has a perfect knowledge of the channel coefficients. In this case, they are h_1 and h_2. Then the Alamouti space-time decoder will use them as the channel state information (CSI). The maximum likelihood (ML) decoder chooses a pair of signals $(\hat{s}_1, \hat{s}_2)$ from the signal constellation to minimize the distance metric over all possible values of $\hat{s}_1$ and $\hat{s}_2$.

$$\begin{aligned} & d^2(r_1, h_1\hat{s}_1 + h_2\hat{s}_2) + d^2(r_2, -h_1\hat{s}_2^* + h_2\hat{s}_1^*) \\ & = \left|r_1 - h_1\hat{s}_1 - h_2\hat{s}_2\right|^2 + \left|r_2 + h_1\hat{s}_2^* - h_2\hat{s}_1^*\right|^2 \end{aligned} \tag{2.5}$$

For phase-shift keying (PSK) signals, the decision rule can be expressed by:

$$\begin{aligned} & d^2(\hat{s}_1, s_i) \le d^2(\hat{s}_1, s_k) \forall i \ne k \\ & d^2(\hat{s}_2, s_i) \le d^2(\hat{s}_2, s_k) \forall i \ne k \end{aligned} \tag{2.6}$$

The combiner shown in Figure 2.3 builds the following two combined signals that are sent to the maximum likelihood detector.

$$\begin{bmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{bmatrix} = \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1^* r_1 + h_2 r_2^* \\ h_2^* r_1 - h_1 r_2^* \end{bmatrix} \tag{2.7}$$

Substituting r_1 and r_2 from Equation (2.4), into Equation (2.7), then the decision statistic can be written as:

$$\begin{aligned} \tilde{s}_1 &= (|h_1|^2 + |h_2|^2)s_1 + h_1^* n_1 + h_2 n_2^* \\ \tilde{s}_2 &= (|h_1|^2 + |h_2|^2)s_2 - h_1 n_2^* + h_2^* n_1 \end{aligned} \tag{2.8}$$

The maximum likelihood decoding rule in Equation (2.5) can be separated using Equation (2.8) into two independent decoding rules for s_1 and s_2:

$$\begin{aligned} \hat{s}_1 &= \arg \min_{(\hat{s}_1, \hat{s}_2) \in C} (|h_1|^2 + |h_2|^2 - 1)|\hat{s}_1|^2 + d^2(\tilde{s}_1, \hat{s}_1) \\ \hat{s}_2 &= \arg \min_{(\hat{s}_1, \hat{s}_2) \in C} (|h_1|^2 + |h_2|^2 - 1)|\hat{s}_2|^2 + d^2(\tilde{s}_2, \hat{s}_2) \end{aligned} \tag{2.9}$$

where C is the set of all possible modulated symbol pairs $(\hat{s}_1, \hat{s}_2)$.

2.2.3 Performance of Alamouti Scheme

Alamouti space-time code is an orthogonal scheme that can achieve the full transmit diversity of n_T = 2. The codeword difference matrix between the transmitted symbols (s_1, s_2) and the detected symbols $(\hat{s}_1, \hat{s}_2)$ is given by:

$$B(S, \hat{S}) = \begin{bmatrix} s_1 - \hat{s}_1 & s_2 - \hat{s}_2 \\ -s_2^* + \hat{s}_2^* & s_1^* - \hat{s}_1^* \end{bmatrix} \tag{2.10}$$

The rows of the codeword difference are orthogonal since the rows of the code matrix are orthogonal. However, Alamouti scheme does not provide any coding gain. This is because the minimum distance between any two transmitted codes remains the same, since the codeword distance matrix for the Alamouti has two identical eigenvalues and the minimum squared Euclidean distance in a single constellation is equal to the minimum eigenvalue.

The bit-error-rate (BER) verses signal-to-noise-ratio (Eb/No (dB)) performance for Alamouti transmit diversity scheme on slow fading channels is evaluated by simulation [10]. In the simulation, it is assumed that the receiver has the perfect knowledge of the channel coefficient. It is also assumed that the fading is mutually independent from each transmit antenna to each receive antenna and the total transmit power is the same for all cases. Figure 2.4 shows the Alamouti scheme BER versus Eb/No performance with coherent BPSK modulation. From the simulation result, it is very clear to see that Alamouti scheme has the same diversity as the two-branch maximal ratio combining (MRC). However, from Figure 2.4, we can see that Almouti scheme performance is worse than the two-branch MRC by 3 dB and that is because the energy radiated from the single antenna in the MRC is the double of what radiates from each transmit antenna in the Alamouti scheme. To reach the same results, the total transmit power from each transmit antenna in the Alamouti scheme has to be equal to the transmit power of the MRC. Moreover, the performance of Alamouti scheme with two transmit antennas and two receive antennas have the same diversity as the MRC with four receive antennas. However, the performance of the Alamouti case is again 3 dB worse for the same reason as in the first case.

Figure 2.5 shows the BER versus Eb/No performance for the Alamouti transmit diversity scheme on flat Rayleigh fading channels. In addition to that, 16-QAM and QPSK modulation are used in the simulation. From the figure, it can be easily seen that the BER for the Alamouti scheme using QPSK modulation is better than when 16-QAM modulation is used. This better performance is due to the fact that higher order modulation schemes do carry more bits per symbol than lower order modulation schemes. In this case, 16-QAM scheme modulates four bits per symbol and QPSK scheme modulates two bits per symbol.

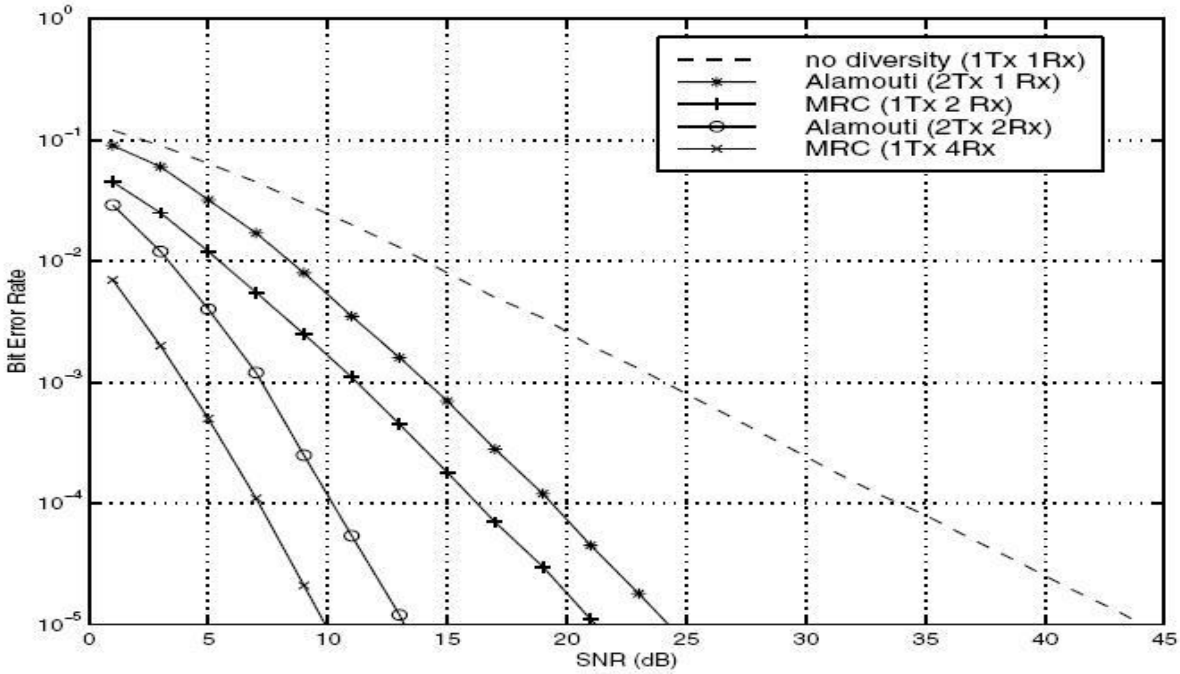

Figure 2.4: The performance of Alamouti scheme using BPSK modulation [7].

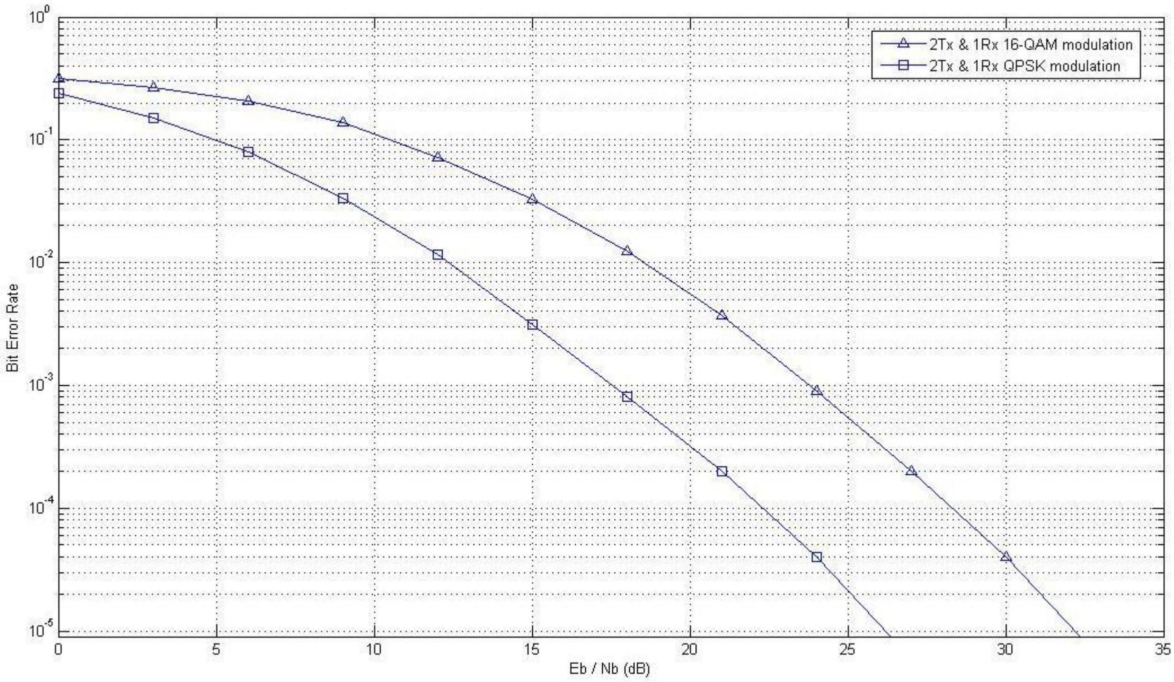

Figure 2.5: The performance of Alamouti scheme using 16-QAM and QPSK.

2.3 Space-Time Block Codes

Space-time block codes (STBC) are a generalized version of Alamouti scheme. These codes have the same key features. That is, they are orthogonal and can achieve full transmit diversity specified by the number of transmit antennas. In other words, space-time block codes are a complex version of Alamouti's space-time code, where the encoding and decoding schemes are the same as in both the transmitter and receiver sides. The data are constructed as a matrix which has its rows equal to the number of the transmit antennas and its columns equal to the number of the time slots required to transmit the data. At the receiver side, when signals are received, they are first combined and then sent to the maximum likelihood detector where the decision rules are applied.

Space-time block code was designed to achieve the maximum diversity order for the given number of transmit and receive antennas subject to the constraint of having a simple decoding algorithm. In addition, space-time block coding provides full diversity advantage but is not optimized for coding gain.

In the following, different implementations of space-time block codes are explained in details. This includes the encoding, decoding and system performance for the two and four transmit antennas and two and four receive antennas for both real and complex signal constellations.

2.3.1 Space-Time Block Encoding and Decoding

Figure 2.1 shows the structure of space-time block encoder for two transmit and one receive antennas which is the same as Alamouti encoder. As known, in general, space-time block code is defined by $n_T \times p$ transmission matrix S, where n_T represents the number of transmit antennas and p represents the number of time periods needed to transmit one block of coded symbols. The ratio between the number of symbols that space-time block encoder takes as its input (k) and the number of space-time coded symbols transmitted from each antenna defines the rate of a space-time block code. The rate of any space-time block codes with two transmit antennas is equal to one. The rate of a space-time block code can be calculated by:

$$R = \frac{k}{p} \tag{2.11}$$

In all simulations, the first step to consider before creating a space-time block code is the type of signal needed to be transmitted. There are two types of signals that can be created and transmitted. The first type of signals is the complex signal that can be generated by using any complex modulation schemes like M-QPSK and M-QAM. The second type of signals is the real signal that can be generated using any real modulation schemes like BPSK or PAM.

The creation of any space-time block code matrix depends on the type of the transmitted signal. If the transmitted signal is real, then the transmission matrix would be G_2, G_4, or any other real square matrix of rate of one. However, if the transmitted signal is complex, then a square G_2 is used if the number of transmit antennas is equal to two but if the number of transmit antennas is greater than two, then a complex, non-square matrix is used. The rate of such matrices could be either 1/2 or 3/4. These matrices can never achieve the full rate of one. The only exception is the Alamouti case for two transmit antennas using a G_2 matrix. However, a lot of research is currently going on finding new square matrices for complex constellations. In [11], a new scheme was proposed to use two orthogonal PAM modulators to create a QAM modulator. This was done by using a real matrix with complex signals. Moreover, in [12], a new square matrix with rate of $1/2$ was proposed. In [13], Jafarkhani proposed the quasi-orthogonal space-time block code that uses a four by four square transmission matrix with full rate of one. Although the new designed matrices are square matrices, most of them do not achieve the full rate.

2.4 Space-Time Block Code for Complex Constellations

The code design goal is to construct high-rate complex transmission matrices with low decoding complexity that achieves the full diversity if the number of transmit antennas is greater than two. For any given number of transmit antennas, there are space-time codes that can achieve a rate of $1/2$.

2.4.1 Two Transmit and Two Receive Antennas

The encoding for all space-time block codes that use two transmit antennas is exactly the same as the encoding for Alamouti space-time code. The transmission matrix used is the same as in Equation (2.1). Figure 2.6 show the Encoder block diagram.

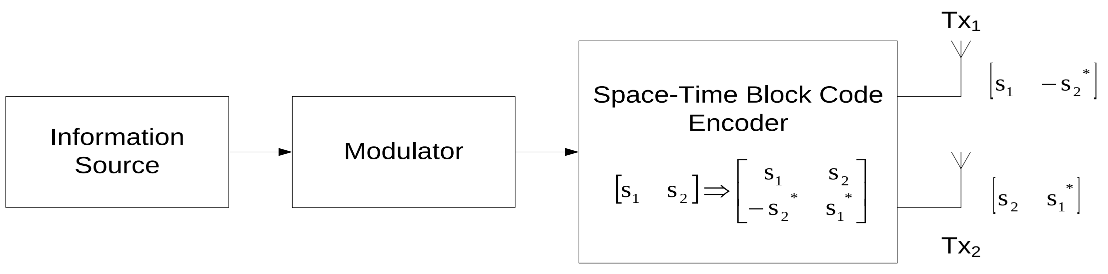

Figure 2.6: Space-time block encoder diagram.

Although the transmission sides are the same, the receiver sides are quite different. The receiver in this case has two receive antennas instead of one, which increases the receive diversity compared with a system with one receive antenna. Table 2.3 shows the channel coefficients for the space-time system with two transmit and two receive antennas.

Table 2.3: Channel configurations for two transmit and two receive antennas.

	Rx_1	Rx_2
Tx_1	h_1	h_3
Tx_2	h_2	h_4

Figure 2.7 shows the two transmit and two receive antennas scheme.

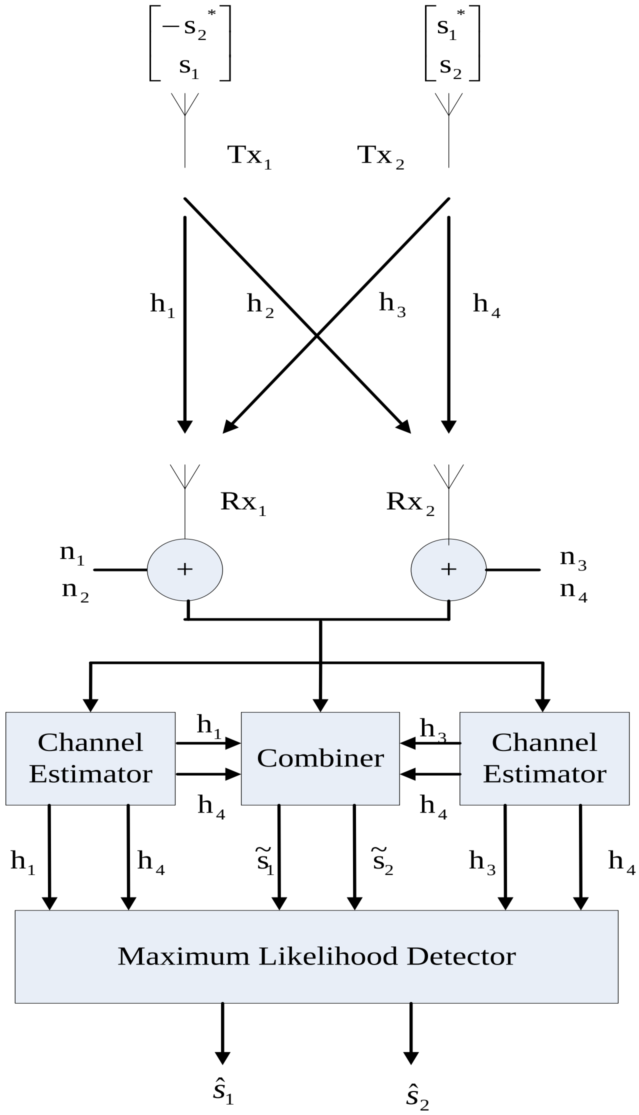

Figure 2.7: Space-time block code scheme with two transmit and two receive antennas.

The received signals at the two receive antennas denoted by r_1, r_2, r_3 and r_4 for t and $t+T$, respectively, can be expressed as:

$$
\begin{aligned}
r_1 &= h_1 s_1 + h_2 s_2 + n_1 \\
r_2 &= -h_1 s_2^* + h_2 s_1^* + n_2
\end{aligned}
\tag{2.12}
$$

$$\begin{aligned} r_3 &= h_3 s_1 + h_4 s_2 + n_3 \\ r_4 &= -h_3 s_2^* + h_4 s_1^* + n_4 \end{aligned} \tag{2.13}$$

The combiner in Figure 2.7 builds the following two combined signals that are sent to the maximum likelihood detector.

$$\begin{aligned} \tilde{s}_1 &= h_1^* r_1 + h_2 r_2^* + h_3^* r_3 + h_4 r_4^* \\ \tilde{s}_2 &= h_2^* r_1 - h_1 r_2^* + h_4^* r_3 - h_3 r_4^* \end{aligned} \tag{2.14}$$

The maximum likelihood decoding rule for s_1 and s_2 can be derived as [14]:

$$\begin{aligned} \hat{s}_1 &= \arg \min_{(\hat{s}_1, \hat{s}_2) \in C} (|h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2 - 1)|\hat{s}_1|^2 + d^2(\tilde{s}_1, \hat{s}_1) \\ \hat{s}_2 &= \arg \min_{(\hat{s}_1, \hat{s}_2) \in C} (|h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2 - 1)|\hat{s}_2|^2 + d^2(\tilde{s}_2, \hat{s}_2) \end{aligned} \tag{2.15}$$

2.4.2 Four Transmit and One Receive Antenna

At a given symbol period, four signals are transmitted simultaneously from four transmit antennas. The signal transmitted from antenna one is denoted by s_1, the signal from antenna two by s_2, the signal from antenna three by s_3 and the signal from antenna four by s_4. This process will go on in the same manner until transmitting the last column of the G_4 transmission matrix as given in Equation (2.16) is transmitted.

$$S = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} \tag{2.16}$$

The matrix in Equation (2.16) has a rate of half and is used as STBC encoder to transmit any complex signal constellations. The encoding, mapping and transmission of the STBC can be summarized in the following table:

Table 2.4: Encoding and mapping of STBC for four transmit antennas using complex signals.

	Tx_1	Tx_2	Tx_3	Tx_4
t	s_1	s_2	s_3	s_4
$t+T$	$-s_2$	s_1	$-s_4$	s_3
$t+2T$	$-s_3$	s_4	s_1	$-s_2$
$t+3T$	$-s_4$	$-s_3$	s_2	s_1
$t+4T$	s_1^*	s_2^*	s_3^*	s_4^*
$t+5T$	$-s_2^*$	s_1^*	$-s_4^*$	s_3^*
$t+6T$	$-s_3^*$	s_4^*	s_1^*	$-s_2^*$
$t+7T$	$-s_4^*$	$-s_3^*$	s_2^*	s_1^*

For a four transmit and one receive antenna system, the channel coefficients are modeled by a complex multiplicative distortions, h_1 for the first transmit antenna, h_2 for the second transmit antenna, h_3 for the third transmit antenna and h_4 for the fourth transmit antenna. Figure 2.8 shows the four transmit and one receive antenna scheme.

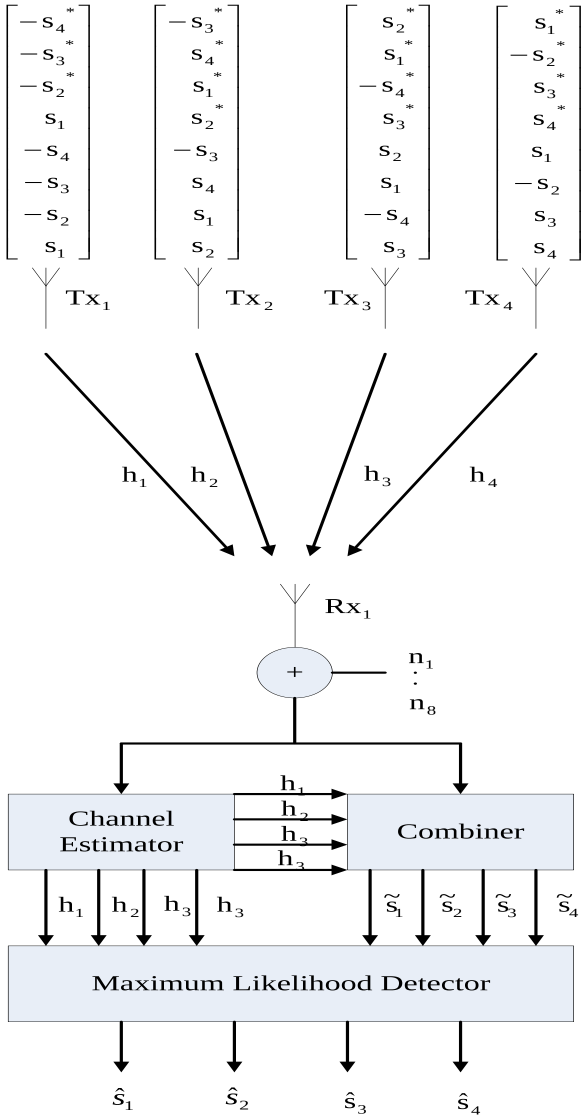

Figure 2.8: Space-time block code scheme with four transmit and one receive antennas.

Assuming the fading is constant across four consecutive symbols then channel coefficients can be represented as:

$$\begin{aligned} h_1(t) &= h_1(t+T) = h_1 = |h_1| e^{j\theta_1} \\ h_2(t) &= h_2(t+T) = h_2 = |h_2| e^{j\theta_2} \\ h_3(t) &= h_3(t+T) = h_3 = |h_3| e^{j\theta_3} \\ h_4(t) &= h_4(t+T) = h_4 = |h_4| e^{j\theta 4} \end{aligned} \tag{2.16}$$

where $|h_i|$ and θ_i, i = 1,2,3 and 4 are the amplitude and phase shift for the path from transmit antenna i to receive antenna j.

The channel coefficients for space-time block codes with four transmit and one receive antenna is shown in Table 2.5.

Table 2.5: Four transmit and one receive antenna channel coefficients.

	Rx_1
Tx_1	h_1
Tx_2	h_2
Tx_3	h_3
Tx_4	h_4

The receiver in this case will receive eight different signals in eight different time slots. The received signals can be represented as:

$$\begin{aligned}
r_1 &= h_1 s_1 + h_2 s_2 + h_3 s_3 + h_4 s_4 + n_1 \\
r_2 &= -h_1 s_2 + h_2 s_1 - h_3 s_4 + h_4 s_3 + n_2 \\
r_3 &= -h_1 s_3 + h_2 s_4 + h_3 s_1 - h_4 s_2 + n_3 \\
r_4 &= -h_1 s_4 - h_2 s_3 + h_3 s_2 + h_4 s_1 + n_4 \\
r_5 &= h_1 s_1^* + h_2 s_2^* + h_3 s_3^* + h_4 s_4^* + n_5 \\
r_6 &= -h_1 s_2^* + h_2 s_1^* - h_3 s_4^* + h_4 s_3^* + n_6 \\
r_7 &= -h_1 s_3^* + h_2 s_4^* + h_3 s_1^* - h_4 s_2^* + n_7 \\
r_8 &= -h_1 s_4^* - h_2 s_3^* + h_3 s_2^* + h_4 s_1^* + n_8
\end{aligned} \qquad (2.17)$$

The combiner in Figure 2.8 builds the following four combined signals:

$$
\begin{aligned}
\tilde{s}_1 &= h_1^* r_1 + h_2^* r_2 + h_3^* r_3 + h_4^* r_4 + h_1 r_5^* + h_2 r_6^* + h_3 r_7^* + h_4 r_8^* \\
\tilde{s}_2 &= h_2^* r_1 - h_1^* r_2 - h_4^* r_3 + h_3^* r_4 + h_2 r_5^* - h_1 r_6^* - h_4 r_7^* + h_3 r_8^* \\
\tilde{s}_3 &= h_3^* r_1 + h_4^* r_2 - h_1^* r_3 - h_2^* r_4 + h_3 r_5^* + h_4 r_6^* - h_1 r_7^* - h_2 r_8^* \\
\tilde{s}_4 &= -h_4^* r_1 - h_3^* r_2 + h_2^* r_3 - h_1^* r_4 - h_4 r_5^* - h_3 r_6^* + h_2 r_7^* - h_1 r_8^*
\end{aligned} \qquad (2.18)
$$

These four combined signals are then sent to the maximum likelihood detector.

2.4.3 Four Transmit and Two Receive Antennas

The implementation of four transmit and two receive antennas is the same as the four transmit and one receive antennas except that there are two receivers instead of one, each of which receives eight different signals that come through four different channels.

Table 2.6 shows the channel coefficients for space-time block codes with four transmit and two receive antennas.

Table 2.6: Four transmit and two receive antenna channel coefficients.

	Rx_1	Rx_2
Tx_1	h_1	h_5
Tx_2	h_2	h_6
Tx_3	h_3	h_7
Tx_4	h_4	h_8

Figure 2.9 shows the diagram of space-time block codes system with four transmit and two receive antennas.

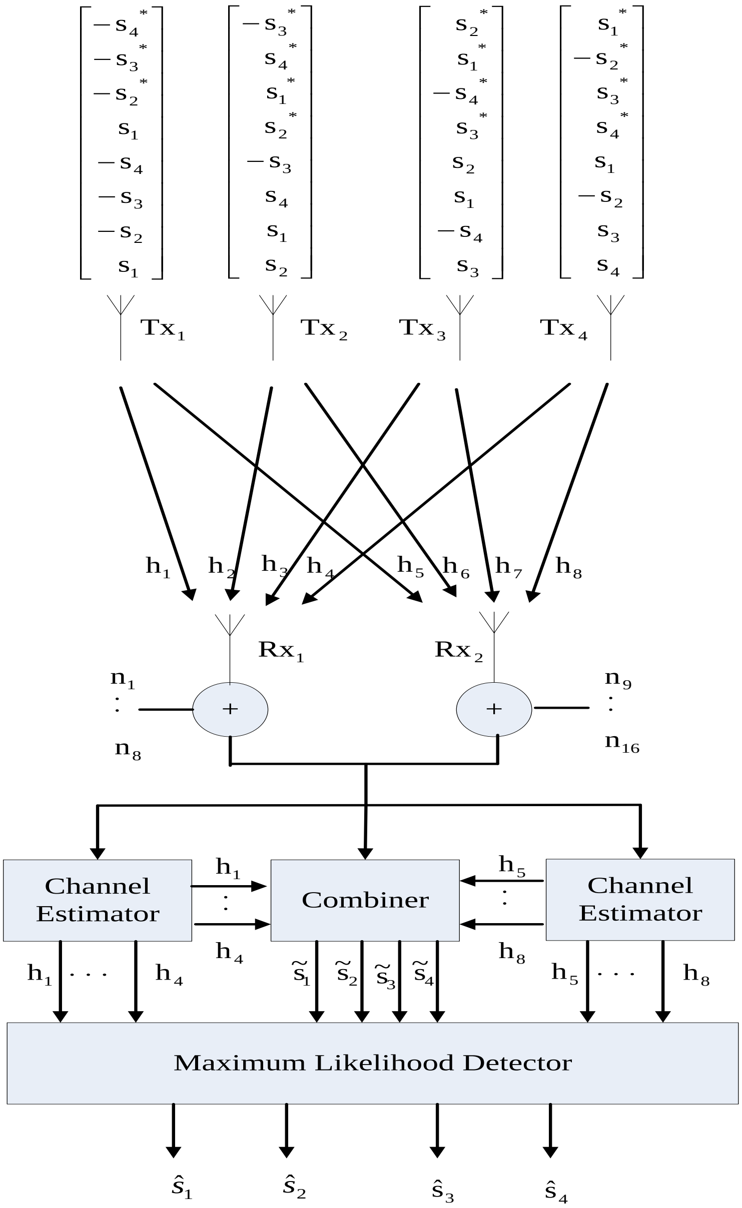

Figure 2.9: Space-time block code scheme with four transmit and two receive antennas.

The two receivers in this case receive eight different signals in eight different time slots. These received signals can be presented as:

$$
\begin{aligned}
r_1 &= h_1 s_1 + h_2 s_2 + h_3 s_3 + h_4 s_4 + n_1 \\
r_2 &= -h_1 s_2 + h_2 s_1 - h_3 s_4 + h_4 s_3 + n_2 \\
r_3 &= -h_1 s_3 + h_2 s_4 + h_3 s_1 - h_4 s_2 + n_3 \\
r_4 &= -h_1 s_4 - h_2 s_3 + h_3 s_2 + h_4 s_1 + n_4 \\
r_5 &= h_1 s_1^* + h_2 s_2^* + h_3 s_3^* + h_4 s_4^* + n_5 \\
r_6 &= -h_1 s_2^* + h_2 s_1^* - h_3 s_4^* + h_4 s_3^* + n_6 \\
r_7 &= -h_1 s_3^* + h_2 s_4^* + h_3 s_1^* - h_4 s_2^* + n_7 \\
r_8 &= -h_1 s_4^* - h_2 s_3^* + h_3 s_2^* + h_4 s_1^* + n_8
\end{aligned} \tag{2.19}
$$

$$
\begin{aligned}
r_9 &= h_5 s_1 + h_6 s_2 + h_7 s_3 + h_8 s_4 + n_9 \\
r_{10} &= -h_5 s_2 + h_6 s_1 - h_7 s_4 + h_8 s_3 + n_{10} \\
r_{11} &= -h_5 s_3 + h_6 s_4 + h_7 s_1 - h_8 s_2 + n_{11} \\
r_{12} &= -h_5 s_4 - h_6 s_3 + h_7 s_2 + h_8 s_1 + n_{12} \\
r_{13} &= h_5 s_1^* + h_6 s_2^* + h_7 s_3^* + h_8 s_4^* + n_{13} \\
r_{14} &= -h_5 s_2^* + h_6 s_1^* - h_7 s_4^* + h_8 s_3^* + n_{14} \\
r_{15} &= -h_5 s_3^* + h_6 s_4^* + h_7 s_1^* - h_8 s_2^* + n_{15} \\
r_{16} &= -h_5 s_4^* - h_6 s_3^* + h_7 s_2^* + h_8 s_1^* + n_{16}
\end{aligned} \tag{2.20}
$$

The combiner in Figure 2.9 combines the eight signals arrived at each of the receiver antennas and adds them in the same way as done in Equation (2.14) creating four new signals. These four combined signals are then sent to the maximum likelihood detector to estimate the original transmitted signal.

2.5 Space-Time Block Codes for Real Constellations

Space-time block codes can also be constructed with real signals if a real signal constellation (modulation) is used. There space-time block codes can achieve the full rate and offer the full transmit diversity of n_T if and only if a real signal constellation square matrix is used.

Real square transmission matrix S for space-time block codes exist if and only if the number of transmit antennas n_T = 2, 4, or 8 [15]. These codes offer the full transmit diversity of n_T because they are full rate $R = 1$.

2.5.1 Two Transmit and One Receive Antennas

The transmission matrix for two transmit antennas is exactly the same as the G_2 square matrix for Alamouti scheme except that in the real case, there are no symbol conjugations. Therefore, the transmission matrix is given by:

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{bmatrix} \tag{2.21}$$

The encoding and decoding here can be constructed in exactly the same way as in the Alamouti's scheme. The receiver receives:

$$\begin{aligned} r_1 &= h_1 s_1 + h_2 s_2 + n_1 \\ r_2 &= -h_1 s_2 + h_2 s_1 + n_2 \end{aligned} \tag{2.22}$$

The combiner combines the received signals as:

$$\begin{aligned} \tilde{s}_1 &= h_1 r_1 + h_2 r_2 \\ \tilde{s}_2 &= h_2 r_1 - h_1 r_2 \end{aligned} \tag{2.23}$$

The combined signals then are sent to ML detector following the same rule in Equation (2.5).

2.5.2 Four Transmit and One Receive Antennas

The space-time block code transmission matrix for four transmit antennas is given by:

$$S = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \tag{2.24}$$

The encoding and decoding for the real space-time block code can be created out in the same manner as the encoding and decoding for the space-time block code with complex constellations except in this case there are four symbols transmitted in four time transmission periods instead of eight.

The encoder maps the created matrix to the four transmit antennas as in the following table.

Table 2.7: Encoding and mapping STBC for four transmit antennas using real signals.

	Tx_1	Tx_2	Tx_3	Tx_4
t	s_1	$-s_2$	$-s_3$	$-s_4$
$t+T$	s_2	s_1	s_4	$-s_3$
$t+2T$	s_3	$-s_4$	s_1	s_2
$t+3T$	s_4	s_3	$-s_2$	s_1

The receiver receives the four transmitted signals. The four received signals can be written as:

$$\begin{aligned} r_1 &= h_1 s_1 + h_2 s_2 + h_3 s_3 + h_4 s_4 + n_1 \\ r_2 &= -h_1 s_2 + h_2 s_1 - h_3 s_4 + h_4 s_3 + n_2 \\ r_3 &= -h_1 s_3 + h_2 s_4 + h_3 s_1 - h_4 s_2 + n_3 \\ r_4 &= -h_1 s_4 - h_2 s_3 + h_3 s_2 + h_4 s_1 + n_4 \end{aligned} \tag{2.25}$$

The combiner in Figure 2.9 builds the following four combined signals:

$$\begin{aligned}
\tilde{s}_1 &= h_1 r_1 + h_2 r_2 + h_3 r_3 + h_4 r_4 \\
\tilde{s}_2 &= h_2 r_1 - h_1 r_2 - h_4 r_3 + h_3 r_4 \\
\tilde{s}_3 &= h_3 r_1 + h_4 r_2 - h_1 r_3 - h_2 r_4 \\
\tilde{s}_4 &= -h_4 r_1 - h_3 r_2 + h_2 r_3 - h_1 r_4
\end{aligned} \tag{2.26}$$

These four combined signals are then sent to the maximum likelihood detector to recover the four original transmitted symbols.

2.6 Performance of Space-time Block Codes

The performance of space-time block codes depends on the type of modulation and the number of transmit and receive antennas used. Complex modulations give better bit-error-rate performance than real modulations and it is especially true when the number of transmit antennas is larger than two. As an example, if space-time block codes with four transmit antennas and complex modulation scheme are used, then a four by eight (rate of 1/2) transmission matrix will be used. This would give a better performance than the same space-time block code with real modulation of rate of one. However, space-time block code with real modulation would have better bandwidth efficiency performance than complex modulation. This is because space-time block codes with real modulation require transmitting less data than space-time block codes with complex modulation. On the other hand, space-time block codes with larger number of transmit antennas always give better performance than space-time block codes with lower number of transmit antennas. This is true because lager number of transmit antennas means larger transmission matrices which means transmitting more data. This would give the receiver the ability to recover the transmitted data. Moreover, with larger number of receive antennas, the same transmitted data would be received by more than one receive antenna. This is an advantage because if one receive antenna did not recover the transmitted data correctly, the second receive antenna could. The chance that at least one out of two receive antennas would receive the transmitted data uncorrupted is always higher than if there is only one receive antenna.

Many simulations have been done on the performance of different space-time block codes using different types of modulation schemes and different numbers of transmit and receive antennas. In our simulation on the different implementations of space-time block codes, the channel coefficients are always assumed flat Rayleigh. Figures 2.10 and 2.11 show the performance of G_2 and G_4 space-time block codes with 16-QAM modulation. Also, Figures 2.12 and 2.13 show the performance of the same system using QPSK modulation. And as last, Figures 2.14 and 2.15 show the performance using BPSK modulation.

From the figures below, it is very clear to see the performance of space-time block codes using 16-QAM, QPSK, and BPSK modulation schemes. The performance of bit-error-rate using BPSK modulation is better than the performance of space-time block codes using QPSK and 16-QAM modulations. The performance of space-time block codes using QPSK modulation is better than the performance of space-time block codes using 16-QAM modulation. This better performance is due to the number of bits that each modulated symbol can take. All BPSK modulated symbols can take only one bit at a time. However, QPSK modulated symbols take two bits and 16-QAM takes four bits per modulated symbol.

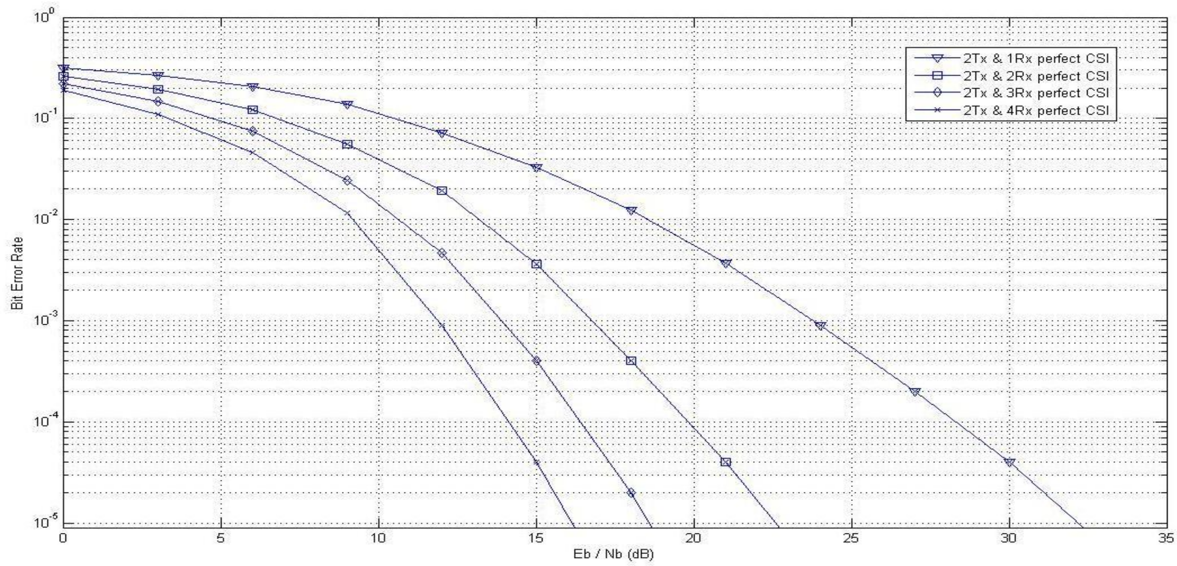

Figure 2.10: Space-time block code scheme with two transmit and M receive antennas using 16-QAM modulation.

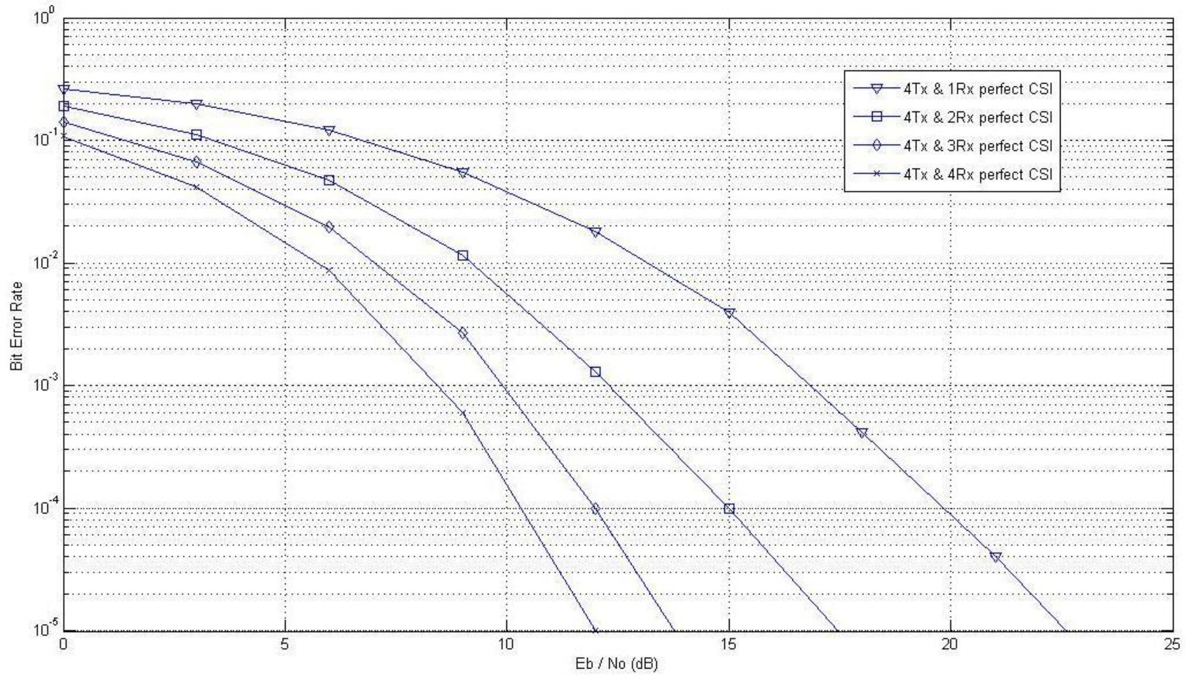

Figure 2.11: Space-time block code scheme with four transmit and M receive antennas using 16-QAM modulation.

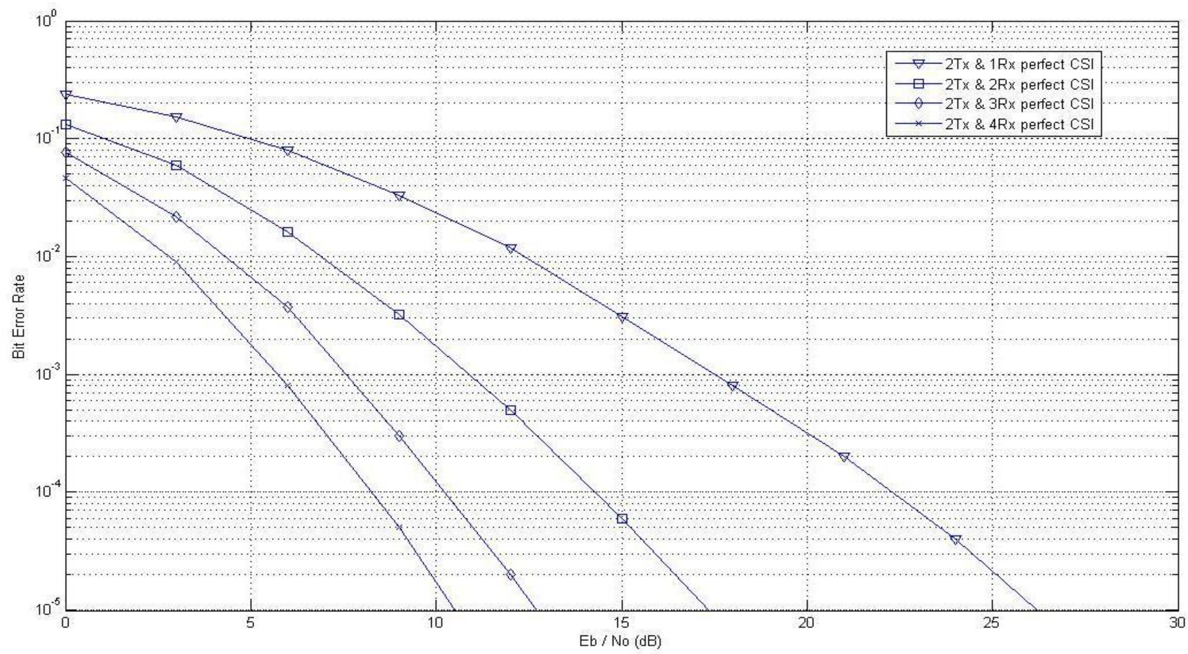

Figure 2.12: Space-time block code scheme with two transmit and M receive antennas using QPSK modulation.

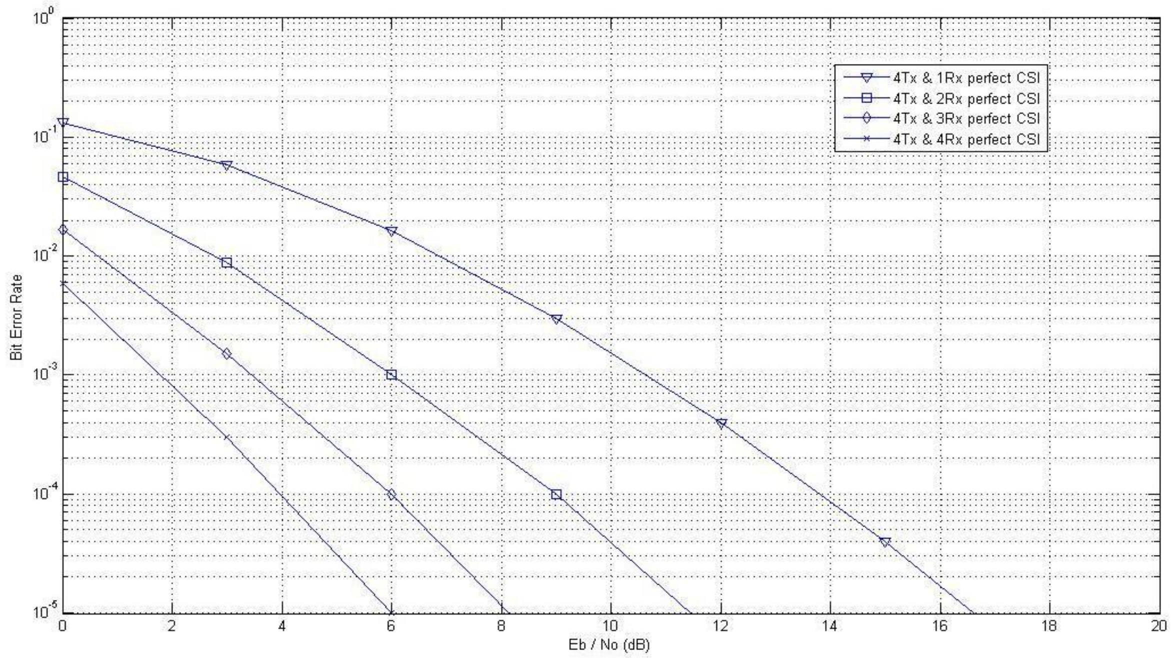

Figure 2.13: Space-time block code scheme with two transmit and M receive antennas using QPSK modulation.

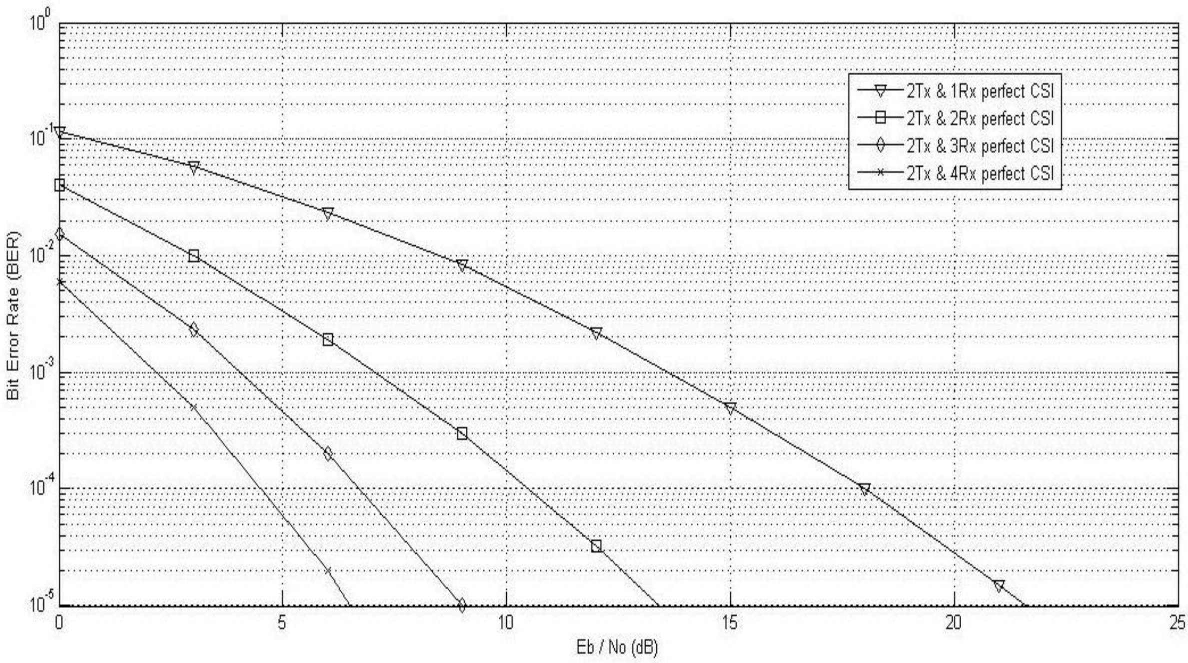

Figure 2.14: Space-time block code scheme with two transmit and M receive antennas using BPSK modulation.

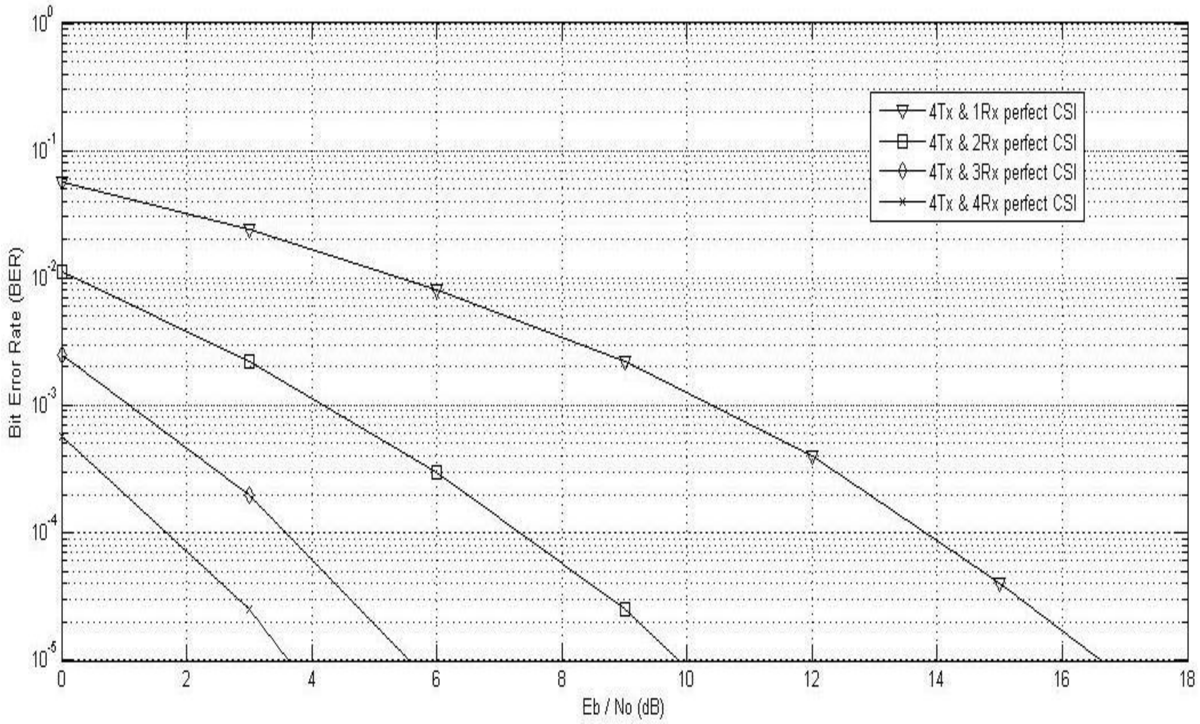

Figure 2.15: Space-time block code scheme with four transmit and M receive antennas using BPSK modulation.

Table 2.8 summarizes the bit-error-rate performance of space-time block codes using BPSK, QPSk, and 16-QAM modulation.

Table 2.8: Performance of space-time block codes using BPSK, QPSK, and 16-QAM modulation.

Modulation	Number of $Tx - Rx$	SNR (dB) for BER 10^{-2}	SNR (dB) for BER 10^{-3}	SNR (dB) for BER 10^{-4}
BPSK	2:1	8	13	18
BPSK	4:1	5	10.5	14
QPSK	2:1	13	17	23
QPSK	4:1	7	11	14
16-QAM	2:1	18	24	28
16-QAM	4:1	13	17	20

From the table above, it is very clear that the best bit-error-rate performance was given by space-time block codes using BPSK, QPSK, and 16-QAM. The performance of space-time block codes with BPSK modulation is better than the performance of space-time block codes with QPSK modulation by approximately 4 dB. The performance of space-time block codes with QPSK modulation is better than the performance of space-time block codes with 16-QAM modulation by approximately 5~6 dB. The BER performance of space-time block codes that employs 16-QAM modulation method is worse than the BER performance of space-time block codes that employs QPSK modulation method. This worse in performance is due the number of bit 16-QAM modulation method takes when compared with the number of bits QPSK modulation method take. This is also true when the performance of space-time block codes that employs QPSK modulation method is compared with the performance of space-time block codes that employs BPSK modulation method.

2.7 Conclusions

In this chapter, Alamouti scheme and space-time block codes encoding, decoding and performances were covered and explained in details. Different modulation schemes were used with the different implementations (different numbers of transmit and receive antennas) of space-time block codes. This includes complex and real signal constellation. All simulation results were shown and explained in details.

This chapter has introduced the concept of transmit diversity from first principles. In section 2.2, we studied Alamouti scheme with perfect channel knowledge at the receiver. The encoding, decoding, and maximum likelihood detection scheme of the Alamouti's code were explored in details. Next, section 2.3 we went on discussing analyzing the performance of the different implementations of space-time block codes that use higher number of transmit and receive antennas. In the section 2.4, space-time block codes were implemented using complex and real signals. In this chapter, BPSK, QPSK and 16-QAM signal constellations were employed. Section 2.6 show the bit-error-rate performance of the different space-time block code implementations.

In this chapter all simulations were based on perfect knowledge of the channel coefficients at the receiver. In real wireless communication systems, this assumption would not hold because channel coefficients are always needed to be estimated. In the next two chapters, we propose two new channel estimation schemes [16, 17].

References

[1] A. Paulraj, R. Nabar and D. Gore, "Introduction to Space-time Wireless Communications", Cambridge university Press. 2003.

[2] Gregory D. Durgin, "Space-time Wireless Channels", Prentice Hall PTR. Pearson Education, Inc. 2003.

[3] B. Vucetic, J. Yuan, "Space-time Coding", John Wiley & Sons Ltd, England. 2003.

[4] Erik G. Larsson and P. Stoica, "Space-time Block Coding for Wireless Communications", Cambridge University Press. 2003.

[5] J.C. Guey, M.R. Fitz, M.R. Bell, and W.Y. Kuo, "Signal Design for Transmitter Diversity Wireless Communication Systems Over Rayleigh Fading Channels," IEEE Transactions on Communications, Vol. 47, No. 4, pp. 527-537, April 1999.

[6] J. H. Winters, "Diversity Gain of Transmit Diversity in Wireless System with Rayleigh Fading,". IEEE Transactions, Vol. 47,pp. 119-123, 1998

[7] G. W. Wornell and M. D. Trott, "Efficient Signal Proccessing Techniques for Exploiting Transmit Antenna Diversity on Fading Channels", IEEE Transactions on Signal Processing, Vol. 45,pp. 191-205, 1997.

[8] W. Y. Kuo and M. P. Fitz, "Design and Analysis of Transmitter Diversity Using Intentional Frequency Offset for Wireless Communications,". IEEE Transactions, Vol. 46, pp. 871-881, 1997.

[9] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, "Space-time Block Codes from Orthogonal Designs," IEEE Transactions on Information Theory, Vol. 45, No. 5, pp. 1456-1467, July 1999.

[10] S.M Alamouti, “A simple Transmitter Diversity Scheme for Wireless Communications”, IEEE Journal on Selected Areas in Communications, Vol. SAC-16, pp. 1451-1458, October 1998.

[11] S. H. Nam, J. Chung, C. Hwang, and Y. Jung, “Differential Space-time Block Codes using Non-constant Modulus Constellations for Four Transmit Antennas”, IEICE Transactions on Communications, Vol. E88-B, No. 4, April 2005.

[12] B. M. Popovic, ”New Complex Space-time Block Codes for Efficient Transmit Diversity”, IEEE 6th International Symposium On Spread-Spectrum Tech & Applications, Sept. 6-8, 2000.

[13] H. Jafarkhani, “A quasi-orthogonal Space-time Block Code, ” IEEE Transactions on Communications, Vol. 49, No. 1, pp. 1-4, January 2001.

[14] H. Jafarkhani, “Space-Time Coding: Theory and Practice”, Cambridge University Press, 2005.

[15] V. Tarokh, N. Seshadri and A. R. Calderbank, “Space-time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction”, IEEE Transactions on Information Theory, Vol. 44, No. 2, pp. 744-765, March. 1998.

[16] V. Tarokh, S. M. Alamouti, and P. Poon, “New Detection Schemes for Transmit Diversity with no Channel Estimation,” IEEE International Conference, Universal Personal Communications, pp. 917-920, 1998.

[17] J. Yang, E. Masood and Y. Sun, “Performance of Space-time Block Coding Using Estimated Channel Parameters”, London Communications Symposium Conference UCL, 2004.

3 Joint Channel Estimation and Data Detection for Space-Time Block Coding with no Channel State Information

3.1 Introduction

The decoding of space-time codes requires the knowledge of channel state information at the receiver, which is usually difficult to obtain. All space-time schemes assume ideal channel state information. However, channel parameters are normally not known in practice due to changing environments and thus need to be estimated.

There is a substantial literature addressing the channel estimation issue for MIMO systems. There are several coherent STC schemes that do require channel information at the receiver, ranging from standard training based techniques that relay on pilot symbols in the data stream to blind and semi-blind estimations. In semi-blind the observations corresponding to data and pilot are used jointly. Other non-coherent STC schemes do not require the channel information at the receiver. These are called differential STC schemes; they suffer a significant performance penalty from coherent techniques. The non-coherent techniques are more suitable for rapidly-fading channels that experience significant variation within the transmission block. For quasi-static or slow-varying fading channels, training-based channel estimation at the receiver is very common in practice.

A channel estimator extracts from the received signal an approximation to the fade coefficients during each data frame. This can be done using training or pilot symbols or sequences to estimate the channels from each of the transmit antennas to each receive antenna. The advantage of pilot symbol insertion is that it neither requires a complex signal process nor does it increase the peak factor of the modulated carrier. One method of MIMO channel estimation is to turn off all transmit antennas apart from antenna i at some time instant and to send a pilot signal using antenna i. The fade coefficients h_{ij} are then estimated for all j. This procedure is repeated for all i until all the coefficients are estimated. The general system including channel estimation using pilot symbols is shown in Figure 3.1.

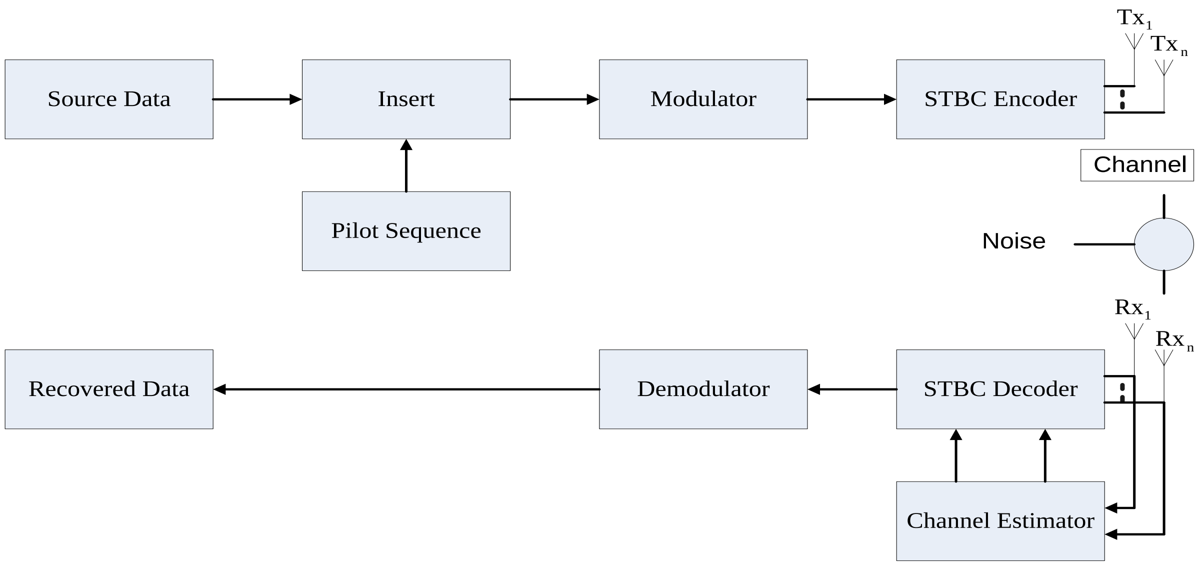

Figure 3.1: General system for channel estimation using pilot symbols.

A second method of estimation is to send orthogonal sequence of signals for pilot signals, one from each transmit antenna. This has been used for space-time Trellis coded systems [1]. The use of the orthogonal pilot sequence can ensure a full rank of the coefficient matrix. A pilot based method for channel estimation has also been proposed for space-time block coded systems [2]. In [2] if the training/pilot sequence is treated by the modulator and STBC encoder in the same rules as for user data, the coefficient matrix is always non-singular because of the orthogonality of STBC codes of the user data. This is obviously a convenience, which takes the advantage of space-time block code systems. All these methods, however, deal with channel estimation and signal detection separately.

Moreover, other researchers have considered non-coherent detection schemes based on differential encoding that do not require channel state information [2] [3] [4]. Although these methods avoid the need for channel estimation, they often suffer from problems such as error propagation.

Commonly, pilot sequences are used for the advantage of recovering the channel parameters at the receiver side. However, the use of these sequences has some disadvantages. The increase in the number of channel parameters, due to the use of multiple antennas, makes the conventional training based scheme less reliable and prone to multi-access interference. For a reasonable performance, the conventional training based method requires more power and larger number of pilot symbols which reduces system efficiency.

Because of the reasons mentioned above, a lot of research has been carried out on finding new better channel estimation methods that would give better results than the existing estimation schemes. These reasons also motivated Tarokh to work with other researchers on finding better schemes. Indeed, they proposed a new joint estimation and detection scheme that works with the simple Alamouti code using QPSK modulation [5].

This chapter starts with a review of Tarokh's simple joint channel estimation and data detection scheme in section 3.2. The chapter continues with the proposed new general version of the joint estimation and detection scheme in section 3.3. The new scheme is fully investigated and tested with all combinations of transmit and receive antennas. This chapter includes the performance of Tarokh joint and detection scheme and the proposed new scheme using two types of complex signals that use QPSK and 16-QAM modulations. All simulation results are produced in section 3.4. However, the performance of the two schemes with real signals will be covered in Chapter 5. A brief conclusion in section 3.5 will end up the chapter.

3.2 Tarokh's Joint Estimation and Detection Scheme for Alamouti's Code

Vahid Tarokh in [3] used transmit diversity scheme invented by Alamouti in [6] which was also given in Chapter Two, and proposed a new detection scheme that does not require channel state information (CSI). To keep presentation simple, Taorkh assumed the fading coefficients are constant over every four consecutive transmissions. This assumption is reasonable because the symbol duration T is small compared to the speed of change in wireless channel often described by the maximum Doppler frequency d_f. Further, Tarokh assumed that the constellation points have an equal energy that is normalized to 1/2. It is also assumed that the receiver knows the transmitted signals s_1, s_2, and the received words r_1, r_2, ... , r_n. It proceeds to detect the transmitted signals s_3, s_4. Having s_3 and s_4 computed the process is repeated to compute s_5 and s_6 and then s_7 and s_8 and so on. Moreover, Tarokh assumed that the path gains between distinct transmit and receive antennas are independent. In this scheme, Tarokh divided the transmit data into a number of blocks. Each block consists of 50 QPSK symbols. At the beginning of block two known symbols are transmitted. This will ensure that the error propagation is confined within a single block. The noise and interference are assumed to have a Gaussian distribution.

The first encoded matrix is $S_1(s_1 \& s_2)$ and the second encoded matrix is $S_2(s_3 \& s_4)$.

$$S_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{3.1}$$

$$S_2 = \begin{bmatrix} s_3 & s_4 \\ -s_4^* & s_3^* \end{bmatrix} \tag{3.2}$$

The channel coefficients $H_1(h_1 \& h_2)$ are assumed constant over four consecutive transmissions and defined as:

$$H_1 = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} |h_1|e^{j\theta_1} \\ |h_2|e^{j\theta_2} \end{bmatrix} \tag{3.3}$$

The noise and interference coefficients $N_1(n_1 \,\&\, n_2)$ and $N_2(n_3 \,\&\, n_4)$ are expressed by complex random variables as:

$$N_1 = \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{3.4}$$

$$N_2 = \begin{bmatrix} n_3 \\ n_4 \end{bmatrix} \tag{3.5}$$

The receiver receives $R_1(r_1 \,\&\, r_2)$ for the first two transmission signals and then receives $R_2(r_3 \,\&\, r_4)$ for the second two transmission signals. The four received signals are given as:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = S_1 H_1 + N_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \begin{bmatrix} s_1 h_1 + s_2 h_2 + n_1 \\ -s_2^* h_1 + s_1^* h_2 + n_2 \end{bmatrix} \tag{3.6}$$

$$R_2 = \begin{bmatrix} r_3 \\ r_4 \end{bmatrix} = S_2 H_1 + N_2 = \begin{bmatrix} s_3 & s_4 \\ -s_4^* & s_3^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_3 \\ n_4 \end{bmatrix} = \begin{bmatrix} s_3 h_1 + s_4 h_2 + n_3 \\ -s_4^* h_1 + s_3^* h_2 + n_4 \end{bmatrix} \tag{3.7}$$

At the receiver side, the receiver first receives the pilot sequence S_1 in Equation (3.1) and uses it to estimate the channel coefficients H_1 using the minimum mean square error (MMSE) as:

$$\dot{H}_1 = \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{bmatrix} = S_1^{-1} R_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}^{-1} \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} \tag{3.8}$$

Using $\dot{H}_1$ in Equation (3.8), the receiver constructs a new matrix $\ddot{H}_1$ that can be expressed by:

$$\ddot{H}_1 = \begin{bmatrix} \tilde{h}_1^* & \tilde{h}_2 \\ \tilde{h}_2^* & -\tilde{h}_1 \end{bmatrix} \quad (3.9)$$

Where the vectors $\tilde{h}_1$ and $\tilde{h}_2$ are the estimated channel coefficient vectors and equal to:

$$\tilde{h}_1 = \frac{r_1 s_1^* - r_2 s_2}{|s_1|^2 + |s_2|^2} \quad (3.10)$$

$$\tilde{h}_2 = \frac{r_1 s_2^* - r_2 s_1}{|s_1|^2 + |s_2|^2} \quad (3.11)$$

The receiver then constructs another new matrix $\ddot{R}_1$ from Equation (3.7). The new constructed matrix is given by:

$$\ddot{R}_1 = \begin{bmatrix} r_3 \\ r_4^* \end{bmatrix} \quad (3.12)$$

The receiver uses the constructed channel matrix $\ddot{H}_1$ and the constructed received data vector $\ddot{R}_1$ for the combining scheme. The combined signals can be shown as:

$$\tilde{S}_2 = \begin{bmatrix} \tilde{s}_3 \\ \tilde{s}_4 \end{bmatrix} = \ddot{H}_1 \ddot{R}_1 = \begin{bmatrix} \tilde{h}_1^* & \tilde{h}_2 \\ \tilde{h}_2^* & -\tilde{h}_1 \end{bmatrix} \begin{bmatrix} r_3 \\ r_4^* \end{bmatrix} \quad (3.13)$$

After combining all the received signals, the resultant are then sent to the maximum-likelihood detector to detect the user data vector $\hat{S}_2(\hat{s}_3 \,\&\, \hat{s}_4)$. After recovering the vector $\hat{S}_2$, the receiver saves it as S_1 and saves the vector R_2 as the vector R_1 for next iteration. The procedure will go on until all the transmitted data are received and recovered by the receiver.

3.3 Generalized Scheme for Space-time Block Codes (STBCs)

To keep presentation simple, we discuss the generalizations of Tarokh scheme for three representative cases: two transmit and two receive antennas, four transmit and one receive antenna and four transmit and two receive antennas in detail. For the four transmit and four receive antennas case, more channel coefficients have to be considered. The same procedure for increasing the receive antennas from one to two given in the section can be readily followed.

3.3.1 Joint Scheme for Two Transmit and Two Receive Antennas

In this implementation, there are two transmit and two receive antennas. All assumptions in Section 3.2 are followed and applied. The transmitter takes four symbols and constructs two G_2 matrices S_1 and S_2. The transmission matrix S_1 is used to transmit the pilot sequence and it is equal to the transmission matrix S_1 in Equation (3.1). The transmission matrix S_2 is used to transmit the user data and it is equal to the transmission matrix S_2 in Equation (3.2).

At the receiver side, there are two receive antennas, each of which receives four consecutive signals. The first receive antenna receives $r_{1,1}$ and $r_{2,1}$ representing the pilot sequence and then receives $r_{3,1}$ and $r_{4,1}$ representing the information data. The second receive antenna receives $r_{1,2}$ and $r_{2,2}$ representing the pilot sequence and then receives $r_{3,2}$ and $r_{4,2}$ representing the information data. The four received signals at the first receive antenna can be written as:

$$R_1 = \begin{bmatrix} r_{1,1} \\ r_{2,1} \end{bmatrix} = S_1 H_1 + N_1 = \begin{bmatrix} s_1 h_1 + s_2 h_2 + n_{1,1} \\ -s_2^* h_1 + s_1^* h_2 + n_{2,1} \end{bmatrix} \tag{3.14}$$

$$R_2 = \begin{bmatrix} r_{3,1} \\ r_{4,1} \end{bmatrix} = S_2 H_1 + N_2 = \begin{bmatrix} s_3 h_1 + s_4 h_2 + n_{3,1} \\ -s_4^{*} h_1 + s_3^{*} h_2 + n_{4,1} \end{bmatrix} \tag{3.15}$$

the other four received signals at the second receiver antenna can be written as

$$R_3 = \begin{bmatrix} r_{1,2} \\ r_{2,2} \end{bmatrix} = S_1 H_2 + N_3 = \begin{bmatrix} s_1 h_3 + s_2 h_4 + n_{1,2} \\ -s_2^{*} h_3 + s_1^{*} h_4 + n_{2,2} \end{bmatrix} \tag{3.16}$$

$$R_4 = \begin{bmatrix} r_{3,2} \\ r_{4,2} \end{bmatrix} = S_2 H_2 + N_4 = \begin{bmatrix} s_3 h_3 + s_4 h_4 + n_{3,2} \\ -s_4^{*} h_3 + s_3^{*} h_4 + n_{4,2} \end{bmatrix} \tag{3.17}$$

After receiving all the transmitted eight signals, the receiver estimate the channel vector H_1 from Equation (3.14) and estimates the channel vector H_2 from Equation (3.16) as in the following:

$$\dot{H}_1 = S_1^{-1} R_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2^{*} & s_1^{*} \end{bmatrix}^{-1} \begin{bmatrix} r_{1,1} \\ r_2,1 \end{bmatrix} \tag{3.18}$$

$$\dot{H}_2 = S_1^{-1} R_3 = \begin{bmatrix} s_1 & s_2 \\ -s_2^{*} & s_1^{*} \end{bmatrix}^{-1} \begin{bmatrix} r_{1,2} \\ r_{2,2} \end{bmatrix} \tag{3.19}$$

The receiver constructs the channel matrix $\ddot{H}_1$ from Equation (3.18) and constructs the channel matrix $\ddot{H}_2$ from Equation (3.19). The new constructed the channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ can be expressed as in Equation (3.9).

After estimating the required channel coefficients vectors, the receiver constructs the vector $\ddot{R}_1$ from the received data vector in Equation (3.15) and constructs the vector $\ddot{R}_2$ from the received data vector in Equation (3.17). The constructed vectors would have the same format as the constructed vector in Equation (3.12). The receiver next uses the constructed matrices

$\ddot{H}_1$, $\ddot{H}_2$ and the constructed vectors $\ddot{R}_1$ and $\ddot{R}_2$ for the combining scheme. The combining scheme in this case can be expressed as:

$$\tilde{S}_2 = \ddot{H}_1\ddot{R}_1 + \ddot{H}_2\ddot{R}_2 = \begin{bmatrix} \tilde{h}_1^{\ *} & \tilde{h}_2 \\ \tilde{h}_2^{\ *} & -\tilde{h}_1 \end{bmatrix} \begin{bmatrix} r_{3,1} \\ r_{4,1}^{\ *} \end{bmatrix} + \begin{bmatrix} \tilde{h}_3^{\ *} & \tilde{h}_4 \\ \tilde{h}_4^{\ *} & -\tilde{h}_3 \end{bmatrix} \begin{bmatrix} r_{3,2} \\ r_{4,2}^{\ *} \end{bmatrix} \tag{3.20}$$

The combined signals in Equation (3.20) are sent to the maximum-likelihood detector to detect $\hat{S}_2(\hat{s}_3 \,\&\, \hat{s}_4)$. After that, the receiver saves the vector $\hat{S}_2$ as S_1 and saves the vector R_2 as R_1 for next iteration. The procedure will go on until all the transmitted data are received and recovered by the receiver.

3.3.2 Joint Scheme for Four Transmit and One Receive Antennas

In this joint scheme implementation, there are four transmit and one receive antennas. Again, all the mentioned assumptions above in Section 3.2 are applied. The transmitter takes eight symbols and constructs two G_4 matrices S_1 and S_2. In this case, complex G_4 matrices only are considered.

The transmitter takes four modulated symbols to construct the transmission matrix S_1 to transmit the pilot sequences and takes another four modulated symbols to construct the transmission matrix S_2 to transmit the source data. The two constructed transmission matrices can be shown as:

$$S_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} \tag{3.21}$$

$$S_2 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \\ s_5^* & s_6^* & s_7^* & s_8^* \\ -s_6^* & s_5^* & -s_8^* & s_7^* \\ -s_7^* & s_8^* & s_5^* & -s_6^* \\ -s_8^* & -s_7^* & s_6^* & s_5^* \end{bmatrix} \tag{3.22}$$

The two matrices S_1 and S_2 are transmitted consecutively through a Rayleigh channel. The channel vector H can be defined by:

$$H_1 = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} = \begin{bmatrix} |h_1|e^{j\theta_1} \\ |h_2|e^{j\theta_2} \\ |h_3|e^{j\theta_3} \\ |h_4|e^{j\theta_4} \end{bmatrix} \tag{3.23}$$

At the receiver side, the receiver receives sixteen consecutive signals. The first eight signals r_1, r_2,.., and r_8 represent the pilot sequence and the other eight signals r_9, r_{10}, …, and r_{16} represents the information data. The sixteen received signals can be expressed by:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \\ r_7 \\ r_8 \end{bmatrix} = S_1 H_1 + N_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} . \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \\ n_7 \\ n_8 \end{bmatrix} \qquad (3.24)$$

$$R_2 = \begin{bmatrix} r_9 \\ r_{10} \\ r_{11} \\ r_{12} \\ r_{13} \\ r_{14} \\ r_{15} \\ r_{16} \end{bmatrix} = S_2 H_1 + N_2 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \\ s_5^* & s_6^* & s_7^* & s_8^* \\ -s_6^* & s_5^* & -s_8^* & s_7^* \\ -s_7^* & s_8^* & s_5^* & -s_6^* \\ -s_8^* & -s_7^* & s_6^* & s_5^* \end{bmatrix} . \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_9 \\ n_{10} \\ n_{11} \\ n_{12} \\ n_{13} \\ n_{14} \\ n_{15} \\ n_{16} \end{bmatrix} \qquad (3.25)$$

After receiving all sixteen signals, the receiver estimates the channel coefficient vector H_1 from Equation (3.24) using the minimum mean square error (MMSE). The channel coefficient vector H_1 can be illustrated by:

$$\dot{H}_1 = \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \\ \tilde{h}_3 \\ \tilde{h}_4 \end{bmatrix} = (S_1^H S_1)^{-1} S_1^H R_1 = \frac{1}{\sum_{j=1}^{8} |s_j|^2} S_1^H R_1 \qquad (3.26)$$

where the superscript H represents the operation of transpose and conjugate. After estimating the channel coefficients vector as in Equation (3.26), the receiver then use it to construct the channel matrix $\ddot{H}_1$. The constructed matrix $\ddot{H}_1$ can be presented by:

$$\ddot{H}_1 = \begin{bmatrix} \tilde{h}_1^* & \tilde{h}_2^* & \tilde{h}_3^* & \tilde{h}_4^* & \tilde{h}_1 & \tilde{h}_2 & \tilde{h}_3 & \tilde{h}_4 \\ \tilde{h}_2^* & -\tilde{h}_1^* & -\tilde{h}_4^* & \tilde{h}_3^* & \tilde{h}_2 & -\tilde{h}_1 & -\tilde{h}_4 & \tilde{h}_3 \\ \tilde{h}_3^* & \tilde{h}_4^* & -\tilde{h}_1^* & -\tilde{h}_2^* & \tilde{h}_3 & \tilde{h}_4 & -\tilde{h}_1 & -\tilde{h}_2 \\ \tilde{h}_4^* & -\tilde{h}_3^* & \tilde{h}_2^* & -\tilde{h}_1^* & \tilde{h}_4 & -\tilde{h}_3 & \tilde{h}_2 & -\tilde{h}_1 \end{bmatrix} \tag{3.27}$$

the receiver also constructs the vector $\ddot{R}_1$ from the data vector in Equation (3.25). The constructed $\ddot{R}_1$ can be expressed by:

$$\ddot{R}_1 = \begin{bmatrix} r_9 \\ r_{10} \\ r_{11} \\ r_{12} \\ r_{13}^* \\ r_{14}^* \\ r_{15}^* \\ r_{16}^* \end{bmatrix} \tag{3.28}$$

The receiver uses the constructed matrix $\ddot{H}_1$ and the constructed vector $\ddot{R}_1$ for the combining purposes. The combined scheme can be expressed by:

$$\tilde{S}_2 = \ddot{H}_1 \ddot{R}_1 = \begin{bmatrix} \tilde{h}_1^* & \tilde{h}_2^* & \tilde{h}_3^* & \tilde{h}_4^* & \tilde{h}_1 & \tilde{h}_2 & \tilde{h}_3 & \tilde{h}_4 \\ \tilde{h}_2^* & -\tilde{h}_1^* & -\tilde{h}_4^* & \tilde{h}_3^* & \tilde{h}_2 & -\tilde{h}_1 & -\tilde{h}_4 & \tilde{h}_3 \\ \tilde{h}_3^* & \tilde{h}_4^* & -\tilde{h}_1^* & -\tilde{h}_2^* & \tilde{h}_3 & \tilde{h}_4 & -\tilde{h}_1 & -\tilde{h}_2 \\ \tilde{h}_4^* & -\tilde{h}_3^* & \tilde{h}_2^* & -\tilde{h}_1^* & \tilde{h}_4 & -\tilde{h}_3 & \tilde{h}_2 & -\tilde{h}_1 \end{bmatrix} \begin{bmatrix} r_9 \\ r_{10} \\ r_{11} \\ r_{12} \\ r_{13}^* \\ r_{14}^* \\ r_{15}^* \\ r_{16}^* \end{bmatrix} \tag{3.29}$$

The new combined signals are then sent to the maximum-likelihood detector to detect $\hat{S}_2(\hat{s}_5, \hat{s}_6, \hat{s}_7 \,\&\, \hat{s}_8)$. The receiver saves the received user data vector R_2 as the coming pilot sequence vector R_1 and saves the detected user data vector $\hat{S}_2$ as S_1 for the next coming transmitted symbols. This process will repeat until all transmissions are done.

3.3.3 Joint Scheme for Four Transmit and Two Receive Antennas

In this joint scheme, the implementation at the transmitter side is exactly the same as in Section 3.3.2. The only difference is the receiver side. In this case there are two receiving antennas instead of one. This means that each receive antenna will receive a copy of the sixteen transmitted signals through eight different Rayleigh channels, four channels from the transmit antennas to each receive antenna. The first receive antenna receives the following two vector signals R_1 and R_2:

$$R_1 = \begin{bmatrix} r_{1,1} \\ r_{2,1} \\ r_{3,1} \\ r_{4,1} \\ r_{5,1} \\ r_{6,1} \\ r_{7,1} \\ r_{8,1} \end{bmatrix} = S_1 H_1 + N_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} . \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_{1,1} \\ n_{2,1} \\ n_{3,1} \\ n_{4,1} \\ n_{5,1} \\ n_{6,1} \\ n_{7,1} \\ n_{8,1} \end{bmatrix} \quad (3.30)$$

$$R_2 = \begin{bmatrix} r_{9,1} \\ r_{10,1} \\ r_{11,1} \\ r_{12,1} \\ r_{13,1} \\ r_{14,1} \\ r_{15,1} \\ r_{16,1} \end{bmatrix} = S_2 H_1 + N_2 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \\ s_5^* & s_6^* & s_7^* & s_8^* \\ -s_6^* & s_5^* & -s_8^* & s_7^* \\ -s_7^* & s_8^* & s_5^* & -s_6^* \\ -s_8^* & -s_7^* & s_6^* & s_5^* \end{bmatrix} . \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_{9,1} \\ n_{10,1} \\ n_{11,1} \\ n_{12,1} \\ n_{13,1} \\ n_{14,1} \\ n_{15,1} \\ n_{16,1} \end{bmatrix} \quad (3.31)$$

The second receive antenna receives the following two vector signals R_3 and R_4:

$$R_3 = \begin{bmatrix} r_{1,2} \\ r_{2,2} \\ r_{3,2} \\ r_{4,2} \\ r_{5,2} \\ r_{6,2} \\ r_{7,2} \\ r_{8,2} \end{bmatrix} = S_1 H_2 + N_3 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} . \begin{bmatrix} h_5 \\ h_6 \\ h_7 \\ h_8 \end{bmatrix} + \begin{bmatrix} n_{1,2} \\ n_{2,2} \\ n_{3,2} \\ n_{4,2} \\ n_{5,2} \\ n_{6,2} \\ n_{7,2} \\ n_{8,2} \end{bmatrix} \qquad (3.32)$$

$$R_4 = \begin{bmatrix} r_{9,2} \\ r_{10,2} \\ r_{11,2} \\ r_{12,2} \\ r_{13,2} \\ r_{14,2} \\ r_{15,2} \\ r_{16,2} \end{bmatrix} = S_2 H_2 + N_4 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \\ s_5^* & s_6^* & s_7^* & s_8^* \\ -s_6^* & s_5^* & -s_8^* & s_7^* \\ -s_7^* & s_8^* & s_5^* & -s_6^* \\ -s_8^* & -s_7^* & s_6^* & s_5^* \end{bmatrix} . \begin{bmatrix} h_5 \\ h_6 \\ h_7 \\ h_8 \end{bmatrix} + \begin{bmatrix} n_{9,2} \\ n_{10,2} \\ n_{11,2} \\ n_{12,2} \\ n_{13,2} \\ n_{14,2} \\ n_{15,2} \\ n_{16,2} \end{bmatrix} \qquad (3.33)$$

After receiving all four vector signals, the receiver uses them to estimate the channel vector H_1 from Equation (3.30) and estimate the channel vector H_2 from Equation (3.32). The two estimated channel vectors can be illustrated by:

$$\dot{H}_1 = \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \\ \tilde{h}_3 \\ \tilde{h}_4 \end{bmatrix} = (S_1^H S_1)^{-1} S_1^H R_1 \qquad (3.34)$$

$$\dot{H}_2 = \begin{bmatrix} \tilde{h}_5 \\ \tilde{h}_6 \\ \tilde{h}_7 \\ \tilde{h}_8 \end{bmatrix} = (S_1^H S_1)^{-1} S_1^H R_3 \qquad (3.35)$$

The receiver use the estimated channel vectors $\dot{H}_1$ and $\dot{H}_2$ to construct the channel matrix $\ddot{H}_1$ from Equation (3.34) and the channel matrix $\ddot{H}_2$ from Equation (3.35). The two constructed channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ can be presented by:

$$\ddot{H}_1 = \begin{bmatrix} \tilde{h}_1^* & \tilde{h}_2^* & \tilde{h}_3^* & \tilde{h}_4^* & \tilde{h}_1 & \tilde{h}_2 & \tilde{h}_3 & \tilde{h}_4 \\ \tilde{h}_2^* & -\tilde{h}_1^* & -\tilde{h}_4^* & \tilde{h}_3^* & \tilde{h}_2 & -\tilde{h}_1 & -\tilde{h}_4 & \tilde{h}_3 \\ \tilde{h}_3^* & \tilde{h}_4^* & -\tilde{h}_1^* & -\tilde{h}_2^* & \tilde{h}_3 & \tilde{h}_4 & -\tilde{h}_1 & -\tilde{h}_2 \\ \tilde{h}_4^* & -\tilde{h}_3^* & \tilde{h}_2^* & -\tilde{h}_1^* & \tilde{h}_4 & -\tilde{h}_3 & \tilde{h}_2 & -\tilde{h}_1 \end{bmatrix} \quad (3.36)$$

$$\ddot{H}_2 = \begin{bmatrix} \tilde{h}_5^* & \tilde{h}_6^* & \tilde{h}_7^* & \tilde{h}_8^* & \tilde{h}_5 & \tilde{h}_6 & \tilde{h}_7 & \tilde{h}_8 \\ \tilde{h}_6^* & -\tilde{h}_5^* & -\tilde{h}_8^* & \tilde{h}_7^* & \tilde{h}_6 & -\tilde{h}_5 & -\tilde{h}_8 & \tilde{h}_7 \\ \tilde{h}_7^* & \tilde{h}_8^* & -\tilde{h}_5^* & -\tilde{h}_6^* & \tilde{h}_7 & \tilde{h}_8 & -\tilde{h}_5 & -\tilde{h}_6 \\ \tilde{h}_8^* & -\tilde{h}_7^* & \tilde{h}_6^* & -\tilde{h}_5^* & \tilde{h}_8 & -\tilde{h}_7 & \tilde{h}_6 & -\tilde{h}_5 \end{bmatrix} \quad (3.37)$$

The receiver also constructs the vector $\ddot{R}_1$ from Equation (3.31) and the vector $\ddot{R}_2$ from Equation (3.33) as:

$$\ddot{R}_1 = \begin{bmatrix} r_{9,1} \\ r_{10,1} \\ r_{11,1} \\ r_{12,1} \\ r_{13,1}^* \\ r_{14,1}^* \\ r_{15,1}^* \\ r_{16,1}^* \end{bmatrix} \quad (3.38)$$

$$\ddot{R}_2 = \begin{bmatrix} r_{9,2} \\ r_{10,2} \\ r_{11,2} \\ r_{12,2} \\ r_{13,2}^* \\ r_{14,2}^* \\ r_{15,2}^* \\ r_{16,2}^* \end{bmatrix} \tag{3.39}$$

The receiver then uses $\ddot{H}_1$, $\ddot{H}_2$, $\ddot{R}_1$ and $\ddot{R}_2$ to combine all the required signals to recover S_2 :

$$\tilde{S}_2 = \ddot{H}_1\ddot{R}_1 + \ddot{H}_2\ddot{R}_2 \tag{3.40}$$

The receiver then sends the combined signals vector $\tilde{S}_2$ to the maximum-likelihood detector to detect the transmitted signal vector $\hat{S}_2$. After that, the receiver saves the received user data vector R_2 as R_1, R_4 as R_3 and $\hat{S}_2$ as S_1. The process will go on until all transmissions are completed.

3.4 Simulation and Results

Computer simulations of the joint channel estimation and data detection scheme for radio links using space-time block coding have been carried out. The environment of simulation is MATLAB which is a powerful tool for mathematical calculation and system simulation. A pseudo random sequence generator is used for producing source data. The methods of modulations chosen are QPSK and 16-QAM.

In this section, we show the simulation results for the performance of STBC on Rayleigh fading channels. In the simulation, the receivers do not know the channel state information (CSI) and have to estimate them using the joint channel estimation and data detection scheme. The performances of the bit error rate (BER) for STBC with different numbers of transmit and receive antennas are shown in different figures depending on the modulation scheme used and number of transmit antennas. In our simulations, the rate of the transmission matrices is one for STBC with two transmit antennas and half for STBC with four transmit antennas. The simulation results for the performance of STBC with estimated channel parameters are recorded for the purpose of plotting and comparing with the performance of STBC with known channel parameters at the receiver.

Figure 3.2 shows the error performance of transmit diversity with Tarokh new joint channel estimation and data detection scheme in Jakes Rayleigh fading model [7]. In the figure, three block error rate curves are included: the transmit diversity scheme with the new joint and detection scheme, the transmit diversity scheme with perfect channel estimation, and the performance of coherent QPSK with perfect channel estimation. The performance of the new joint channel estimation and data detection scheme is about 3 dB worse than coherent detection with ideal channel estimation. The transmit diversity scheme with the new detection techniques provides 6 dB diversity gain at bit-error rate (BER) of 10^{-2}.

In our simulations, the channels used are flat Rayleigh fading channels, this would not change the patter of the error performance of the transmit diversity. In other words, the loss in the error performance of the new generalized joint channel estimation and data detection scheme compared with the same system with channel known to the receiver is the same as in Tarokh case which is about 3 dB. The only difference is that the performance under flat Rayleigh fading is better than the same system using Jakes Rayleigh fading.

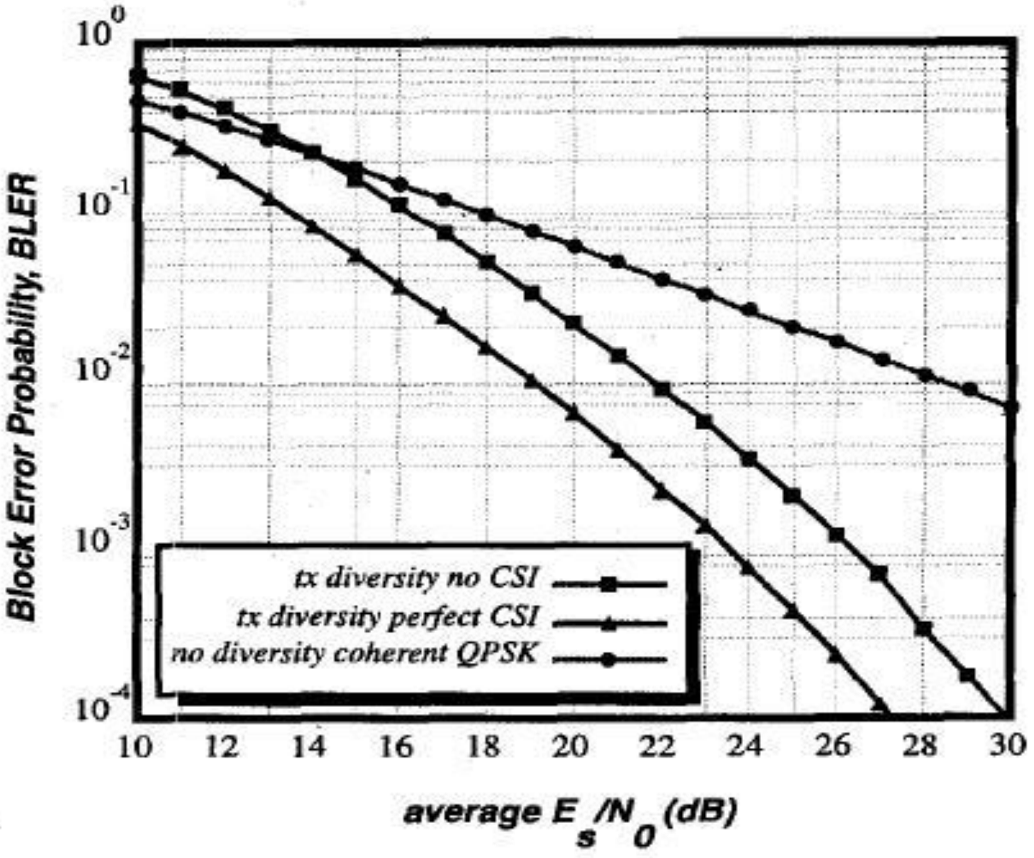

Figure 3.2: The Error Performance of Transmit Diversity with New Detection Scheme in Jakes Rayleigh Fading [5].

Figure 3.3 illustrate the bit-error rate for the new joint channel estimation and data detection scheme for space-time block codes with two transmit antennas and one, two, three, and four receive antennas. The rate of transmission data of this space-time block code is one and the modulation used to in these two figures is QPSK. However, Figure 3.4 illustrate the bit-error rate for the new joint estimation and data detection scheme for space-time block codes with four transmit and one, two, three, and four receive antennas. The rate of transmission data of this space-time block code is half and the modulation used to in these two figures is QPSK.

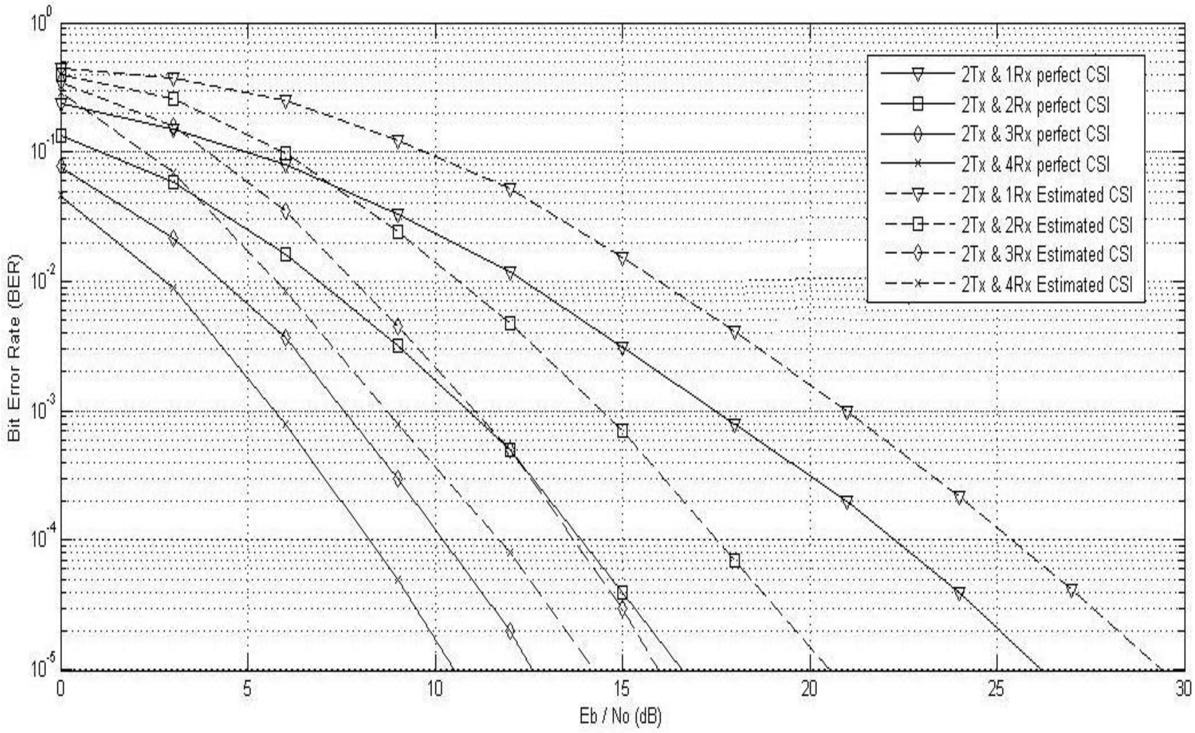

Figure 3.3: New joint scheme with two transmit antennas using QPSK modulation.

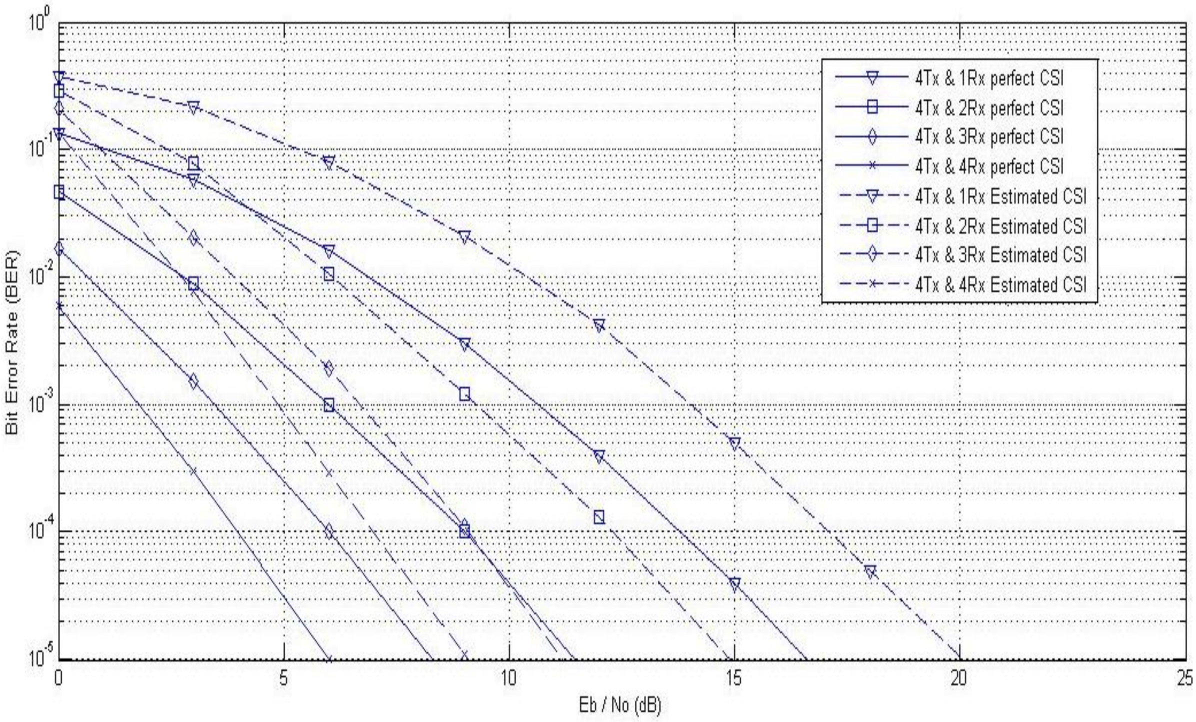

Figure 3.4: New joint scheme with four transmit antennas using QPSK modulation.

From Figure 3.3, Figure 3.4, Table 3.1 and Table 3.2, it is very clear that the bit-error rate of the new scheme is worse by 3 dB. The bit-error rate performance of the new joint channel estimation and data detection scheme for space-time block codes with two transmit and two receive antennas is better than the performance of space-time block codes with two transmit and one receive antennas with known channel estate information. However, the bit-error rate performance of the new joint channel estimation and data detection scheme for space-time block codes with two transmit and there receive antennas is almost the same as the performance of space-time block codes with two transmit and two receive antennas with known channel estate information. Similarly, the bit-error rate for space-time block codes with four transmit and two receive antennas is better than the performance of space-time block codes with four transmit and one receive antenna with known, ideal channels at the receiver. And, the performance for space-time block codes with four transmit and three receive antennas is better than the performance of space-time block codes with four transmit and two receiver antennas. Table 3.1 shows the different results for STBC with two transmit antennas and different number of receive antennas using QPSK modulation in flat Rayleigh channel.

Table 3.1: The BER performances of STBC with two transmit antennas using QPSK modulation.

BER	Perfect CSI 2Tx,1Rx Eb / No	No CSI 2Tx,1Rx Eb / No	Perfect CSI 2Tx,2Rx Eb / No	No CSI 2Tx,2Rx Eb / No	Perfect CSI 2Tx,3Rx Eb / No	No CSI 2Tx,3Rx Eb / No	Perfect CSI 2Tx,4Rx Eb / No	No CSI 2Tx,4Rx Eb / No
10^{-1}	5	9	2	6	-	4	-	2.5
10^{-2}	13	16	7.5	10.5	4	7	3	6
10^{-3}	17.5	21	11	14	7.5	11	6	9
10^{-4}	22.5	25.5	14	17	10	13.5	8	12
10^{-5}	26	29	17	20.5	12.5	16	11	14

Table 3.2 shows the different results for STBC with four transmit antennas and different number of receive antennas using QPSK modulation in flat Rayleigh fading channel.

Table 3.2: The BER performances of STBC with four transmit antennas using QPSK modulation.

BER	Perfect CSI 4Tx,1Rx Eb / No	No CSI 4Tx,1Rx Eb / No	Perfect CSI 4Tx,2Rx Eb / No	No CSI 4Tx,2Rx Eb / No	Perfect CSI 4Tx,3Rx Eb / No	No CSI 4Tx,3Rx Eb / No	Perfect CSI 4Tx,4Rx Eb / No	No CSI 4Tx,4Rx Eb / No
10^{-1}	2	5	-	2.5	-	1.5	-	0.5
10^{-2}	7.5	10.5	3	6	1	4	-	2.5
10^{-3}	11	14	6	9	3	7	2	5
10^{-4}	14	17	9	12	6	9	4	7
10^{-5}	17	20	12	15	8	11	6	9

Figure 3.5 shows the bit-error rate for the new joint channel estimation and data detection scheme for space-time block codes with two transmit antennas and one, two, three, and four receive antennas. The rate of transmission data of this space-time block code is one. The modulation used is 16-QAM. Figure 3.6 illustrates the bit-error rate for the new joint channel estimation and data detection scheme for space-time block codes with four transmit and one, two, three, and four receive antennas. The rate of transmission data of this space-time block code is half. The modulation used is 16-QAM.

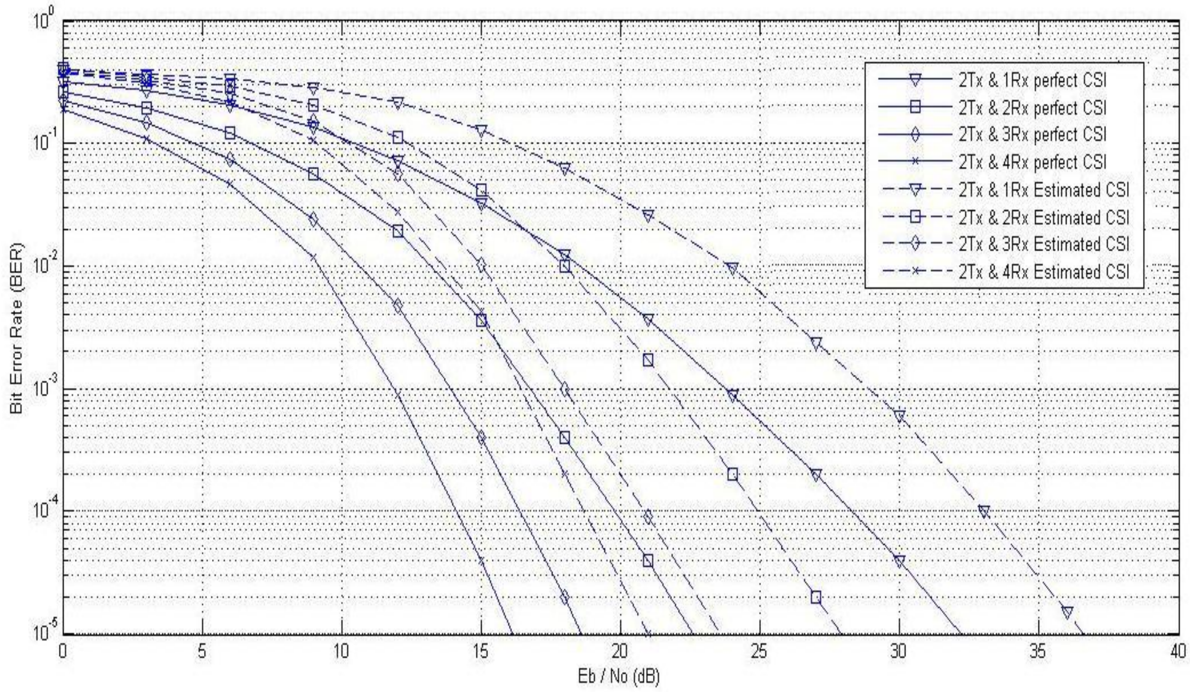

Figure 3.5: The new joint scheme with two transmit antennas using 16-QAM modulation.

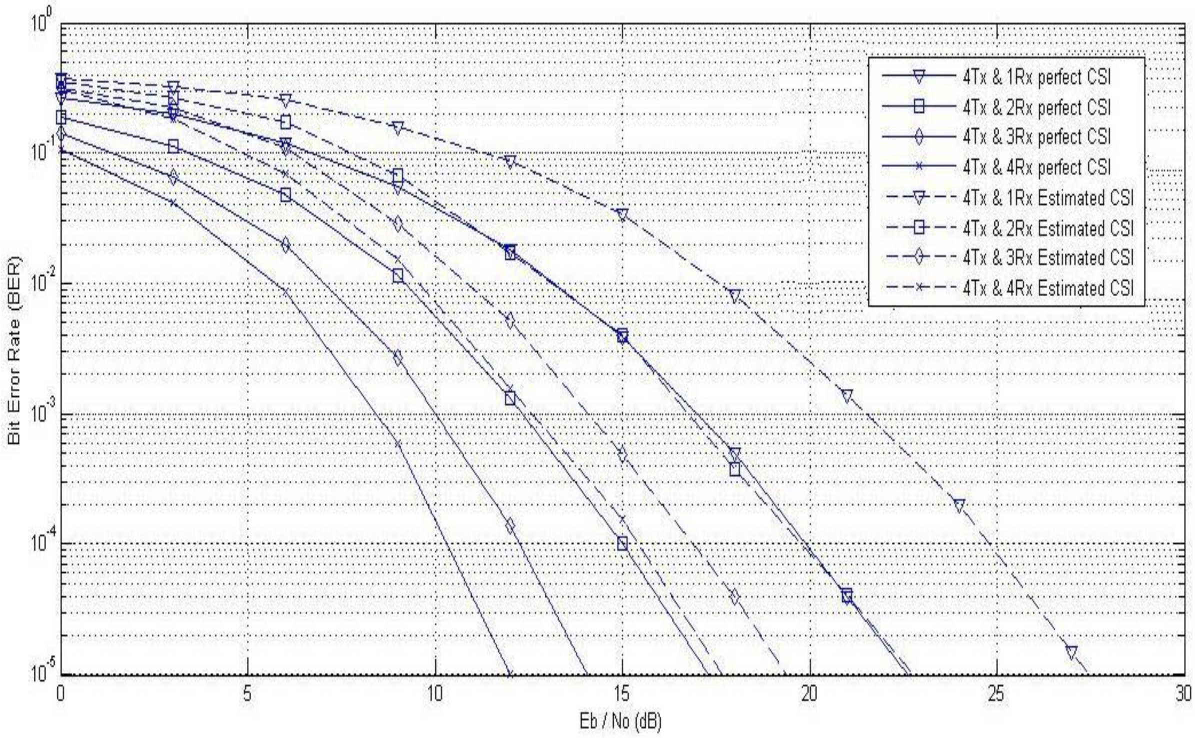

Figure 3.6: The new joint scheme with four transmit antennas using 16-QAM modulation.

Table 3.3 shows the different results for STBC with two transmit antennas and different number of receive antennas using 16-QAM modulation and flat Rayleigh channel.

Table 3.3: The BER performances of STBC with two transmit antennas using 16-QAM modulation.

BER	Perfect CSI 2Tx,1Rx Eb / No	No CSI 2Tx,1Rx Eb / No	Perfect CSI 2Tx,2Rx Eb / No	No CSI 2Tx,2Rx Eb / No	Perfect CSI 2Tx,3Rx Eb / No	No CSI 2Tx,3Rx Eb / No	Perfect CSI 2Tx,4Rx Eb / No	No CSI 2Tx,4Rx Eb / No
10^{-1}	10	16	7	12	5	10	3	8
10^{-2}	18	24	13	18	11	15	9	14
10^{-3}	24	29	17	22	14	18	12	17
10^{-4}	28	33	20	25	16	21	14	19
10^{-5}	33	37	23	28	18	23	16	21

Table 3.4 shows the different results for STBC with four transmit antennas and different number of receive antennas using 16-QAM modulation and again using flat Rayleigh fading channel.

Table 3.4: The BER performances of STBC with four transmit antennas using 16-QAM modulation.

BER	Perfect CSI 2Tx,1Rx Eb / No	No CSI 2Tx,1Rx Eb / No	Perfect CSI 2Tx,2Rx Eb / No	No CSI 2Tx,2Rx Eb / No	Perfect CSI 2Tx,3Rx Eb / No	No CSI 2Tx,3Rx Eb / No	Perfect CSI 2Tx,4Rx Eb / No	No CSI 2Tx,4Rx Eb / No
10^{-1}	7	12	3	8	2	7	0	5
10^{-2}	13	18	8	13	7	11	6	9.5
10^{-3}	17	22	12	17	10	14	8	13
10^{-4}	20	25	15	20	12	17	10	15
10^{-5}	23	27	17	22	14	19	12	17

The increases in the number of transmit and receive antennas gives a better performance in the diversity but does not change the performance pattern of the joint channel estimation and data detection scheme. The Eb/No loss is always the same regardless of any increase of either transmit or receive antennas. Therefore, bit-error rate of space-time block codes that use joint channel estimation and data detection and QPSK modulation is always 3 dB worse than the performance of the same space-time block codes with known channel coefficients at the receiver and using the same modulation scheme. Moreover, the bit-error rate of all space-time block codes that use joint channel estimation and data detection and 16-QAM modulation is always 5 ~ 6 dB worse than the performance of the same space-time block codes with known channel coefficients at the receiver using the same modulation.

The only factor that changes the performance of the joint estimation and data detection is the type of modulation used.

Table 3.5 illustrate the difference in the bit-error rate performance of space-time block codes with two transmit antennas that use joint channel estimation and data detection with QPSK modulation and 16-QAM modulation respectively.

Table 3.5: The differences in BER performance of STBC with two transmit antennas for different modulations.

BER	No CSI 2Tx,Rx1 QPSK Eb/No	No CSI 2Tx,Rx1 16-QAM Eb/No	No CSI 2Tx,Rx2 QPSK Eb/No	No CSI 2Tx,Rx2 16-QAM Eb/No	No CSI 2Tx,Rx3 QPSK Eb/No	No CSI 2Tx,Rx3 16-QAM Eb/No	No CSI 2Tx,Rx4 QPSK Eb/No	No CSI 2Tx,Rx4 16-QAM Eb/No
10^{-1}	9	16	6	12	4	10	2.5	8
10^{-2}	16	24	10.5	18	7	15	6	14
10^{-3}	21	29	14	22	11	18	9	17
10^{-4}	22.5	33	17	25	13.5	21	12	19
10^{-5}	29	37	20.5	28	16	23	14	21

Table 3.6 illustrate the difference in the bit-error rate performance of space-time block codes with four transmit antennas that uses joint channel estimation and data detection with QPSK modulation and 16-QAM modulation respectively.

Table 3.6: The differences in BER performance of STBC with four transmit antennas for different modulations.

BER	No CSI 4Tx,Rx1 QPSK Eb / No	No CSI 4Tx,Rx1 16-QAM Eb / No	No CSI 4Tx,Rx2 QPSK Eb / No	No CSI 4Tx,Rx2 16-QAM Eb / No	No CSI 4Tx,Rx3 QPSK Eb / No	No CSI 4Tx,Rx3 16-QAM Eb / No	No CSI 4Tx,Rx4 QPSK Eb / No	No CSI 4Tx,Rx4 16-QAM Eb / No
10^{-1}	5	12	2.5	8	1.5	7	0.5	5
10^{-2}	10.5	18	6	13	4	11	2.5	9.5
10^{-3}	14	22	9	17	7	14	5	13
10^{-4}	17	25	12	20	9	17	7	15
10^{-5}	20	27	15	22	11	19	9	17

From Table 3.5 and Table 3.6, the bit-error rate performance of space-time block codes that uses 16QAM modulation is worse than the same space-time block code that uses QPSK modulation. There is an approximation of 7 ~ 8 dB better in performance and this is because 16-QAM modulated symbols carry more bits than QPSK modulated symbols by at least the double.

3.5 Conclusions

In this chapter, a comprehensive investigation into Tarokh joint channel estimation and data detection scheme for radio links with space-time block codes was conducted. A new general scheme of the joint channel estimation and data detection was proposed. The proposed joint channel estimation and data detection method was tested with different combinations of transmit and receive antennas. Different complex signals modulated using either QPSK and

16-QAM modulation schemes were used with all different implementations. The results of all simulations were presented in data and graph, and analyzed and compared.

Estimation of channel parameters which are necessary for ML detection of STBC is important for practicability of space-time coding techniques. The presented joint scheme that does not require CSI is thus a useful contribution toward solving the problem.

References

[1] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, “Space-time Block Codes from Orthogonal Designs,” IEEE Transactions on Information Theory, Vol . 45, No. 5, pp. 1456-1467, July 1999.

[2] B. M. Hochwald and T. L. Marzetta, “Unitary Space-time Modulation for Multiple Antenna Communications in Rayleigh Flat Fading,” IEEE Transactions on Information Theory, Vol. 46, No. 2, pp. 543-564, March 2000.

[3] V. Tarokh and H. Jafarkhani, “A differential Detection Scheme for Transmit Diversity,” IEEE Journal on Selected Areas in Communications, Vol. 18, No. 7, pp. 1169-1174, July 2000.

[4] B. L. Hughes, “Differential Space-time Modulation,” IEEE Wireless Communications and Networking Conference, Vol. 1, pp. 145-149, 1999.

[5] V. Tarokh, S. M. Alamouti, and P. Poon, “New Detection Schemes for Transmit Diversity with no Channel Estimation,” IEEE International Conference on Universal Personal Communications, pp. 917-920, 1998.

[6] S.M Alamouti, “A simple Transmitter Diversity Scheme for Wireless Communications,” IEEE Journal on Selected Areas in Communications, Vol. SAC-16, pp. 1451-1458, October 1998.

[7] W. C. Jakes, Ed., Microwave Mobile Communications. New York: Wiley, 1974.

[8] N. Ammar and Z. Ding, “Flat Fading Channel Estimation Under Generic Linear Space-time Block Coded Transmissions”, IEEE Communications Society. pp. 2616-2620, 2004.

[9] J. Wu and Gary J. Saulnier, “Orthogonal Space-time Block Code Over Time-varying Flat-fading Channels: Channel Estimation, Detection, and Performance Analysis”, IEEE Transactions on Communications, Vol. 55, no. 5, May 2007.

[10] C. Fragouli, N. Al-Dhahir, and W. Turin, “Training-based Channel Estimation for Multiple-antenna Broadband Transmissions”, IEEE Transactions on Wireless Communications, Vol. 2, No. 2, March 2003.

[11] F. Chan, J. Choi, P. Rapajic and J. Yuan, “Information Theoretic Comparisons of Training Based Channel Estimation and Semi-blind Estimation in Fading Channels with Memory”, IEEE Transactions on Communications, 2004.

[12] E. Carvalho and D.T.M. Slock, “Signal Processing Advances in Wireless Communications”, IEEE Processing Workshop, pp. 129-132, 1997.

[13] S. Diggavi, N. Al-Dharhir, A. Stamoulis, and A. R. Calderbank, “Differential Space-time Transmission for Frequency-selective Channels”, IEEE Communications. Letter, Vol. 6, pp. 253-255, June 2002.

4 Channel Estimation and Performance of Space-Time Block Coding using Estimated Channel Parameters

4.1 Introduction

Recently in wireless and mobile communications, multiple input multiple output (MIMO) technology has emerged as one of the most significant technologies. An improvement in the quality of service and an increase in the system capacity can be achieved by using MIMO technology [1, 2, 3, 4]. Relying heavily on the requirement of accurate channel estimation is the main aspect to fully utilize the MIMO capacity. In order to adequately demonstrate the performance of a system via simulation, it is necessary to develop an accurate model of the system as it would be physically implemented. The assumption that perfect channel state information (CSI) would be available to the receiver is inappropriate when simulating a physical system because in a real system the effect of the channel can never be known. Rather, some form of estimation is performed to find an approximation to the channel. MIMO channel estimation methods can be classified into three categories: training-based (pilot sequence) methods, blind and semi-blind methods.

Training-based methods seem to give very good results on the performance of channel estimation at the receiver. Pure training-based schemes can be considered as an advantage when an accurate and reliable MIMO channel needs to be obtained. However, this could be a disadvantage when bandwidth efficiency is required. This is because pure training-based schemes reduce the bandwidth efficiency considerably due to the use of a long training which is necessarily needed in order to obtain a reliable MIMO channel estimate.

Three families of blind equalization techniques have emerged since the pioneering work of Y. Sato [5]. The first family of blind adaptive algorithms is known as Bussgang algorithm. This algorithm constructs a transversal equalizer directly to unravel the effects of the channel impulse response [5, 6, 7, 8]. This class is very general and powerful but requires an extensive computation on the large amount of the required received data samples needed to estimate higher order cumulants. The second family of blind equalization algorithm is based on higher order cumulants [9, 10, 11, 12]. The last family of blind adaptive algorithms is blind approximations on the maximum likelihood sequence estimation (MLSE) to perform a joint channel and data estimation [13 - 16]. The resulting blind equalizers are therefore computationally very expansive.

The third MIMO channel estimations are semi-blind methods. The semi-blind methods are a mixture of training and blind based techniques. This means that semi-blind methods are blind methods with an addition of small amount of training (extra known symbols). Information theoretic comparisons of training based channel estimation and semi-blind estimation in fading channels with memory is given in [17].

Because of the computation complexity of blind and semi-blind methods, many wireless communication systems still use pilot sequences to estimate the channel parameters at the receiver side. For this reason, in [18], Yang, et al have proposed a new channel estimation algorithm that uses pilot sequences to estimate the channel parameters.

In Chapter 3, a joint channel estimation and data detection scheme based on Tarokh’s method is proposed. In this chapter, another channel estimation scheme is investigated, implemented and then tested with different types of modulation methods. The chapter is organized as follows. In Section 4.2, the channel estimation scheme proposed in [18] is fully explained. In Section 4.3, the channel estimation scheme is tested on space-time block codes with different combinations of transmit and receive antennas. The new scheme is also tested with different types of modulation techniques. The modulation techniques used are QPSK, and 16-QAM. In Section 4.4, the bit-error rate performances of space-time block codes using the new channel estimation scheme are recorded, plotted, and compared with the same space-time block codes with known channel state information at the receiver.

In Chapter 5, real modulation (BPSK) schemes that output real signals will be tested with the proposed estimation scheme described in this chapter.

4.2 Channel Estimation Method for Space-time Block Codes (STBC)

The basic principle of space-time block codes is as the following: it is assumed that there are N transmit antennas and M receive antennas in a wireless communication system in which STBC is employed. As known about STBC from previous chapters, the input source data bits are firstly modulated, and then carried into a space-time block encoder. Different modulation schemes can be employed; in this chapter, QPSK and 16-QAM are used. Mapping from the modulated symbols to a transmission matrix, which is completed by the space-time block encoder, is a key step in space-time block code systems. The input symbols of the encoder are divided into groups of several symbols. The number of symbols in a group is according to the number of transmit antennas and the mapping rule. A $P \text{ x } N$ transmission matrix means that there are N transmit antennas and P time slots. Different symbol columns are transmitted through different antennas separately and different symbol rows in different time slots. Different space-time block codes transmit different encoded data symbols through different channels h_{ij} in different time slot t. The received signal at receive antenna j at time t, $r_j(t)$ is given by:

$$r_j(t) = \sum_{i=1}^{N} h_{ij} c_i(t) + \eta_j(t) \tag{4.1}$$

where $c_i(t)$ is the transmitted symbol at time t, $j = 1,...,M$, $t = 1,....,P$, and the noise samples $\eta_j(t)$ are the independent samples of a zero-mean complex Gaussian random variable.

Let S be defined as the set of all possible symbol groups, $S = \{s_1, s_2, ..., s_N\}$. The receiver computes the optimal maximum likelihood (ML) decision metric:

$$d_m = \sum_{i=1}^{P} \sum_{j=1}^{M} \left| r_j(t) - \sum_{i=1}^{N} h_{ij} c_i(t) \right|^2 \qquad (4.2)$$

over the set S and decides in favor of the symbol group that minimizes the metric d_m. The ML decoding rule in Equation (4.2) can be further simplified according to the orthogonality of space-time block code encoding [13], [14]. It is clearly indicated in Equation (4.2) that the knowledge of channel parameters, h_{ij}, are required for ML decoding.

4.2.1 System Description

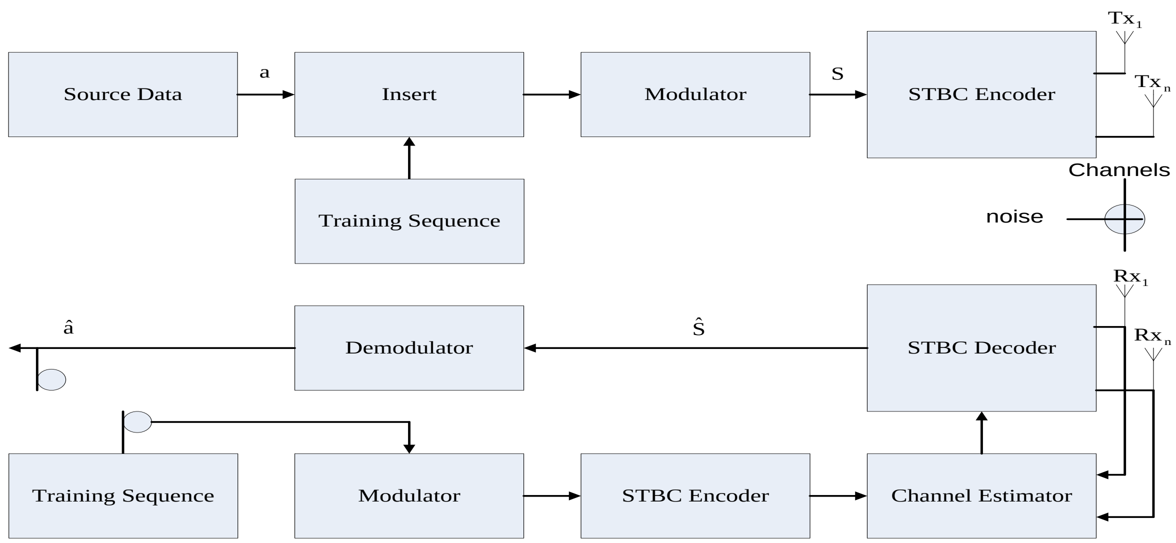

Figure 4.1: System for estimating channel parameters for STBC.

Based on the above briefly explained space-time block code system, in [18] a new channel estimation algorithm to estimate the channel parameters at the receiver has been proposed. The architecture of the radio transmission system using STBC with channel estimation is given in Figure 4.1.

In this scheme, the user data of source are divided into a frame structure. At the beginning of each frame, a training or pilot sequence is inserted. The inserted pilot sequence is known to the receiver and used to estimate the channel parameters. The bursts of the source data are grouped as several blocks for space-time block coding. The bit number in a group depends on the number of transmit antennas and the coding method of space-time block codes.

In this scheme, we let the vector $A = [a_1,\ldots,a_K]^T$ denote the transmitted data group, T is the transpose of the vector A and K is the index of the last bit in the data vector. Different pilot bits are inserted in the front of the data vector A. The number of bits inserted depends on the type of modulation and number of transmit antennas used in a space-time block code. After modulation, the transmitted symbol vector, $S = [s_1,\ldots,s_K]^T$, is formed and carried into the space-time block code encoder. In the encoder, S is mapped to the transmission matrix C of $P \times N$. The C transmission matrix can be illustrated as:

$$C = \begin{bmatrix} c_1(1) & \ldots & c_N(1) \\ & \ldots & \\ c_1(P) & \ldots & c_N(P) \end{bmatrix} \tag{4.3}$$

The symbols of columns i of matrix C are transmitted through antenna i and those of rows t are transmitted in time slot t.

Let $M \times N$ matrix H be the channel parameters for the MIMO channels and let $M \times P$ matrix R be the received signals, then Equation (4.1) can be written in matrix form as:

$$R = HC^T + \eta \tag{4.4}$$

where the matrix H is illustrated in Equation (4.5) and the receive signal matrix R illustrated in Equation (4.6).

$$H = \begin{bmatrix} h_{11} & \dots & h_{N1} \\ & \dots & \\ h_{1M} & \dots & h_{NM} \end{bmatrix} \tag{4.5}$$

$$R = \begin{bmatrix} r_1(1) & \dots & r_1(P) \\ & \dots & \\ r_M(1) & \dots & r_M(P) \end{bmatrix} \tag{4.6}$$

and η is an $M \times P$ noise matrix, the elements of which are independent samples of a zero-mean complex Gaussian random variable.

The element h_{ij} of H is the parameter of the channel from transmit antenna i to the receive antenna j. The channel coefficients are assumed to be a flat Rayleigh fading as in [21] and [19]. In R, $r_j(t)$ is the signal received at the receiver antenna j at time slot t. In the receiver, the received symbol vector $\hat{S}$ is recovered from R by STBC decoder according to Equation (4.4) or using some simplified methods [19]. After demodulation, the received user data S can be obtained.

The channel parameters which are needed for decoding the transmitted user data are obtained by the channel estimator. In the training period, the training sequence is encoded and transmitted by the space-time block code encoder in the same manner as encoding and transmitting the user data. At the receiver side, when the receiver receives the first transmitted signal, the receiver starts to generate a training sequence equal to the training sequence generated by the transmitter. The generated training sequence is then sent to the modulator and to space-time block code encoder. At the receiver, the generated space-time block code should be equal to the training sequence received. The space-time block matrix produced at the receiver side is sent to the channels estimator to estimate the channel parameters required to recover the transmitted user data. The algorithm of channel parameter estimation is analyzed in the following section.

4.2.2 Algorithm for Estimation of the Channel Parameters

Let $\breve{h}_{ij}$ be the estimated channel parameter from transmit antenna i to the receive antenna j. The channel parameters can be obtained by minimizing the mean square error (MSE) cost function:

$$D(\breve{h}_{ij}) = \sum_{t=1}^{P} \left| r_j(t) - \sum_{i=1}^{N} \breve{h}_{ij} c_i(t) \right|^2 \tag{4.7}$$

where $j = 1,...,M$. This is the extreme value of multi-variable function problem solving. Hence, h_{ij} can be obtained by solving the following equation:

$$\frac{\partial D(\breve{h}_{ij})}{\partial \breve{h}_{ij}} = 0 \tag{4.8}$$

Direct calculation yields that Equation (4.8) is equivalent to:

$$\sum_{t=1}^{P} \left[r_j(t) - \sum_{i=1}^{N} \breve{h}_{ij} c_i(t) \right] c_i^*(t) = 0 \tag{4.9}$$

where $c_i^*(t)$ is the complex conjugate of $c_i(t)$. Equation (4.9) can be rewritten in a matrix form as:

$$\breve{r}_j = R_c \breve{h}_j \tag{4.10}$$

where R_c is the sum of $N \times N$ correlation matrices of the signals transmitted in time slot t. R_c is given by Equation (4.11).

$$R_c = \sum_{t=1}^{P} R_c(t) \qquad (4.11)$$

where $R_c(t)$ can be expressed by:

$$R_c(t) = \begin{bmatrix} c_1(t)c_1^*(t) & \dots & c_N(t)c_1^*(t) \\ & \dots & \\ c_1(t)c_N^*(t) & \dots & c_N(t)c_N^*(t) \end{bmatrix} \qquad (4.12)$$

where $\breve{r}_j$ is the sum of the vectors:

$$\breve{r}_j(t) = \left[r_j(t)c_1^*(t), \dots, r_j(t)c_N^*(t) \right]^T \qquad (4.13)$$

and it is equal to:

$$\breve{r}_j = \sum_{t=1}^{P} \breve{r}_j(t) \qquad (4.14)$$

$\breve{h}_j$ is the estimated channel vector whose elements are the parameters of the channels from N transmit antennas to receive antenna j, that is $\breve{h}_j = \left[\breve{h}_{1j}, \breve{h}_{2j}, \dots, \breve{h}_{Nj} \right]^T$. If the coefficients matrix R_c is non-singular, then $\breve{h}_j$ can be calculated using the following equation:

$$\breve{h}_j = R_c^{-1} \breve{r}_j \qquad (4.15)$$

where $j = 1,...,M$, and R_c^{-1} is the inverse of the matrix R_c. The key of this algorithm is that the matrix R_c is non-singular. We find that if the training sequence is treated by the modulator and space-time block code encoder with the same rules as for the user data, then R_c is always non-singular because of the orthogonality of the space-time block codes.

4.3 Detection Scheme for Space-time Block Codes (STBCs)

To keep presentation simple, we discuss the scheme for four representative cases: two transmit and one receive antennas, two transmit and two receive antennas, four transmit and one receive antennas, and four transmit and two receive antennas.

4.3.1 Detection Scheme for Two Transmit and One Receive Antennas

In this implementation, there are two transmit and one receive antennas. All assumptions in Section 4.2 are followed and applied. The transmitter creates a transmission frame consisting of fifty two modulated symbols. The first two symbols are training symbols and the rest are the user data modulated symbols. During modulation and space-time block code encoding, all the user data and pilot symbols are treated in the same manner (STBC transmission rules are applied).

At the receiver side, the receiver receives consecutive signals that correspond to the number of symbols in a transmission frame. The receiver first estimates the channel coefficients and then uses them to recover the transmitted user data. The channel coefficients vector $\breve{h}_1$ can be calculated using:

$$\breve{h}_1 = R_c^{-1}\breve{r}_1 \tag{4.16}$$

where R_c is the sum of 2×2 correlation matrices of the signals transmitted in time slot t. R_c can be written as:

$$R_c = R_c(1) + R_c(2) \tag{4.17}$$

The matrices $R_c(1)$ and $R_c(2)$ can be illustrated by:

$$R_c(1) = \begin{bmatrix} c_1(1)c_1^*(1) & c_2(1)c_1^*(1) \\ c_1(1)c_2^*(1) & c_2(1)c_2^*(1) \end{bmatrix} \tag{4.18}$$

$$R_c(2) = \begin{bmatrix} c_1(2)c_1^*(2) & c_2(2)c_1^*(2) \\ c_1(2)c_2^*(2) & c_2(2)c_2^*(2) \end{bmatrix} \tag{4.19}$$

and $\breve{r}_1$ can be calculated using:

$$\breve{r}_1 = \breve{r}_1(1) + \breve{r}_1(2) \tag{4.20}$$

where $\breve{r}_1(1)$ and $\breve{r}_1(2)$ can be expressed by:

$$\breve{r}_1(1) = \begin{bmatrix} r_1(1)c_1^*(1) \\ r_1(1)c_2^*(1) \end{bmatrix} \tag{4.21}$$

$$\breve{r}_1(2) = \begin{bmatrix} r_2(2)c_1^*(2) \\ r_2(2)c_2^*(2) \end{bmatrix} \tag{4.22}$$

Substituting Equations (4.17) to (4.22) into Equation (4.16), results the following equation:

$$\breve{h}_1 = \begin{bmatrix} \breve{h}_{11} \\ \breve{h}_{21} \end{bmatrix} = R_c^{-1}\breve{r}_1 = (R_c(1) + R_c(2))^{-1}(\breve{r}_1(1) + \breve{r}_1(2)) \tag{4.23}$$

After estimating the channel coefficients vector $\breve{h}_1$, the receiver uses it to detect the rest of the symbols in the received frame (user data symbols). The receiver uses the standard STBC receiving rules for two transmit and one receive antenna to detect the received user data of source as described in Chapter 2. The received user data R_1 in this case can be presented by:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = SH_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{4.24}$$

The channel vector H_1 is set equal to the estimated channel coefficients vector $\breve{h}_1$ in Equation (4.23), that is, $h_1 = \breve{h}_{11}$ and $h_2 = \breve{h}_{21}$. For combining, the receiver takes the channel coefficients vector H_1 and constructs the channel matrix $\ddot{H}_1$. Matrix $\ddot{H}_1$ can be given by:

$$\ddot{H}_1 = \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \tag{4.25}$$

the receiver also takes the received user data vector R_1 and constructs vector $\ddot{R}_1$. Vector $\ddot{R}_1$ can be given by:

$$\ddot{R}_1 = \begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} \tag{4.26}$$

The constructed channel matrix and the received user data vectors are used to combine the received signals. The combined signal can be expressed by:

$$\hat{S} = \ddot{H}_1 \ddot{R}_1 \tag{4.27}$$

The resultant combined signal is then sent to the maximum-likelihood detector to detect the user data of source S.

4.3.2 Detection Scheme for Two Transmit and Two Receive Antennas

In this implementation, there are two transmit and two receive antennas. All steps in Section 4.3.1 are followed to estimate the channel coefficients. The same procedure is needed for every receive antenna because there are two receive antennas. The copy of the transmitted user data goes through different channels to each receiver.

At the receiver side, each receiver receives consecutive signals that correspond to the number of symbols in a transmitted frame. The channel coefficients from transmit to the receive antennas are estimated. These estimated channel coefficients are then used to detect the user data transmitted in the rest of the received frame. To do this, each receiver uses Equation (4.15). The channel coefficient vectors $\breve{h}_1$ and $\breve{h}_2$ can be calculated using the following equations:

$$\breve{h}_1 = R_c^{-1}\breve{r}_1 \tag{4.28}$$

$$\breve{h}_2 = R_c^{-1}\breve{r}_2 \tag{4.29}$$

where R_c can be calculated using Equation (4.17). However, the received vectors $\breve{r}_1$ and $\breve{r}_2$ can be calculated using:

$$\breve{r}_1 = \breve{r}_1(1) + \breve{r}_1(2) \tag{4.30}$$

$$\breve{r}_2 = \breve{r}_2(1) + r_2(2) \tag{4.31}$$

where the vectors $r_1(1)$ and $r_1(2)$ can be expressed as in Equations (4.21) and (4.22). And $r_2(1)$ and $r_2(2)$ can be written similarly. Substituting Equations (4.17), (4.30) and (4.31) into Equations (4.28) and (4.29), this results in the following equations:

$$\breve{h}_1 = \begin{bmatrix} \breve{h}_{11} \\ \breve{h}_{21} \end{bmatrix} = R_c^{-1}\breve{r}_1 = (R_c(1) + R_c(2))^{-1}(\breve{r}_1(1) + \breve{r}_1(2)) \tag{4.32}$$

$$\breve{h}_2 = \begin{bmatrix} \breve{h}_{12} \\ \breve{h}_{22} \end{bmatrix} = R_c^{-1}\breve{r}_2 = (R_c(1) + R_c(2))^{-1}(\breve{r}_2(1) + \breve{r}_2(2)) \tag{4.33}$$

After estimating the channel coefficient vectors $\breve{h}_1$ and $\breve{h}_2$, the receiver uses them to detect the rest of the symbols in the received frame (user data symbols). The receiver uses the standard STBC receiving rules for two transmit and two receive antennas to detect the received user data of source as described in Chapter 2. The received user data vectors R_1 and R_2 can be presented by:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = SH_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{4.34}$$

$$R_2 = \begin{bmatrix} r_3 \\ r_4 \end{bmatrix} = SH_2 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_3 \\ n_4 \end{bmatrix} \tag{4.35}$$

The STBC channel vector H_1 is set equal to the estimated channel vector $\breve{h}_1$ in Equation (4.32) and the vector H_2 is set equal to the estimated channel vector $\breve{h}_2$ in Equation (4.33). The receiver then takes the channel vectors H_1, H_2 and constructs the channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ as in Equation (4.25). In addition, the receiver takes the received user data vectors R_1 and R_2 and constructs the vector $\ddot{R}_1$ and $\ddot{R}_2$ as in Equation (4.26). This is done for the purpose of the combining scheme. The combined signal can be expressed as:

$$\hat{S} = \ddot{H}_1\ddot{R}_1 + \ddot{H}_2\ddot{R}_2 \tag{4.36}$$

The resultant vector then is sent to the maximum-likelihood detector to detect the user data S.

4.3.3 Detection Scheme for Four Transmit and One Receive Antennas

In this implementation, there are four transmit and one receive antenna, that is, $N = 4$ and $M = 1$. All the mentioned assumptions above in Section (4.2) are applied. The transmitter transmits all symbols in the transmission frame. The receiver then takes the first four transmitted symbols (transmitted in eight different time slots) and uses them as pilot symbols to estimate the channel coefficients at the receiver. After estimating the channel coefficients, the receiver then uses them to detect the transmitted user data.

The receiver uses Equation (4.15) to estimate the channel coefficients, uses Equation (4.11) to calculated R_c and uses Equation (4.14) to calculate $\breve{r}_1$. In four transmit antennas systems, we have $R_c(t)$ and $\breve{r}_1(t)$ can be presented by:

$$R_c(t) = \begin{bmatrix} c_1(t)c_1^*(t) & c_2(t)c_1^*(t) & \dots & c_8(t)c_1^*(t) \\ c_1(t)c_2^*(t) & c_2(t)c_2^*(t) & \dots & c_8(t)c_2^*(t) \\ \dots & \dots & \dots & \dots \\ c_1(t)c_8^*(t) & c_2(t)c_8^*(t) & \dots & c_8(t)c_8^*(t) \end{bmatrix} \quad (4.37)$$

$$\breve{r}_1(t) = \begin{bmatrix} r_1(t)c_1^*(t) \\ r_1(t)c_2^*(t) \\ r_1(t)c_3^*(t) \\ r_1(t)c_4^*(t) \end{bmatrix} \quad (4.38)$$

where $t = 1, 2, \dots, 8$, $R_c = R_c(1) + R_c(2) + R_c(3) + R_c(4) + R_c(5) + R_c(6) + R_c(7) + R_c(8)$, and $\breve{r}_1 = \breve{r}_1(1) + \breve{r}_1(2) + \breve{r}_1(3) + \breve{r}_1(4) + \breve{r}_1(5) + \breve{r}_1(6) + \breve{r}_1(7) + \breve{r}_1(8)$.

Substituting Equations (4.11) and (4.14) into Equation (4.15), we obtain the following equation:

$$\breve{h}_1 = \begin{bmatrix} \breve{h}_{11} \\ \breve{h}_{21} \\ \breve{h}_{31} \\ \breve{h}_{41} \end{bmatrix} = R_c \breve{r}_1 \tag{4.39}$$

For STBC signal detection as discussed in Chapter 2, we replace the transmission matrix C for four transmit antennas with STBC G_4 transmission matrix S. The received user data is treated in the same manner as the received user data with the four transmit antenna STBC system. The receiver receives the transmitted user data as:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \\ r_7 \\ r_8 \end{bmatrix} = SH_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \\ n_7 \\ n_8 \end{bmatrix} \tag{4.40}$$

The channel vector H_1 is set equal to the estimated channel vector $\breve{h}_1$ in Equation (4.39), that is, $h_j = h_{j1}$, $j = 1, 2, 3, 4$. The receiver takes the channel vector H_1 and constructs the channel matrix $\ddot{H}_1$. The channel matrix $\ddot{H}_1$ can be presented as:

$$\ddot{H}_1 = \begin{bmatrix} h_1^* & h_2^* & h_3^* & h_4^* & h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & -h_4^* & h_3^* & h_2 & -h_1 & -h_4 & h_3 \\ h_3^* & h_4^* & -h_1^* & -h_2^* & h_3 & h_4 & -h_1 & -h_2 \\ h_4^* & -h_3^* & h_2^* & -h_1^* & h_4 & -h_3 & h_2 & -h_1 \end{bmatrix} \tag{4.41}$$

The receiver also takes the received user data vector R_1 and constructs the vector $\ddot{R}_1$. The vector $\ddot{R}_1$ can be presented as:

$$\ddot{R}_1 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5^* \\ r_6^* \\ r_7^* \\ r_8^* \end{bmatrix} \quad (4.42)$$

The combined signal can be presented as:

$$\hat{S} = \ddot{H}_1 \ddot{R}_1 \quad (4.43)$$

The result is then sent to the maximum-likelihood detector to detect S.

4.3.4 Detection Scheme for Four Transmit and Two Receive Antennas

In this implementation, there are four transmit and two receive antennas. All the mentioned assumptions above in Section 4.2 are applied. This includes the transmission matrix used and this is because the number of transmit antennas is the same.

The receiver takes the first four transmitted symbols (transmitted in eight different time periods) and uses them as pilot symbols to estimate the channel coefficients at every receive antenna. After estimating the channel coefficients, the receiver uses them to detect the received user data. As done for one receive antenna is Section 4.3.3, the estimated channel parameters for each receive antenna can be derived from Equations (4.15), (4.11) and (4.14):

$$\breve{h}_1 = \begin{bmatrix} \breve{h}_{11} \\ \breve{h}_{21} \\ \breve{h}_{31} \\ \breve{h}_{41} \end{bmatrix} = R_c \breve{r}_1 \quad (4.44)$$

$$\breve{h}_2 = \begin{bmatrix} \breve{h}_{12} \\ \breve{h}_{22} \\ \breve{h}_{32} \\ \breve{h}_{42} \end{bmatrix} = R_c \breve{r}_2 \qquad (4.45)$$

Where the matrix $R_c = R_c(1) + R_c(2) + R_c(3) + R_c(4) + R_c(5) + R_c(6) + R_c(7) + R_c(8)$, the vector $\breve{r}_1 = \breve{r}_1(1) + \breve{r}_1(2) + \breve{r}_1(3) + \breve{r}_1(4) + \breve{r}_1(5) + \breve{r}_1(6) + \breve{r}_1(7) + \breve{r}_1(8)$, and the vector $\breve{r}_2 = \breve{r}_2(1) + \breve{r}_2(2) + \breve{r}_2(3) + \breve{r}_2(4) + \breve{r}_2(5) + \breve{r}_2(6) + \breve{r}_2(7) + \breve{r}_2(8)$.

For STBC signal detection, the channel coefficients vectors H_1 and H_2 are set equal to the estimated channel vectors $\breve{h}_1$ and $\breve{h}_2$ respectively. Space-time block code G_4 matrix for four transmit antenna system is used instead of the transmission matrix C . The receiver receives the transmitted user data as:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \\ r_7 \\ r_8 \end{bmatrix} = SH_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \\ n_7 \\ n_8 \end{bmatrix} \qquad (4.46)$$

$$R_2 = \begin{bmatrix} r_9 \\ r_{10} \\ r_{11} \\ r_{12} \\ r_{13} \\ r_{14} \\ r_{15} \\ r_{16} \end{bmatrix} = SH_2 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_5 \\ h_6 \\ h_7 \\ h_8 \end{bmatrix} + \begin{bmatrix} n_9 \\ n_{10} \\ n_{11} \\ n_{12} \\ n_{13} \\ n_{14} \\ n_{15} \\ n_{16} \end{bmatrix} \qquad (4.47)$$

The receiver takes the channel vectors H_1, H_2 and constructs the channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ as in Equation (4.43). The receiver also takes the received user data vectors R_1, R_2 and constructs the vectors $\ddot{R}_1$ and $\ddot{R}_2$ as in Equation (4.44). This is done for the purpose of the combining scheme. The combined signal can be expressed as:

$$\hat{S} = \ddot{H}_1\ddot{R}_1 + \ddot{H}_2\ddot{R}_2 \tag{4.48}$$

The resultant is then sent to the maximum-likelihood detector to detect S.

4.4 Simulations and Results

Many software simulations to estimate the channel parameters at the receiver for space-time block coding have been carried out. MATLAB was used as the environment of the simulations.

The user source of data was produced using a random sequence generator. The modulation schemes used are QPSK and 16-QAM. The channel parameter matrices and noise matrices are generated separately by two model functions using corresponding algorithms. Modulation and demodulation, encoding and decoding, and channel estimation are also performed by relevant model functions, the algorithms of which are described in Sections 4.2 and 4.3. Two and four antennas are used in the transmitter, and one, two, three and four antennas are used in the receiver. Correspondingly, G_2 and G_4 of STBC codes are employed. The transmission code rate is one for STBC with two transmit antennas and half for STBC with four transmit antennas. The bit streams are long enough for confidence in the results.

In this section, we show the simulation results for the performance of STBC on Rayleigh flat fading channels. In the simulation, the receivers do not know the channel coefficients and have to estimate them using the new channel estimation scheme proposed in this chapter. The performances of the bit error rate (BER) for STBC with different numbers of transmit and receive antennas are shown in different figures depending on the modulation scheme used and number of transmit antennas. The simulation results for the performance of STBC with estimated channel parameters are recorded for the purpose of plotting and comparing with the performance of STBC with known channel parameters at the receiver. In Figures 4.2 and 4.3, we provide the bit-error rate for transmission using two and four transmit antennas and different numbers of receive antennas and using QPSK modulation.

Table 4.1 shows all the results for STBC with two transmit antennas and different receive antennas using QPSK modulation in flat Rayleigh fading channels. And Table 4.2 shows all the results for STBC with four transmit antennas and different receive antennas using QPSK modulation in flat Rayleigh fading channels.

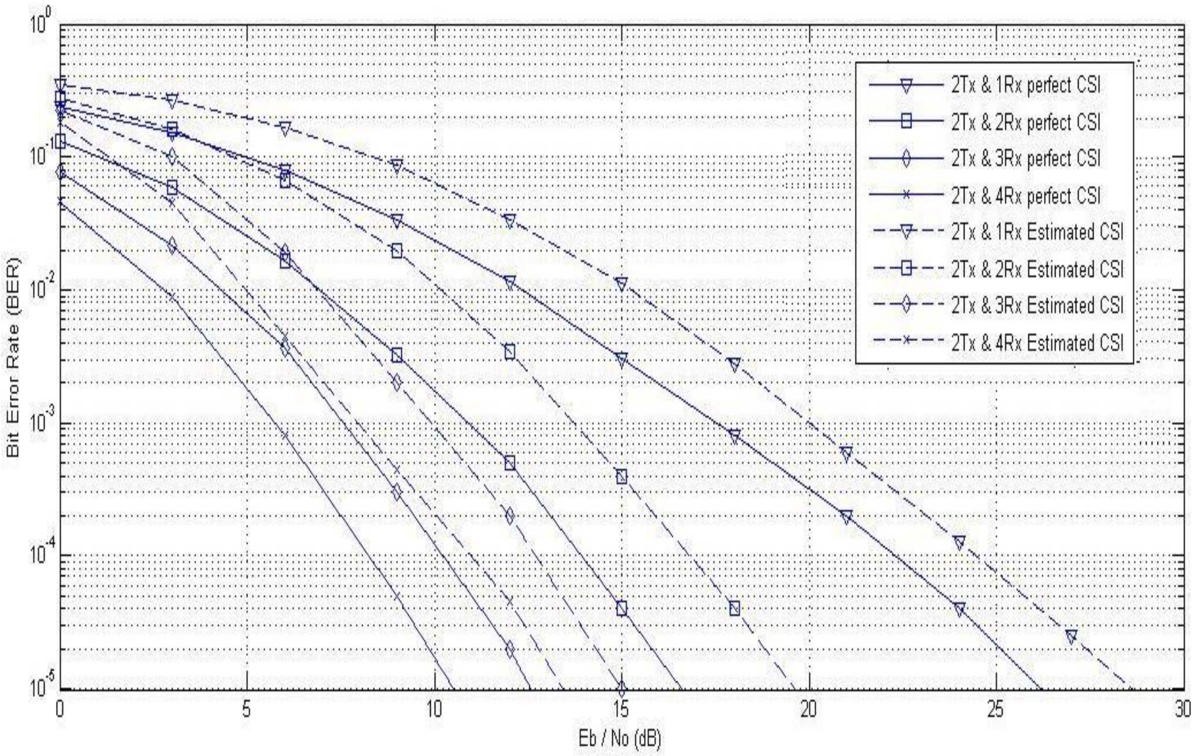

Figure 4.2: The new channel estimation scheme with two transmit antennas using QPSK modulation.

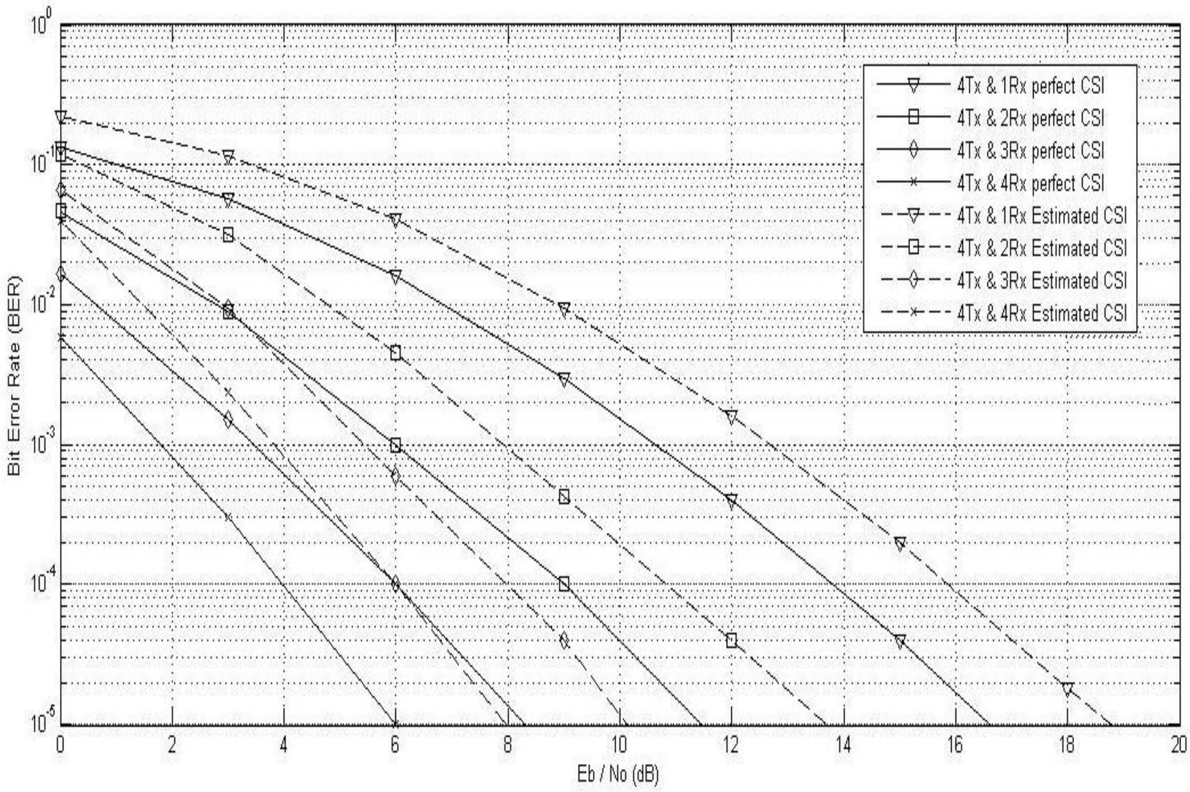

Figure 4.3: The new channel estimation scheme with four transmit antennas using QPSK modulation.

Table 4.1: The BER performances of STBC with two transmit antennas using QPSK modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Estimated CSI 2Tx,1Rx Eb / No	Known CSI 2Tx,2Rx Eb / No	Estimated CSI 2Tx,2Rx Eb / No	Known CSI 2Tx,3Rx Eb / No	Estimated CSI 2Tx,3Rx Eb / No	Known CSI 2Tx,4Rx Eb / No	Estimated CSI 2Tx,4Rx Eb / No
10^{-1}	5	7	2	4.5	-	-	-	-
10^{-2}	12.5	15	7.5	10	4.5	7	2.5	5
10^{-3}	17.5	20	11	13.5	7.5	10	5.5	8
10^{-4}	22	24	14	16.6	10	12.5	8.5	11
10^{-5}	26	28	17	19.5	12.5	15	10.5	13

Table 4.2: The BER performances of STBC with four transmit antennas using QPSK modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Estimated CSI 4Tx,1Rx Eb / No	Known CSI 4Tx,2Rx Eb / No	Estimated CSI 4Tx,2Rx Eb / No	Known CSI 4Tx,3Rx Eb / No	Estimated CSI 4Tx,3Rx Eb / No	Known CSI 4Tx,4Rx Eb / No	Estimated CSI 4Tx,4Rx Eb / No
10^{-1}	1	3	-	-	-	-	-	-
10^{-2}	7	9	3	5	1	3	-	-
10^{-3}	11	13	6	8	3.5	5.5	1.5	3.5
10^{-4}	14	16	9	11	6	8	4	6
10^{-5}	17	19	11.5	13.5	8.5	10.5	6	8

In Figures 4.4 and 4.5, we provide the bit-error rate performance for STBC with two and four transmit antennas and different numbers of receive antennas and using 16-QAM modulation.

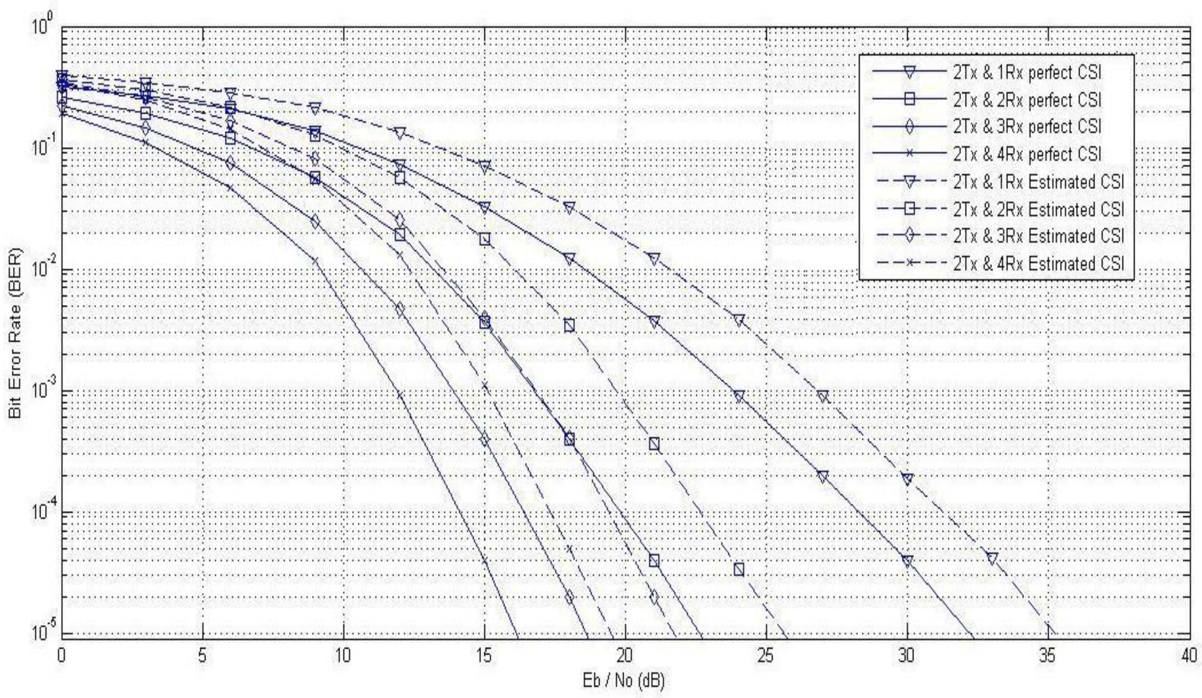

Figure 4.4: The new channel estimation scheme with two transmit antennas using 16-QAM modulation.

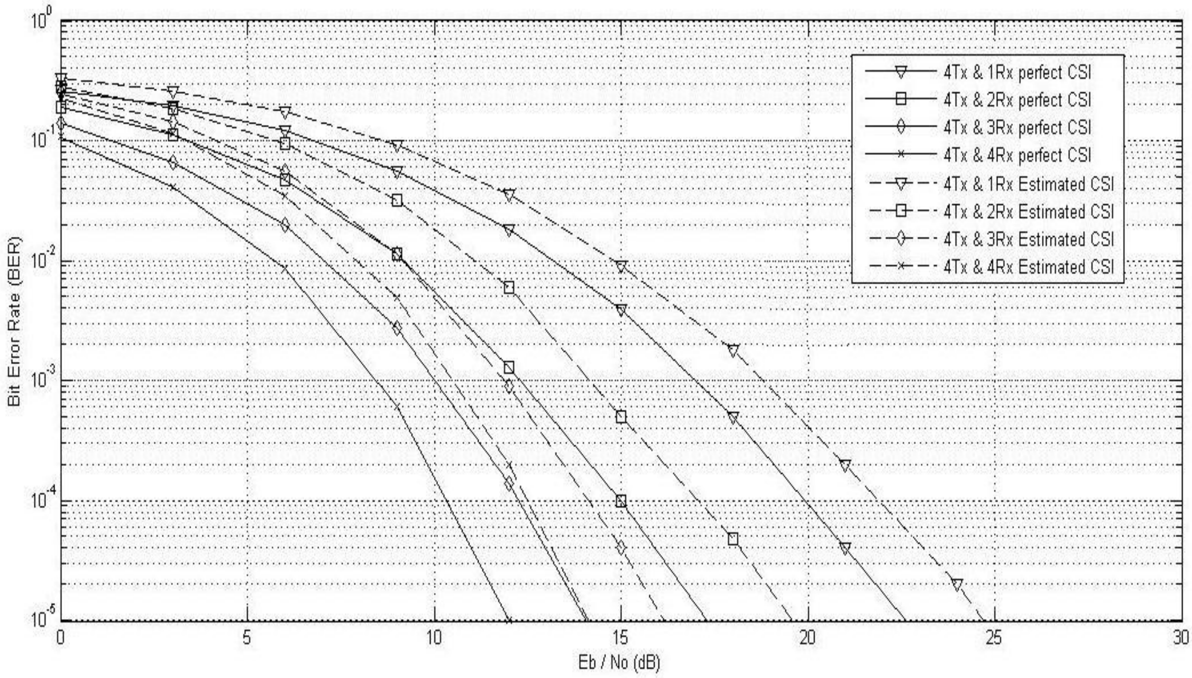

Figure 4.5: The new channel estimation scheme with four tranmit antennas using 16-QAM modulation.

Table 4.3 shows all the results for STBC with two transmit antennas and different receive antennas using 16-QAM modulation in flat Rayleigh fading channels.

Table 4.3: The BER performances of STBC with two transmit antennas using 16-QAM modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Estimated CSI 2Tx,1Rx Eb / No	Known CSI 2Tx,2Rx Eb / No	Estimated CSI 2Tx,2Rx Eb / No	Known CSI 2Tx,3Rx Eb / No	Estimated CSI 2Tx,3Rx Eb / No	Known CSI 2Tx,4Rx Eb / No	Estimated CSI 2Tx,4Rx Eb / No
10^{-1}	10.5	12.5	7	9.5	5	7.5	3.5	6
10^{-2}	19	21	14	16	11	13	9.5	12
10^{-3}	24	26	17	19.5	14	16	12.5	15
10^{-4}	28.5	31	20	22.5	17	19	14	17
10^{-5}	32.5	35	23	25.5	18.5	21.5	16.5	19

Table 4.4 shows all the results for STBC with four transmit antennas and different receive antennas using 16-QAM modulation in flat Rayleigh fading channels.

Table 4.4: The BER performances of STBC with four transmit antennas using 16-QAM modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Estimated CSI 4Tx,1Rx Eb / No	Known CSI 4Tx,2Rx Eb / No	Estimated CSI 4Tx,2Rx Eb / No	Known CSI 4Tx,3Rx Eb / No	Estimated CSI 4Tx,3Rx Eb / No	Known CSI 4Tx,4Rx Eb / No	Estimated CSI 4Tx,4Rx Eb / No
10^{-1}	7	9	4	6	2	4	-	-
10^{-2}	13	15	9	11	7	9	6	8
10^{-3}	17	19	12	14	10	12	8	10.5
10^{-4}	20	22	15	17	12	14	10.5	13
10^{-5}	22	24	17	19	14	16	12	14

The results for channel parameters known and estimated are separately exhibited in each figure. It can be seen from Figure 4.2, Figure 4.3, Table 4.1 and Table 4.2 that at the bit-error rates from 10^{-2} to 10^{-5}, the average loss of performance for channel parameter estimation is approximately $2 \sim 2.5$ dB, lower than that of known channel parameters. It also can be seen from Figure 4.4, Figure 4.5, Table 4.3 and Table 4.4 that at the bit-error rates from 10^{-2} to 10^{-5}, the average loss of performance for channel parameter estimation is approximately $4 \sim 4.5$ dB, worse than that of known channel parameters.

Table 4.5 presents the difference in the bit-error rate performance of space-time block codes with two transmit antennas using the new proposed channel estimation scheme with QPSK modulation and 16-QAM modulation respectively. And Table 4.6 presents the difference in the bit-error rate performance of space-time block codes with four transmit antennas using the new proposed channel estimation scheme with QPSK modulation and 16-QAM modulation respectively.

From Table 4.5 and Table 4.6, the bit-error rate performance of space-time block codes that use QPSK modulation is better than the same space-time block codes that use 16-QAM modulation. There is an approximation of 6 ~ 8 dB better in performance and this is because 16-QAM modulated symbols carry more bits than QPSK modulated symbols by at least the double.

Table 4.5: The differences in BER performance of STBC with two transmit antennas for different modulations.

BER	Est_CSI 2Tx,Rx1 QPSK Eb / No	Est_CSI 2Tx,Rx1 16-QAM Eb / No	Est_CSI 2Tx,Rx2 QPSK Eb / No	Est_CSI 2Tx,Rx2 16-QAM Eb / No	Est_CSI 2Tx,Rx3 QPSK Eb / No	Est_CSI 2Tx,Rx3 16-QAM Eb / No	Est_CSI 2Tx,Rx4 QPSK Eb / No	Est_CSI 2Tx,Rx4 16-QAM Eb / No
10^{-1}	7	12.5	4.5	9.5	-	7.5	-	6
10^{-2}	15	21	10	16	7	13	5	12
10^{-3}	20	26	13.5	19.5	10	16	8	15
10^{-4}	24	31	16.5	22.5	12.5	19	11	17
10^{-5}	28	35	19.5	25.5	15	21.5	13	19

Table 4.6: The differences in BER performance of STBC with four transmit antennas for different modulations.

BER	Est_CSI 4Tx,Rx1 QPSK Eb / No	Est_CSI 4Tx,Rx1 16-QAM Eb / No	Est_CSI 4Tx,Rx2 QPSK Eb / No	Est_CSI 4Tx,Rx2 16-QAM Eb / No	Est_CSI 4Tx,Rx3 QPSK Eb / No	Est_CSI 4Tx,Rx3 16-QAM Eb / No	Est_CSI 4Tx,Rx4 QPSK Eb / No	Est_CSI 4Tx,Rx4 16-QAM Eb / No
10^{-1}	3	9	-	6	-	4	-	-
10^{-2}	9	15	5	11	3	9	-	8
10^{-3}	13	19	8	14	5.5	12	3.5	10.5
10^{-4}	16	22	11	17	8	14	6	13
10^{-5}	19	24	13.5	19	10.5	16	8	14

From the figures and tables above, it could be seen very clearly that the bit-error rate performance of space-time block codes with two transmit and two receive antennas with estimated channels parameters is better than the performance of space-time block codes with two transmit and one receive antennas with known channel parameters at the receiver. If the two performances are compared, then at 10^{-2}, the bit-error rate difference of STBC with estimated channel parameters is approximately better by 2.5 dB and if the bit-error rate is compared at 10^{-3}, then STBC with estimated channel parameters is approximately better by 4.5 dB. The bit-error rate performance of space-time block codes with two transmit and three receive antennas with estimated channels parameters is better than the performance of space-time block codes with two transmit and two receive antennas with known channel parameters at the receiver. This is true for all space-time block codes that use QPSK and 16-QAM.

Similarly, the bit-error-rate performance of space-time block codes with four transmit and two receive antennas with estimated channel parameters is better than the bit-error-rate performance of space-time block codes with four transmit and one receive antenna with known channel parameters at the receiver. And, the bit-error-rate performance for space-time block codes with four transmit and three receive antennas with estimated channel parameters is better than the bit-error-rate performance of space-time block codes with four transmit and two receiver antennas with known channel parameters. This is true for all space-time block codes that use QPSK and 16-QAM.

4.5 Conclusions

In this chapter, another channel estimation scheme for radio links with space-time block codes was investigated, implemented and tested with different types of modulation methods like QPSK and 16-QAM. The channel estimation method was tested with different combinations of transmit and receive antennas. The results of all simulations were presented in data and graph, and analyzed and compared.

Estimation of channel parameters which are necessary for ML detection of STBC is important for practicability of space-time coding techniques. The presented estimation scheme in this chapter is another useful contribution toward solving the channel estimation problem.

References

[1] E. Telatar, “Capacity of Multi-antenna Gaussian Channels”, European Transactions on Telecommunications, Vol. 10, No. 6, pp. 585-595, Nov./ Dec. 1999.

[2] G. J. Foschini and M. J. Gans, “On Limits of Wireless Communications in a Fading Environment When using Multiple Antennas”, Wireless Personal Communications, Vol. 6, pp. 311-335, 1998.

[3] V. Tarokh, N. Seshadri and A. R. Calderbank, “Space-time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction”, IEEE Transactions on Inform Theory, Vol. 44, No. 2, pp. 744-765, March. 1998.

[4] G. J. Foschini, “Layered Space-time Architecture for Wireless Communication in a Fading Environment When using Multiple Antennas,” Bell Labs Technical Journal, Vol.1, No. 2, pp. 41-59, Autumn 1996.

[5] Y. Sato, “A method of Self-recovering Equalization for Multilevel Amplitude-modulation Systems”, IEEE Transactions on Communications, Vol. 23, pp. 679-682, 1975.

[6] D. Godard, “Self-recovering Equalization and Carrier Tracking in Two-dimentional Data Communication Systems”, IEEE Transactions on Communications, Vol. 28, pp. 1867-1875, 1983.

[7] J. R. Treichler and B. G. Agee, “A new Approach to Multipath Correction of Constant Modulus Signals”, IEEE Transactions on Signal Processing, Vol. 31, pp. 459-472, April 1983.

[8] G. Picchi and G. Prati, “Blind Equalization and Carrier Recovering using a Stop-and-go Decision-directed Algorithm”, IEEE Transactions on Communications, Vol. 35, pp. 877-887, 1987.

[9] K. S. Lii and M. Rosenblatt, “Deconvolution and Estimation of Transfer Function Phase and Coefficients for non-Gaussian Linear Processes”, Ann. Statist, Vol. 10, pp. 1195-1208, 1982.

[10] H. H. Chiang and C. L. Nikias, “Adaptive De-convolution and Identification of non-Minimum Phase FIR Systems Based on Cumulants”, IEEE Transactions on Automat. Contr, Vol. 35, pp. 36-47, 1990.

[11] D. Hatzinakos and C. L. Nikias, “Blind Equalization using a Tricepstrum-based Algorithm”, IEEE Transactions on Communications, Vol. 39, pp. 669-682, May 1991.

[12] F. C. Zheng, S. McLaughlin, and B. Mulgrew, “Blind Equalization of non-Minimum Phase Channels: Higher Order Cumulant Based Algorithm”, IEEE Transactions on Signal Processing, Vol. 41, pp. 681-691, Feb 1993.

[13] M. Ghosh and C. L. Weber, “Maximum-likelihood Blind Equalization”, In proc. spie, Vol. 1565, pp. 188-195, San Diego, Ca, 1991

[14] N. Seshadri, “Joint Data and Channel Estimation using Blind Trellis Search Techniques”, IEEE Transactions on Communications, Vol. 42, pp. 1000-1011, Feb/Mar/April 1994.

[15] E.Zervas, J. Proakis, and V. Eyuboglu, “A quantized Channel Approach to Blind Equalization”, In Proc on ICC, Vol. 3, pp. 351.8.1-351.8.5, Chicago, IL, 1992.

[16] J. G. Proakis, “Adaptive Algorithms for Blind Channel Equalization”, In Proc, 3rd IMA Conference. Math. Signal Process, Univ. Warwick, Warwick, UK, 1992.

[17] F. Chan, J. Choi, P. Rapajic and J. Yuan, “Information Theoretic Comparisons of Training Based Channel Estimation and Semi-blind Estimation in Fading Channels with Memory ”, IEEE transactions, pp. 6-10, 18-19 Nov. 2004

[18] J. Yang, E. Masood and Y. Sun, "Performance of Space-time Block Coding Using Estimated Channel Parameters", London Communications Symposium Conference UCL, 2004.

[19] V. Tarokh, H. Jafarkham, A. R. Calderbank, "Space-Time Block Coding for Wireless Communications: Performance Results", IEEE Journal on Selected Areas in Communications. Vol. 17, No. 3, pp. 451-460, March 1999.

[20] A. F. Naguib, A. R. Calderbank, "Space-time Coding and Signal Processing for High Data Rate Wireless Communications", Wireless Communications and Mobile Computing, Vol. 1, pp. 13-34, 2001.

[21] S.M Alamouti, "A simple Transmitter Diversity Scheme for Wireless Communications", IEEE Journal on Selected Areas in Communications, Vol. SAC-16, pp. 1451-1458, October 1998.

[22] Y. LiY,J. C. Chuang, N. R. Sollenberger, "Transmitter Diversity for OFDM Systems and Its Impact on High-Rate Data Wireless Networks", IEEE Journal on Selected Areas in Communications, Vol. 17, pp. 1233-1243, 1999.

[23] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Va;enzuela, "V-BLAST: an Architecture for Realizing Very High Data Rates Over the Rich-scattering Wireless Channel", International Symposium on Signals, Systems, and Electronics, pp. 295-300, 1998.

[24] H. Huang, H. Viswanathan, and G. J. Foschini, "Achieving High Data Rates in CDMA Systems using BLAST Techniques", Proc. Globe-communications, Vol. 5, pp. 2316-2320, 1999.

[25] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, “Space-time Block Codes from Orthogonal Designs”, IEEE Transactions on Information Theory, Vol. 45, No. 5, pp. 1456-1467, July 1999.

[26] B. M. Hochwald and T. L. Marzetta, “Unitary Space-time Modulation for Multiple Antenna Communications in Rayleigh Flat Fading”, IEEE Transactions on Information Theory, Vol. 46, No. 2, pp. 543-564, March 2000.

[27] V. Tarokh and H. Jafarkhani, “A differential Detection Scheme for Transmit Diversity”, IEEE Journal on Selected Areas in Communications, Vol. 18, No. 7, pp. 1169-1174, July 2000.

[28] B. L. Hughes, “Differential Space-time Modulation”, IEEE Wireless Communications and Networking Conference, Vol. 1, pp. 145-149, 1999.

[29] J. G. Proakis, “Digital Communications, 4th Ed”, McGraw-Hill, New York, 2001.

5 Joint Detection with no CSI and Separate Channel Estimation for Space-Time Block Coding using Real Signal Constellations

5.1 Introduction

Decoding of space-time codes requires the knowledge of channel state information at the receiver, which is usually difficult to obtain. Most STBC schemes assumed ideal channel state information [1, 2, 3]. However, channel parameters are normally not known in practice due to changing environments and thus need to be estimated.

Channel estimation for space-time coded wireless communications has thus been widely studied. A channel estimator extracts the fade coefficients from the received signal approximations during each data frame. This can be done using training or pilot symbols or sequences to estimate the channel for each of the transmit antennas to each receive antenna.

In Chapters 3 and 4, two channel estimation schemes based on the use of training symbols were presented [4, 5]. The formulations in these two chapters were based on using complex signal constellation produced by QPSK and 16 QAM modulations. The work in this chapter is to reformulate the two channel estimation schemes presented in Chapters 3 and 4 to work with real signals produced by BPSK modulation.

The chapter is organized as in the following; Section 5.2 reformulates the channel estimation scheme in Chapter 3 to work with BPSK modulation and Section 5.3 reformulates the channel estimation scheme in Chapter 4 to work with BPSK modulation. Section 5.4 presents the results that came out from the simulations done on the systems described in Sections 5.2 and 5.3. The chapter is finalized by a brief conclusion in Section 5.5.

5.2 Joint Data Detection for Space-time Block Codes with Real Constellations

In this section, we reformulate the channel estimation method in Chapter 3 to work with real constellation signals produced by BPSK modulation scheme. To keep presentation simple, we discuss two representative cases: two and four transmit and two receive antennas. For any other combinations of transmit and receive antennas, different channel coefficients have to be considered but in a similar way.

5.2.1 Joint Scheme for Two Transmit and Two Receive Antennas

In this implementation, there are two transmit and two receive antennas. All the mentioned assumptions made in Section 3.2 are followed and applied. In two transmit antennas systems, the transmitter takes four symbols at a time and constructs two G_2 matrices S_1 and S_2. The matrix S_1 represents the pilot sequence and matrix S_2 represents the user data and they can be presented by:

$$\mathrm{S}_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{bmatrix} \tag{5.1}$$

$$\mathrm{S}_2 = \begin{bmatrix} s_3 & s_4 \\ -s_4 & s_3 \end{bmatrix} \tag{5.2}$$

At the receiver side, there are two receive antennas, each of which receives four different consecutive signals. At first, the two receive antennas receive the transmitted pilot sequences as $r_{1,1}$ and $r_{2,1}$ at the first receive antenna and as $r_{1,2}$ and $r_{2,2}$ at the second receive antenna. The two receive antennas also receive the transmitted data user as $r_{3,1}$ and $r_{4,1}$ at the first receive antenna and as $r_{3,2}$ and $r_{4,2}$ at the second receive antenna. The four received signals at the first receive antenna can be expressed by:

$$R_1 = \begin{bmatrix} r_{1,1} \\ r_{2,1} \end{bmatrix} = S_1 H_1 + N_1 = \begin{bmatrix} s_1 h_1 + s_2 h_2 + n_{1,1} \\ -s_2 h_1 + s_1 h_2 + n_{2,1} \end{bmatrix} \tag{5.3}$$

$$R_2 = \begin{bmatrix} r_{3,1} \\ r_{4,1} \end{bmatrix} = S_2 H_1 + N_2 = \begin{bmatrix} s_3 h_1 + s_4 h_2 + n_{3,1} \\ -s_4 h_1 + s_3 h_2 + n_{4,1} \end{bmatrix} \tag{5.4}$$

the other four received signals at the second receiver antenna can be expressed by:

$$R_3 = \begin{bmatrix} r_{1,2} \\ r_{2,2} \end{bmatrix} = S_1 H_2 + N_3 = \begin{bmatrix} s_1 h_3 + s_2 h_4 + n_{1,2} \\ -s_2 h_3 + s_1 h_4 + n_{2,2} \end{bmatrix} \tag{5.5}$$

$$R_4 = \begin{bmatrix} r_{3,2} \\ r_{4,2} \end{bmatrix} = S_2 H_2 + N_4 = \begin{bmatrix} s_3 h_3 + s_4 h_4 + n_{3,2} \\ -s_4 h_3 + s_3 h_4 + n_{4,2} \end{bmatrix} \tag{5.6}$$

Using Equations (5.3) and (5.5), the receiver estimate the channel vectors H_1 and H_2. The two estimated channel vectors can be written as:

$$\dot{H}_1 = \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{bmatrix} = S_1^{-1} R_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{bmatrix}^{-1} \begin{bmatrix} r_{1,1} \\ r_{2,1} \end{bmatrix} \tag{5.7}$$

$$\dot{H}_2 = \begin{bmatrix} \tilde{h}_3 \\ \tilde{h}_4 \end{bmatrix} = S_1^{-1} R_3 = \begin{bmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{bmatrix}^{-1} \begin{bmatrix} r_{1,2} \\ r_{2,2} \end{bmatrix} \tag{5.8}$$

For the combining purposes, the receiver constructs two channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ from the estimated channel vectors in Equations (5.7) and (5.8). The two channel matrices can be written as:

$$\ddot{H}_1 = \begin{bmatrix} \tilde{h}_1 & \tilde{h}_2 \\ \tilde{h}_2 & -\tilde{h}_1 \end{bmatrix} \tag{5.9}$$

$$\ddot{H}_2 = \begin{bmatrix} \tilde{h}_3 & \tilde{h}_4 \\ \tilde{h}_4 & -\tilde{h}_3 \end{bmatrix} \tag{5.10}$$

The receiver also constructs the vectors $\ddot{R}_1$ and $\ddot{R}_2$ from the received signal vector in Equations (5.4) and (5.6). The two new vectors can be written as:

$$\ddot{R}_1 = \begin{bmatrix} r_{3,1} \\ r_{4,1} \end{bmatrix} \tag{5.11}$$

$$\ddot{R}_2 = \begin{bmatrix} r_{3,2} \\ r_{4,2} \end{bmatrix} \tag{5.12}$$

The combining scheme at the receiver can be expressed as:

$$\tilde{S}_2 = \ddot{H}_1\ddot{R}_1 + \ddot{H}_2\ddot{R}_2 = \begin{bmatrix} \tilde{h}_1 & \tilde{h}_2 \\ \tilde{h}_2 & -\tilde{h}_1 \end{bmatrix}\begin{bmatrix} r_{3,1} \\ r_{4,1} \end{bmatrix} + \begin{bmatrix} \tilde{h}_3 & \tilde{h}_4 \\ \tilde{h}_4 & -\tilde{h}_3 \end{bmatrix}\begin{bmatrix} r_{3,2} \\ r_{4,2} \end{bmatrix} \tag{5.13}$$

After the combining scheme, the produced vector $\hat{S}_2$ is sent to the maximum likelihood detector to detect the user data S_2. For the next iteration, the receiver saves $\hat{S}_2$ as S_1 and R_2 as R_1. This procedure will go on until all the transmitted data are received and recovered by the receiver.

5.2.2 Joint Scheme for Four Transmit and Two Receive Antennas

In this implementation, there are four transmit and two receive antennas. All assumptions in Section 3.2 are followed and applied. In the four transmit antenna system, the transmitter takes eight symbols at a time and constructs two G_4 transmission matrices S_1 and S_2. The transmission matrix S_1 is used to transmit the first four symbols used as a pilot sequence and matrix S_2 is used to transmit the other four symbols as the user source of data. The two transmission matrices are real and can be written as :

$$S_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \tag{5.14}$$

$$S_2 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \end{bmatrix} \tag{5.15}$$

At the receiver side, there are two receive antennas, each of which will receive eight consecutive signals. The first receive antenna receives $r_{1,1}$, $r_{2,1}$, $r_{3,1}$, and $r_{4,1}$ for the pilot sequence and then receives $r_{5,1}$, $r_{6,1}$, $r_{7,1}$, and $r_{8,1}$ for the user data. The second receive antenna receives $r_{1,2}$, $r_{2,2}$, $r_{3,2}$, and $r_{4,2}$ for the pilot sequence and receives $r_{5,2}$, $r_{6,2}$, $r_{7,2}$, and $r_{8,2}$ for the user data. The received signals at the first receive antenna can be written as:

$$R_1 = \begin{bmatrix} r_{1,1} \\ r_{2,1} \\ r_{3,1} \\ r_{4,1} \end{bmatrix} = S_1 H_1 + N_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_{1,1} \\ n_{2,1} \\ n_{3,1} \\ n_{4,1} \end{bmatrix} \tag{5.16}$$

$$R_2 = \begin{bmatrix} r_{5,1} \\ r_{6,1} \\ r_{7,1} \\ r_{8,1} \end{bmatrix} = S_2 H_1 + N_2 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_{5,1} \\ n_{6,1} \\ n_{7,1} \\ n_{8,1} \end{bmatrix} \tag{5.17}$$

the received signals at the second receive antenna can be written as:

$$R_3 = \begin{bmatrix} r_{1,2} \\ r_{2,2} \\ r_{3,2} \\ r_{4,2} \end{bmatrix} = S_1 H_2 + N_3 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \begin{bmatrix} h_5 \\ h_6 \\ h_7 \\ h_8 \end{bmatrix} + \begin{bmatrix} n_{1,2} \\ n_{2,2} \\ n_{3,2} \\ n_{4,2} \end{bmatrix} \tag{5.18}$$

$$R_4 = \begin{bmatrix} r_{5,2} \\ r_{6,2} \\ r_{7,2} \\ r_{8,2} \end{bmatrix} = S_2 H_2 + N_4 = \begin{bmatrix} s_5 & s_6 & s_7 & s_8 \\ -s_6 & s_5 & -s_8 & s_7 \\ -s_7 & s_8 & s_5 & -s_6 \\ -s_8 & -s_7 & s_6 & s_5 \end{bmatrix} \begin{bmatrix} h_5 \\ h_6 \\ h_7 \\ h_8 \end{bmatrix} + \begin{bmatrix} n_{5,2} \\ n_{6,2} \\ n_{7,2} \\ n_{8,2} \end{bmatrix} \tag{5.19}$$

The receiver estimates the channel vectors H_1 and H_2 from Equations (5.16) and (5.18). The two estimated channel vectors can be written as:

$$\dot{H}_1 = S_1^{-1} R_1 \tag{5.20}$$

$$\dot{H}_2 = S_1^{-1} R_3 \tag{5.21}$$

For the combining purposes, the receiver constructs the channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ from the estimated channel vectors in Equations (5.20) and (5.21). The constructed channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ can be presented as:

$$\ddot{H}_1 = \begin{bmatrix} \tilde{h}_1 & \tilde{h}_2 & \tilde{h}_3 & \tilde{h}_4 \\ \tilde{h}_2 & -\tilde{h}_1 & -\tilde{h}_4 & \tilde{h}_3 \\ \tilde{h}_3 & \tilde{h}_4 & -\tilde{h}_1 & -\tilde{h}_2 \\ \tilde{h}_4 & -\tilde{h}_3 & \tilde{h}_2 & -\tilde{h}_1 \end{bmatrix} \quad (5.22)$$

$$\ddot{H}_2 = \begin{bmatrix} \tilde{h}_5 & \tilde{h}_6 & \tilde{h}_7 & \tilde{h}_8 \\ \tilde{h}_6 & -\tilde{h}_5 & -\tilde{h}_8 & \tilde{h}_7 \\ \tilde{h}_7 & \tilde{h}_8 & -\tilde{h}_5 & -\tilde{h}_6 \\ \tilde{h}_8 & -\tilde{h}_7 & \tilde{h}_6 & -\tilde{h}_5 \end{bmatrix} \quad (5.23)$$

The receiver also constructs the vectors $\ddot{R}_1$ and $\ddot{R}_2$ from the received signal vector in Equations (5.17) and (5.19). The two new vectors can be written as:

$$\ddot{R}_1 = \begin{bmatrix} r_{5,1} \\ r_{6,1} \\ r_{7,1} \\ r_{8,1} \end{bmatrix} \quad (5.24)$$

$$\ddot{R}_2 = \begin{bmatrix} r_{5,2} \\ r_{6,2} \\ r_{7,2} \\ r_{8,2} \end{bmatrix} \quad (5.25)$$

The receiver uses $\ddot{H}_1, \ddot{H}_2$, $\ddot{R}_1$ and $\ddot{R}_2$ for the combining scheme to recover S_2. The combining scheme can be expressed as:

$$\tilde{S}_2 = \ddot{H}_1 \ddot{R}_1 + \ddot{H}_2 \ddot{R}_2 \quad (5.26)$$

The resultant vector $\hat{S}_2$ from the combining scheme is then sent to the maximum likelihood detector to detect the user data S_2. For the next iteration, the receiver saves $\hat{S}_2$ as S_1, R_2 as

R_1 and R_4 as R_3. This procedure will go on until all the transmitted data are received and recovered by the receiver.

5.3 Separate Channel Estimation Scheme for Space-time Block Codes using Real Constellations

In this section, we discuss the channel estimation scheme in Chapter 4 for real signals produced by BPSK modulation. For simplicity, we discuss two representative cases: two and four transmit and two receive antennas in detail.

5.3.1 Estimation Scheme for Two Transmit and Two Receive Antennas

In this implementation, there are two transmit and two receive antennas. All assumptions in Section 4.2 are applied. In this scheme, the transmitter creates a transmission frame that contains 52 transmitting symbols. The first two symbols are modulated pilot sequence and the rest are modulated user data. The transmitter takes two symbols at a time and constructs a G_2 transmission matrix S_1 in Equation (5.1). During modulation and space-time block code encoding, all transmitted symbols (pilot sequences and user data) are treated in the same manner.

At the receiver side, each antenna receives consecutive signals that correspond to the number of symbols in a transmitted frame. The receiver first estimates the channel coefficients and then uses them to recover the user data. To do this, each receiver uses Equation (4.15) to estimate the channel coefficients vectors $\breve{h}_1$ and $\breve{h}_2$. The estimated channel coefficients vectors $\breve{h}_1$ and $\breve{h}_2$ can be calculated by:

$$\breve{h}_1 = R_c^{-1}\breve{r}_1 \tag{5.27}$$

$$\breve{h}_2 = R_c^{-1}\breve{r}_2 \tag{5.28}$$

where R_c is equal to:

$$R_c = R_c(1) + R_c(2) \tag{5.29}$$

And the vectors $\breve{r}_1$ and $\breve{r}_2$ can be presented by:

$$\breve{r}_1 = r_1(1) + r_1(2) \tag{5.30}$$

$$\breve{r}_2 = r_2(1) + r_2(2) \tag{5.31}$$

where the matrices $R_c(1)$ and $R_c(2)$ can be calculated using Equations (4.11) and the vectors $\breve{r}_1$ and $\breve{r}_2$ can be calculated using Equation (4.14). Substituting the Equations (4.24), (4.25) and (4.26) into Equations (5.27) and (5.28), the resultant vectors $\breve{h}_1$ and $\breve{h}_2$ can be expressed by:

$$\breve{h}_1 = \begin{bmatrix} \breve{h}_{11} \\ \breve{h}_{21} \end{bmatrix} = R_c^{-1}\breve{r}_1 = (R_c(1) + R_c(2))^{-1}(r_1(1) + r_1(2)) \tag{5.32}$$

$$\breve{h}_2 = \begin{bmatrix} \breve{h}_{12} \\ \breve{h}_{22} \end{bmatrix} = R_c^{-1}\breve{r}_2 = (R_c(1) + R_c(2))^{-1}(r_2(1) + r_2(2)) \tag{5.33}$$

After estimating the channel coefficients vectors $\breve{h}_1$ and $\breve{h}_2$, the receiver uses them to detect the transmitted user data. The receivers treat the user data in different manner than the pilot sequences. The receiver use simple STBC scheme methods to detect the transmitted user data. The received data user can be illustrated by:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = SH_1 = \begin{bmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{bmatrix}\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{5.34}$$

$$R_2 = \begin{bmatrix} r_3 \\ r_4 \end{bmatrix} = SH_2 = \begin{bmatrix} s_1 & s_2 \\ -s_2 & s_1 \end{bmatrix} \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_3 \\ n_4 \end{bmatrix} \quad (5.35)$$

where R_1 is the received user data vector at the first receive antenna and R_2 is the received user data vector at the second receive antenna. The channel vector H_1 is set equal to the estimated channel vector $\breve{h}_1$ in Equation (5.32) and the channel vector H_2 is set equal to the estimated channel vector $\breve{h}_2$ in Equation (5.33). The receiver then takes the vectors H_1 and H_2 and construct two channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ as in Equations (5.9) and (5.10). The receiver also takes the received user data vectors R_1 and R_2 and construct two new vectors $\ddot{R}_1$ and $\ddot{R}_2$ as in Equation (5.11) and (5.12). Then, the combined signal can be expressed as:

$$\hat{S} = \ddot{H}_1 \ddot{R}_1 + \ddot{H}_2 \ddot{R}_2 \quad (4.36)$$

The resultant then is sent to the maximum-likelihood detector to detect S. This will be done with the entire data user in one frame. For the next receive, all the process explained in this section is repeated until the receiver recovers all the transmitted frames.

5.3.2 Estimation Scheme for Four Transmit and Two Receive Antennas

In this implementation, there are four transmit and two receive antennas. The same process done in Section 5.3.1 is used here; the only difference is that there are four transmit antennas instead of two. At the transmitter side, a frame of 52 symbols is constructed. The first four symbols are modulated pilot sequence and the rest are modulated user data. The transmitter transmit all the pilot symbols and user data in the same manner as in STBC [STBC with four transmit antennas]. The transmitter takes four symbols at a time and constructs a G_4 square transmission matrix S_1 as in Equation (5.14). The transmitter transmits four symbols at a time; four transmission times are required to recover four symbols.

At the receiver side, each receive antenna receives the 52 transmitted symbols that make up a transmission frame. The receiver first estimates the required channel parameter vectors and then uses them to detect the transmitted user data. The first receive antenna estimate the channel coefficients vector $\breve{h}_1$ and the second receive antenna estimate the channel coefficients vector $\breve{h}_2$. The channel coefficients vectors $\breve{h}_1$ and $\breve{h}_2$ can be calculated using Equations (5.27) and (5.28) where R_c can be calculated using Equation (5.29), $\breve{r}_1$ and $\breve{r}_2$ can be calculated using Equations (5.30) and (5.31). For real STBC signals, the matrices $R_c(t)$ and $\breve{r}_j(t)$ can be written as:

$$R_c(t) = \begin{bmatrix} c_1(t)c_1(t) & c_2(t)c_1(t) & c_3(t)c_1(t) & c_4(t)c_1(t) \\ c_1(t)c_2(t) & c_2(t)c_2(t) & c_3(t)c_2(t) & c_4(t)c_2(t) \\ c_1(t)c_3(t) & c_2(t)c_3(t) & c_3(t)c_3(t) & c_4(t)c_3(t) \\ c_1(t)c_4(t) & c_2(t)c_4(t) & c_3(t)c_4(t) & c_4(t)c_4(t) \end{bmatrix} \quad (5.37)$$

$$r_j(t) = \begin{bmatrix} r_j(t)c_1(t) \\ r_j(t)c_2(t) \\ r_j(t)c_3(t) \\ r_j(t)c_4(t) \end{bmatrix} \quad (5.38)$$

where $t = 1, 2, 3, 4$, $j = 1, 2$, $R_c = R_c(1) + R_c(2) + R_c(3) + R_c(4)$, $\breve{r}_1 = \breve{r}_1(1) + \breve{r}_1(2) + \breve{r}_1(3) + \breve{r}_1(4)$ and $\breve{r}_2 = \breve{r}_2(1) + \breve{r}_2(2) + \breve{r}_2(3) + \breve{r}_2(4)$. From Equation (4.15), the following equations are obtained:

$$\breve{h}_1 = \begin{bmatrix} \breve{h}_{11} \\ \breve{h}_{21} \\ \breve{h}_{31} \\ \breve{h}_{41} \end{bmatrix} = R_c^{-1}\breve{r}_1 \quad (5.39)$$

$$\breve{h}_2 = \begin{bmatrix} \breve{h}_{12} \\ \breve{h}_{22} \\ \breve{h}_{32} \\ \breve{h}_{42} \end{bmatrix} = R_c^{-1}\breve{r}_2 \qquad (5.40)$$

For STBC symbol detection, the channel coefficient vectors H_1 and H_2 are set equal to the estimated channel vectors $\breve{h}_1$ and $\breve{h}_2$ respectively. Space-time block codes G_4 matrix for the four transmit antenna system is used instead of the transmission matrix C. the receiver receives the transmitted user data as:

$$R_1 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = SH_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix} \qquad (5.41)$$

$$R_2 = \begin{bmatrix} r_5 \\ r_6 \\ r_7 \\ r_8 \end{bmatrix} = SH_2 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \begin{bmatrix} h_5 \\ h_6 \\ h_7 \\ h_8 \end{bmatrix} + \begin{bmatrix} n_5 \\ n_6 \\ n_7 \\ n_8 \end{bmatrix} \qquad (5.42)$$

The receiver takes the vectors H_1 and H_2 and constructs the channel matrices $\ddot{H}_1$ and $\ddot{H}_2$ as in Equations (5.22) and (5.23). the receiver also takes the received user data vectors R_1 and R_2 and constructs the vectors $\ddot{R}_1$ and $\ddot{R}_2$ as:

$$\ddot{R}_1 = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} \qquad (5.41)$$

$$\ddot{R}_2 = \begin{bmatrix} r_5 \\ r_6 \\ r_7 \\ r_8 \end{bmatrix} \tag{5.42}$$

This is done for the purpose of the combining scheme. The combined signal can be illustrated by:

$$\hat{S} = \ddot{H}_1\ddot{R}_1 + \ddot{H}_2\ddot{R}_2 \tag{4.43}$$

The resultant then is sent to the maximum-likelihood detector to detect S. This will be done with the entire user data in one frame. For the next receive, all the process explained in this section is done again until the receiver recovers all the transmitted frames.

5.4 Simulations and Results

A pseudo random sequence generator is used for producing pilot sequences and source user data. The channel parameter matrices and noise matrices are generated separately by using different model functions that use the corresponding algorithms. Modulation and demodulation, encoding and decoding, and channel estimation are also performed by relevant model functions. The bit streams that are run in our simulations are long enough for confidence in the results. The method of modulation used in this chapter is BPSK.

In this section, we show the simulation results for the performance of STBC on Rayleigh fading channels. In the simulation, the receivers do not know the channel state information (CSI) and have to estimate them using both estimation schemes described above. The performances of the bit error rate (BER) for the different implementations of STBC that uses different numbers of transmit and receive antennas are shown in four different figures depending on the estimation method and the number of transmit antennas used. In the simulations, the transmission code rate is always 1 because all the transmission matrices used for real signal constellations are always square matrices.

The simulation results for the performance of STBC with estimated channel parameters are recorded for the purpose of plotting and comparing with the performance of STBC with known channel parameters at the receiver.

In Figure 5.1 and 5.2, we provide the bit-error rate for the joint channel estimation and data detection using two and four transmit antennas and different numbers of receive antennas. Data in tables can be obtained from the figures. The giving tables are used for easier numerical comparisons. Table 5.1 shows the results for STBC with two transmit antennas and different receive antennas using BPSK modulation in flat Rayleigh fading channels. And Table 5.2 shows the results for STBC with four transmit antennas and different receive antennas using BPSK modulation in flat Rayleigh fading channels.

Figures 5.1 and 5.2, Tables 5.1 and 5.2 illustrate the bit-error-rate (BER) results for channel parameters known and estimated. The average loss of performance for estimated channel parameter is approximately 2 ~ 2.5 dB lower than that of known channel parameters.

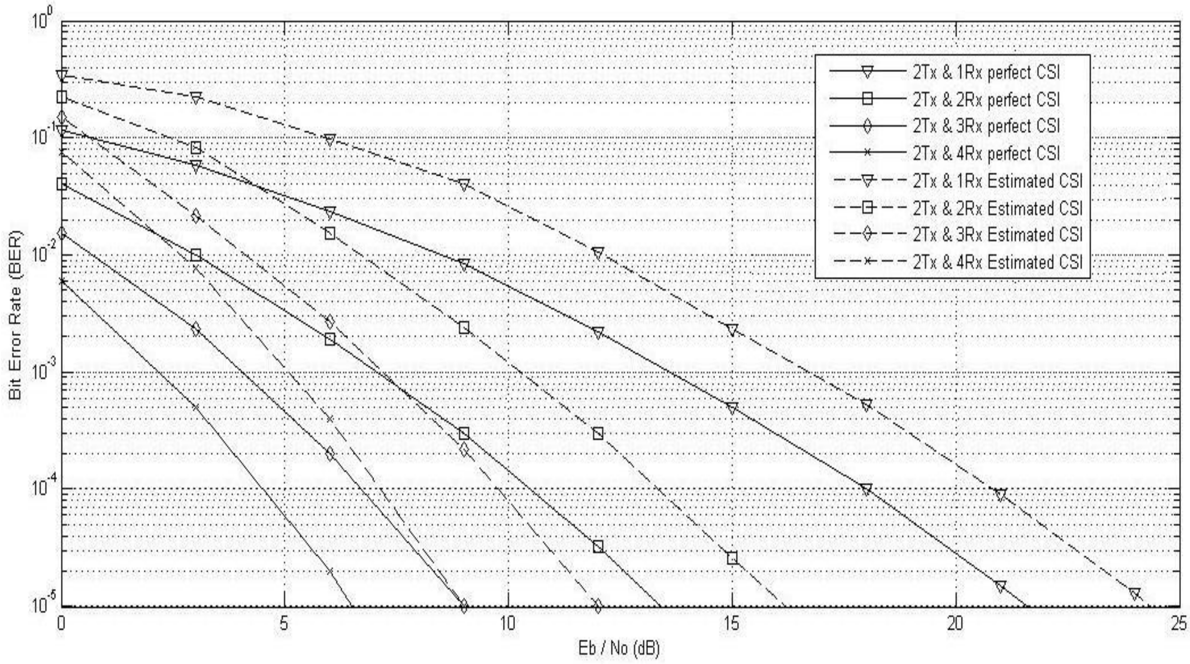

Figure 5.1: Joint data detection for STBC with two transmit antennas using BPSK modulation.

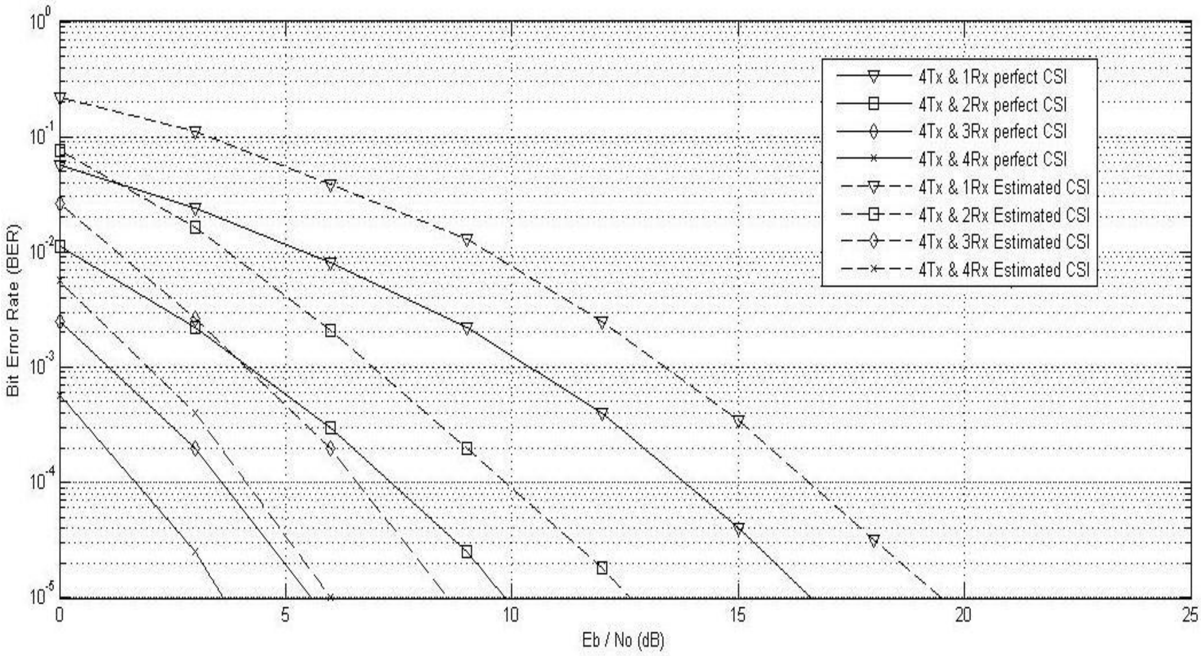

Figure 5.2: Joint data detection for STBC with four transmit antennas using BPSK modulation.

Table 5.1: BER performances of joint data detection for STBC with two transmit antennas using BPSK modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Estimated CSI 2Tx,1Rx Eb / No	Known CSI 2Tx,2Rx Eb / No	Estimated CSI 2Tx,2Rx Eb / No	Known CSI 2Tx,3Rx Eb / No	Estimated CSI 2Tx,3Rx Eb / No	Known CSI 2Tx,4Rx Eb / No	Estimated CSI 2Tx,4Rx Eb / No
10^{-2}	8	12	3	7	1	4	-	3
10^{-3}	14	16.5	7	10	4	7	2.5	5
10^{-4}	18	21	11	13.5	7.5	10	4.5	7
10^{-5}	21.5	24	13.5	16	9	12	6.5	9

Table 5.2: BER performances of joint data detection for STBC with four transmit antennas using BPSK modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Estimated CSI 4Tx,1Rx Eb / No	Known CSI 4Tx,2Rx Eb / No	Estimated CSI 4Tx,2Rx Eb / No	Known CSI 4Tx,3Rx Eb / No	Estimated CSI 4Tx,3Rx Eb / No	Known CSI 4Tx,4Rx Eb / No	Estimated CSI 4Tx,4Rx Eb / No
10^{-2}	6	9	0.5	3.5	-	2	-	-
10^{-3}	10.5	13.5	4	7	1.5	4	-	2.5
10^{-4}	14	16	7	10	4	7	2	4
10^{-5}	16	19.5	9.5	12.5	5.5	8.5	3.5	6

In Figure 5.3 and 5.4, we provide the bit-error rate for transmissions using two and four transmit antennas and different numbers of receive antennas and using BPSK modulation.

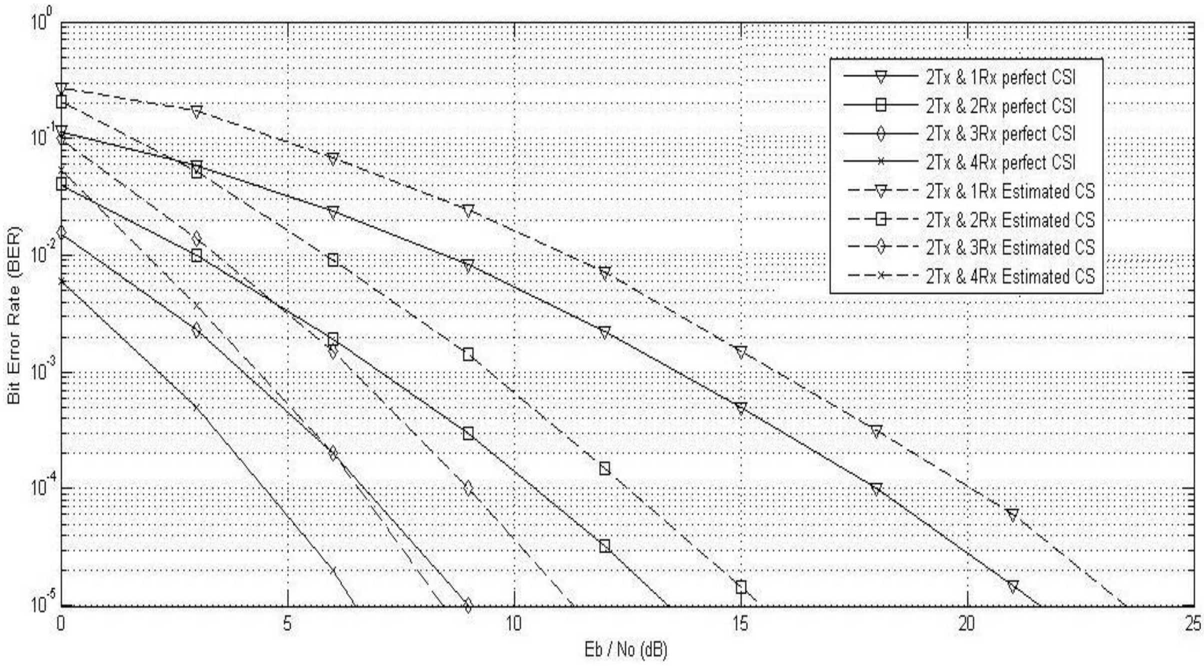

Figure 5.3: Channel estimation scheme for STBC with two transmit antennas using BPSK modulation.

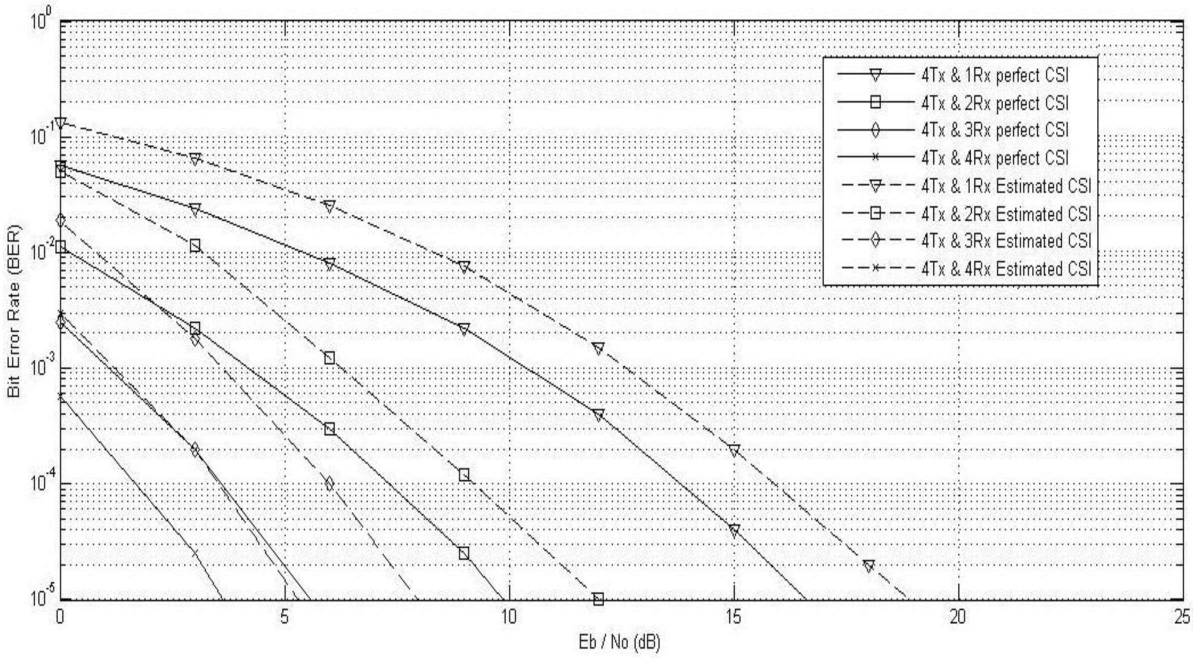

Figure 5.4: Channel estimation scheme for STBC with four transmit antennas using BPSK modulation.

Table 5.3 shows the results for STBC with two transmit antennas and different receive antennas using BPSK modulation in flat Rayleigh fading channels. And Table 5.4 shows the results for STBC with four transmit antennas and different receive antennas using BPSK modulation in flat Rayleigh fading channels.

Figures 5.3 and 5.4 and Tables 5.3 and 5.4 illustrate the bit-error rates (BER) for the separate channel estimation scheme explained in Section 5.3. The average loss of performance is approximately 2 ~ 2.5 dB lower than that of known channel parameters.

Table 5.3: BER performances of channel estimation for STBC with two transmit antennas using BPSK modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Estimated CSI 2Tx,1Rx Eb / No	Known CSI 2Tx,2Rx Eb / No	Estimated CSI 2Tx,2Rx Eb / No	Known CSI 2Tx,3Rx Eb / No	Estimated CSI 2Tx,3Rx Eb / No	Known CSI 2Tx,4Rx Eb / No	Estimated CSI 2Tx,4Rx Eb / No
10^{-2}	8	10.5	3	5.5	1	3.5	-	2.5
10^{-3}	14	16	7.5	9.5	5.5	7.5	2.5	4.5
10^{-4}	17.5	20	10.5	13	6.5	9	4.5	7
10^{-5}	21.5	24	13.5	15.5	9	11	6	8.5

Table 5.4: BER performances of channel estimation for STBC with four transmit antennas using 16-QAM modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Estimated CSI 4Tx,1Rx Eb / No	Known CSI 4Tx,2Rx Eb / No	Estimated CSI 4Tx,2Rx Eb / No	Known CSI 4Tx,3Rx Eb / No	Estimated CSI 4Tx,3Rx Eb / No	Known CSI 4Tx,4Rx Eb / No	Estimated CSI 4Tx,4Rx Eb / No
10^{-2}	5.5	8	0	2.5	-	1.5	-	-
10^{-3}	10.5	12.5	4	6	1.5	4	-	2
10^{-4}	14	16	6.5	9.5	4	6	2	4
10^{-5}	16	18	10	12	6	8	4	6

5.5 Conclusions

In this chapter, a comprehensive investigation into two different channel estimation schemes for radio links with space-time block codes was conducted for real signal constellations. The two schemes were tested with different combinations of transmit and receive antennas. The modulation scheme BPSK of real constellation was used with all different implementations. The results of all simulations were presented in data and graph, and analyzed and compared.

Estimation of channel parameters which are necessary for ML detection of STBC is important for practicability of space-time coding techniques. The presented estimation schemes that do not require CSI are thus a useful contribution toward solving the problem.

This chapter together with Chapters 3 and 4 has new completed the research of the proposed two schemes for both real and complex constellations. In the next chapter, chapter 6, we will compare the performances between the two schemes.

References

[1] V. tarokh, N. Seshadri and A. R. Calderbank, “Space-time codes for high data rate wireless communication: performance criterion and code construction”, IEEE Trans. Inform. Theory, vol. 44, no. 2, pp. 744-765, March. 1998.

[2] S.M Alamouti, “A simple transmitter diversity scheme for wireless communications,” IEEE Journal on Selected Areas in Communications, vol. SAC-16, pp. 1451-1458, October 1998.

[3] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, “Space-time block codes from orthogonal designs,” IEEE Trans. on Information Theory, vol . 45, no. 5, pp. 1456-1467, July 1999.

[4] V. Tarokh, S. M. Alamouti, and P. Poon, “New Detection Schemes for Transmit Diversity with no Channel Estimation,” IEEE International Conference on Universal Personal Communications, pp. 917-920, 1998.

[5] J. Yang, E. Masood and Y. Sun, “Performance of Space-time Block Coding Using Estimated Channel Parameters”, London Communications Symposium Conference UCL, 2004.

[6] A. Paulraj, R. Nabar and D. Gore, “Introduction to Space-time Wireless Communications”, Cambridge university Press. 2003.

[7] Gregory D. Durgin, “Space-time Wireless Channels”, Prentice Hall PTR. Pearson Education, Inc. 2003.

[8] B. Vucetic, J. Yuan, “Space-time Coding”, John Wiley & Sons Ltd, England. 2003.

[9] Erik G. Larsson and P. Stoica, “Space-time Block Coding for Wireless Communications”, Cambridge University Press. 2003.

6 Performance Comparisons of Space-time Block Codes using Joint Detection Scheme and Separate Channel

6.1 Introduction

Space-time codes can be divided basically into two groups: space-time trellis codes [1] and space-time block codes [2] [3]. In this thesis, we focus on the space-time block coded systems because they are capable of providing wireless systems with the full diversity promised by the number of transmit and receive antennas with simple maximum likelihood decoding algorithm based only on linear processing. The space-time decoding algorithm at the receiver requires accurate channel state information (CSI) that must be updated according to channel variations within a transmission frame.

Numerous channel estimation methods exist for traditional single-input single-output (SISO) systems. However, most of them cannot be used in systems with multiple transmit and receive antennas referred to as multiple-input multiple-output (MIMO) systems, since the received signal is a sum of transmitted signals and it contains the effect of all the sub-channels from transmit antennas to receive antennas.

In Chapter 3, the joint channel estimation and data detection scheme was generalized and tested on different combinations of transmit and receive antenna diversities. In addition, QPSK and 16-QAM modulation methods were used. In Chapter 4, a new channel estimation and performance of space-time block coding using estimated channel parameters method were discussed and tested with QPSK and 16-QAM modulation. In Chapter 5, the two estimation schemes presented in Chapters 3 and 4 were further investigated and tested for space-time block codes using BPSK real signal modulation method.

In this chapter, the two channel estimation schemes are compared from the points of view of bandwidth efficiency and in particular bit-error-rate performances.

6.2 Bandwidth Efficiency

The bandwidth efficiency is usually the most common factor required when implementing any wireless communication system. In single-input single-output (SISO) systems, a training sequence is often inserted into the data stream for the purpose of channel estimation. Because training-based algorithms have low computational complexity and good robustness in noisy environments, they are very popular in today's digital communication systems. However, if we directly apply purely training-based channel estimation schemes to MIMO systems, the situation becomes quite different. Due to inter-symbol interference and multiple-access interference, the required training length per transmit antenna will be proportional to the product of the channel impulse response length and the number of transmit antennas. This fact presents a fundamental challenge for training-based channel estimation schemes, especially when the system employs many transmit antennas and experience a delay spread channel. The large amount of training symbols required for reliable channel estimation will significantly reduce the system bandwidth-efficiency. Furthermore, for a fast fading channel, it is also possible that the needed training length will spend a complete channel coherence interval, then there will be no time left for data transmission before the channel changes. This situation should be definitely circumvented.

An intuitive countermeasure would be shortening the length of training. But to make this practically attractive, a reduction of training length should not cause considerable system performance degradation. As a matter of fact, all transmitted data systems are actually carrying the same channel information as the training symbols, within the same channel coherence interval. If this channel information can also be exploited, then the required training length can be largely reduced.

The joint channel estimation and data detection scheme described in Chapter 3 reduces the number of pilot symbols by using the user information data in a transmission frame as pilot symbols. This is done by creating a transmission frame. The first symbols on the transmission frame are pilot symbols and the rest are user data symbols. The number of pilot symbols inserted in a transmission frame depends on the number of transmit antennas used. In the two transmit antenna case, two pilot symbols are needed. The transmitter starts transmission by sending consecutive signals. The pilot symbols are transmitted only once and that is during the first transmission period.

At the receiver, the receiver receives the entire transmitted signals that make up a transmission frame. The receiver at first estimates the channel coefficients from the first received signals that contains the pilot sequences then uses them to detect the first received user data. In the following transmission, the channel coefficients are estimated again but this time using the received previously detected user data. This procedure will go on until all user data are recovered. The number of recovered user data should be equal to the number of transmitted user data in a transmission frame.

The channel estimation scheme described in Chapter 4 uses the same number of pilot symbols as that used by the joint detection scheme. This is true because pilot symbols are inserted and placed on the beginning of the transmission frame. The number of pilot symbols depends on the number of transmit antennas used. In the two transmit antenna case, for example, two pilot symbols are needed.

The joint detection scheme in Chapter 3 and the channel estimation scheme in Chapter 4 both are bandwidth efficient because they both use very few pilot symbols, once at the beginning of the transmission frame. This is considered as a common factor between the two estimation schemes.

6.3 The Bit-Error-Rate Performance

In this section, we compare the simulation results for the performance of STBC on Rayleigh fading channels. In the simulation, the receivers do not know the channel state information (CSI) and have to estimate them using both, the joint estimation and detection scheme described in Chapter 3 (Estimation Scheme 1) and the channel estimation scheme described in Chapter 4 (Estimation Scheme 2). The performances of the bit-error-rate (BER) of both channel estimation schemes tested on STBCs with different numbers of transmit and receive antennas are shown in different figures depending on the modulation methods and number of transmit antennas used. The modulation methods used are BPSK, QPSK, and 16-QAM. For STBC with complex modulation methods, the transmission rate is one when two transmit antennas are employed and half when four transmit antennas are employed. For STBC with real modulation methods, the transmission rate is always one.

The simulation results for the performance for STBC with both channel estimation schemes are recorded for the purpose of plotting and comparing their performances when compared with STBC with known channel parameters at the receiver. For simplicity, only STBCs with two and four transmit and one receive antennas are discussed. In all the figures, three bite-error-rate curves of space-time block codes are included which used known perfect channel parameters, the joint channel estimation and detection scheme in Chapter 3, and the channel estimation scheme in Chapter 4.

Figures 6.1 and 6.2 show the bit-error-rate performances for STBCs with two and four transmit and one receive antenna using the modulation scheme of BPSK.

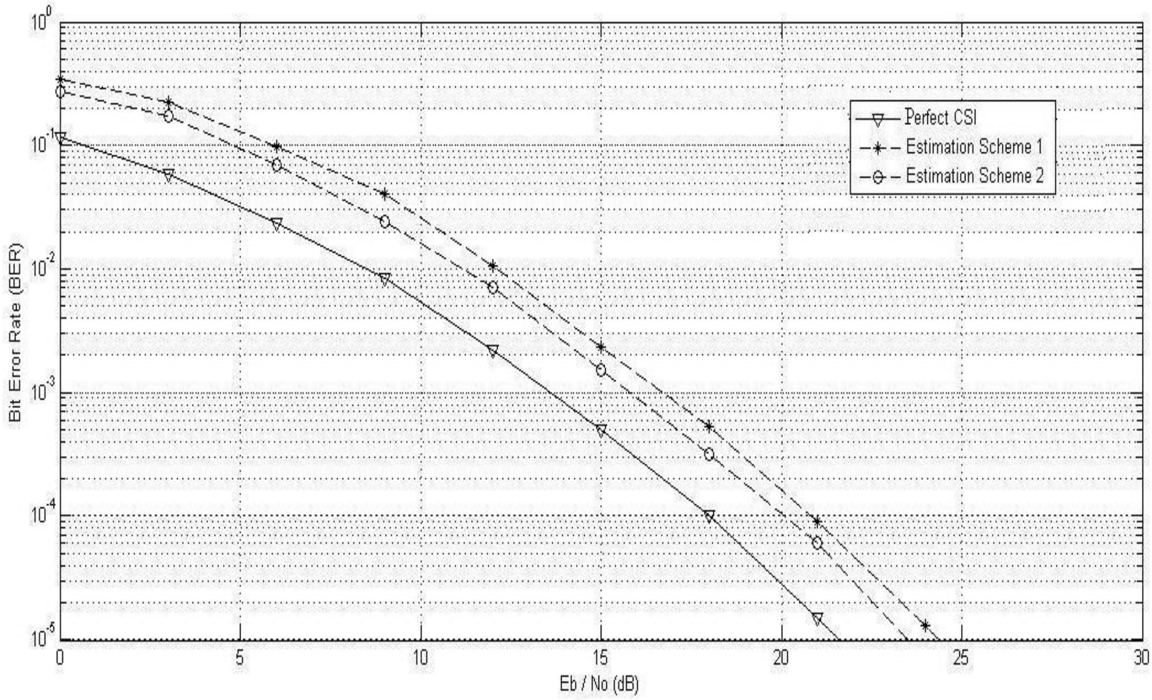

Figure 6.1: The bit-error-rate performances for STBCs with two transmit and one receive antenna using BPSK modulation.

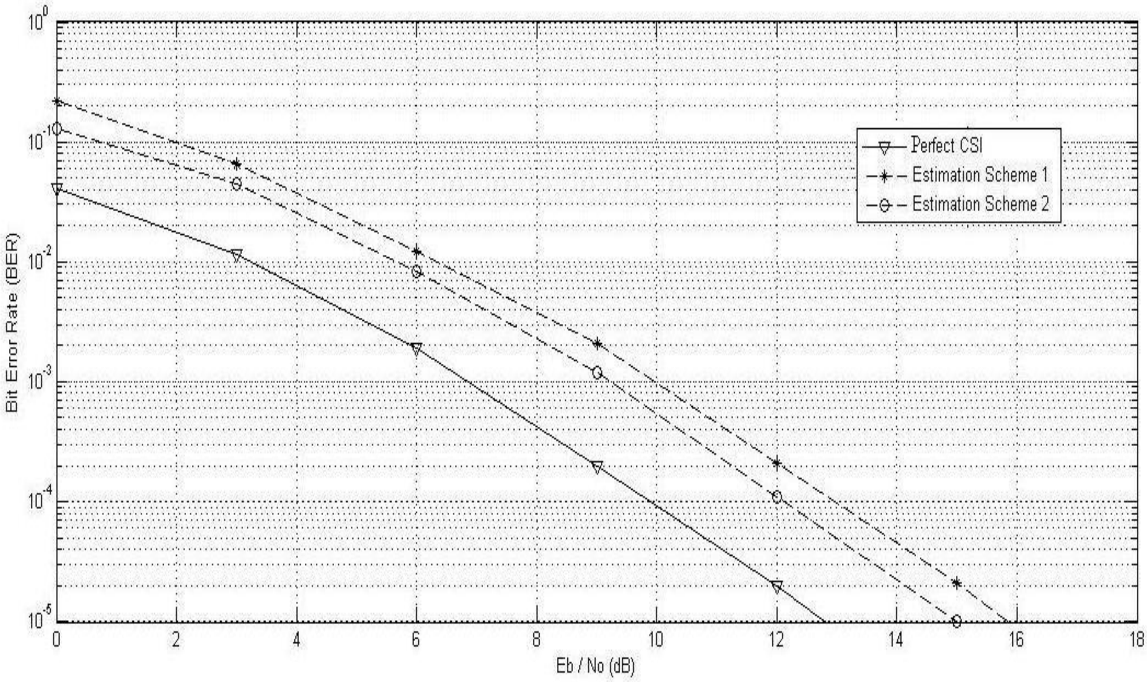

Figure 6.2: The bit-error-rate performances for STBCs with four transmit and one receive antenna using BPSK modulation.

Figures 6.3 and 6.4 show the bit-error-rate performances for STBCs with two and four transmit and one receive antenna using the modulation scheme of QPSK. And Figures 6.5 and 6.6 shows the bit-error-rate performances for STBCs with two and four transmit and one receive antenna using the modulation scheme of 16-QAM.

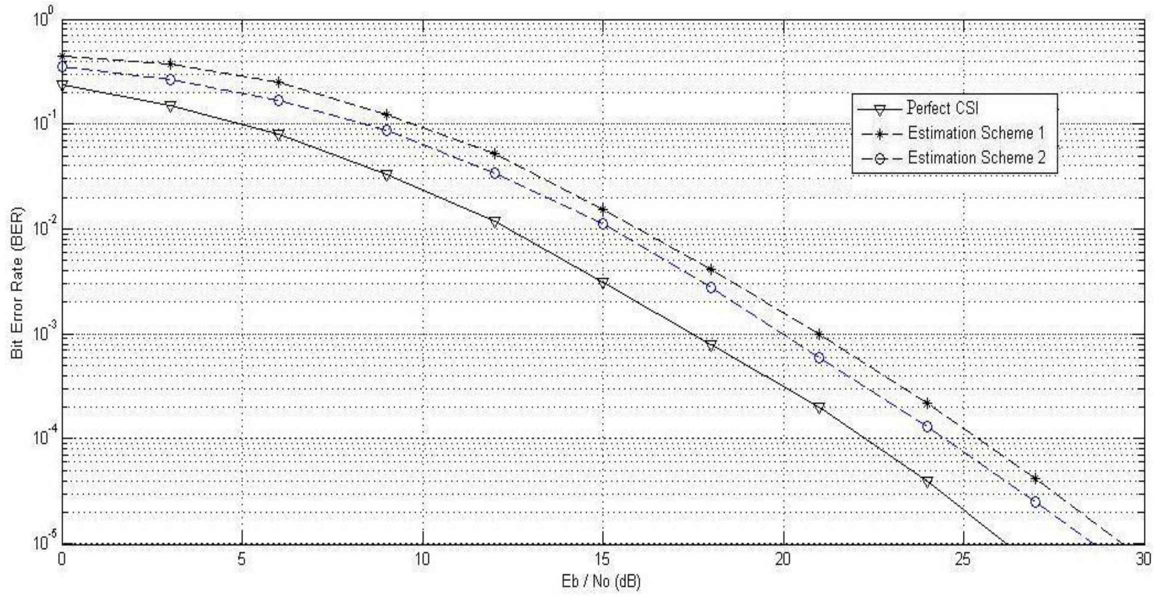

Figure 6.3: The bit-error-rate performances for STBCs with two transmit and one receive antenna using QPSK modulation.

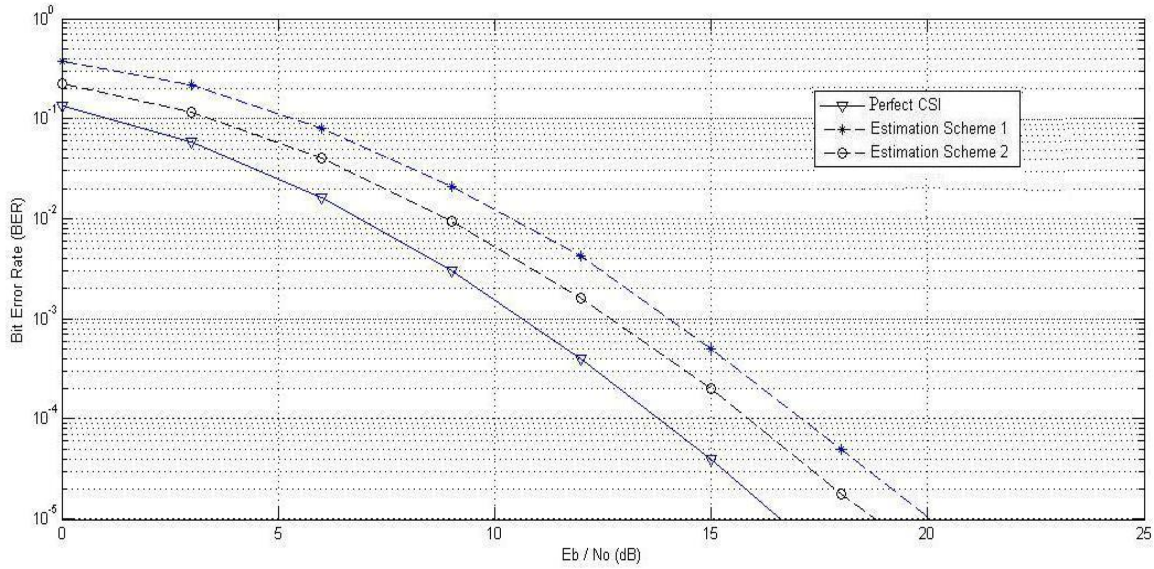

Figure 6.4: The bit-error-rate performances for STBCs with four transmit and one receive antenna using QPSK modulation.

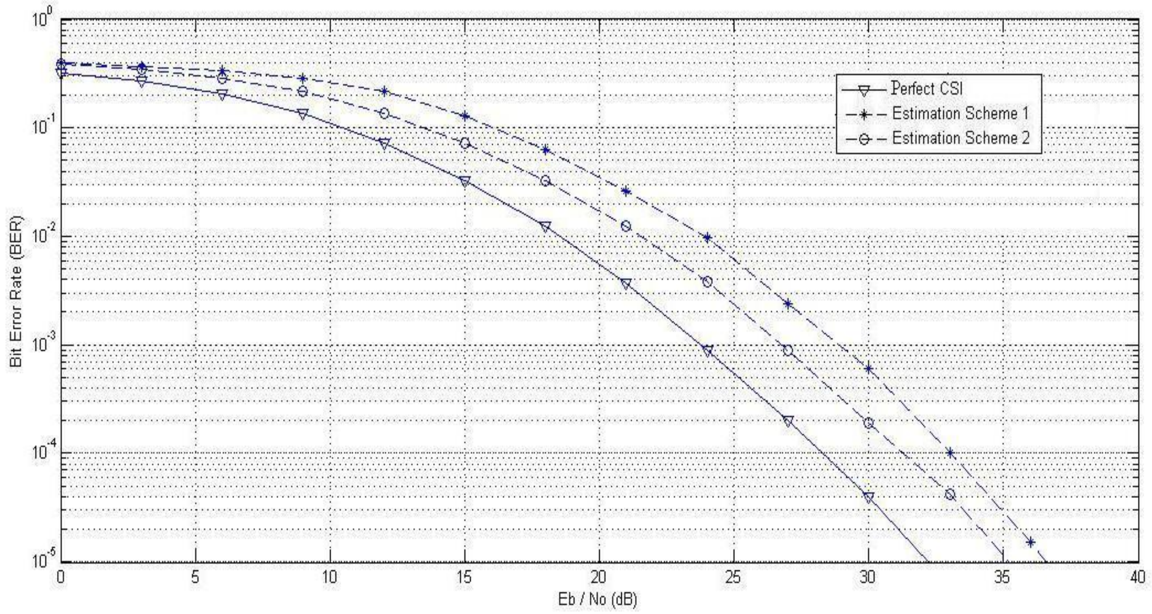

Figure 6.5: The bit-error-rate performances for STBCs with two transmit and one receive antenna using 16-QAM modulation.

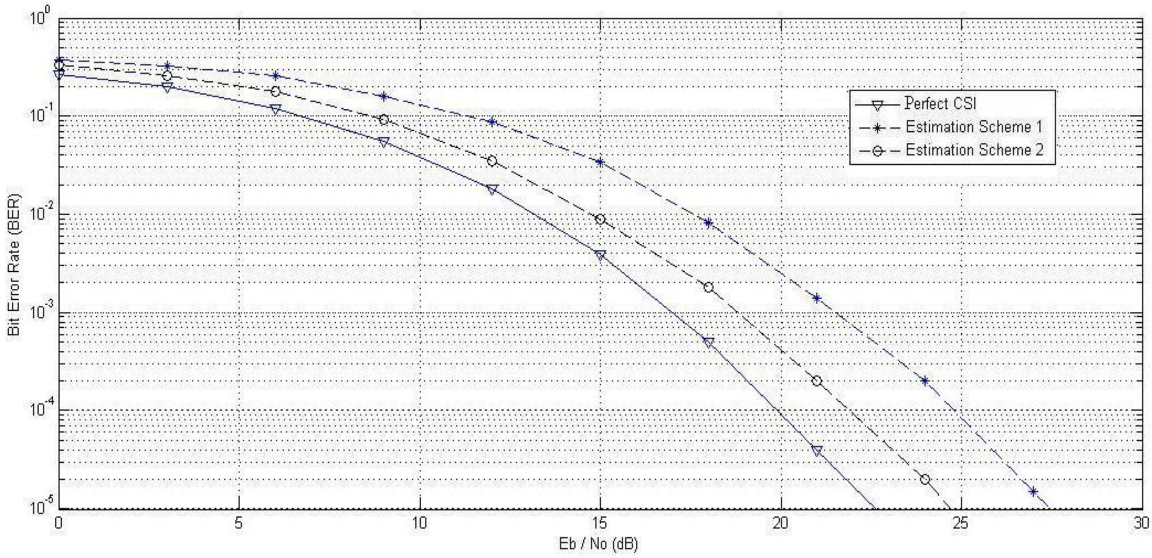

Figure 6.6: The bit-error-rate performances for STBCs with four transmit and one receive antenna using 16-QAM modulation.

Tables 6.1 and 6.2 show the performances for STBCs with two and four transmit and one receive antenna using the modulation method BPSK.

Table 6.1: The BER performances of STBC with two transmit antennas using BPSK modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Joint detection scheme (Chapter 3) 2Tx,1Rx Eb / No	Channel estimation (Chapter 4) 2Tx,1Rx Eb / No
10^{-2}	9	12	11
10^{-3}	14	16.5	15.5
10^{-4}	18	20.5	20
10^{-5}	21.5	24	23

Table 6.2: The BER performances of STBC with four transmit antennas using BPSK modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Joint detection scheme (Chapter 3) 4Tx,1Rx Eb / No	Channel estimation (Chapter 4) 4Tx,1Rx Eb / No
10^{-2}	3.5	6	5.5
10^{-3}	7	10	9
10^{-4}	10	13	12
10^{-5}	13	15.5	15

Tables 6.3 and 6.4 show the performances for STBCs with two and four transmit and one receive antenna using the modulation method QPSK.

Table 6.3: The BER performances of STBC with two transmit antennas using QPSK modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Joint detection scheme (Chapter 3) 2Tx,1Rx Eb / No	Channel estimation (Chapter 4) 2Tx,1Rx Eb / No
10^{-1}	5	9	7
10^{-2}	13	16	15
10^{-3}	17.5	21	20
10^{-4}	22.5	25.5	24
10^{-5}	26	29	28

Table 6.4: The BER performances of STBC with four transmit antennas using QPSK modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Joint detection scheme (Chapter 3) 4Tx,1Rx Eb / No	Channel estimation (Chapter 4) 4Tx,1Rx Eb / No
10^{-1}	2	5	3
10^{-2}	7.5	10.5	9
10^{-3}	11	14	13
10^{-4}	14	17	16
10^{-5}	17	20	19

Tables 6.5 and 6.6 show the performances for STBCs with two and four transmit and one receive antenna using the modulation method 16-QAM.

Table 6.5: The BER performances of STBC with two transmit antennas using 16-QAM modulation.

BER	Known CSI 2Tx,1Rx Eb / No	Joint detection scheme (Chapter 3) 2Tx,1Rx Eb / No	Channel estimation (Chapter 4) 2Tx,1Rx Eb / No
10^{-1}	10	16	12.5
10^{-2}	18	24	21
10^{-3}	24	29	26
10^{-4}	28	33	31
10^{-5}	33	37	35

Table 6.6: The BER performances of STBC with four transmit antennas using 16-QAM modulation.

BER	Known CSI 4Tx,1Rx Eb / No	Joint detection scheme (Chapter 3) 4Tx,1Rx Eb / No	Channel estimation (Chapter 4) 4Tx,1Rx Eb / No
10^{-1}	7	12	9
10^{-2}	13	18	15
10^{-3}	17	22	19
10^{-4}	20	25	22
10^{-5}	23	27	24

The performances of STBC using the channel estimation method described in Chapter 4 have an average loss of 2 ~ 2.5 dB when BPSK and QPSK modulation methods are used and have an average loss of 4 dB when 16-QAM modulation method is used. However, the performances of STBC using the joint detection scheme in Chapter 3 have an average loss of 2.5 ~ 3 dB when BPSK and QPSK modulation methods are used and have an average loss of 5 dB when 16-QAM modulation method is used.

The performance of the channel estimation scheme in Chapter 4 is always better by at least 1 dB when compared with the performance of the joint detection scheme in Chapter 3. This is true in all STBC cases with all different transmit and receive antenna combinations and all different modulation methods (BPSK, QPSK, and 16-QAM). This is due to the way of estimation; both schemes are very similar, the only difference is joint detection scheme in Chapter 3, estimate the channel parameters (using pilot sequence) and then used them to detect the user data. After that, the detected user data are used to estimate the channel parameters and then the channel parameters are used to detect the user data. This procedure goes on until all user data are detected. However, in the channel estimation scheme in Chapter 4, all signals are received and then channel estimation is done and the parameters with the minimum square error is used to detect all the transmitted symbols.

6.4 Conclusions

In this chapter, both channel estimation schemes for radio links with space-time block codes were compared from the two most important points. The first point was the bandwidth efficiency and the second was the bit-error-rate performance. The two channel estimation schemes were also compared with STBC with perfect channel parameters at the receiver. Different figures were produced depending on the number of transmit antennas and the modulation methods used. The results of all simulations were presented in data and graph, analyzed and compared. While the schemes have similar bandwidth efficiency, the estimation method in Chapter 4 is at least 1 dB better off in signal to noise ratio than the joint scheme in Chapter 3.

Estimation of channel parameters which are necessary for ML detection of STBC is important for practicability of space-time coding techniques. The compared two estimation schemes in this chapter are very useful contribution toward solving estimating channel problems.

References

[1] V. tarokh, N. Seshadri and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction", IEEE Trans. Inform. Theory, vol. 44, no. 2, pp. 744-765, March. 1998.

[2] S.M Alamouti, "A simple transmitter diversity scheme for wireless communications," IEEE Journal on Selected Areas in Communications, vol. SAC-16, pp. 1451-1458, October 1998.

[3] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, "Space-time block codes from orthogonal designs," IEEE Trans. on Information Theory, vol . 45, no. 5, pp. 1456-1467, July 1999.

7 Summary and Further Research Work

7.1 Summary

This thesis has investigated the different implementations of space-time block codes and their performances when used with different modulation methods and different combinations of transmit and receive antennas. The thesis also has investigated two different channel estimation schemes that are required by the maximal likelihood detector (ML) to detect the transmitted space-time block coded signals at the receiver. The thesis started by introducing the general background of space-time codes and their use for the wireless communication systems. The thesis also present the fundamentals of different implementations of space-time block codes and their performance when tested with BPSK, QPSK, and 16-QAM modulation methods. The thesis then present the first new proposed joint channel estimation and data detection scheme and their performances when used on different combinations of transmit and receive antennas. Their performances are also tested for different complex modulation methods (QPSK and 16-QAM). after that, the thesis introduce a new, second channel estimation scheme that used on different combinations of transmit and receive antennas and the same modulation methods as used with the first channel estion scheme. The thesis then test the two new proposed channel schemes with real signal produced by BPSK modulation method. The thesis then continue by comparing the two channel estimation schemes from different important points including the similarities, differences and bit-error-rate performance. At last, the thesis is finalized with a conclusion and future work.

7.2 Conclusions of the Work

Space-time block codes and their performance on MIMO fading channels were presented and evaluated. First, the two-branch transmit diversity scheme referred to as Alamouti space-time code was introduced and its key features were described. After that, space-time block codes with large number of transmit and receive antennas based on orthogonal designs were explained. This includes the coding and decoding algorithms for space-time block codes with both complex and real signal constellations. The performances of space-time block codes on MIMO fading channels using different modulation methods were simulated. Moreover, The performances of the different implementations of Alamouti space-time code and space-time block codes were recorded, discussed and analyzed. Results showed that space-time block codes could achieve better bit-error-rate performance when more antennas were employed at each end. In addition, space-time block codes with lower modulation order always gave low bit-error-rate when compared with space-time block codes that employ higher order modulation methods. In this chapter all simulations were based on perfect knowledge of the channel coefficients at the receiver.

A new joint channel estimation and data detection scheme was proposed and different implementations and simulation results were presented. In addition, two and four transmit antennas and one, two, three, and four receive antennas were used for the different channel estimation implementations. Two different complex signals that were produced by QPSK and 16-QAM modulation schemes were used. The channel parameters were estimated continuously, at first, the channel parameters were estimated using the transmitted pilot sequence. In the second time and after, the channel parameters were estimated using the previous detected user data information. The scheme in general gave out a bit-error-rate loss of 3dB. This is considered as a main advantage when we recall that the scheme does not use a lot of pilot symbols which usually make any wireless system less efficient. In this scheme only two pilot symbols were needed and inserted at the beginning of every transmission frame. The simulation results demonstrated that the bit-error-rate performance of the joint channel estimation and data detection scheme with two transmit and two receive antennas should be considered because they gave better performance than space-time block codes with two transmit and one receive antenna with known channel parameters at the receiver. This should be considered as a break through because MIMIO technology is new and few wireless equipment have more than one transmit and receive antennas.

Another channel estimation scheme was investigated and tested with different combinations of transmit and receive antenna diversities. The channel estimation scheme was also tested with two different modulation methods, QPSK and 16-QAM. The channel parameters were estimated only once and then used to detect the transmitted data symbols. The channel parameters were estimated by using a recursive minimum square error technique. The scheme in general gave out a very good performance; the bit-error-rate loss was 3dB. This is considered a good advantage recalling that the scheme does not use/need many pilot symbols. Only two pilot symbols were needed and inserted at the beginning of every transmission frame that was containing 52 different symbols. The simulation results demonstrated that the bit-error-rate performance of the channel estimation scheme with two transmit and two receive antennas should be considered.

In the next step, the two above mentioned channel estimation schemes were implemented with real signals that were produced by BPSK modulation method. Different types of transmission matrices were used depending on the number of transmit antennas used. The channel parameters were estimated depending on the estimated channel scheme used.

As last, the two new channel estimation schemes were compared from three different viewpoints; similarities, differences, and bit-error-rate performance.

7.3 Further Research Work

Space-time coding finds its applications in cellular communications as well as in wireless local area networks. Some of the work on space-time coding focuses on explicitly improving the performance of existing systems (in terms of the probability of incorrectly detected data packets) by employing extra transmit antennas, and other research capitalizes on the promises of information theory to use the extra antennas for increasing the throughput. Speaking in very general terms, the design of space-time codes amounts to finding a constellation of matrices that satisfy certain optimality criteria. In particular, the construction of space-time coding schemes is to a large extent a trade-off between the three conflicting goals of maintaining a simple decoding, maximizing the error performance, and maximizing the information rate. Space-time block codes seem known by their coding and decoding simplicities and their promise to increase the information rate with a very good error performance. These space-time block codes always require a good knowledge of the channel parameters at the receiver. This has motivated a lot of researchers, including us to look for different schemes to estimate the channel parameters. The two proposed channel estimation schemes described in this thesis give very promising results which, we hope, that will motivate other researchers to take our work to a new level.

In this thesis we have investigated and demonstrated different implementations and test techniques for the two different types of channel estimation schemes. Further research work can usefully be performed in these areas of channel estimation techniques, therefore, a number of suggestion are given in the following sub-sections.

7.3.1 Testing Higher Order Modulation Methods

In this thesis, we have evaluated space-time block codes that use BPSK, QPSK, and 16-QAM modulation methods. This may be further investigated and higher order modulation schemes (64-QAM, 256-QAM, 512-QAM, and even higher) should be considered. Higher order modulations means higher throughput with higher bit-error-rate. Different wireless communication technologies have different purposes. Some technologies provide high data rate and others give better bit-error-rate performance. In technologies like TV satellite transmission higher modulation methods (256-QAM and 512-QAM) could be employed because the accuracy of received data at the user end is not essential. Other correction techniques could be employed to improve the performance of such systems. However, in mobile technology, the bit-error-rate is very important. In this case, accuracy is essential. Therefore, lower order modulation methods (QPSK and 16-QAM) are usually employed.

7.3.2 Testing Other Types of Channel Characteristics

In this thesis, only Rayleigh flat fading channels were tested and used. This is due to their implementation simplicities. For simulating real wireless communication scenarios, Jake’s Rayleigh channels are used due to their realistic characteristics. For further work of this thesis, Rican and Jake’s Rayleigh fading channels can be added to space-time block codes that employ one of the two channel estimation schemes discussed in this thesis. Their bit-error-rate performances can be recoded, investigated and analyzed.

7.3.3 Testing Higher Number of Transmit and Receive Antennas

In this thesis, the two channel estimation schemes can be used with any number of transmit and receive antennas. However, in this thesis, only two and four transmit and one, two, three, and four receive antennas were considered. As further research of this work, the two channel estimation schemes can be tested with higher number of transmit and receive antennas.

To conduct the further research and investigation mentioned in Sections 7.1, 7.2 and 7.3, the following work may be required:

- Investigate the new structure of the design methods.
- Design new channel vectors with the correct required information.
- Reformulation of some of the used formulas in Chapters 3, 4, and 5 will be required.
- The number of symbols required to be transmitted should always be equal for the purpose of comparisons.
- Other types of noise maybe need to be used.

7.3.4 Channel Estimation for Other Space-time Codes

The two proposed channel estimation schemes described in this thesis could be further investigated and tested on other space-time codes like space-time trellis codes and space-time turbo codes.