Optimal Cross Layer Design for CDMA-SFBC Wireless Systems

Taimour Aldalgamouni

A Thesis

in

The Department

of

Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy at

Concordia University

Montreal, Quebec, Canada

September, 2009

Your file Votre référence
ISBN: 978-0-494-63353-3
Our file Notre référence
ISBN: 978-0-494-63353-3

ABSTRACT

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Taimour Aldalgamouni, Ph.D.

Concordia University, 2009

The demand for high speed reliable wireless services has been rapidly growing. Wireless networks have limited resources while wireless channels suffer from fading, interference and time variations. Furthermore, wireless applications have diverse end to end quality of service (QoS) requirements. The aforementioned challenges require the design of spectrally efficient transmission systems coupled with the collaboration of the different OSI layers i.e. cross layer design. To this end, we propose a code division multiple access (CDMA)-space frequency block coded (SFBC) systems for both uplink and downlink transmissions. The proposed systems exploit code, frequency and spatial diversities to improve reception. Furthermore, we derive closed form expressions for the average bit error rate of the proposed systems.

In this thesis, we also propose a cross layer resource allocation algorithm for star CDMA-SFBC wireless networks. The proposed resource allocation algorithm assigns base transceiver stations (BTS), antenna arrays and frequency bands to users based on their locations such that their pair wise channel cross correlation is minimized while each user is assigned channels with maximum coherence time. The cooperation between the medium access control (MAC) and physical layers as applied by the optimized resource

allocation algorithm improves the bit error rate of the users and the spectral efficiency of the network.

A joint cross layer routing and resource allocation algorithm for multi radio CDMA-SFBC wireless mesh networks is also proposed in this thesis. The proposed cross layer algorithm assigns frequency bands to links to minimize the interference and channel estimation errors experienced by those links. Channel estimation errors are minimized by selecting channels with maximum coherence time. On top, the optimization algorithm routes network traffic such that the average end to end packet delay is minimized while avoiding links with high interference and short coherence time. The cooperation between physical, MAC and network layers as applied by the optimization algorithm provides noticeable improvements in average end to end packet delay and success rate.

Acknowledgement

I would like to express my sincere gratitude and thanks to my supervisor, Professor Ahmed Elhakeem, for his valuable support, enlightening guidance, and sincere encouragement throughout the course of this thesis.

Dedication

To my parents, to my wife, and to my children.

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List of Acronyms

3G	Third Generation
4G	Fourth Generation
AMC	Adaptive Modulation and Coding
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
BTS	Base Transceiver Station
CDMA	Code Division Multiple Access
CMMSE	Constrained Minimum Mean Square Error
CS	Code Spread
CSI	Channel State Information
DFT	Discrete Fourier Transform
DOC	Double Orthogonal Codes
DS	Direct Sequence
FFT	Fast Fourier Transform
HDR	High Data Rate
i.i.d	independent and identically distributed
IFFT	Inverse Fast Fourier Transform
ILP	Integer Linear Programming
ISI	Inter Symbol Interference

MAC	Medium Access Control
MAI	Multiple Access Interference
MC-CDMA	Multi Carrier Code Division Multiple Access
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MPSK	M-ary Phase Shift Keying
MQAM	M-ary Quadrature Amplitude Modulation
MS	Mobile Station
MT-CDMA	Multi-Tone Code Division Multiple Access
MTU	Maximum Transmit Unit
MUD	Multi-User detection
NRT	Non-Real time
OFDM	Orthogonal Frequency division Multiplexing
OSI	Open System Interconnections
OSTBC	Orthogonal Space Time Block Code
pdf	probability density function
QoS	Quality of Service
RT	Real Time
SDMA	Space division Multiple Access
SFBC	Space Frequency Block Code
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output

SNR	Signal to Noise Ratio
SS	Subscriber Station
STBC	Space Time Block Code
STS	Space Time Spreading
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
WCDMA	Wideband Code Division multiple Access

Chapter 1: Introduction

1.1 Motivation and Objectives

The growing demand for high speed reliable wireless networks introduced multiple challenges to the network designers. The nature of the wireless channel and the diversity of wireless applications are the most challenging design factors. The wireless channel is time varying and has a fading nature. The wireless channel has limited bandwidth and other physical resources for which many users compete. Wireless users have different environments in terms of mobility and require different applications. The wireless applications have diverse quality of service (QoS) demands in terms of delay and throughput.

Many schemes have been proposed in the literature to overcome the impact of the wireless channel at the physical layer. The use of multiple input multiple output (MIMO) systems along with space time block codes (STBC) can efficiently improve the capacity and the performance of wireless channels by exploiting the time and space diversities of the wireless channel [1-3]. Orthogonal frequency division multiplexing (OFDM) can be used to divide the frequency selective wireless channel into multiple flat fading channels. The code division multiple access (CDMA) technique has the capability to cope with the asynchronous nature of multimedia traffic, to provide higher capacity and to combat the frequency selectivity of the wireless channel. This makes the CDMA technique a good candidate to support multimedia traffic over wireless channels [4].

Although the previously mentioned schemes can help overcome the physical challenges of the wireless channel, they do not address the QoS demands of the different users. In order to allocate channel resources to different users while maintaining the QoS requirements of the different users, a joint optimization of the physical, medium access control (MAC) and other higher layers is needed. This joint optimization of the different layers is called cross layer design in which the different layers share information with each other to optimize their performance.

In this thesis we aim at reducing the probability of bit errors at the same load or number of subscribers by optimally assigning the same scarce wireless resources to existing users. This will lead to improving the QoS provided to existing users and hence allow them to use more applications which improves the cost effectiveness of the system. Needless to say that the same cost effectiveness can be achieved by increasing the number of users at the same level of bit error rate or QoS by optimally assigning the available resources.

In this thesis, we first propose a CDMA-space frequency block coded (SFBC) system for uplink transmission. The proposed CDMA-SFBC system exploits the time, space, code and frequency diversities of the channel which can greatly improve reception. We also derive and evaluate closed form expressions for the bit error rate (BER) of the proposed CDMA-SFBC system. Moreover, we propose another CDMA-SFBC system for downlink transmission. The proposed system assigns orthogonal Walsh codes to users such that the multiple access interference (MAI) is eliminated.

Second, we introduce an optimized resource allocation scheme for star wireless CDMA-SFBC networks. The resource allocation scheme assigns base transceiver stations (BTS), antenna arrays and OFDM frequency bands to users based on the pair wise cross correlation between their channels and the coherence time of their channels. This optimal assignment improves the BER performance of each user and the bandwidth efficiency of the system.

Last, we introduce a joint cross layer routing and channel assignment algorithm for multi radio wireless mesh networks. The channel assignment part assigns frequency bands to links such that the interference between those links is minimized while each link is assigned the channel with the maximum coherence time. The routing part selects the paths with the best end to end delay while avoiding links with high interference and short coherence time.

1.2 Preliminaries

1.2.1 Multiple Input Multiple Output Systems

The use of multiple antennas at the transmitter and receiver in wireless systems is known as MIMO. Wireless communications suffer from multipath fading and limited bandwidth. The use of MIMO systems in wireless communications offers a number of benefits that can be used to overcome the impairments of the wireless channel [5, 6]. The two most important benefits of MIMO systems are spatial diversity gain and spatial multiplexing gain. In addition to temporal and frequency diversities that can be exploited by the single input single output (SISO) systems, MIMO systems add the spatial diversity benefit to the system [6]. Spatial diversity is realized by providing the receiver with multiple copies of the transmitted signal in space. This transmission of several copies of the transmitted signal increases the probability that at least one of the copies will not experience deep fading thus increasing the reliability and quality of reception. A MIMO system with n transmit and p receive antennas can provide a diversity gain up to $n \times p$. Spatial multiplexing gain can be achieved by transmitting multiple independent data streams from the different antennas at different time intervals [5]. This will increase the transmission data rate utilizing the same bandwidth used by SISO systems. A MIMO system with n transmit and p receive antennas can provide a multiplexing gain equal to the minimum of n and p. Depending on the application and channel conditions, a tradeoff between spatial diversity gain and spatial multiplexing can be achieved using appropriate coding techniques.

1.2.2 Space Time Block Codes

In STBCs input symbols are grouped into blocks. The size of the block is governed by the STBC generating matrix. A subset of STBCs is called general complex orthogonal designs. Maximum diversity gain at full rate can be achieved using Alamouti's scheme [1] for the two transmit antennas case. For more than two transmit antennas there are STBCs that achieve full diversity gain but at a data rate less than one [2].

Complex orthogonal STBCs provide multiple benefits to wireless communication systems [1-3]. First, they provide full diversity gain since they decouple the MIMO system into multiple SISO systems which improves reception. Second, no channel state information (CSI) is needed at the transmitter. Third, maximum likelihood (ML) decoding which involves linear processing can be used at the receiver.

In order to utilize the diversities in both spatial and frequency domains, STBC can be used along with OFDM to form what is known as SFBC.

1.2.3 CDMA/OFDM

CDMA is a spread spectrum communication technique. Direct sequence (DS) CDMA systems support multiple users sharing the same bandwidth by assigning different codes to different users such that their signals can be distinguished at the receiver. CDMA systems were first used by the military because of their resilience to jamming. In civilian wireless communications CDMA is used because of its soft capacity limit [4]. The capacity of CDMA systems is limited by the amount of MAI experienced by users in the system. Reducing MAI increases the capacity of CDMA systems and that is why it is very important to find ways to reduce the MAI. In wireless communications and because of multipath fading, multiple images of the same signal arrive at the receiver at different times which causes inter symbol interference (ISI). CDMA systems can resolve the different paths when the chip time is smaller than the delay spread of the multipath and consequently take advantage of these multiple images e.g. by Rake reception [7].

OFDM is used in wireless communications because it converts frequency selective channels into multiple flat fading channels. OFDM can be used with a cyclic prefix larger than the delay spread of the channel to eliminate the effects of ISI [8]. This is especially important when CDMA cannot resolve the multipath components.

1.2.4 Cross Layer Design

The Open Systems Interconnection Reference Model (OSI) divides the network architecture into seven different layers. These layers, from top to bottom, are the

Application, Presentation, Session, Transport, Network, Data-Link and Physical layers as shown in Table 1-1.

Table 1-1 OSI Model

Application
Presentation
Session
Transport
Network
Data-Link
Physical

The TCP/IP architecture is another model that allows communication across multiple diverse networks. The TCP/IP architecture has four layers as shown in Table 1-2. The TCP/IP application layer corresponds to the top three layers of the OSI model and the internet layer corresponds to the network layer of the OSI model. The network interface layer of the TCP/IP architecture deals with the physical and the data-link layers of the OSI model.

Table 1-2 TCP/IP Model

Application layer
Transport layer
Internet layer
Network interface

Although the TCP/IP architecture is more common, in this section we will be referring to the OSI model in order to explain the basic idea of cross layer design. However, the work in this thesis is equally applicable to both the OSI and the TCP/IP models.

A layer is defined as a set of conceptually similar functions. A layer receives services from the layer bellow it and provides service to the layer above it. Traditionally, each layer is designed separately and the interaction between layers is done through a well-defined interface. Architectural flexibility is the main advantage of this approach. This means that the protocols or functions of any layer can be modified or replaced without affecting the performance of the other layers.

In wired networks, this approach of separately designing and optimizing the performance of each layer does not introduce any performance penalty i.e. separate wired links are independent of each other and do not interfere with each other's performance.

In wireless networks, the independency of the OSI layers and their performances is not the case anymore. In star wireless networks, the transmission of any wireless node can interfere with the transmission of other nodes in its neighborhood which degrades the performance of these nodes. Therefore, it is necessary to have a medium access control that minimizes the interference and maximize the spectral efficiency. Maximizing spectral efficiency and minimizing interference at the same time requires a medium access control that allocates the available physical resources (e.g. frequency tones and antenna arrays) efficiently. This cannot happen without jointly optimizing the design and performance of the physical and MAC layers which is an instance of cross layer design.

In wireless mesh networks, routing which is a network layer entity adds another dimension to cross layer design. Routing in wireless mesh networks decides the route and the number of hops that a certain transmission has to follow from source to destination in order to satisfy a predetermined criterion or QoS factor. At the same time routing affects the amount of interference in the network since it determines the active links in the network and the amount of traffic carried by each link. This in turn will affect the resource allocation process and the performance of both the MAC and physical layers. So it is necessary to jointly optimize the network, MAC and physical layers in wireless mesh networks to improve the overall performance of the network and this is also called cross layer design.

1.3 Literature Review

As mentioned earlier in this chapter, the use of CDMA in conjunction with MIMO, STBC and OFDM can bring multiple benefits to the quality of wireless reception. This motivated many researchers to introduce transmission systems that combine the above mentioned techniques.

Jung et al proposed an adaptive constrained minimum mean square error (CMMSE) receiver for single carrier STBC-CDMA systems in [9]. However, their system suffers from ISI since they are not using OFDM. The complexity of the CMMSE receiver increases with the number of receive antennas and the number of resolvable paths since each receive antenna requires a CMMSE block for each resolvable path. They also assumed perfect CSI at the receiver in their SNIR analysis which is not very realistic.

In [10], STBC has been combined with single carrier CDMA for uplink transmission. However the system performs poorly when the number of users in the system is greater than half of the system capacity due to the increased MAI.

In [11], STBC transceivers were presented for both uplink and downlink multi carrier CDMA (MC-CDMA) systems in which a different set of subcarriers is assigned to each user. However, the authors limited the number of receive antennas to one which makes the maximum spatial diversity gain equal to the number of transmit antennas instead of the product of the number of transmit and number of receive antennas. This also moves the hardware complexity to the mobile station.

A multi user receiver for STBC MC-CDMA system that utilizes different spreading signatures for different transmit antennas was introduced in [12]. Assigning different spreading codes to different transmit antennas reduces the processing gain of the system by a factor equal to the number of transmit antennas and hence the system will be able to accommodate fewer number of users.

Vook et al in [13] showed that the performance of downlink cyclic prefix single carrier CDMA systems can be improved by transmit and receive antenna diversity. Single carrier transmission systems may suffer from deep fading especially in frequency selective channels.

The performance of MC-CDMA combined with STBC over Rayleigh fading channels for one or two transmit antennas has been studied in [14]. However, the authors assumed perfect CSI at the receiver which may not be always the case.

In [15], the authors derived bit error rate expressions for QAM data and studied the effects of adaptive modulation on the throughput of the RAKE receiver assisted space time spreading (STS) based CDMA system.

In [16], the author analytically evaluated the performances of different detection techniques for MC-CDMA downlink systems. However, the analysis was done for SISO systems with perfect CSI. Also, the author did not provide closed form expressions for the BER of the system.

In [17], the authors analytically evaluated the performance of Code Spread (CS)-OFDM systems in which data symbols are treated as virtual users. However, the system is designed for point to point communications with no multiuser capabilities. Also, the authors only addressed SISO systems with perfect CSI at the receiver.

In [18], the authors designed a minimum mean square error (MMSE) receiver for multi user detection (MUD) in MC-CDMA MIMO-OFDM systems. However, the authors assumed perfect CSI knowledge at the receiver for MUD which is known to have high computational complexity.

In [19], the authors designed special spreading codes called double orthogonal codes (DOC) for downlink transmission in MC-CDMA systems. However, the authors evaluated the performance of the proposed system by computer simulations only and provided no closed form BER expressions.

Torabi et al in [20] derived closed form BER expressions for the SFBC-OFDM systems over Rayleigh fading channels. However, they only discussed point to point links with no multiuser environment.

To satisfy the QoS requirements of the different users by efficiently utilizing the available physical resources, it is necessary to jointly optimize the performance of the different OSI layers. The idea of resource allocation in star wireless networks in a cross layer fashion has been the subject of many research efforts.

In [21], the authors proposed a power allocation scheme for star wireless networks that maximizes the system throughput while not exceeding the total received power by the BTS and maintaining a minimum signal to interference noise ratio (SINR) for each user in uplink CDMA systems. However, the algorithm was done for SISO DS-CDMA systems which have less capacity than MIMO-CDMA systems.

In [22], users are assigned power levels and data rates that maximizes the system throughput in downlink CDMA systems. Moreover, the scheduler assigns the least congested BTS to transmit to a user based on his transmission environment. However, the algorithm was developed for single carrier SISO CDMA systems assuming perfect channel estimation.

A cognitive resource allocation algorithm is proposed for multicarrier DS-CDMA in [23]. The algorithm allocates frequency tones and power levels are assigned to emerging users such that the data rates and power levels of the new users are satisfied while not disturbing existing users. However, the algorithm was developed for ad hoc wireless local area networks employing MC-CDMA SISO transmission scheme.

A dynamic resource allocation algorithm for a DS-CDMA network that supports both real time (RT) and non real time (NRT) users is proposed in [24]. The algorithm assigns processing gain and transmit power levels to NRT users such that their aggregate throughput is maximized without violating the delay and capacity constraints of the RT users. However, NRT users are allowed to transmit only when their channel conditions are good else they are not allowed to transmit which can starve NRT users with bad channel conditions. Also, the algorithm was developed for SISO DS-CDMA systems with single carrier and single BS.

In [25], a resource allocation algorithm for uplink WCDMA is proposed to support both RT and NRT users. RT users are assigned fixed resources to maintain their statistical delay requirements. NRT users are dynamically assigned resources based on their channel condition to achieve prescribed statistical traffic fairness. However, the authors assumed single carrier SISO transmission system with perfect CSI.

The authors of [26] assigned different spreading codes with different lengths to users such that the capacity of each user is maximized in DS-CDMA systems. The authors also allowed power control to satisfy the SINR goals for users. However, the authors assumed flat fading channels only. Also, no antenna or frequency band allocation was done since the algorithm was developed for SISO CDMA systems with single carrier and perfect CSI.

In [27], the authors used optimized beam forming and power allocation for space time division multiple access (SDMA) downlink systems to maximize the total rate and provide QoS to users. However, beam forming is very difficult to apply in uplink transmission. Another limiting factor of this scheme is that the number of BS antennas should be large compared to the total number of users' antennas which limits the number of users that can be served.

The authors of [28] optimized the allocation of transmit power and transmission rate over multiple CDMA channels as well as optimizing the channel coding rate for downlink wireless video transmission. However, the authors assumed single carrier SISO CDMA systems.

A joint BS assignment and packet scheduling algorithm for the downlink in CDMA/ time division multiple access (TDMA) systems is proposed in [29]. The algorithm allows a BS to transmit only to its corresponding user at a time which can cause large amount of delay and make the algorithm non applicable to RT traffic. However, the authors did not discuss the effect of CSI on BS assignment and they only considered single carrier SISO CDMA systems.

In [30], a power allocation algorithm that maximizes the sum capacity of the uplink in CDMA systems while satisfying the QoS requirements in terms of minimum SINR of every user is proposed. However, the algorithm is designed for single carrier SISO DS-CDMA systems.

A suboptimal analytical model for the single mobile station (MS) optimization is proposed in [31]. The model takes into account adaptive modulation and coding (AMC) and multi codes, as well as power and multi codes constraints to maximize the bit rate of the MS. The authors considered only single carrier SISO CDMA systems with one BS.

In [32], a joint multiuser detection and resource allocation algorithm is used in uplink CDMA systems. The algorithm allows each MS to vary its transmit power, spreading code and uplink receiver such that the ratio of the MS throughput to its own transmit power is maximized. The algorithm runs on each MS which increases the complexity of the MS. Also, the authors did not consider MIMO or OFDM in their system model.

In [33], an optimal assignment of transmit power, rate and BS that maximizes the spectral efficiency while satisfying QoS constraints is proposed for multimedia WCDMA uplink systems. However, the authors assumed synchronous single carrier SISO CDMA systems.

In [34], radio resources are allocated to users in a time division duplex (TDD)-CDMA system by using directional antennas at the BS and by the assignment of time slots to support asymmetric traffic while minimizing cross slot interference. The authors considered single carrier CDMA systems with perfect CSI.

A utility based joint power control and rate allocation in a downlink CDMA system with blind detection is presented in [35]. The algorithm assigns as many users to the system as possible while guaranteeing fairness among all users such that the instantaneous system throughput is maximized. However, the authors assumed single carrier SISO CDMA systems with no CSI information.

In [36], the authors assigned orthogonal signature sequences and power levels to users according to their CSI. Only a number of users equal to the processing gain with the best CSI are assigned resources such that the ergodic sum capacity of the CDMA system is maximized. However, the authors did not consider MIMO or OFDM systems in their analysis.

A scheduling algorithm for the downlink of a MIMO-CDMA system that assigns time slots in a time division multiplexing (TDM) frame to users such that the per user mean throughput is maximized is proposed in [37]. However, the authors assumed single carrier transmission with perfect CSI at the receiver.

In [38], a closed loop resource allocation algorithm for high data rate (HDR) CDMA reverse link system is proposed. Rate allocation is done at the MS whereas fairness is guaranteed by busy tones sent by the BSs to MS to inform about their queue status, rate history and minimum rate guarantee. However, the algorithm was designed for single carrier SISO CDMA systems with perfect CSI.

A dynamic resource allocation scheme for the downlink of CDMA2000 1xEV-DV networks is proposed in [39]. The scheme dynamically assigns number of time slots, number of Walsh codes and the modulation and coding schemes to users such that their QoS requirements in terms of delay, average throughput and packet loss rates are satisfied while maximizing the overall network throughput in every time slot. However, the algorithm was based on a link-layer wireless channel model which cannot capture physical layer parameters such as interference and channel estimation errors.

In [40], time slots and orthogonal codes are assigned to users in downlink multicarrier CDMA/TDMA such that the total transmit power is minimized while satisfying the data rate requirement of each user. However, the authors did not use MIMO systems and they assumed perfect CSI.

The authors of [41] proposed an incentive-compatible algorithm that leverages downlink demand to ensure that users truthfully reveal their uplink utilities to enable a socially optimal uplink rate allocation for single hop wireless CDMA network. However, the authors did not discuss the effects of channel estimation errors on their resource allocation algorithm or the effects of using OFDM and MIMO techniques.

A fair adaptive rate allocation algorithm for uplink CDMA system is proposed in[42]. The algorithm assigns more rates to users with good channels while users with bad channels get less rates such that the throughput of the system is maximized. Fairness is achieved by assigning users with bad channels more rates when their channel conditions improve. However, the algorithm was designed for single carrier SISO CDMA systems.

In [43], a joint user-network centric resource allocation algorithm for multi cell CDMA uplink system is defined. The algorithm assigns BS and power level to users such that the users' utility function in terms of throughput is maximized while the network objective in terms of global revenue is also maximized. The authors did not discuss the effect of CSI on their algorithm which was designed for single carrier SISO CDMA systems.

In [44], the authors proposed a scheme that assigns OFDM tones and antenna elements to users in downlink SDMA system to reduce the pair wise cross correlation between the users and improve the system performance. Although their scheme showed improvement in BER it cannot be used in uplink systems because it is very hard to form a beam from the MS to the BS. Also, their scheme allowed the user to be connected to multiple geographically separated antenna arrays which can lead to synchronization problems. Another limiting factor of this scheme is that the number of BS antennas should be large compared to the total number of users' antennas which limits the number of users that can be served.

In [45] the authors proposed a sub carrier allocation scheme for OFDM-CDMA systems that maximizes throughput while minimizing the scheduling delay. However, they assumed only one BTS with one antenna array which may suffer from near far problems. They also did not discuss the effects of channel estimation errors on the performance of their algorithm.

In wireless mesh networks, routing adds another dimension to cross layer design. Routing and resource allocation have to be done simultaneously in order to satisfy QoS requirements in terms of end to end packet delay and success rate.

In [46], a traffic independent base channel assignment for multi radio wireless mesh networks has been proposed. The algorithm provides an initial, well-connected topology with reduced overall interference. However, the algorithm is traffic independent and does not address dynamic channel assignment based on traffic routing which is very important for wireless mesh networks. Also, the authors did not discuss the interface architecture or the effects of channel estimation errors on their algorithm.

In [47], distributed and centralized channel assignment algorithms for wireless mesh networks with multiple radios have been proposed to minimize the interference between links while preserving the topology. However, the proposed algorithm does not discuss the effects of routing on interference levels or the channel assignment problem.

A distributed channel assignment/routing algorithm has been proposed in [48]. The algorithm assigns neighbors to interfaces and channels to interfaces such that the capacity requirement of each link is satisfied. However, the authors did not discuss the architecture of their interfaces or how to measure the interference between links assigned to interfering channels or the effect of channel estimation errors on the performance of their algorithm.

Raniwala et al. in [49] proposed a channel assignment algorithm based on network topology only and a combined load-ware channel assignment and routing algorithm for multi radio wireless mesh networks. Channel assignment is done such that the capacity of each link is greater than the expected load of the link to maximize the goodput of the network. However, the algorithm does not address the end to end packet delay or success rate. Also, the authors did not discuss the effects of channel estimation errors on the performance of their algorithm.

In [50], a channel assignment algorithm that preserves network topology has been proposed for multi radio wireless mesh networks. The authors did not address the effects of routing and traffic loads on channel assignment. Moreover, they did not address the effects of channel estimation errors on their algorithm.

A cross-layer tree-based interference aware routing that maximizes the throughput of wireless mesh network has been proposed in [51]. However, it assumes a centralized architecture in which a central base station collects bandwidth requests from subscriber stations (SS) and allocates channels to links.

In [52], an interference aware routing algorithm that finds paths with minimum inter flow and intra flow interference in wireless mesh networks with multiple radios has been proposed. However, the authors did not discuss the effects of channel estimation errors on their algorithm.

A routing algorithm based on a metric that accounts for interference and expected transmission time of a packet in multi radio wireless mesh networks has been proposed in [53].

In [54], routing and centralized scheduling algorithms have been proposed for single radio mesh networks. However, routing was assumed to be fixed and not dependent on channel conditions and thus cannot cope with the fading and time varying nature of wireless channels. Also, the authors did not discuss the effects of channel estimation errors on their algorithm.

A joint routing and channel assignment algorithm for throughput optimization in multi radio wireless mesh networks has been proposed in [55]. However, the algorithm assumes that all radios on each node are assigned orthogonal channels. Furthermore, the algorithm does not quantify the quality of these orthogonal channels.

1.4 Contributions

In this thesis CDMA-SFBC transmission systems for both uplink and downlink have been proposed. CDMA-SFBC transmission systems combine the advantages of CDMA, STBC, MIMO and OFDM. In CDMA-SFBC systems spreading is done after OFDM modulation which enables the use of longer spreading codes and hence the proposed CDMA-SFBC systems accommodate more users when compared to single carrier MIMO DS-CDMA systems or MIMO MC-CDMA systems.

In order to study the performance of the proposed CDMA-SFBC systems, closed form expressions for the bit error rate of both systems have been derived. The closed form expressions show the effects of channel estimation errors, channel cross correlation, number of users, code cross correlation and the number of transmit and receive antennas on the performance of both systems.

In CDMA systems, it is known that reducing interference increases the capacity of the CDMA system. Also channel estimation errors are known to degrade the performance of MIMO systems. This thesis provides a cross layer resource allocation algorithm for uplink CDMA-SFBC star networks. The resource allocation algorithm assigns BTSs, antenna arrays and OFDM tones to users such that both interference and channel estimation errors are minimized.

This thesis also provides a joint cross layer routing and resource allocation algorithm for CDMA-SFBC mesh networks. The proposed algorithm assigns OFDM tones to links such that interference and channel estimation errors are minimized. On top, the routing algorithm selects end to end paths with minimum packet delay and maximum packet success rates. This is achieved by avoiding congested links and by routing traffic through links with minimum interference and minimum channel estimation errors.

1.5 Outline

The rest of this thesis is organized as follows. In Chapter 2 we introduce a CDMA-SFBC system for uplink transmission. We also derive closed form BER expressions for the proposed CDMA-SFBC uplink system considering different STBCs and modulation techniques. The BER expressions are numerically evaluated for different STBC configurations, different modulation techniques and for different amounts of channel estimation error variance and channel cross correlation.

In Chapter 3, we introduce a CDMA-SFBC system for downlink transmission. The proposed CDMA-SFBC system uses Walsh orthogonal codes to eliminate MAI. Closed form BER expressions for the proposed CDMA-SFBC system are derived for different STBC configurations and different modulation techniques. The closed form BER expressions are numerically evaluated for the different STBC configurations, the different modulation techniques and for different amounts of channel estimation errors.

In Chapter 4, we introduce a resource allocation scheme for uplink CDMA-SFBC star networks. The resource allocation scheme assigns BTSs, antenna arrays and OFDM frequency bands to users such that their overall BER performance and bandwidth efficiency are optimized. The optimization problem is solved for different cell configurations and different number of users.

In Chapter 5, we introduce a joint cross layer routing and channel assignment algorithm for multi radio wireless mesh networks. We solve the optimization problem for different amounts of traffic and call probabilities.

Finally, in Chapter 6 we provide concluding remarks.

Part of the work presented in this thesis has been published in [56-59].

Chapter 2: Uplink CDMA-SFBC Transmission System

2.1 Introduction

The growing demand for high speed reliable wireless systems introduces multiple challenges to network designers. The time varying and fading nature of wireless channels proved to be a major challenge. The use of multiple antennas at both the transmitter and the receiver known as MIMO can significantly improve the spectral efficiency of the system by exploiting spatial diversity. In order to get maximum diversity gain from the MIMO system, several STBCs have been designed [1-3]. OFDM divides the frequency selective channel into multiple flat fading channels. It is also used to cancel the effects of ISI by inserting a cyclic prefix larger than the maximum delay spread of the channel [8]. Moreover, OFDM is used to support variable rate users. OFDM can also be combined with CDMA such that spreading is done after OFDM modulation which is also known as multi tone CDMA (MT-CDMA). MT-CDMA systems use longer spreading codes when compared to single carrier MIMO DS-CDMA systems or MIMO MC-CDMA systems and hence can accommodate more users than the DS-CDMA systems [60].

Jung et al proposed an adaptive CMMSE receiver for single carrier STBC-CDMA systems in [9]. However, their system suffers from ISI since they are not using OFDM. The complexity of the CMMSE receiver increases with the number of receive antennas and the number of resolvable paths since each receive antenna requires a CMMSE block for each resolvable path. They also assumed perfect CSI at the receiver in their SNIR analysis which is not very realistic.

In [10], STBC has been combined with single carrier CDMA for uplink transmission. However the system performs poorly when the number of users in the system is greater than half of the system capacity due to the increased MAI.

Torabi et al in [20] derived closed form BER expressions for the SFBC-OFDM systems over Rayleigh fading channels. However, they only discussed point to point links with no multiuser capability.

In this chapter we propose a CDMA-SFBC uplink transmission system that combines the advantages of MIMO, STBC, OFDM and CDMA systems. The proposed CDMA-SFBC system exploits the time, space, code and frequency diversities of the channel which can greatly improve reception. In the proposed system, spreading is done after OFDM modulation which increases the processing gain of the system by a factor equal to the number of OFDM tones when compared to single carrier DS-CDMA systems. This will allow the system to use longer spreading codes and hence accommodate more users. We also derive and evaluate closed form expressions for the BER of the proposed CDMA-SFBC system. These expressions show the combined effects of channel estimation error, code cross-correlation, user channel cross-correlation and the number of users on the BER performance. The closed form BER expressions are derived for both the M-ary phase shift keying (MPSK) and the M-ary quadrature amplitude modulation (MQAM) techniques considering different CDMA-SFBC configurations. The performance analysis and results comparisons for CDMA-SFBC system are provided. The results shed light on the merits gained by the combined use of OFDM and spreading in different error environments and impairments.

The rest of this chapter will be organized as follows. The system model is introduced in Section 2.2. Signal to noise ratio (SNR) analysis of the proposed system is discussed in Section 2.3. BER analysis of the proposed system for MQAM and MPSK are discussed in Sections 2.4 and 2.5 respectively. Results are presented in Section 2.6 and the chapter is concluded in Section 2.7.

2.2 System Model

The block diagram for the baseband model of the proposed uplink CDMA-SFBC system is shown in Figure 2.1. The transmitter resides in the mobile station whereas the receiver is assumed to be at the base station. For simplicity, the figure shows the transmitter of one user only. Each link is equipped with M_T transmit and M_R receive antennas. In the transmitter, the data bits from the user are first converted from serial to parallel and fed to the MQAM/MPSK modulator where $M = 2^b$ and b is the number of allocated bits per symbol. The MQAM/MPSK modulator generates a signal vector **S**. There are $L \times R_c$ information symbols in **S** where L is equal to the total number of available OFDM tones and R_c is the rate of the STBC. The signal vector **S** is then fed to the STBC encoder. The STBC encoder is defined by its $q \times M_T$ generating matrix. The STBC encoder generates M_T blocks $\boldsymbol{S_1} \cdots \boldsymbol{S_{M_T}}$. Each one of these blocks has a length of L. There are F sub-blocks in each of the $\boldsymbol{S_1} \cdots \boldsymbol{S_{M_T}}$ blocks such that $F = L/q$ and each sub block has a length of q symbols. The OFDM modulation is then performed on $\boldsymbol{S_1} \cdots \boldsymbol{S_{M_T}}$ by using the inverse fast Fourier transform (IFFT). The IFFT generates blocks $\boldsymbol{X_1} \cdots \boldsymbol{X_{M_T}}$ which will be spread by the spreading code C_1 then transmitted by its corresponding transmit antenna. The channel is assumed to be a quasi-static Rayleigh fading channel which means the channel does not change within one OFDM symbol. For the two transmit antenna case we will use Alamouti's scheme [1].

Using Alamouti scheme we will have $\boldsymbol{S} = [s(0)\ s(1)\ \cdots s(L-1)]^T$, $\mathbf{S_1} = [\mathrm{s(2k)} - \mathrm{s^*(2k+1)}]^\mathrm{T}$ and $\mathbf{S_2} = [\mathrm{s(2k+1)}\ \mathrm{s^*(2k)}]^\mathrm{T}$ where $0 \le \mathrm{k} \le \mathrm{F} - 1$. The (.)* and (.)T operators denote the complex conjugate and the vector transpose respectively. The OFDM tones are assigned to symbols such that the first symbol transmitted from each antenna is transmitted on the first tone, the second symbol transmitted from each antenna is transmitted on the second tone and so on until the *L-th* symbol is transmitted on the *L-th* tone as shown in Table 2.1.

Table 2-1 Uplink frequency mapping

	Antenna1	Antenna 2
Subcarrier 2k	$\mathrm{s(2k)}$	$\mathrm{s(2k+1)}$
Subcarrier 2k+1	$-\mathrm{s^*(2k+1)}$	$\mathrm{s^*(2k)}$

At the receiver side the signals are de-spread and low pass filtered. The OFDM demodulation is done by the fast Fourier transform (FFT). The demodulated received signal at the j-th receive antenna $\boldsymbol{r}_j$ can then be decoded using the ML detection by the space time decoder to generate an estimate of the signal $\tilde{S}$. The signal estimate $\tilde{S}$ is then detected by the MQAM/MPSK demodulator and converted from parallel to serial.

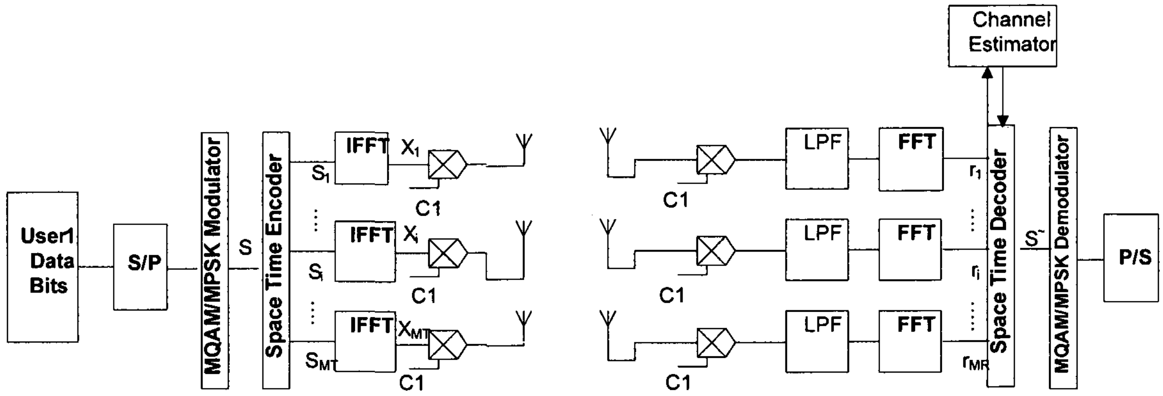

Figure 2.1 The proposed CDMA-SFBC uplink system

We will use Alamouti's scheme [1] for the 2 transmit antennas case while we will use the g_c^3 and g_c^4 OSTBCs proposed in [2] for the three and four transmit antennas respectively.

2.3 SNR Analysis of the Uplink CDMA-SFBC System

For the two transmit antenna case we will use the STBC proposed by Alamouti in [1]. At the receiver, the received signal will be de-spread by being multiplied by the intended user's code, assuming perfect spreading code synchronization, and then it will be low pass filtered. OFDM demodulation of the received signal is then performed by the FFT block. The OFDM is assumed to have a cyclic prefix larger than the maximum delay spread of the channel to prevent ISI [8]. The demodulated received signal at the j-th receive antenna can be expressed as:

$$r_j(2k) = H_{j,1,1}(2k)s(2k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(2k) s_u(2k) + H_{j,2,1}(2k) s(2k+1) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(2k) s_u(2k+1) + W_j(2k) \quad (2.1)$$

$$r_j(2k+1) = -H_{j,1,1}(2k)s^*(2k+1) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(2k) s_u^*(2k+1) +$$

$$H_{j,2,1}(2k)s^*(2k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(2k) s_u^*(2k) + W_j(2k+1) \qquad (2.2)$$

$0 \leq k \leq F-1\,, 1 \leq j \leq M_R \; and \; 1 < u \leq U$

In (2.1) and (2.2) we assumed perfect user's spreading code synchronization i.e. the BS synchronizes on each user's code separately and no global synchronization is assumed. $H_{j,i,u}$ is the discrete Fourier transform (DFT) of the Rayleigh channel coefficient between i-th transmit and j-th receive antennas of the u-th user. The fading channels are assumed to be quasi static Rayleigh fading channels which means that the channels do not change within one OFDM block and hence $H_{j,i,u}(2k) = H_{j,i,u}(2k+1)$ for $0 \leq k \leq F-1$. W_j is a Gaussian random variable that represents the DFT of the additive white Gaussian noise (AWGN) at receive antenna j after being multiplied by the intended user code and low pass filtered. W_j has zero mean and a variance of σ_n^2. The random variable $\zeta_{1u}(t)$ represents the cross correlation between intended user's code ($C_1(t)$) and the codes of other users ($C_u(t)$) and it has the same statistical properties for all users. It has approximately zero mean and a variance of σ_ζ^2 which is equal to (1/CL) for maximal length PN codes and the average of three values for Gold codes as in [61] where CL is the code length. In (2.1) and (2.2) we ignored the effects of ISI assuming that we have a cyclic prefix larger than the maximum delay spread of the channel [8]. The first user is assumed to be the intended user. The first and third terms on the right hand side of (2.1) & (2.2) are the contributions of the intended user while the second and fourth terms are the contributions of all other users and the last term is the contribution of the AWGN.

The STBC decoder will utilize the channel estimation information to decode the received signal using ML detection. The extracted signal can be expressed as:

$$\tilde{s}(2k) = \sum_{j=1}^{M_R}\left(H^*_{j,1,1}(2k) + \epsilon^*_{j,1,1}(2k)\right) r_j(2k) + \sum_{j=1}^{M_R}\left(H_{j,2,1}(2k) + \epsilon_{j,2,1}(2k)\right) r^*_j(2k+1) \quad (2.3)$$

The estimation error of the intended user (the first user) channel between the i-th transmit and the j-th receive antennas is denoted by $\epsilon_{j,i,1}$. Estimation errors of different channels are assumed to be independent and identically distributed (i.i.d) random variables with zero mean and σ_e^2 variance. Substituting (2.1) and (2.2) in (2.3), the detected signal $\tilde{s}$ can be expressed as:

$$\begin{aligned}
&\tilde{s}(2k) = \\
&\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2 + \left|H_{j,2,1}(2k)\right|^2\right) s(2k) + \\
&\sum_{j=1}^{M_R}\left(\epsilon^*_{j,1,1}(2k)H_{j,1,1}(2k) + \epsilon_{j,2,1}(2k)H^*_{j,2,1}(2k)\right) s(2k) + \sum_{j=1}^{M_R}\left(\epsilon^*_{j,1,1}(2k)H_{j,2,1}(2k) - \right.\\
&\left.\epsilon_{j,2,1}(2k)H^*_{j,1,1}(2k)\right) s(2k+1) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H^*_{j,1,1}(2k)H_{j,1,u}(2k)s_u(2k) + \\
&\sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H^*_{j,1,1}(2k)H_{j,2,u}(2k)s_u(2k+1) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon^*_{j,1,1}(2k)H_{j,1,u}(2k)s_u(2k) + \\
&\sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon^*_{j,1,1}(2k)H_{j,2,u}(2k)s_u(2k+1) - \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,1}(2k)H^*_{j,1,u}(2k)s_u(2k+ \\
&1) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon_{j,2,1}(2k)H^*_{j,2,u}(2k)s_u(2k) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,1}(2k)H^*_{j,2,u}(2k)s_u(2k) - \\
&\sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon_{j,2,1}(2k)H^*_{j,1,u}(2k)s_u(2k+1) + \sum_{j=1}^{M_R}H^*_{j,1,1}(2k)W_j(2k) + \\
&\sum_{j=1}^{M_R}H_{j,2,1}(2k)W^*_j(2k+1) \qquad (2.4)
\end{aligned}$$

Now we will write $\tilde{s}(2k) = D(2k) + I(2k)$ where D(2k) is the useful signal of the intended user and I(2k) is the interference from all other users plus the AWGN and the channel estimation error contributions.

$$D(2k) = \sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2 + \left|H_{j,2,1}(2k)\right|^2\right) S(2k) \quad (2.5)$$

$$I(2k) = \sum_{j=1}^{M_R}\left(\epsilon_{j,1,1}^*(2k)H_{j,1,1}(2k) + \epsilon_{j,2,1}(2k)H_{j,2,1}^*(2k)\right)s(2k) + \sum_{j=1}^{M_R}\left(\epsilon_{j,1,1}^*(2k)H_{j,2,1}(2k) - \epsilon_{j,2,1}(2k)H_{j,1,1}^*(2k)\right)s(2k+1) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H_{j,1,1}^*(2k)H_{j,1,u}(2k)s_u(2k) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H_{j,1,1}^*(2k)H_{j,2,u}(2k)s_u(2k+1) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon_{j,1,1}^*(2k)H_{j,1,u}(2k)s_u(2k) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon_{j,1,1}^*(2k)H_{j,2,u}(2k)s_u(2k+1) - \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,1}(2k)H_{j,1,u}^*(2k)s_u(2k+1) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon_{j,2,1}(2k)H_{j,2,u}^*(2k)s_u(2k) + \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,1}(2k)H_{j,2,u}^*(2k)s_u(2k) - \sum_{j=1}^{M_R}\sum_{u=2}^{U}\zeta_{1u}(t)\epsilon_{j,2,1}(2k)H_{j,1,u}^*(2k)s_u(2k+1) + \sum_{j=1}^{M_R}H_{j,1,1}^*(2k)W_j(2k) + \sum_{j=1}^{M_R}H_{j,2,1}(2k)W_j^*(2k+1) \quad (2.6)$$

At this point it is useful to note that multiplying the AWGN by the spreading code will not change the statistical properties of the AWGN. In order to find the signal to noise ratio, we need to find the power of D(2k) and that of I(2k) which is nothing but the variance of each of the signals. $Var(D(2k)) = E(D(2k)D^*(2k))$

$$Var(D(2k)) = \left(\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2 + \left|H_{j,2,1}(2k)\right|^2\right)\right)^2 P_s \quad (2.7)$$

P_s denotes the symbol power at the transmitter. To find the power of the interference plus the power of the noise we need to find $Var(I(2k)) = E(I(2k)I^*(2k))$. We will need though to define a new variable to represent the cross correlation between the intended user channels and those of the users, this we denote as ϕ such that $\phi_{j,1,1} = H_{j,1,1}(2k)H_{j,1,u}(2k), \phi_{j,1,2} = H_{j,1,1}(2k)H_{j,2,u}(2k), \phi_{j,2,1} = H_{j,2,1}(2k)H_{j,1,u}(2k)$ and $\phi_{j,2,2} = H_{j,2,1}(2k)H_{j,2,u}(2k)$

$$Var(\phi_{j,1,1}) = Var(\phi_{j,1,2}) = Var(\phi_{j,2,1}) = Var(\phi_{j,2,2}) = \sigma_{uc}^2 \quad (2.8)$$

While calculating the Var(I(2k)) we get terms with four summations such as $\sigma_\zeta^2 E\left(\left(\sum_{j=1}^{M_R}\sum_{u=2}^{U} H_{j,1,1}^*(2k)H_{j,1,u}(2k)S_u(2k)\right)\left(\sum_{j=1}^{M_R}\sum_{u=2}^{U} H_{j,1,1}(2k)H_{j,1,u}^*(2k)S_u(2k)\right)\right)$ but since the data symbols from different users are independent, the above term will be equal to $\sigma_\zeta^2\sigma_{uc}^2P_s(U-1)M_R$. Many other terms of four summations that represent the cross correlation of the channels between different transmit and receive antenna pairs will be cancelled out by the SFBC. Finally and after developing (2.6) we obtain

$$Var(I(2k)) = 2P_s\sigma_e^2\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)+4\,\sigma_\zeta^2\sigma_{uc}^2P_s(U-1)M_R + 2\,\sigma_\zeta^2\sigma_e^2P_s\sum_{j=1}^{M_R}\sum_{u=2}^{U}\left(\left|H_{j,1,u}(2k)\right|^2+\left|H_{j,2,u}(2k)\right|^2\right)+\sigma_n^2\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right) \tag{2.9}$$

and the SNR becomes

$$SNR(2k) = \frac{\left(\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)\right)^2 P_s}{\left(\begin{array}{c} 2P_s\sigma_e^2\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)+4\,\sigma_\zeta^2\sigma_{uc}^2P_s(U-1)M_R \\ +2\,\sigma_\zeta^2\sigma_e^2P_s\sum_{j=1}^{M_R}\sum_{u=2}^{U}\left(\left|H_{j,1,u}(2k)\right|^2+\left|H_{j,2,u}(2k)\right|^2\right) \\ +\sigma_n^2\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)\end{array}\right)} \tag{2.10}$$

The total power of the symbols transmitted through the M_T transmit antennas is normalized to the number of transmit antennas and the normalized SNR can be expressed as:

$$SNR(2k) = \frac{\left(\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)\right)\eta_s}{M_T\left(\eta_s\sigma_e^2+\frac{2\,\sigma_\zeta^2\sigma_{uc}^2\eta_s(U-1)M_R}{\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)}+\frac{\sigma_\zeta^2\sigma_e^2\eta_s(U-1)\sum_{j=1}^{M_R}\left(\left|H_{j,1,u}(2k)\right|^2+\left|H_{j,2,u}(2k)\right|^2\right)}{\sum_{j=1}^{M_R}\left(\left|H_{j,1,1}(2k)\right|^2+\left|H_{j,2,1}(2k)\right|^2\right)}+1\right)} \tag{2.11}$$

$$\eta_s = \frac{P_s}{\sigma_n^2} \tag{2.12}$$

We will assume that $\frac{\sum_{j=1}^{M_R}\left(|H_{j,1,u}(2k)|^2+|H_{j,2,u}(2k)|^2\right)}{\sum_{j=1}^{M_R}\left(|H_{j,1,1}(2k)|^2+|H_{j,2,1}(2k)|^2\right)} \approx 1$, which means that the total channel powers over all transmit and receive antennas is the same for all users. This is inherently more or less guaranteed by the power control mechanism of the CDMA standards [62, 63].Yes they work on the total power received, but this total power received is nothing but the multiplication of channel power, transmit power and the power control factor.

We will also define $\rho = \frac{\sigma_{uc}^2}{\sum_{j=1}^{M_R}\left(|H_{j,1,1}(2k)|^2+|H_{j,2,1}(2k)|^2\right)}$ which is the users channels cross-correlation normalized by the total channel power of any user. Finally the SNR can be expressed as:

$$SNR(2k) = \frac{\left(\sum_{j=1}^{M_R}\left(|H_{j,1,1}(2k)|^2+|H_{j,2,1}(2k)|^2\right)\right)\eta_s}{M_T R_c\left(\eta_s\sigma_e^2+M_T\,\sigma_\zeta^2\rho\eta_s(U-1)M_R+\,\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)} \quad (2.13)$$

The same result for SNR shown in (2.13) can be used for the 3 and 4 transmit antennas cases as shown in appendix A and appendix B using the right values for R_c, M_T and M_R.

For the uplink uncoded SISO CDMA-OFDM system, the demodulated received signal at the receive antenna can be expressed as:

$$r(k) = H_1(k)s_1(k) + \sum_{u=2}^{U}\zeta_{1u}(t)H_u(k)s_u(k) + W(k) \quad (2.14)$$

and from that we can find the detected signal as:

$$\tilde{s}(k) = \left(H_1^*(k) + \epsilon_1^*(k)\right)r(k) \quad (2.15)$$

$\tilde{s}(k) =$

$$|H_1(k)|^2 s_1(k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_1^*(k) H_u(k) s_u(k) + + \sum_{u=2}^{U} \zeta_{1u}(t) \epsilon_1^*(k) H_u(k) s_u(k) + \epsilon_1^*(k) H_1(k) s_1(k) + H_1^*(k) W(k) \quad (2.16)$$

By analysis similar to the one we did for the uplink with two transmit antennas we find the SNR to be

$$SNR(k) = \frac{|H_1(k)|^2 \eta_s}{\left(\eta_s \sigma_e^2 + \sigma_\zeta^2 \rho \eta_s (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)} \quad (2.17)$$

For the uncoded system with one transmit antenna and multiple receive antennas, the demodulated received signal at the j-th receive antenna can be expressed as:

$$r_j(k) = H_{1,j}(k) s_1(k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{u,j}(k) s_u(k) + W_j(k) \quad (2.18)$$

and from that we can find the detected signal as:

$$\tilde{s}(k) = \sum_{j=1}^{M_R} \left(H_{1,j}^*(k) + \epsilon_{1,j}^*(k)\right) r_j(k) \quad (2.19)$$

$\tilde{s}(k) =$

$$\sum_{j=1}^{M_R} \left|H_{1,j}(k)\right|^2 s_1(k) + \sum_{j=1}^{M_R} \sum_{u=2}^{U} \zeta_{1u}(t) H_{1,j}^*(k) H_{u,j}(k) s_u(k) + \sum_{j=1}^{M_R} \sum_{u=2}^{U} \zeta_{1u}(t) \epsilon_{1,j}^*(k) H_{u,j}(k) s_u(k) + \sum_{j=1}^{M_R} \epsilon_{1,j}^*(k) H_{1,j}(k) s_1(k) + \sum_{j=1}^{M_R} H_{1,j}^*(k) W_j(k) \quad (2.20)$$

By analysis similar to the one we did for the uplink with two transmit antennas we find the SNR to be

$$SNR(k) = \frac{\sum_{j=1}^{M_R} \left|H_{1,j}(k)\right|^2 \eta_s}{\left(\eta_s \sigma_e^2 + \sigma_\zeta^2 \rho \eta_s M_R (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)} \quad (2.21)$$

2.4 BER Performance of the Uplink CDMA-SFBC MQAM System

Assuming MQAM modulation and grey bit mapping with $M = 2^b$ where b is the number of bits/symbol. The expression for the instantaneous BER of the k-th sub-channel can be expressed as in [64] by:

$$BER_{MQAM}[2k] = \frac{2\left(1-\frac{1}{\sqrt{2^b}}\right)}{b} erfc\left(\sqrt{\frac{1.5SNR[2k]}{2^b-1}}\right) \tag{2.22}$$

For our purposes, we will use the exponential approximation defined in [65]. So the expression in (2.22) can be approximated as in [66, 67] by:

$$BER_{MQAM}[2k] = 0.2exp\left(\frac{-1.6SNR[2k]}{2^b-1}\right) \tag{2.23}$$

The average BER can be obtained by integrating over the probability density function (pdf) of the SNR denoted by η then summing the k-th result over all sub-channels and dividing by L as:

$$\overline{BER}_{MQAM} = \frac{1}{L}\sum_{k=0}^{L-1}\int_0^{\infty}\cdots\int_0^{\infty} BER_{MQAM}[k]P(\eta_{1,1})\cdots P(\eta_{M_R,M_T})d\eta_{1,1}\cdots d\eta_{M_R,M_T} \tag{2.24}$$

where $\eta_{j,i}$ is the instantaneous SNR of the channel between the i-th transmit and the j-th receive antennas. Since $|H_{j,1,1}(2k)|$ is Rayleigh distributed with variance one then $|H_{j,1,1}(2k)|^2$ has a chi-square pdf with two degrees of freedom. Therefore η which is the instantaneous SNR is chi-square distributed i.e.

$$P(\eta) = \frac{1}{\bar{\eta}}exp\left(-\frac{\eta}{\bar{\eta}}\right), \eta > 0 \tag{2.25}$$

where $\bar{\eta} = E(\eta) = \frac{\eta_s}{M_T\left(\eta_s\sigma_e^2+2M_R\rho\eta_s\sigma_\zeta^2(U-1)+\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)}$ (2.26)

Substituting (2.26) into (2.25) and (2.13) into (2.23) and using these results in (2.24) and noting that each term of the summation over k in (2.24) is not a function of k yields the BER expression:

$$\overline{BER}_{MQAM} = 0.2\left[1 + \frac{1.6\eta_s}{R_c M_T(2^b-1)\left(\eta_s\sigma_e^2 + M_T M_R \eta_s \rho\, \sigma_\zeta^2 (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)}\right]^{-M_T M_R} \tag{2.27}$$

For the three and four transmit antennas the same result in (2.27) can be used to calculate the BER of the MQAM system as shown in Appendix A and Appendix B using the right values for R_c, M_T and M_R.

Similarly, we can find the BER of the MQAM SISO-CDMA-OFDM system as:

$$\overline{BER}_{MQAM} = 0.2\left[1 + \frac{1.6\eta_s}{(2^b-1)\left(\eta_s\sigma_e^2 + \eta_s \rho\, \sigma_\zeta^2 (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)}\right]^{-1} \tag{2.28}$$

And for the system with one transmit antenna and multiple receive antennas the BER of the MQAM system is:

$$\overline{BER}_{MQAM} = 0.2\left[1 + \frac{1.6\eta_s}{(2^b-1)\left(\eta_s\sigma_e^2 + M_R \eta_s \rho\, \sigma_\zeta^2 (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)}\right]^{-M_R} \tag{2.29}$$

2.5 BER Performance of the Uplink CDMA-SFBC MPSK System

Using the same approach we used for the MQAM system, the BER of the CDMA-SFBC MPSK system can be approximated as in [66] by:

$$BER_{MPSK} = \frac{0.2}{L} \sum_{k=0}^{L-1} exp\left(\frac{-7SNR[k]}{2^{1.9b}+1}\right) \tag{2.30}$$

For our purpose we will take the k-th term which is $BER_{MPSK}[k] = 0.2exp\left(\frac{-7SNR[k]}{2^{1.9b}+1}\right)$ and follow the same steps that led to (2.27) noting that the average BER is independent of k then the average BER can be expressed as:

$$\overline{BER}_{MPSK} = 0.2\left[1+\frac{7\eta_s}{R_c M_T(2^{1.9b}+1)\left(\eta_s\sigma_e^2+M_T M_R\eta_s\rho\,\sigma_\zeta^2(U-1)+\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)}\right]^{-M_T M_R} \tag{2.31}$$

For the three and four transmit antennas the same result in (2.31) can be used to calculate the BER of the MPSK system as shown in Appendix A and Appendix B using the right values for R_c, M_T and M_R.

Similarly, we can find the BER of the MPSK SISO-CDMA-OFDM system as:

$$\overline{BER}_{MPSK} = 0.2\left[1+\frac{7\eta_s}{(2^{1.9b}+1)\left(\eta_s\sigma_e^2+\eta_s\rho\,\sigma_\zeta^2(U-1)+\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)}\right]^{-1} \tag{2.32}$$

and for the system with one transmit antenna and multiple receive antennas the BER of the MPSK system is:

$$\overline{BER}_{MPSK} = 0.2\left[1+\frac{7\eta_s}{(2^{1.9b}+1)\left(\eta_s\sigma_e^2+M_R\eta_s\rho\,\sigma_\zeta^2(U-1)+\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)}\right]^{-M_R} \tag{2.33}$$

2.6 Results

The performance of the proposed CDMA-SFBC system is compared to that of the CMMSE STBC-CDMA receiver proposed in [9] as shown in Figure 2.2. The proposed CDMA-SFBC system shows a noticeable improvement in BER performance over the CMMSE receiver. This BER improvement can be explained by the fact that the utilization of OFDM with a cyclic prefix larger than the maximum delay spread of the channel in the proposed system cancels the ISI and multipath interference which the CMMSE receiver suffers from.

The performance of the proposed uplink CDMA-SFBC system is investigated by numerically evaluating the derived closed form BER expressions. The BER expressions are evaluated for a wide range of channel estimation error variances, normalized-user-channel cross correlation(ρ), different modulation techniques and different spreading sequences including PN and Gold codes. Both the receiver and transmitter are equipped with two antennas. Figures 2.3 and 2.4 show that for the same number of users, the same amount of channel cross correlation and code length, the BER of the QPSK system degrades as the channel estimation error variance increases. We also note the existence of noise floors which means that increasing the symbol power has less effect on the BER performance at high values of channel estimation error variance. The degrading effect of the cross correlation between the channels of different users on BER performance is shown in Figures 2.5 and 2.6 which is similar to the effect of channel estimation error variance in Figures 2.3 and 2.4. Figure 2.7 shows that the BER performance degrades as the number of users increases while Figure 2.8 shows that for the same number of users, the BER increases with increasing the cross correlation between the channels. Figure 2.9 shows the BER performance of the proposed system for different MQAM and MPSK modulation schemes. In Figure 2.10 two PN sequences with lengths equal to 64 and 128 were used for spreading. The results show that the BER performance improves with increasing the spreading code length since longer codes have less cross correlation.

2.7 Conclusion

In this chapter we proposed a novel CDMA-SFBC system for uplink transmission. Closed form expressions for the BER of the proposed system were derived. The expressions were derived for both MQAM and MPSK modulation schemes. The derived expressions were evaluated for a wide range of channel estimation error variance, normalized user channel cross correlation, number of users, spreading codes lengths and different MQAM/MPSK modulation schemes. The results have shed light on the effects of the various operating parameters. The results have also shown that the proposed system performs better at less channel estimation errors and user channel cross correlation. The proposed system can provide a noticeable performance improvement over the constrained minimum mean square error receiver for STBC-CDMA systems.

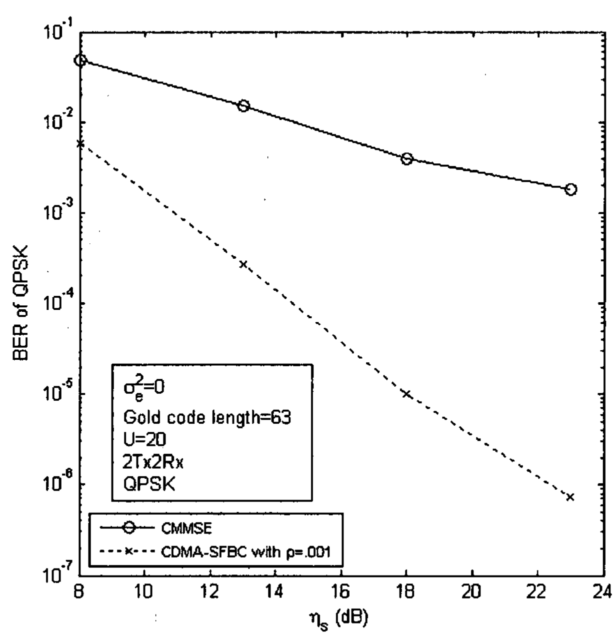

Figure 2.2 Performance comparison between CMMSE and the new CDMA-SFBC systems

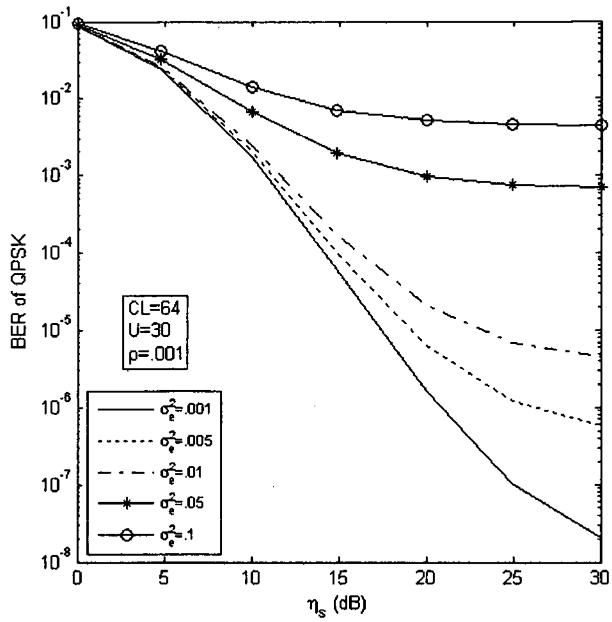

Figure 2.3 BER versus symbol to noise power ratio for different values of channel estimation error variance

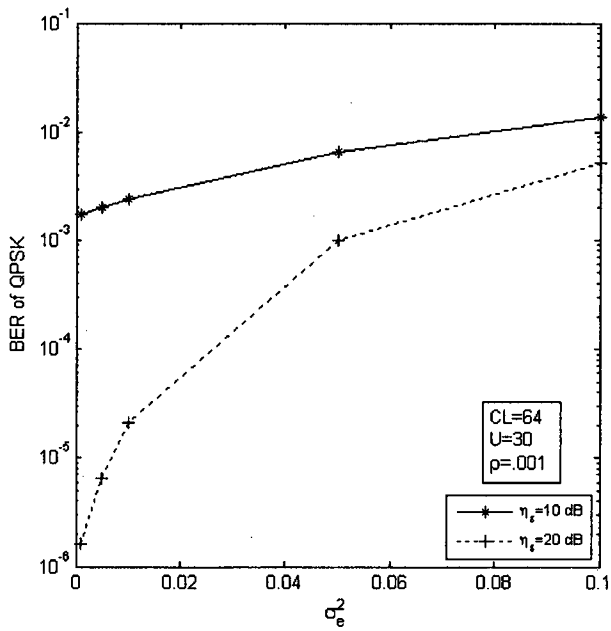

Figure 2.4 BER versus channel estimation error variance

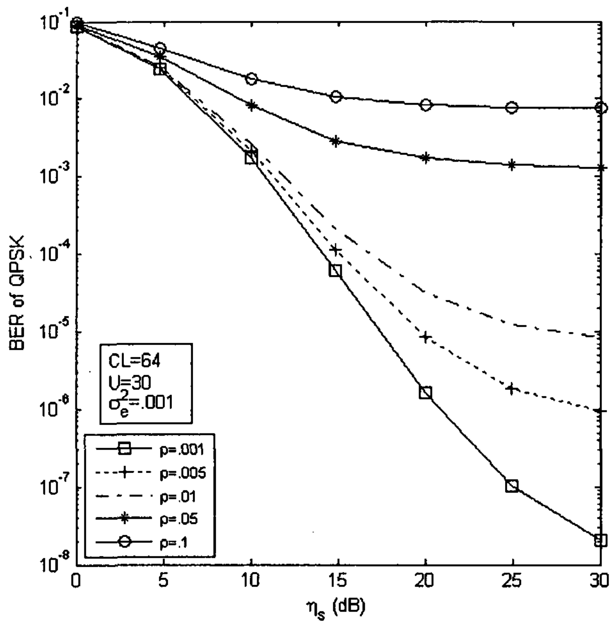

Figure 2.5 BER versus symbol to noise power ratio for different values of normalized user channel cross correlation

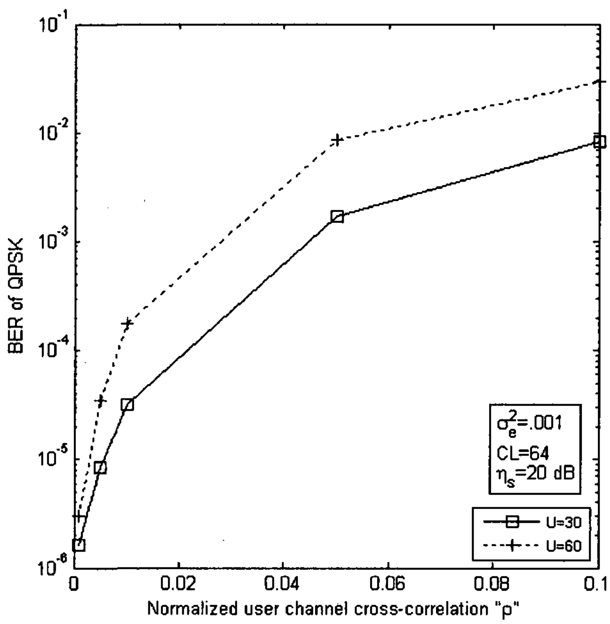

Figure 2.6 BER versus normalized user channel cross correlation

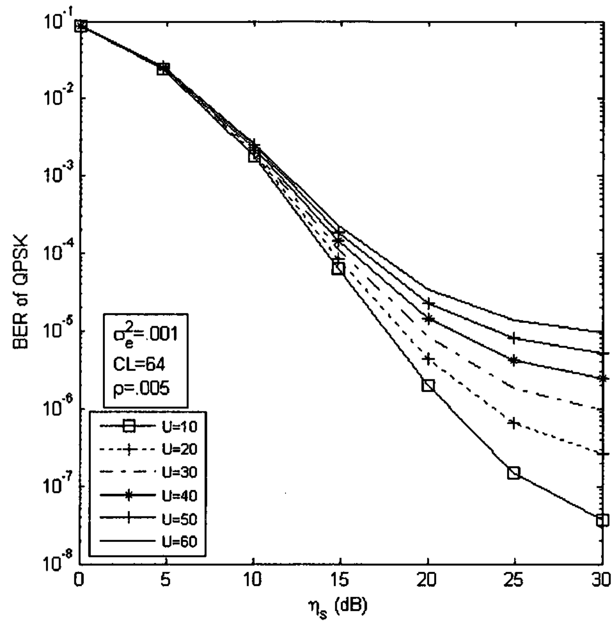

Figure 2.7 BER versus symbol to noise power ratio for different number of users

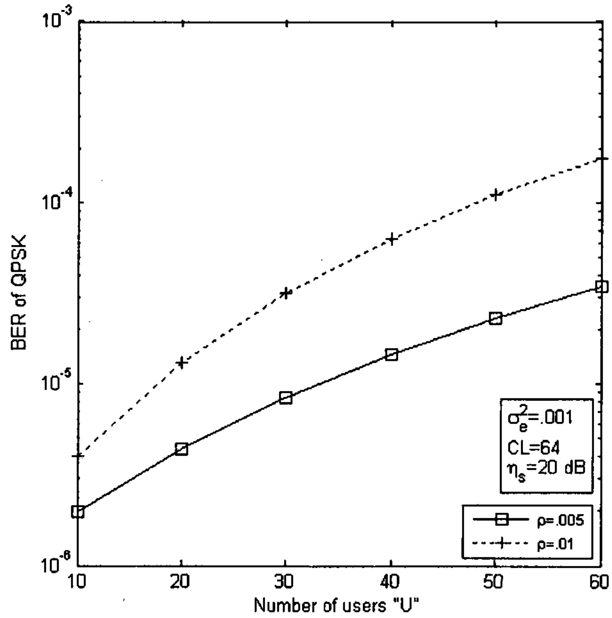

Figure 2.8 BER versus number of users

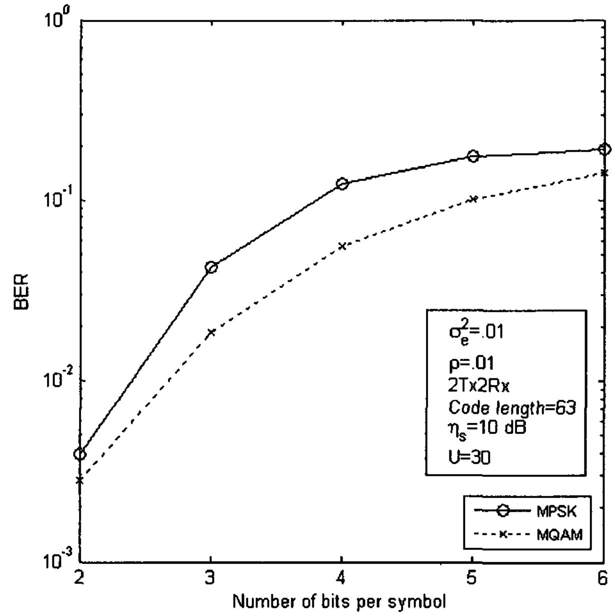

Figure 2.9 BER performance of different modulation schemes

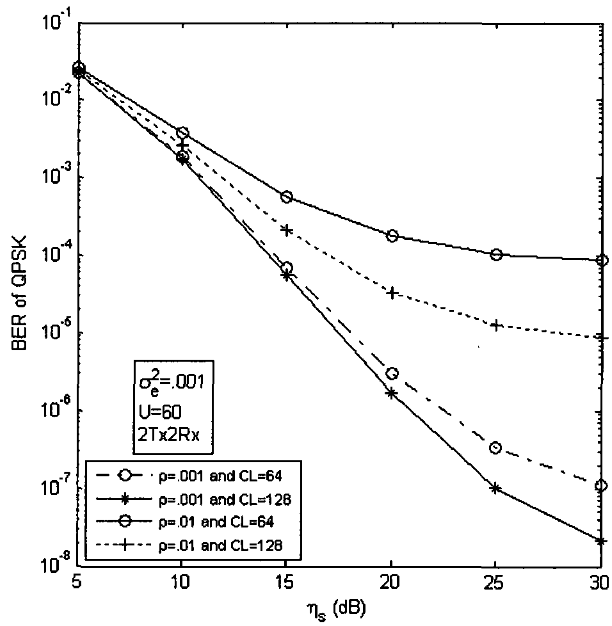

Figure 2.10 Effects of spreading code length on BER

Chapter 3: Downlink CDMA-SFBC Transmission System

3.1 Introduction

In this chapter, we extend the results of Chapter 2 to propose a CDMA-SFBC downlink transmission system that combines the advantages of MIMO, STBC, OFDM and CDMA systems. The proposed CDMA-SFBC system exploits the time, space, code and frequency diversities of the channel which can greatly improve reception.

In the proposed CDMA-SFBC system, spreading is done after OFDM modulation which means that spreading is done on symbols with longer durations when compared to single carrier DS-CDMA systems which reduces the complexity of synchronization. Spreading symbols with longer durations increases the processing gain of the CDMA system which is defined as the symbol duration divided by chip time. Higher processing gain means that the system can accommodate larger number of users. Each user in the system is assigned a Walsh orthogonal code which eliminates MAI.

We also derive and evaluate closed form expressions for the BER of the proposed CDMA-SFBC system. These expressions show the effects of channel estimation error on the BER performance. In our analysis we consider both the MPSK and the MQAM modulation techniques. The performance analysis and results comparisons for different SFBCs are provided. The results shed light on the merits gained by the combined use of OFDM and spreading in different error environments and impairments.

In [11], STBC transceivers were presented for both uplink and downlink MC-CDMA systems in which a different set of subcarriers is assigned to each user. However, the authors limited the number of receive antennas to one which makes the maximum spatial diversity gain equal to the number of transmit antennas instead of the product of the number of transmit and number of receive antennas.

Vook et al in [13] proposed a cyclic prefix single carrier CDMA system for downlink transmission with antenna diversity at both the transmitter and the receiver. Single carrier transmission systems may suffer from deep fading especially in frequency selective channels.

The rest of this chapter will be organized as follows. The system model is introduced in Section 3.2. Signal to noise ratio analysis of the proposed system is discussed in Section 3.3. BER analysis of the proposed system for MQAM and MPSK are discussed in Sections 3.4 and 3.5 respectively. Results are presented in Section 3.6 and the chapter is concluded in Section 3.7.

3.2 System Model

The block diagram for the baseband model of the proposed downlink CDMA-SFBC system is shown in Figure 3.1. The transmitter resides in the base station whereas the receiver is in the mobile station. For simplicity, the figure shows the transmitter of one user only. Each link is equipped with M_T transmit and M_R receive antennas. In the transmitter, the data bits intended to the user are first converted from serial to parallel and fed to the MQAM/MPSK modulator where $M = 2^b$ and b is the number of allocated bits per symbol. The MQAM/MPSK modulator generates a signal vector **S**. There are $L \times R_c$ information symbols in **S** where L is equal to the total number of available OFDM tones and R_c is the rate of the STBC. The signal vector **S** is then fed to the STBC encoder. The

STBC encoder is defined by its $q \times M_T$ generating matrix. The STBC encoder generates M_T blocks $\boldsymbol{S_1} \ldots \boldsymbol{S_{M_T}}$. Each one of these blocks has a length of L. There are F sub-blocks in each of the $\boldsymbol{S_1} \ldots \boldsymbol{S_{M_T}}$ blocks such that $F = L/q$ and each sub-block has a length of q symbols. The OFDM modulation is then performed on $\boldsymbol{S_1} \ldots \boldsymbol{S_{M_T}}$ by IFFT. The IFFT generates blocks $\boldsymbol{X_1} \ldots \boldsymbol{X_{M_T}}$ which will be spread by an orthogonal Walsh code w_l then transmitted by its corresponding transmit antenna. The channel is assumed to be a quasi-static Rayleigh fading channel which means the channel does not change within one OFDM symbol. For the two transmit antenna case we will use Alamouti's scheme [1].

Using Alamouti's scheme we will have $\boldsymbol{S} = [s(0)\ s(1)\ \cdots s(L-1)]^T$, $\mathbf{S_1} = [\mathrm{s}(2\mathrm{k}) - \mathrm{s}^*(2\mathrm{k}+1)]^{\mathrm{T}}$ and $\mathbf{S_2} = [\mathrm{s}(2\mathrm{k}+1)\ \mathrm{s}^*(2\mathrm{k})]^{\mathrm{T}}$ where $0 \leq \mathrm{k} \leq \mathrm{F}-1$. The OFDM tones are assigned to symbols such that the first symbol transmitted from each antenna is transmitted on the first tone, the second symbol transmitted from each antenna is transmitted on the second tone and so on until the *L-th* symbol is transmitted on the *L-th* tone as shown in Table 3.1.

Table 3-1 Downlink frequency mapping

	Antenna1	Antenna 2
Subcarrier 2k	$\mathrm{s}(2\mathrm{k})$	$\mathrm{s}(2\mathrm{k}+1)$
Subcarrier 2k+1	$-\mathrm{s}^*(2\mathrm{k}+1)$	$\mathrm{s}^*(2\mathrm{k})$

At the receiver side the signals are de-spread by being multiplied by the corresponding Walsh code then low pass filtered. The OFDM demodulation is done by FFT. The demodulated received signal at the *j-th* receive antenna $\boldsymbol{r}_j$ can be decoded using ML detection by the space time decoder to generate an estimate of the signal $\tilde{S}$. The signal estimate $\tilde{S}$ is then detected by the MQAM/MPSK demodulator and converted from parallel to serial.

In this chapter, we will use Alamouti's scheme [1] for the 2 transmit antennas case while g_c^3 and g_c^4 general complex orthogonal STBCs introduced by Tarokh in [2] will be used for the 3 and 4 transmit antennas respectively.

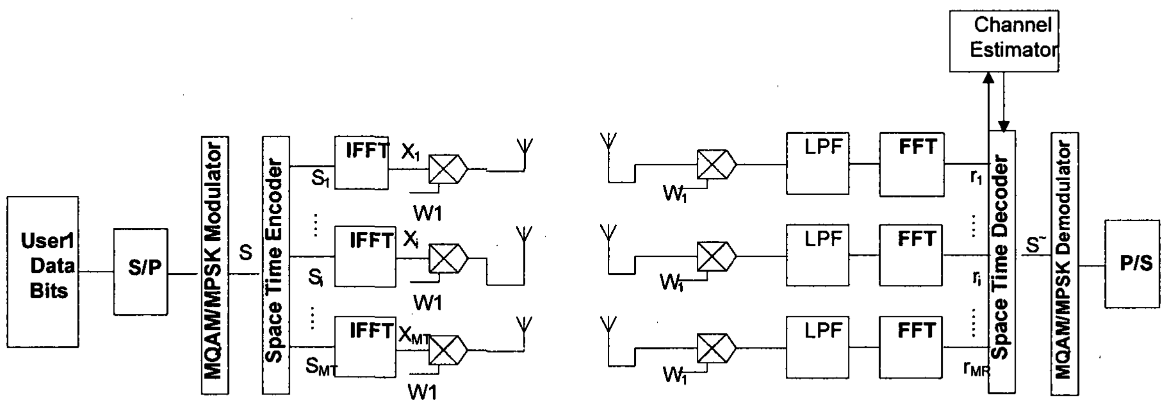

Figure 3.1 The proposed CDMA-SFBC Downlink system

3.3 SNR Analysis of the Downlink CDMA-SFBC System

For the two transmit antenna case we will use the STBC proposed by Alamouti in [1]. At the receiver, the received signals will be de-spread by being multiplied by the corresponding Walsh code. After low pass filtering, OFDM demodulation is performed by FFT. The demodulated received signals at the *j-th* receive antenna can be expressed as:

$$r_j(2k) = \gamma_{j,1}(2k)s(2k) + \sum_{u=2}^{U} \zeta_{1u}(t)\gamma_{j,1}(2k)s_u(2k) + \gamma_{j,2}(2k)s(2k+1) + \sum_{u=2}^{U} \zeta_{1u}(t)\gamma_{j,2}(2k)s_u(2k+1) + W_j(2k) \quad (3.1)$$

$$r_j(2k+1) = -\gamma_{j,1}(2k)s^*(2k+1) - \sum_{u=2}^{U} \zeta_{1u}(t)\gamma_{j,1}(2k)s_u^*(2k+1) + \gamma_{j,2}(2k)s^*(2k) + \sum_{u=2}^{U} \zeta_{1u}(t)\gamma_{j,2}(2k)s_u^*(2k) + W_j(2k+1) \quad (3.2)$$

In (3.1) and (3.2), $\gamma_{j,i}(k)$ is the DFT of the Rayleigh channel coefficient between the i-th transmit and the j-th receive antennas of the intended user which is assumed here to be the first user. The fading channels are assumed to be quasi static Rayleigh fading channels which means that the channels do not change within one OFDM block and hence $\gamma_{j,i}(2k) = \gamma_{j,i}(2k+1)$ for $0 \leq k \leq F-1$. W_j is a Gaussian random variable that represents the DFT of the AWGN at receive antenna j after being multiplied by the intended user code and low pass filtered. W_j has zero mean and a variance of σ_n^2. The random variable $\zeta_{1u}(t)$ represents the multiplication of the intended user's Walsh code (w_1) by that of the u-th user i.e. $\zeta_{1u}(t) = w_1(t)w_u(t)$.The first and third terms on the right hand side of (3.1) & (3.2) are the contributions of the intended user's data while the second and fourth terms are the contributions of all other users' data and the last term is the contribution of the AWGN. In (3.1) & (3.2) we notice the absence of multipath from intended signal and all MAI signals which can be justified by the fact that the cyclic prefix is larger than the maximum delay spread of the channel [8].

We assume that the orthogonality of the Walsh code stays intact which can be justified by the fact that the use of OFDM cancelled all multipath signals of all MAI and intended signals. The above assumptions cancel the MAI effects i.e. $\zeta_{1u}(t) = w_1(t)w_u(t) = 0$ and so (3.1) and (3.2) can be rewritten as:

$$r_j(2k) = \gamma_{j,1}(2k)s(2k) + \gamma_{j,2}(2k)s(2k+1) + W_j(2k) \tag{3.3}$$

$$r_j(2k+1) = -\gamma_{j,1}(2k)s^*(2k+1) + \gamma_{j,2}(2k)s^*(2k) + W_j(2k+1) \tag{3.4}$$

ML detection can be used for the SFBC decoding of the received signal and the information can be extracted as:

$$\tilde{s}(2k) = \sum_{j=1}^{M_R} \left(\gamma_{j,1}^*(2k) + \epsilon_{j,1}^*(2k)\right) r_j(2k) + \left(\gamma_{j,2}(2k) + \epsilon_{j,2}(2k)\right) r_j^*(2k+1) \tag{3.5}$$

$\epsilon_{j,i}$ is the estimation error of the intended user channel between the *i-th* transmit and the *j-th* receive antennas which are assumed to be independent and identically distributed random variables with zero mean and a variance of σ_e^2. After substituting (3.3) & (3.4) in (3.5) the detected signal can be expressed as:

$$\tilde{s}(2k) = \sum_{j=1}^{M_R} \Big(s(2k)\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right) + s(2k)\left(\epsilon_{j,1}^*(2k)\gamma_{j,1}(2k) + \epsilon_{j,2}\gamma_{j,2}^*(2k)\right) + s(2k+1)\left(\epsilon_{j,1}^*(2k)\gamma_{j,2}(2k) - \epsilon_{j,2}(2k)\gamma_{j,1}^*(2k)\right) + \gamma_{j,1}^*(2k)W_j(2k) + \gamma_{j,2}(2k)W_j^*(2k+1)\Big) \tag{3.6}$$

At this point we will write $\tilde{s}(2k) = A(2k) + B(2k)$ where $A(2k)$ is the useful signal of the intended user and $B(2k)$ is the AWGN contribution.

$$A(2k) = \sum_{j=1}^{M_R} s(2k)\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right) \tag{3.7}$$

$$B(2k) = \sum_{j=1}^{M_R} s(2k)\left(\epsilon_{j,1}^{*}(2k)\gamma_{j,1}(2k) + \epsilon_{j,2}\gamma_{j,2}^{*}(2k)\right) + \sum_{j=1}^{M_R} s(2k+1)\left(\epsilon_{j,1}^{*}(2k)\gamma_{j,2}(2k) - \epsilon_{j,2}(2k)\gamma_{j,1}^{*}(2k)\right) + \sum_{j=1}^{M_R} W_j(2k)\gamma_{j,1}^{*}(2k) + \sum_{j=1}^{M_R} W_j^{*}(2k+1)\gamma_{j,2}(2k) \qquad (3.8)$$

In order to find the signal to noise ratio we need to need to find the power of $A(2k)$ and that of $B(2k)$. The power of $A(2k)$ can be found by calculating its variance which can be expressed as:

$$Var(A(2k)) = P_s\left(\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right)\right)^2 \qquad (3.9)$$

P_s is the symbol power at the transmitter. The power of the noise can be found by calculating the variance of $B(2k)$ which can be expressed as:

$$Var(B(2k)) = 2P_s\sigma_e^2\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right) + \sigma_n^2\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right) \qquad (3.10)$$

and the SNR can be expressed as:

$$SNR = \frac{P_s\left(\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right)\right)^2}{M_T\left(P_s\sigma_e^2\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right) + \sigma_n^2\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2 + |\gamma_{j,2}(2k)|^2\right)\right)} \qquad (3.11)$$

In (3.11) the symbol power is normalized to the number of transmit antennas M_T to make sure that the total power transmitted is independent of the number of transmit antennas. By further reduction (3.11) can be written as:

$$SNR = \frac{\eta_s\left(\sum_{j=1}^{M_R}\left(|\gamma_{j,1}(2k)|^2+|\gamma_{j,2}(2k)|^2\right)\right)}{M_T(\eta_s\sigma_e^2+1)} \tag{3.12}$$

where $\eta_s = \frac{P_s}{\sigma_n^2}$

For the downlink uncoded SISO-CDMA-OFDM and after de-spreading, low pass filtering and FFT, the demodulated receive signal can be expressed as:

$$r(k) = \gamma_1(k)S(k) + W(k) \tag{3.13}$$

and the detected signal can be expressed as:

$$\tilde{S}(k) = \left(\gamma_1^*(k) + \epsilon_1^*(k)\right)r(k) \tag{3.14}$$

by analysis similar to the one we did for the downlink with two transmit antennas we find the SNR to be $NR[k] = \frac{\eta_s|\gamma_1(k)|^2}{\eta_s\sigma_e^2+1}$.

For the downlink uncoded CDMA-OFDM with one transmit and multiple receive antennas and after de-spreading, low pass filtering and FFT, the demodulated receive signal at the j-th receive antenna can be expressed as

$$r_j(k) = C_1 w_1 \gamma_j(k)S(k) + W_j(k) \tag{3.15}$$

and the detected signal can be expressed as:

$$\tilde{S}(k) = \sum_{j=1}^{M_R}\left(\gamma_j^*(k) + \epsilon_j^*(k)\right)r_j(k) \tag{3.16}$$

and by analysis similar to the SISO downlink system we find the SNR to be $NR[k] = \frac{\eta_s\sum_{j=1}^{M_R}|\gamma_i(k)|^2}{\eta_s\sigma_e^2+1}$.

3.4 BER Performance of the Downlink CDMA-SFBC MQAM System

Assuming MQAM modulation and grey bit mapping with $M=2^b$ where b is the number of bits/symbol. The expression for the instantaneous BER of the *k-th* sub-channel can be expressed as in [64] by:

$$BER_{MQAM}[2k] = \frac{2\left(1-\frac{1}{\sqrt{2^b}}\right)}{b} erfc\left(\sqrt{\frac{1.5SNR[2k]}{2^b-1}}\right) \tag{3.17}$$

For our purposes we will use the exponential approximation defined in [65]. So the expression in (3.17) can be approximated as in [66, 67] by:

$$BER_{MQAM}[2k] = 0.2exp\left(\frac{-1.6SNR[2k]}{2^b-1}\right) \tag{3.18}$$

The average BER can be obtained by integrating over the probability density function of the SNR denoted by η then summing the *k-th* result over all sub-channels and dividing by L as:

$$\overline{BER}_{MQAM} = \frac{1}{L}\sum_{k=0}^{L-1}\int_0^{\infty} \dots \int_0^{\infty} BER_{MQAM}[k]P(\eta_{1,1}) \dots . P(\eta_{M_T,M_R})d\eta_{1,1} \dots d\eta_{M_T,M_R} \tag{3.19}$$

where $\eta_{i,j}$ is the instantaneous SNR of the channel between the *i-th* transmit and the *j-th* receive antennas. For the two transmit antennas case it can be expressed as:

$$SNR[2k] = \frac{\eta_s \sum_{i=1}^{M_T}\sum_{j=1}^{M_R}|\gamma_{j,i}|^2}{M_T(\eta_s\sigma_e^2+1)} \tag{3.20}$$

Since $|\gamma_{j,i}|$ is Rayleigh distributed with variance one then $|\gamma_{j,i}|^2$ has a chi-square pdf with two degrees of freedom. Therefore η which is the instantaneous SNR is chi-square distributed i.e.

$$P(\eta) = \frac{1}{\bar{\eta}} exp\left(\frac{-\eta}{\bar{\eta}}\right), \ \ \eta > 0 \tag{3.21}$$

where

$$\bar{\eta} = E(\eta) = \frac{\eta_s}{M_T(\eta_s\sigma_e^2+1)} \tag{3.22}$$

Substituting (3.22) into (3.21) and (3.20) into (3.18) and using these results in (3.19) while noting that each term of the summation over k in (3.19) is not a function of k yields the BER expression i.e.

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{1.6\eta_s}{M_T R_c(2^b-1)(\eta_s\sigma_e^2+1)}\right)^{-M_T M_R} \tag{3.23}$$

For the three and four transmit antennas the same result in (3.23) can be used to calculate the BER of the MQAM system as shown in Appendix C and Appendix D using the right values for R_c, M_T and M_R.

Similarly, we can find the BER of the MQAM SISO-CDMA-OFDM system as:

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{1.6\eta_s}{(2^b-1)(\eta_s\sigma_e^2+1)}\right)^{-1} \tag{3.24}$$

and for the system with one transmit antenna and multiple receive antennas the BER of the MQAM system is:

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{1.6\eta_s}{(2^b-1)(\eta_s\sigma_e^2+1)}\right)^{-M_R} \tag{3.25}$$

3.5 BER Performance of the Downlink CDMA-SFBC MPSK System

Using the same approach that we used for the MQAM system, the BER of the CDMA-SFBC system can be approximated as in [66] by:

$$BER_{MPSK} = \frac{0.2}{L} \sum_{k=0}^{L} exp\left(\frac{-7SNR[k]}{2^{1.9b}+1}\right) \tag{3.26}$$

but for our purpose we take first the k-th term which is $BER_{MPSK}[k] = 0.2exp\left(\frac{-7SNR[k]}{2^{1.9b}+1}\right)$ and following the same steps that led to (3.23) and noting that the average BER is independent of k then the average BER can be expressed as:

$$\overline{BER}_{MPSK} = 0.2\left(1 + \frac{7\eta_s}{M_T(2^{1.9b}+1)(\eta_s\sigma_e^2+1)}\right)^{-M_T M_R} \tag{3.27}$$

For the three and four transmit antennas the same result in (3.27) can be used to calculate the BER of the MPSK system as shown in Appendix C and Appendix D using the right values for R_c, M_T and M_R.

Similarly, we can find the BER of the MPSK SISO-CDMA-OFDM system as:

$$\overline{BER}_{MPSK} = 0.2\left(1 + \frac{7\eta_s}{(2^{1.9b}+1)(\eta_s\sigma_e^2+1)}\right)^{-1} \tag{3.28}$$

and for the system with one transmit antenna and multiple receive antennas the BER of the MPSK system is:

$$\overline{BER}_{MPSK} = 0.2\left(1 + \frac{7\eta_s}{(2^{1.9b}+1)(\eta_s\sigma_e^2+1)}\right)^{-M_R} \tag{3.29}$$

3.6 Results and Discussions

The performance of the proposed CDMA-SFBC system is compared to that of the CMMSE STBC-CDMA receiver proposed in [9] as shown in Figure 3.2. The proposed CDMA-SFBC system shows improvement in BER performance over the CMMSE receiver. This BER improvement can be explained by the fact that the utilization of OFDM with cyclic prefix larger than the maximum delay spread of the channel in the proposed system cancels the ISI and multipath interference which the CMMSE receiver suffers from.

The performance of the proposed downlink CDMA-SFBC system is investigated by numerically evaluating the derived closed form expressions. The BER performance is evaluated for different STBCs and different number of transmit and receive antennas. We evaluated the BER performance using different modulation schemes and under a wide range of values for the channel estimation error variance. The resulting downlink performances are depicted in Figures 3.3 to 3.8. Figures 3.3 to 3.6 for the downlink systems show that the BER performance improves with increasing η_s and decreasing channel estimation error variance σ_e^2. We also note the floor versus η_s which is due to σ_e^2. For these figures we see that in general receive antenna diversity has better BER performance than transmit diversity for the same diversity gain. In Figure 3.6 we see that increasing σ_e^2 from .01 to .05 at η_s of 15 dB will degrade the BER of the 4Tx2Rx downlink system from approximately 5×10^{-8} to 5×10^{-6} which is a great increase in the BER. Figure 3.7 shows the degrading effect of σ_e^2 with the 1Tx4Rx system providing better resistance to σ_e^2. Figure 3.8 shows that the BER performance degrades with increasing the size of modulation alphabet. It also shows that under the same amounts of σ_e^2 and η_s and only changing the alphabet size, all systems have almost the same BER performance for $M \geq 32$.

3.7 Conclusion

In this chapter we proposed a novel CDMA-SFBC system for downlink transmission. Closed form expressions for the BER of the proposed system were derived assuming quasi static Rayleigh fading channels. The expressions were derived for both MQAM and MPSK modulation schemes and for different STBCs. The derived expressions were evaluated for a wide range of channel estimation error variance. It was generally observed that BER degrades with the channel estimation error and the size of modulation alphabet. Also, we noticed the existence of floors of BER due to channel estimation errors. The proposed system can provide a noticeable performance improvement over the constrained minimum mean square error receiver for STBC-CDMA systems.

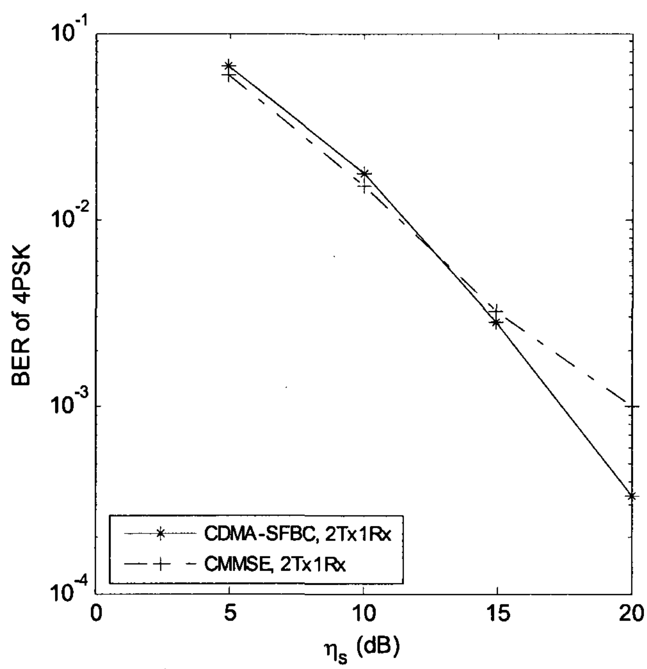

Figure 3.2 Comparison between CDMA-SFBC and CMMSE downlink BER performances

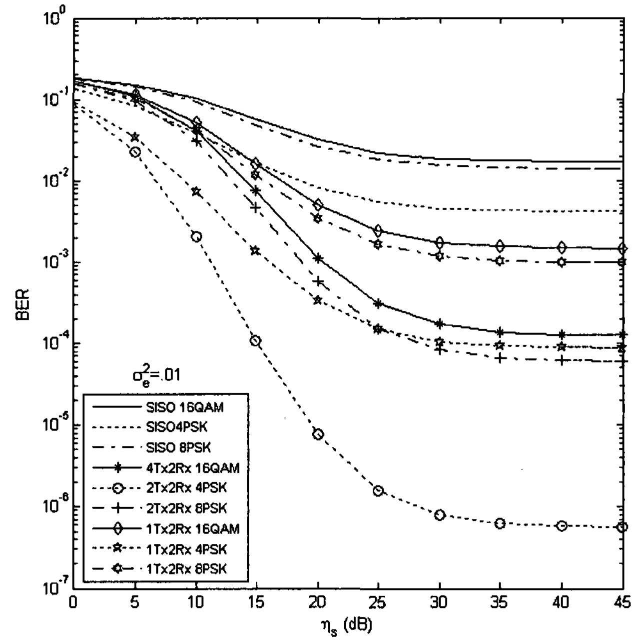

Figure 3.3 Effects of different modulation techniques on downlink BER

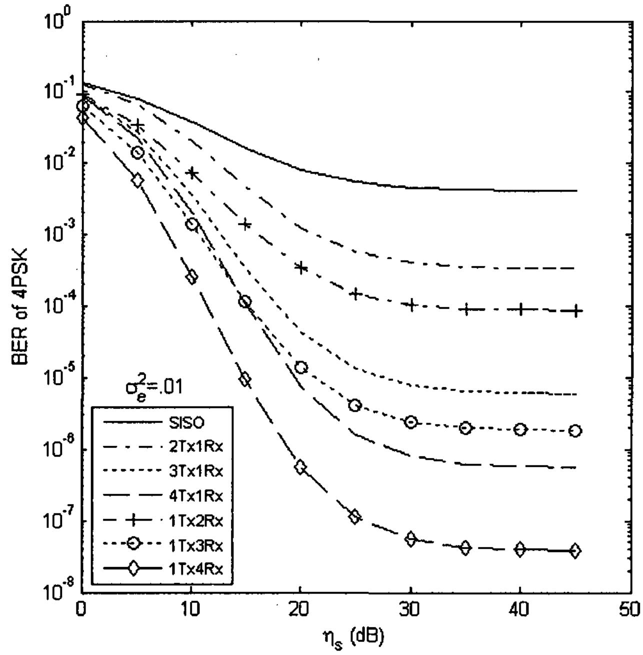

Figure 3.4 Effects of number of transmit antennas on downlink BER

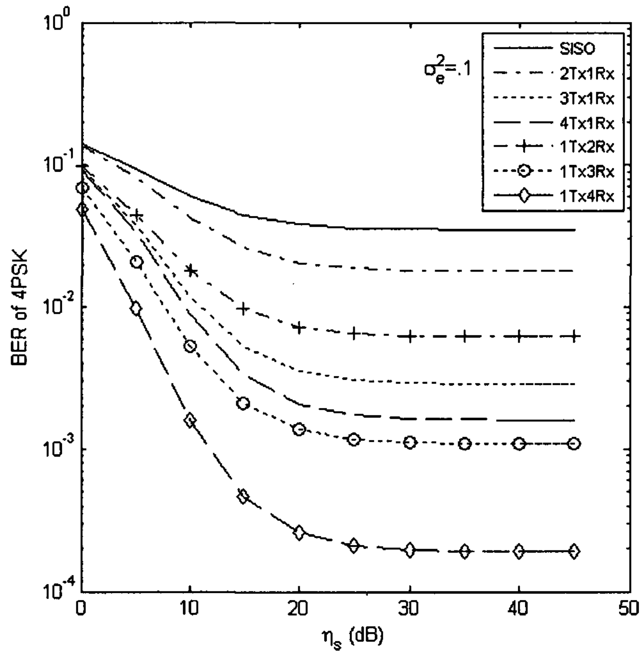

Figure 3.5 BER of downlink with different antenna configurations

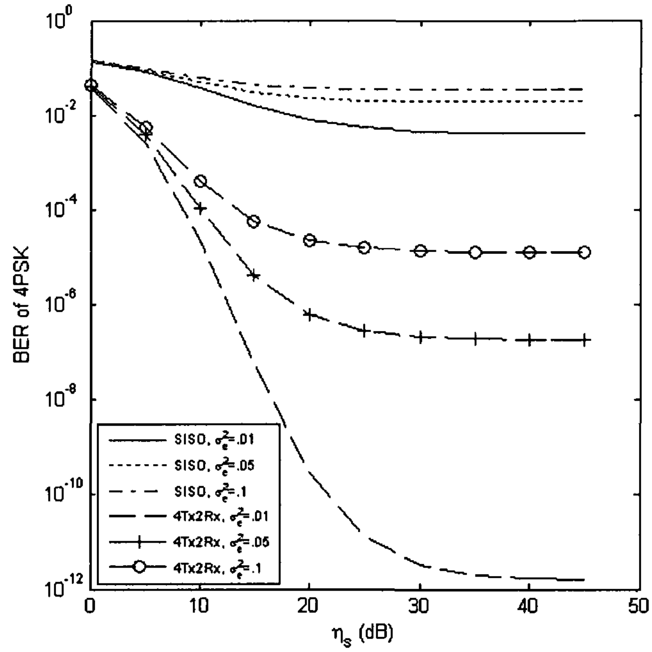

Figure 3.6 BER versus symbol to thermal noise ratio for different values of channel estimation error variance

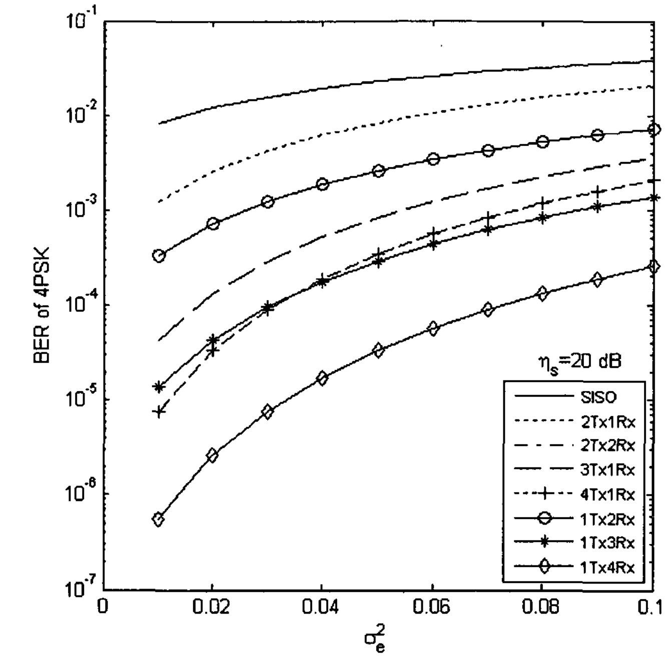

Figure 3.7 BER as a function of channel estimation error variance

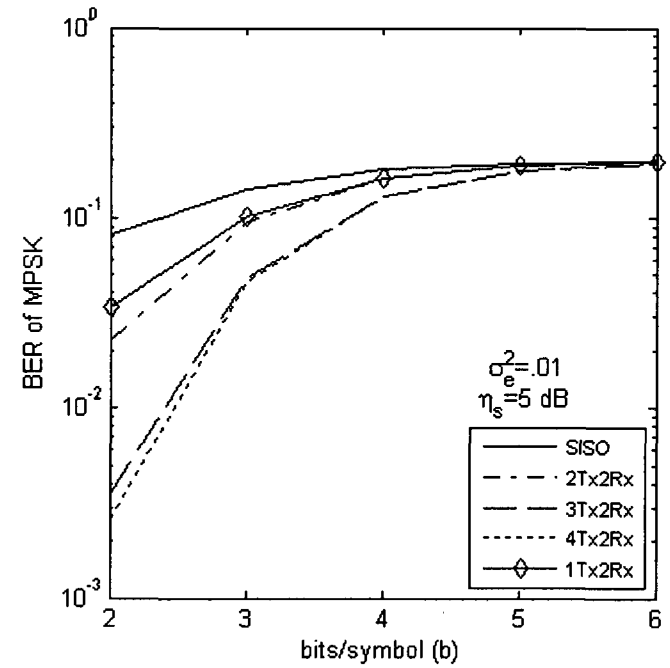

Figure 3.8 Effects of number of bits per symbol on downlink BER

Chapter 4: Optimized Resource Allocation Algorithm for Uplink CDMA-SFBC Systems

4.1 Introduction

The increasing demand for high speed reliable wireless networks and the scarcity of radio resources make the efficient use of radio resources necessary. In order to efficiently assign the available radio resources to users in uplink CDMA-SFBC wireless star networks, it is necessary to jointly optimize the performance of the physical and MAC layers in a cross layer fashion.

In [44], the authors proposed a scheme that assigns OFDM tones and antenna elements to users in downlink SDMA system to reduce the pair wise cross correlation between the users and improve the system performance. Although their scheme showed improvement in BER it cannot be used in uplink systems because it is very hard to form a beam from the MS to the BS. Also, their scheme allowed the user to be connected to multiple geographically separated antenna arrays which can lead to synchronization problems. Another limiting factor of this scheme is that the number of BS antennas should be large compared to the total number of users' antennas which limits the number of users that can be served.

In [45] the authors proposed a sub carrier allocation scheme for OFDM-CDMA systems that maximizes throughput while minimizing the scheduling delay. However, they assumed only one BTS with one antenna array which may suffer from near far problems.

In this Chapter and based on the results of Chapter 2, we utilize the BER expressions in a cross layer fashion to propose a resource allocation algorithm for uplink CDMA-SFBC systems in multi point to single point networks i.e. star networks. The resource allocation algorithm assigns appropriate base transceiver station, antenna array sub system and frequency subcarrier blocks to users such that the pair wise channel cross correlation between users is minimized while selecting the channel with the maximum coherence time for each user. The intermediate effects of the resource optimization algorithm such as reduction of the channel estimation error and higher signal powers culminate into more cost effective MIMO operation. The proposed algorithm shows a noticeable improvement in the bit error rate of the users and the bandwidth efficiency of the system compared to random resource allocation. The underlying cooperation of the physical, MAC and higher layers that gives rise to such optimization and improvement is an example of the versatility of cross layer design.

The rest of this chapter is organized as follows. Section 4.2 presents the system model. The resource allocation algorithm is presented in Section 4.3. Results are provided in Section 4.4 and Section 4.5 concludes the chapter.

4.2 System Model

The system consists of a central BS connected through fiber optic cables to a number of BTS stations assumed herein to be four without losing generality. Each BTS has m antenna arrays, in each antenna array there are p receive antennas. The mobile station has n transmit antennas as in Figure 4.1. In this chapter we will use n=2 but the expansion to more transmit antennas is straight forward. The fading channel between any transmit antenna of the MS and any receive antenna of the BTSs is assumed to be a quasi static Rayleigh fading channel which means the channel remains fixed during the transmission of one block of data. The channels between the different transmit and receive antennas of the same user are considered independent. The $n \times p$ time domain channel matrix between the user transmit antennas and any receive sub-array is represented by $G=PL\beta T$ where PL is the path loss between the user antennas and the receive array as defined by IEEE C802.20-03/70 [68]. For vehicular test environments the mean path loss is defined by:

$$PL = 40(1 - .004 \cdot \Delta h_b) \log_{10} R - 18 \log_{10} \Delta h_b + 21 \log_{10} f + 80 \tag{4.1}$$

where PL is the path loss in dB, Δh_b is the base station antenna height in meters, measured from average rooftop level and f is the carrier frequency in MHz. β is the shadow fading loss component which for vehicular test environments can be modeled as a log-normal random variable with zero mean and variance 10dB in both urban and sub-urban environments. T is a $n \times p$ matrix with complex Gaussian random entries of zero mean and a variance of 1. No perfect CSI is assumed; receiver always estimates channel coefficients with a certain error.

Each link is assumed to be equipped with an uplink CDMA-SFBC system as discussed in Chapter 2 and shown in Figure 2.1. The transmitter is assumed to be at the MS while the receiver is at the BS.

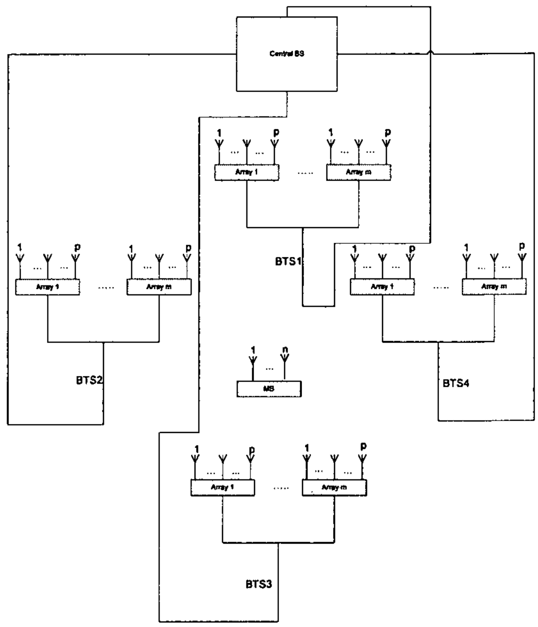

Figure 4.1 Cell configuration

4.3 Resource Allocation Algorithm

The resource allocation algorithm assigns antenna arrays and frequency blocks to users based on their locations such that the cross correlation between the users' channels is minimized while selecting the channel with the maximum coherence time for each user. Selecting the channel with the maximum coherence time allows more accurate channel estimation plus the ability to send larger data packets on good selected channels as executed by the optimization algorithm. Minimizing the cross correlation between the channels of different users will improve the BER. The user is assumed to be able to connect to only one BTS, one antenna array and one frequency block at any time. This assumption will save us the synchronization and data collection problems that may arise if the user is allowed to be connected to more than one BTS at the same time. The channels of any two users are assumed to be correlated only if they are connected to the same BTS, same antenna array and same frequency block simultaneously. The cross correlation between any two users sharing the same resources can be calculated using the Pearson product moment correlation i.e.

$$\rho(i,j,k,l,o) = \frac{\sum_n \sum_p \left([H(i,k,l,o)]_{np} - \bar{H}(i,k,l,o)\right)\left([H(j,k,l,o)]_{np} - \bar{H}(j,k,l,o)\right)}{\sqrt{\left(\sum_n \sum_p \left([H(i,k,l,o)]_{np} - \bar{H}(i,k,l,o)\right)^2\right)\left(\sum_n \sum_p \left([H(j,k,l,o)]_{np} - \bar{H}(j,k,l,o)\right)^2\right)}} \tag{4.2}$$

$H(i,k,l,o)$ is the discrete Fourier transform of the time channel matrix of the *i-th* user connected to the *k-th* BTS, the *l-th* antenna array and the *o-th* frequency block. $[H(i,k,l,o)]_{np}$ is the n, *p-th* element of the H matrix and $\bar{H}$ is the mean of the entries of H. At this point we notice the normalizing presence of users' channels in the denominator of (4.2). This implies that minimizing the cross correlation between the users' channels will inherently maximize the users' channels and hence have more received signal powers.

Each user transmits isotropically a small pilot signal which is received and processed by all antenna arrays of all BTSs. The channel between the mobile station and each antenna array is estimated from such pilot signal. The larger is the coherence time over certain channel the more stable such measurements will be and less channel estimation errors will be obtained. Also, the wideband channel quality in terms of pilot power measured, is directly used in the normalization of the cross correlation as in (4.2).

The resource allocation algorithm (assumed at the MAC entity) is supplied with information from higher layers in regard to user's location. Users could have GPS entity within or utilize other location techniques. Subsequently, the resource allocation algorithm will compute in real time all users' channels cross correlation. The users cross correlation is dependent on their locations which determine their path losses and subsequently their channel coefficients. On top, the physical layer will supply the MAC layer with users' channels estimates. Such processes constitute instances of cross layer design.

To select the channel with the maximum coherence time and to minimize the cross correlation between the channels of different users, we define the cost function as:

min:

$$\sum_{i=1}^{U-1}\sum_{j>i}^{U}\sum_{k=1}^{Z}\sum_{l=1}^{m}\sum_{o=0}^{F-1} \alpha x(i,k,l,o)\rho(i,j,k,l,o)x(j,k,l,o)+\gamma\frac{x(i,k,l,o)}{\tau(i,k,l,o)} \tag{4.3}$$

Subject to:

$$\sum_{k=1}^{S}\sum_{l=1}^{m}\sum_{o=1}^{F} x(i,k,l,o)=1 \text{ for any user } i=1 \dots U \tag{4.4}$$

$$x(i,k,l,o)=1 \; or \; 0 \quad \text{for any } i,k,l \; and \; o \tag{4.5}$$

Where Z is the number of BTSs and F is the total number of OFDM available blocks which is equal to the total number of OFDM tones divided by the number of tones per block assigned to each user. $\tau(i,k,l,o)$ is the coherence time of the i-th user connected to the k-th BTS, the l-th antenna array and the o-th frequency block. τ is modeled as a normal random variable with a mean and standard deviation equal to the inverse of the maximum Doppler frequency. x is a binary control variable (the optimization parameter). The constraint in (4.4) means that any user can be connected only to one BTS, one antenna array and one frequency block at a time. The constraint in (4.5) means that the control variable x is a binary variable with possible values of only 1 or 0. If $x(i,k,l,o)=1$ that means the i-th user is connected to the k-th BTS, the l-th antenna array and the o-th frequency block otherwise it is not connected to these resources. α and γ are non negative weight constants that will be used in the optimization cost function to indicate the importance of ρ and τ under the condition $\alpha + \gamma = 1$. There is a tradeoff in this assignment algorithm; we would like to assign as many users as possible to the same resources while on the other hand we want the cross correlation to be minimized between the different users. The optimization problem described in (4.3)-(4.5) is a nonlinear binary one. The non linearity comes from the multiplication of the assignment binary control variables of the different users ($x(i,k,l,o)$) by each other as shown in the cost function (4.3). Non linear binary optimization problems are difficult to solve and may lead to local optimal solutions. The optimization problem in (4.3)-(4.5) can be transformed into a linear form as in [69] by:

min:

$$\sum_{i=1}^{U-1}\sum_{j>i}^{U}\sum_{k=1}^{Z}\sum_{l=1}^{m}\sum_{o=0}^{F-1} \alpha v(i,j,k,l,o)\rho(i,j,k,l,o) + \gamma\frac{x(i,k,l,o)}{\tau(i,k,l,o)} \tag{4.6}$$

Subject to:

$$\sum_{k=1}^{S}\sum_{l=1}^{m}\sum_{o=1}^{F} x(i,k,l,o) = 1 \text{ for any user } i = 1 \ldots U \tag{4.7}$$

$$x(i,k,l,o) = 1 \; or \; 0 \quad \text{for any } i,k,l \; and \; o \tag{4.8}$$

$$x(i,k,l,o) + x(j,k,l,o) - 1 \le v(i,j,k,l,o) \tag{4.9}$$

$$v(i,j,k,l,o) \ge 0 \tag{4.10}$$

The optimization problem described in (4.6)-(4.10) is a linear integer programming (ILP) problem which can be solved by commercial optimization software.

Both cost functions in (4.3) and (4.6) are equivalent but with different representations. The constraints in (4.9) and (4.10) guarantee that the control variable $v(i,j,k,l,o)$ is equal to one only when each of $x(i,k,l,o)$, $x(j,k,l,o)$ is equal to one and zero otherwise.

The bandwidth efficiency μ of the system can be calculated using:

$$\mu = \frac{U \cdot b \cdot R_c (1-P_b)^a}{F \cdot CL} \tag{4.11}$$

where P_b is the average bit error probability obtained once optimization has been done and appropriate resources assigned to the users. U is the number of users, R_c is the STBC code rate, b is the number of bits per MPSK/MQAM symbol and CL is the spreading code length. The number of bits per packet is denoted by a. We also calculate μ for random cases where resources (BTS, antenna array and frequency block) are randomly assigned to users.

4.4 Results and Discussions

The optimization problem and the subsequent average BER were evaluated for a system that has one central BS, four BTS stations distributed uniformly around the circumference of the coverage area. The coverage area has a radius of 2 Km (only because of computational aspects). However, the resource allocation algorithm herein is straight forwardly applicable to larger cell sites. Each BTS has one antenna sub array and each sub array has two receive antennas. Sixteen consecutive OFDM tones divided into eight blocks of two tones are assumed. We used a carrier frequency of 2GHz and the BTS heights were assumed to be equal to 20 meters. A vehicular test environment with a maximum Doppler shift of 100 Hz was assumed. The results were evaluated for different number of users. The users were uniformly distributed in the coverage area and each user is equipped with two transmit antennas. Alamouti's simple transmit diversity was used for the STBC.

The results of BER were evaluated for QPSK modulation technique which is the technique of choice in many wireless communication standards. In Figures 4.2-4.6 a maximal length PN spreading code of length 128 is used. The relationship between the channel estimation error variance and the channel coherence time is assumed to be an inverse linear relationship with the channel estimation error variance between .001 and .01 and η_s is equal to 20 dB.

Figure 4.2 shows the average BER for both the random assignment of users and the optimized assignment based on intra user cross correlation only. The results show that the optimized assignment yields a better BER for the different number of users.

In Figure 4.3 a comparison was made between the BER performance of the random assignment and the assignment of users based on the optimization of the coherence time only. The results indicate that the coherence time is not the major contributor to the BER especially for a large number of users.

The optimized assignment of users based on cross correlation and coherence time together with $\alpha = \gamma = 0.5$ in Figure 4.4 gives better BER for the different number of users even when it is compared to Figure 4.2.

Figures 4.5 and 4.6 compare the BER performance of the optimized assignment of users with different combinations of α and γ. The results show that the BER improves with more weight given to intra user cross correlation without neglecting the coherence time especially for high number of users.

In Figures 4.7-4.11 a maximal length PN spreading code of length 128 is used. We change the relationship between the channel estimation error variance and the channel coherence time to be an inverse linear relationship with the channel estimation error variance between .01 and .1 and η_s is equal to 20 dB. Figures 4.7 and 4.8 show that none of the optimized assignments based on coherence time or cross correlation only can maintain good performance over different number of users. In Figure 4.7 we see that optimizing based on cross correlation only gives better results at high number of users while Figure 4.8 shows that the optimized assignment based on coherence time performs better at low number of users.

Figures 4.9-4.11 compare the BER performance of the system when the users are optimally assigned using different combinations of α and γ. Figure 4.11 shows that the optimized system BER performance based on τ only outperforms that of the system optimized based on τ and ρ with weights of 0.8 and 0.2 respectively when the number of users is less than 50 and the opposite is true when the number of users is greater than 50. This can be justified by the fact that when the number of users increases their total cross correlation increases to the point that where its contribution to the BER performance dominates the effect of channel estimation error. It can be seen from the results that the resources should be assigned taking into account both τ and ρ giving more weight for τ since the channel estimation error has larger variance compared to that used in Figures 4.2-4.6.

Figure 4.12 compares the BER performance of the system under random resource assignment and the optimized assignment based on equal weights for both τ and ρ. The performance is calculated for different number of BTSs. We assumed having one BTS at the center of the coverage area or more than one BTS equally spaced on the circumference of the coverage area. The results show a large improvement in the optimized performance as the number of BTSs increases.

The bandwidth efficiency of the system is depicted in Figures 4.13-4.15. Figure 4.13 shows that the bandwidth efficiency of the optimized system is superior to that with the resources randomly assigned. It also shows that the optimal number of users for the optimized system is 80 while the optimal number of users is 40 for the system with randomly assigned resources. This can be justified since the optimization algorithm assigns resources to users such that their pair wise cross correlation between the channels of different users is minimized and at the same time each user is assigned channels with the largest coherence time. This in turn will allow the system to accommodate more users with lower cross correlation and more precise channel estimation and hence a lower BER. The exponential decay of bandwidth efficiency with the number of bits per packet which can also be called maximum transmission unit (MTU) is shown in Figure 4.14. Figure 4.15 shows the improvement of bandwidth efficiency with the number of BTSs which can justify the cost of having 4 BTSs.

The results show that the use of SFBC-CDMA which provides users with time, frequency, space and code diversities coupled with the proposed resource allocation algorithm can be a promising candidate for fourth generation wireless networks.

4.5 Conclusion

In this chapter, we have proposed an optimized resource allocation algorithm for the uplink of SFBC-CDMA systems. The algorithm assigns the appropriate BTS, antenna array subsystem and OFDM tones to users such that the pair wise channel cross correlation between the users is minimized while each user is assigned channels with maximum coherence time. The results showed a noticeable improvement in the BER and the bandwidth efficiency of the system gained from the cross layer cooperation of the physical, MAC and higher layers (an instance of cross layer design). The algorithm can also be used to find the optimum number of users that the system can handle while maintaining the best bandwidth efficiency.

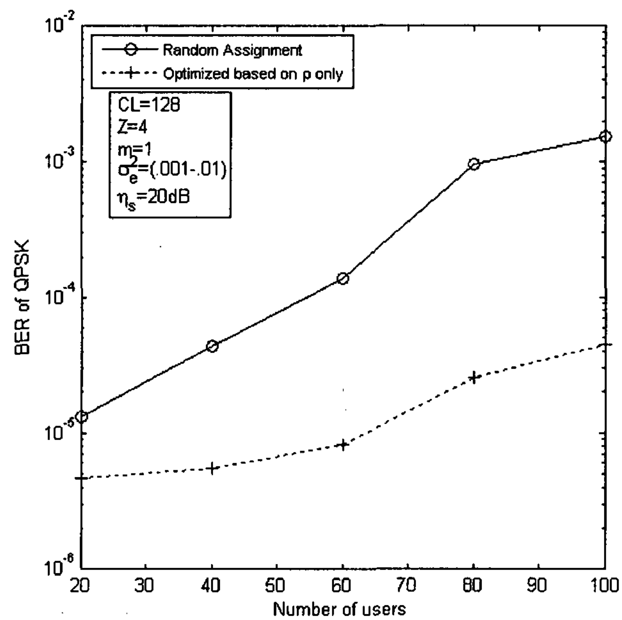

Figure 4.2 BER of random assignment and optimized assignment of resources based on cross correlation only

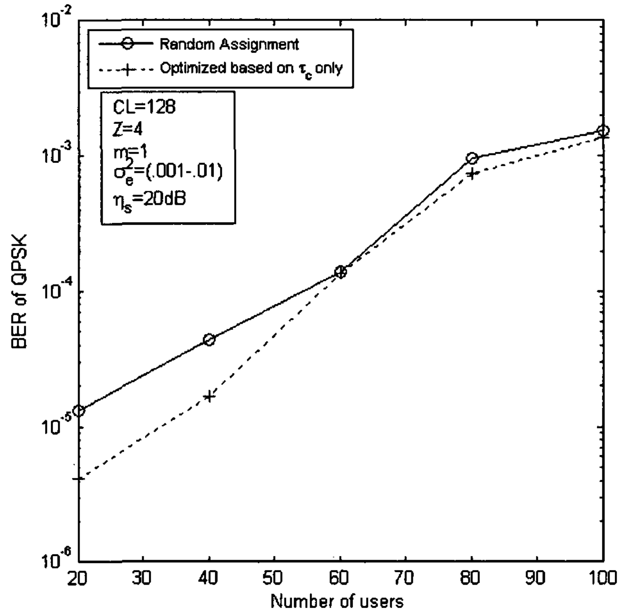

Figure 4.3 BER of random assignment and optimized assignment of resources based on coherence time only

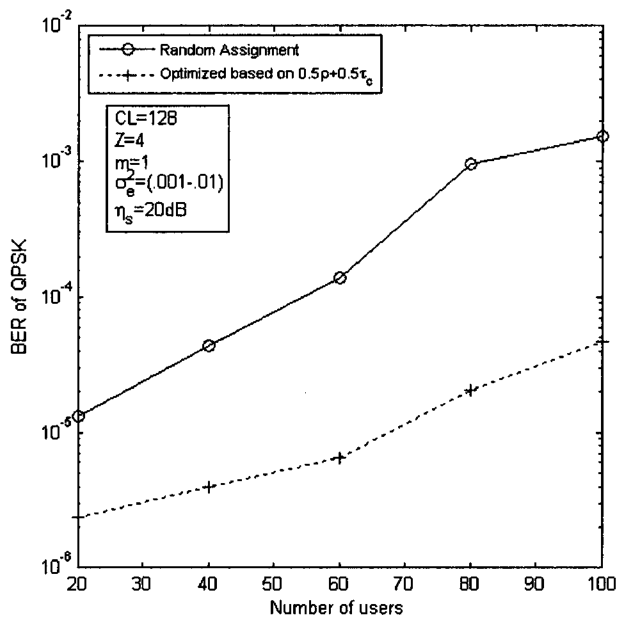

Figure 4.4 BER of random assignment and optimized assignment of resources based on cross correlation and coherence time with equal weights

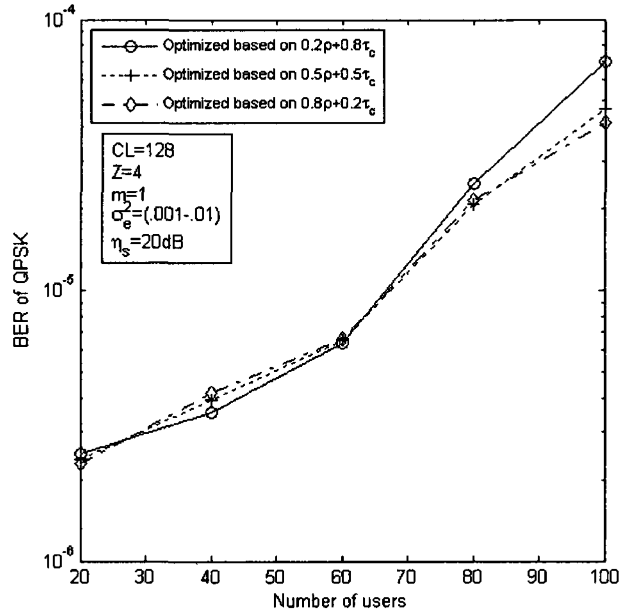

Figure 4.5 BER of optimized assignment of resources based on cross correlation and coherence time with different combination of weights

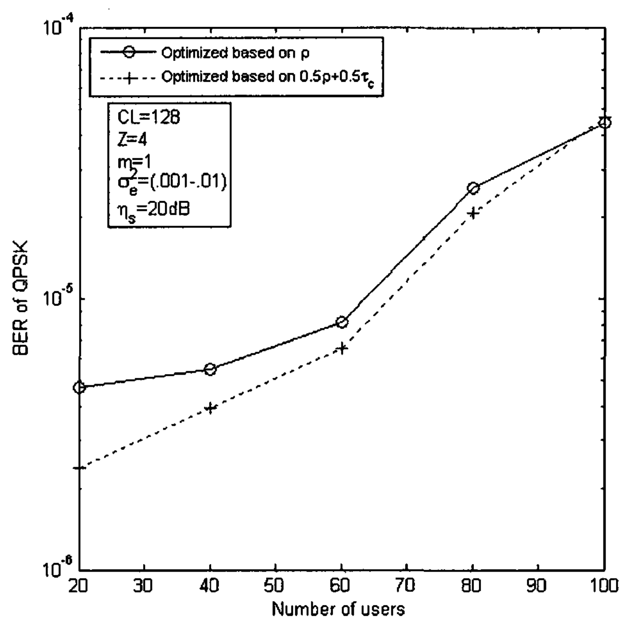

Figure 4.6 BER of optimized assignment of resources based on cross correlation only and based on cross correlation and coherence time together with equal weights

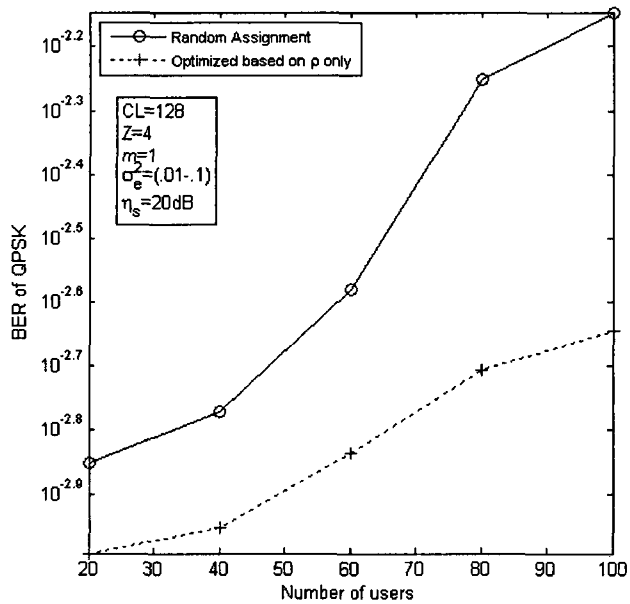

Figure 4.7 BER of random assignment and optimized assignment of resources based on cross correlation only

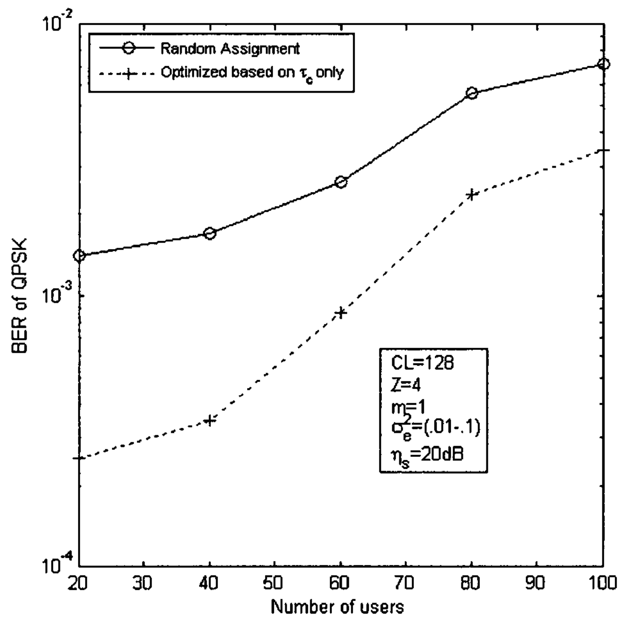

Figure 4.8 BER of random assignment and optimized assignment of resources based on coherence time only

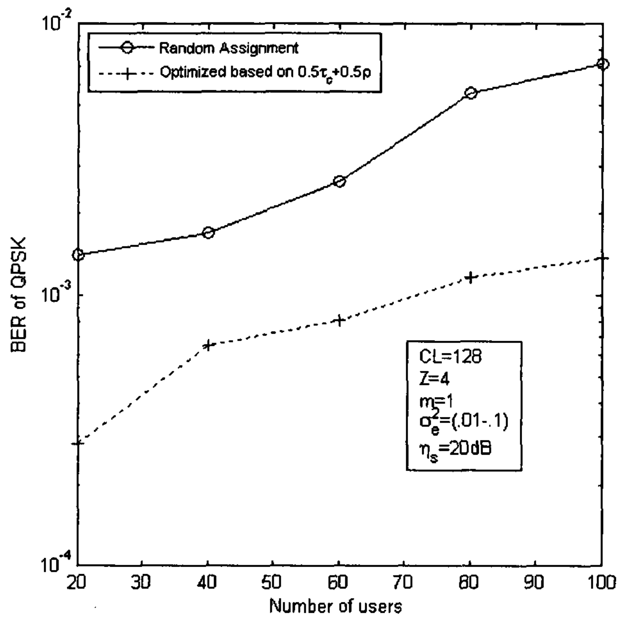

Figure 4.9 BER of random assignment and optimized assignment of resources based on cross correlation and coherence time with equal weights

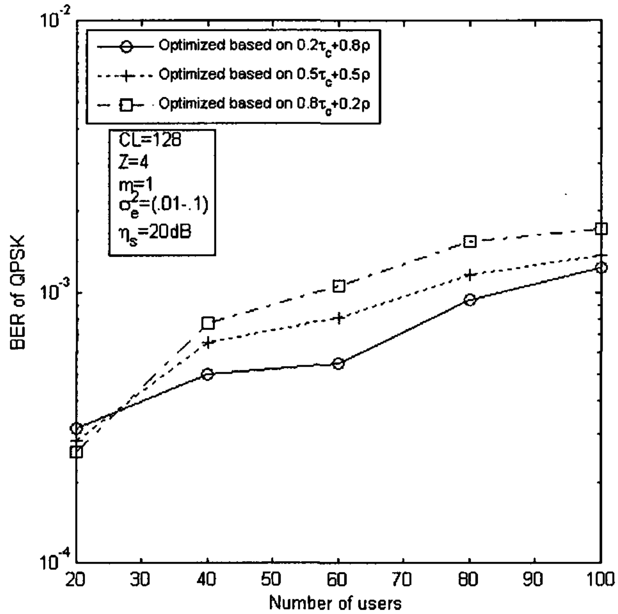

Figure 4.10 BER of optimized assignment of resources based on cross correlation and coherence time with different combination of weights

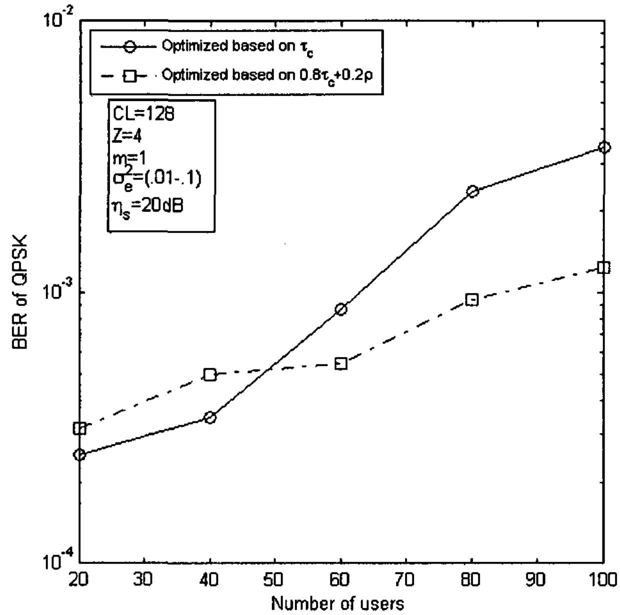

Figure 4.11 BER of optimized assignment of resources based on coherence time only and based on cross correlation and coherence time together with weights of 0.8 and 0.2 respectively

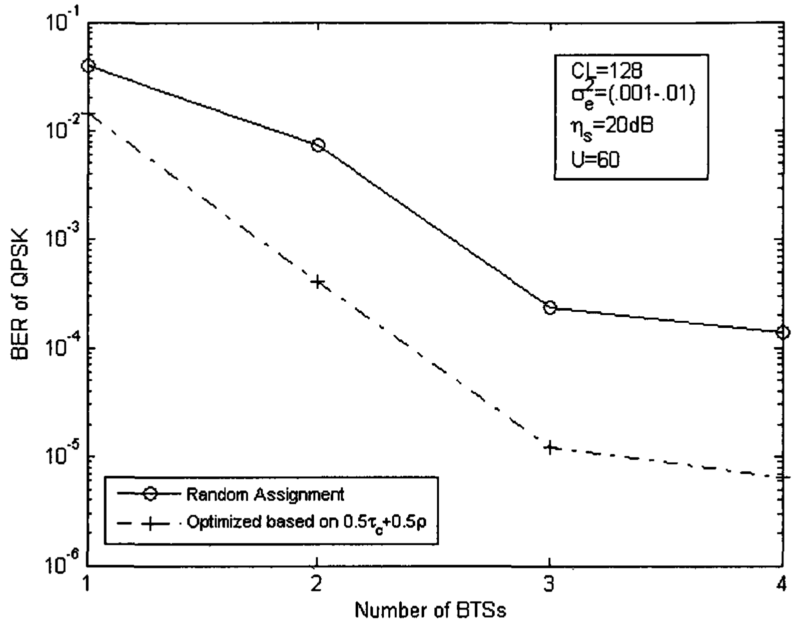

Figure 4.12 BER of random assignment and optimized assignment of resources based on cross correlation and coherence time with equal weights for different number of BTSs

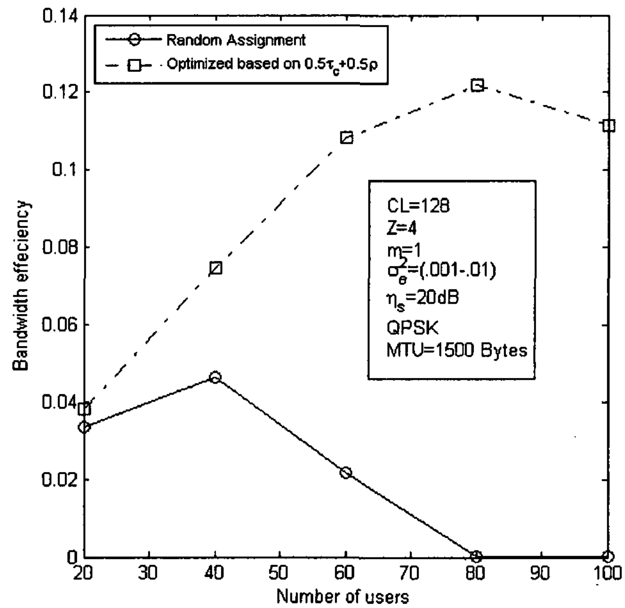

Figure 4.13 Bandwidth efficiency of random assignment and optimized assignment of resources based on cross correlation and coherence time with equal weights

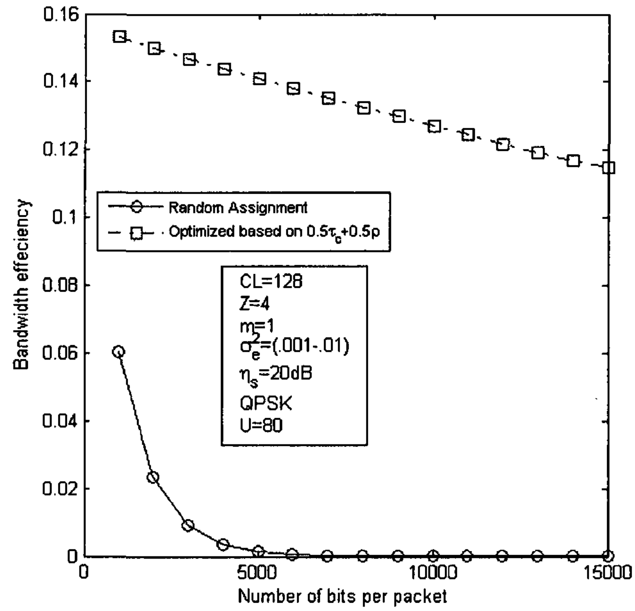

Figure 4.14 Bandwidth efficiency of random assignment and optimized assignment of resources based on cross correlation and coherence time with equal weights for different number of bits per packet

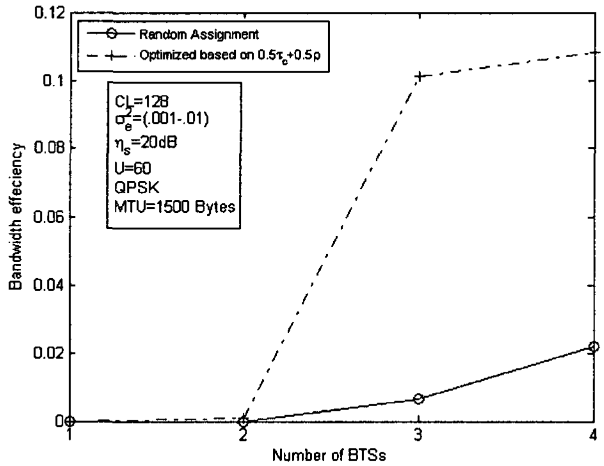

Figure 4.15 Bandwidth efficiency of random assignment and optimized assignment of resources based on cross correlation and coherence time with equal weights for different number of BTSs

Chapter 5: Joint Cross Layer Routing and Resource Allocation Algorithm for Multi Radio Wireless Mesh Networks

5.1 Introduction

Wireless mesh networks are gaining increased attention in the fourth generation (4G) wireless networks. Wireless mesh networks are scalable and easy to deploy. They can be used for last mile broadband wireless connectivity. Moreover, wireless mesh networks can be used to form a wide-area wireless back haul network. It is known that interference has a severe degrading effect on the capacity and performance of wireless mesh networks [70]. The use of multiple orthogonal channels reduces the interference and improves the capacity of wireless mesh networks [71]. Multiple channels can be implemented by using a single radio interface on each node that switches between different frequency bands to communicate with different neighbors. This however requires frequent channel switching overhead of an order comparable to packet transmission times. Another way is to use multiple radio interfaces each with different channel and dedicated to communicate with a specific node.

In order to utilize the available radio resources efficiently while providing network users with QoS measures like delay, delay jitter and packet success rate, the performance of the physical, MAC and network layers should be jointly optimized. This can be accomplished by incorporating routing and resource assignment decisions in a cross layer design.

A cross-layer tree-based interference aware routing that maximizes the throughput of wireless mesh network has been proposed in [51]. However, it assumes a centralized architecture in which a central BS collects bandwidth requests from SSs and allocates channels to links.

A joint routing and channel assignment algorithm for throughput optimization in multi radio wireless mesh networks has been proposed in [55]. However, the algorithm assumes that all radios on each node are assigned orthogonal channels. Furthermore, the algorithm does not quantify the quality of these orthogonal channels.

In this chapter, we utilize the results of chapters 2 and 4 to introduce a joint cross layer routing and channel assignment algorithm for multi radio backbone wireless mesh network. The channel assignment part assigns frequency bands to links such that the interference between those links is minimized while each link is assigned channels with maximum coherence time. The routing part selects the paths with the best end to end delay while avoiding links with high interference and short coherence time.

The rest of this chapter is organized as follows. Section 5.2 includes network architecture and physical link characterization. The proposed cross layer algorithm and its formulation are presented in Section 5.3. Performance measures are described in Section 5.4 and results are presented in Section 5.5. Finally, the chapter is concluded in Section 5.6.

5.2 Multi-Radio Wireless mesh Network Architecture

In this chapter we will assume that the wireless mesh network consists of a number of stationary wireless mesh routers. These wireless mesh routers have traffic aggregation capabilities and provide network connectivity to mobile users within their coverage areas. The wireless mesh routers form a backbone multihop wireless network and relay traffic to and from mobile users. Wireless mesh routers can also be connected to the wired internet and act as gateways. Each wireless mesh router is equipped with a number of interfaces (radios) equal to the number of its neighbors. Each radio is a CDMA-SFBC system as shown in Figure 2.1 where the transmitter has n transmit antennas and the receiver has p receive antennas. There are L frequency bands available and each radio is assigned one of those bands. Any two radios can directly communicate only if they are in each other's range of transmission. A link is defined as a communication channel between two neighboring routers. Both transmitting radio and receiving radio of a link should use the same frequency band. Two links of the same router or of a neighboring router interfere only if they are assigned the same frequency band. TDD operation is also assumed where the mesh routers are divided into groups. Routers in odd numbered groups can transmit in time slot one and receive in time slot two. Whereas routers in even numbered groups receive during time slot one and transmit in time slot two. This means that the transmission of routers in odd groups cannot interfere with the transmission of routers in even groups. This also means that nodes of the same group cannot communicate directly with each other since they will be either transmitting or receiving at the same time. We assumed an initial configuration phase where all nodes exchange Hello and other handshaking messages. Thus each node will have complete information about the topology, e.g. to which TDD group the node belongs, the identities of the immediate neighbors of the node and the identity of the master station. This master station is the station with the smallest ID and keeps the TDD slots in synch by transmitting periodically pilot signals which is beyond the scope of this thesis. The use of TDD reduces the overall interference in the network and simplifies the channel assignment problem. Figure 5.1 shows the original topology without TDD where the lines between the nodes indicate that the nodes can directly communicate with each other. Figure 5.2 shows the effective topology after TDD in which node 1 belongs to group 1, nodes 2,5,6,9 and 10 belong to group 2, nodes 3, 7 and 8 belong to group 3 and node 4 belongs to group 4. In the new effective topology shown in Figure 5.2 we notice the absence of some of the links that were shown in the original topology due to TDD operation. As an example, we note the deletion of links between nodes 2 and 6 due to TDD operation. Each link is assumed to have its own M/M/1 queue of received packets at the corresponding receive node.

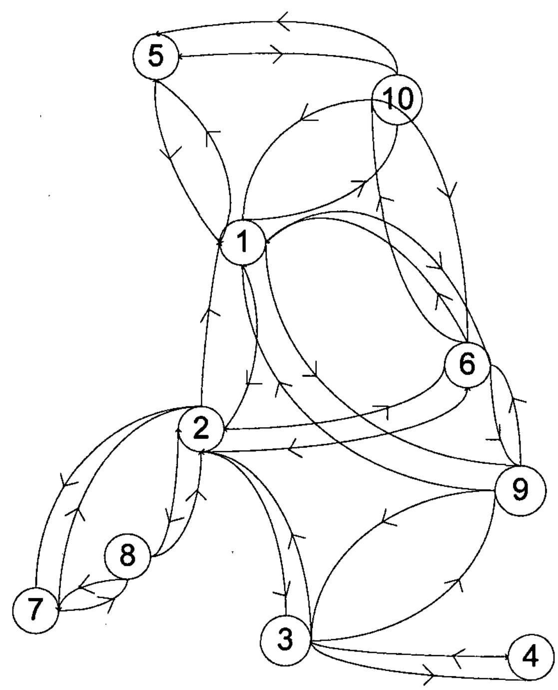

Figure 5.1 Original topology without TDD

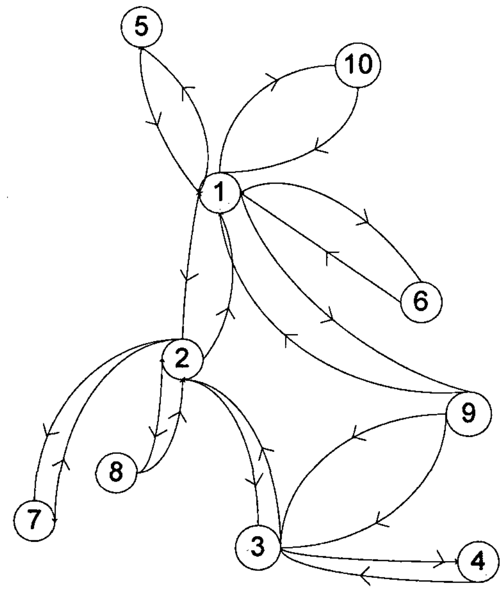

Figure 5.2 Effective topology after TDD

5.2.1 Physical link Characterization

The physical link between any two routers can be characterized by its own channel matrix. The fading channel between any transmit and receive antennas of a link is assumed to be a quasi static Rayleigh fading channel which means that the channel remains fixed for the duration of transmitting one block of data. The $n \times p$ time domain channel matrix between the transmit antenna array and the receive antenna array of a link is represented by G=$PL\beta T$ where PL is the path loss between the transmitting node antennas and the receiving node antennas as defined by [72]. β is the shadowing loss component which is assumed to be a lognormal random variable with zero mean and a variance of 10 dB. T is an $n \times p$ matrix with complex Gaussian random entries of zero mean and a variance of 1. No perfect CSI is assumed; receiver always estimates channel coefficients with a certain error.

At each node, the arrival of signals from different neighbors will be uncoordinated which makes it analogous to uplink transmission in the star oriented third generation (3G) cellular systems. Each node will behave as a BS while links from neighbors will behave as users of this BS. The average bit error rate for each link in uplink SFBC-CDMA systems has been derived in details in Chapter 2, i.e.

$$\overline{BER}_{MPSK} = 0.2\left[1 + \frac{7\eta_s}{R_c n(2^{1.9b}+1)(\eta_s\sigma_e^2 + np\eta_s\rho\sigma_{r_x}^2(U-1) + \sigma_{r_x}^2\sigma_e^2\eta_s(U-1)+1)}\right]^{-np} \quad (5.1)$$

where n is the number of transmit antennas, p is the number of receive antennas, R_c is the STBC code rate, b is the number of bits per symbol, σ_e^2 is the variance of channel estimation error, ρ is the normalized cross correlation between the channels of any two users, $\sigma_{r_x}^2$ is the spreading code cross correlation, U is the total number of interfering links at the intended receiving node and η_s is the symbol to AWGN noise power ratio at the transmitter normalized to the number of transmit antennas.

5.3 The Cross layer Routing and Channel Assignment Algorithm

The channel assignment part of the algorithm assigns frequency bands to links such that the cross correlation or the interference between the links (ρ) is minimized while selecting channels with maximum coherence time for each link. Selecting channels with maximum coherence time allows more accurate channel estimation (less σ_e^2) plus the ability to send larger data packets on good selected channels as executed by the optimization algorithm. Minimizing the cross correlation between links will increase the capacity of each link thus allowing more traffic flow to be accommodated on each link which affects routing. On top of that, the routing part of the algorithm selects a path for each call that minimizes the end to end packet delay and maximizes packet success rate. It achieves that by avoiding congested links with high interference level and short coherence time which in turn affects the channel assignment part. The cross correlation between any two links sharing the same frequency band can be calculated using the Pearson product moment correlation i.e.

$$\rho(i,j,k) = \frac{\sum_n \sum_p \left([H(i,k)]_{np} - \bar{H}(i,k)\right)\left([H(j,k)]_{np} - \bar{H}(j,k)\right)}{\sqrt{\left(\sum_n \sum_p \left([H(i,k)]_{np} - \bar{H}(i,k)\right)^2\right)\left(\sum_n \sum_p \left([H(j,k)]_{np} - \bar{H}(j,k)\right)^2\right)}} \tag{5.2}$$

$H(i,k)$ is the discrete Fourier transform of the time channel matrix of the *i-th* link assigned the *k-th* frequency block. $[H(i,k)]_{np}$ is the n, *p-th* element of the H matrix and $\bar{H}$ is the mean of the entries of H. At this point we notice the normalizing presence of channel powers in the denominator of (5.2). This implies that minimizing the cross correlation between the links will inherently maximize the powers of the links and hence have more received signal powers.

The Coherence time τ will be modeled as a normal random variable with a mean and a standard deviation equal to the inverse of the maximum Doppler frequency. An inverse linear relationship is assumed between the coherence time τ and the channel estimation error variance σ_e^2.

The cooperation between routing which is a network layer entity with channel assignment which is a MAC layer entity based on the physical conditions of the channel is an instance of cross layer design. The routing algorithm in the network layer benefits from the cross-layer information obtained from the physical layer i.e. the values of channels cross correlation and coherence time. Moreover, optimized routing decisions at the network layer inherently determine the optimal assignment of frequency bands to channels at the MAC layer. Finally, the optimal routing decisions will not only determine the best routes for each call but also the MAC layer decisions and channel assignment over each link.

5.3.1 Problem Formulation

A call is defined as a connection between a source node and a destination node. For each call there are a number of routes that the call can pass through. Each route has a set of cascaded links. Each link carries the traffic of all calls and routes combinations that pass through this link. For convenience and without losing generality, we assume that each link has its own M/M/1 queue then the traffic passing through the link is defined as:

$$traffic(l) = \sum_{(c,r)\in S_l} \theta_c \lambda_c x(c,r) \tag{5.3}$$

where l is the link number, c is the call number, r is the route number and S_l is the set of all calls and routes combinations that pass through link l. θ_c is the probability with which call c can occur. Each node estimates the probability with which it calls any other node from its call statistics and transmits these values to all other nodes. This is another instance of cross layer in which the physical layer sends the call probability information to the network layer to be used in routing decisions. λ_c is the number of packets per second that call c can generate, $x(c,r)$ is a binary control variable that has the value of 1 only when call c is taking route r and zero otherwise. Since each link is assumed to have its own M/M/1 queue then the delay experienced by each packet that passes by link l can be defined as:

$$delay(l) = \frac{1}{\mu_l - traffic(l)} \tag{5.4}$$

where μ_l is the service rate of link l in packets per second.

In order to minimize the end to end delay of each call and maximize the packet success rate then we have to minimize the delay of each link, minimize the total interference experienced by each link and select the channel with maximum coherence time of each link. This can be achieved by using the following cost function:

For each link l:

Minimize:

$$delay(l) + \sum_{(c,r)\in S_l} x(c,r) \sum_{j\in Int_l} \sum_{f=1..L} y(l,f)\rho(l,j,f)y(j,f) +$$

$$\sum_{(c,r)\in S_l} x(c,r) \sum_{f=1..L} \frac{y(l,f)}{\tau(l,f)} \tag{5.5}$$

Subject to:

$$\sum_{r=1}^{R} x(c,r) = 1\,, for\ every\ call\ c \tag{5.6}$$

$$\sum_{f=1}^{L} y(l,f) = 1\,, for\ every\ link\ l \tag{5.7}$$

$$traffic(l) < \mu_l\ for\ every\ link\ l \tag{5.8}$$

Int_l is the set of all links that can interfere with link l, $y(l,f)$ is a binary resource control variable that equals to one only if link l is assigned frequency band f and $\tau(l,f)$ is the coherence time of link l when assigned frequency band f.

The cost function in (5.5) means that the algorithm will minimize the delay on each link while trying to minimize the cross correlation or the interference experienced by the link and maximizing the link coherence time. The optimization algorithm will also avoid loading links with high interference and short coherence time with more traffic since both interference and coherence time parts of (5.5) are multiplied by the sum of all calls and routes combinations that pass through the link. This makes the proposed routing algorithm both interference aware and load aware. The constraint in (5.6) means that each call will be assigned only one route. The constraint in (5.7) means that each link will be assigned only one frequency band. The constraint in (5.8) is to assure that no link has traffic more than it can handle and that we are avoiding queue instability by setting the traffic slightly less than μ_l. The optimization problem described in (5.5)-(5.8) is a nonlinear binary one. The non linearity comes from the division by the binary control variable x in the delay expression as shown in (5.4) and (5.5). Another source on non linearity is the multiplication of the y and x control variables in (5.5). Non linear binary optimization problems are difficult to solve and may lead to local optimal solutions. The optimization problem in (5.5)-(5.8) can be transformed into a linear form as in [69] by:

For each link l:

Minimize:

$$\sum_{(c,r)\in S_l} \theta_c \lambda_c x(c,r) + \sum_{(c,r)\in S_l} \sum_{j\in Int_l} \sum_{f=1}^{L} z(c,r,l,j,f)\, \rho(l,j,f)$$

$$+ \frac{\sum_{(c,r)\in S_l} \sum_{f=1}^{L} v(c,r,l,f)}{\tau(l,f)} \tag{5.9}$$

Subject to:

$$\sum_{r=1}^{R} x(c,r) = 1\,, for\ every\ call\ c \tag{5.10}$$

$$\sum_{f=1}^{L} y(l,f) = 1\,, for\ every\ link\ l \tag{5.11}$$

$$traffic(l) < \mu_l\ for\ every\ link\ l \tag{5.12}$$

$$x(c,r) + y(l,f) + y(j,f) - 2 \le z(c,r,l,j,f) \tag{5.13}$$

$$z(c,r,l,j,f) \ge 0 \tag{5.14}$$

$$x(c,r) + y(l,f) - 1 \le v(c,r,l,f) \tag{5.15}$$

$$v(c,r,l,f) \ge 0 \tag{5.16}$$

The optimization problem described in (5.9)-(5.16) is a linear integer programming problem which can be solved by commercial optimization software. Both cost functions in (5.5) and (5.9) are equivalent but with different representations. The delay of each link in (5.5) has been replaced by the traffic of each link since minimizing the traffic will result in minimizing the delay given that the service rate of each link μ_l is constant. The constraints in (5.13) and (5.14) guarantee that the control variable $z(c,r,l,j,f)$ is equal to one only when each of $x(c,r)$, $y(l,f)$ and $y(j,f)$ is equal to one and zero otherwise. The constraints in (5.15) and (5.16) guarantee that the control variable $v(c,r,l,f)$ is equal to one only when each of $x(c,r)$ and $y(l,f)$ is equal to one and zero otherwise.

The optimization problem is assumed to run on each node in the network in a distributive manner. Each node is assumed to have complete knowledge about all other nodes parameters required to solve the optimization problem. These parameters include cross correlation values, coherence time values, set of possible routes for each call, call probability and number of packets per second per call. This information can be exchanged between the different nodes in the network by appropriate signaling protocols. In this thesis we assume that all this information is available for each node and will leave the design of signaling protocols for future work.

For comparison reasons we will be comparing the cross layer joint routing and channel assignment algorithm with optimized routing while channels are assigned randomly. We will also be comparing the cross layer algorithm with optimized channel assignment while routing is done randomly. For optimized routing with random channel assignment the optimization problem can be formulated as follows:

For each link l:

Minimize:

$$\sum_{(c,r)\in S_l} \theta_c \lambda_c x(c,r) \tag{5.17}$$

Subject to:

$$\sum_{r=1}^{R} x(c,r) = 1\,, for\ every\ call\ c \tag{5.18}$$

$$traffic(l) < \mu_l\ for\ every\ link\ l \tag{5.19}$$

This will give us the optimized route for each call while channels will be assigned randomly to links such that each link will be assigned only one frequency. For the optimized channel assignment with random routing the optimization problem can be rewritten as follows:

For each link l:

Minimize:

$$\sum_{j\in Int_l}\sum_{f=1}^{L} y(l,f)\rho(l,j,f)y(j,f) + \sum_{f=1..L}\frac{y(l,f)}{\tau(l,)} \quad (5.20)$$

Subject to:

$$\sum_{f=1}^{L} y(l,f) = 1\,, for\ every\ link\ l \quad (5.21)$$

The nonlinear cost function in (5.20) can be transformed into a linear one as follows:

For each link l:

Minimize:

$$\sum_{j\in Int_l}\sum_{f=1}^{L} zz(l,j,f)\rho(l,j,f) + \sum_{f=1..L}\frac{y(l,f)}{\tau(l,f)} \quad (5.22)$$

Subject to:

$$y(l,f) + y(j,f) - 1 \le zz(l,j,f) \quad (5.23)$$

$$zz(l,j,f) \ge 0 \quad (5.24)$$

$$\sum_{f=1}^{L} y(l,f) = 1\,, for\ every\ link\ l \quad (5.25)$$

5.4 Performance Measures

The performance of the network will be measured by the average end to end packet delay and delay jitter, the average end to end packet success rate and the average carried link utilization. The outcomes of the optimization routine as described in (5.9)-

(5.16) will be the optimized route for each call represented by the values of the control variable $x(c,r)$and the optimized channel assignment represented by the values of the control variable $y(l,f)$. From the values of $x(c,r)$ we can calculate the traffic on each link and the delay experienced by packets passing through that link as in (5.3) and (5.4). This will in turn allow us to calculate the end to end delay for each call and the utilization of each link. The end to end packet delay of any call can be calculated as:

$$EED(c) = \sum_{l \in \pi(c)} delay(l) \tag{5.26}$$

where $\pi(c)$ is the set of cascaded links that call c passes through. The average end to end packet delay can be calculated by averaging the end to end delay over all calls as:

$$\overline{EED} = \frac{\sum_{c=1}^{C} EED(c)}{C} \tag{5.27}$$

where C is the total number of calls in the network.

In this chapter and after computing the optimal $x(c,r)$ values and the average delays above, we also compute packet delay jitter which is defined as:

$$\sigma_{EDD} = \sqrt{\frac{1}{C-1}\sum_{i=1}^{C}\left(EED(c) - \overline{EED}\right)^2} \tag{5.28}$$

From the optimal values of the binary resource control variable $y(l,f)$ we can get the amount of interference experience by each link (second term of (5.5)). We also get the number of interfering links and the coherence time of the link (last term of (5.5)). Channel estimation error variance can be calculated by assuming an inverse linear relationship between channel coherence time and channel estimation error variance. Values of interference, number of interfering links and channel estimation error variance can be used in (5.1) to calculate the bit error rate on each link (BER). The packet success rate on each link can be calculated as:

$$P_s(l) = (1 - BER)^N \tag{5.29}$$

where N is the number of bits per packet. The end to end packet success rate of any call can be calculated as:

$$EEP(c) = \prod_{l \in \pi(c)} P_s(l) \tag{5.30}$$

and the average end to end packet success rate over all calls can be calculated as:

$$\overline{P_s} = \frac{\sum_{c=1}^{C} EEP(c)}{C} \tag{5.31}$$

Another performance measure that will be used is the average carried link utilization. Carried link utilization is defined as the amount of successful traffic that passes through a certain link divided by the service rate of that link, i.e.

$$\zeta(l) = traffic(l) * P_s(l)/\mu_l \tag{5.32}$$

which can be averaged over all links as:

$$\bar{\zeta} = \sum_{l=1}^{NL} \zeta(l)\,/NL \tag{5.33}$$

where NL is the total number of links in the network. It is important here to note that (5.32) is valid only when the traffic passing through each link is less than the service rate of the link, i.e. $traffic(l) < \mu_l \ for\ every\ link\ l$. In our cross layer optimization this is always the case, but in case of random routing the link may be occasionally flooded with traffic more than it can handle and will not deliver any packet successfully. In such case its utilization will be set to zero.

5.5 Results

In this section we present the results for the cross-layer routing and channel assignment algorithm. Without losing generality, we assume a wireless mesh network with 10 stationary nodes. All the cross layer optimizations in this chapter are straight forwardly applicable to other topologies. The nodes are randomly distributed in a coverage area of 2Km radius. Any two nodes can directly communicate with each other if they are in the transmission range of each other. Each wireless mesh router is equipped with a number of interfaces (radios) equal to the number of its neighbors. Each radio is a CDMA-SFBC system as shown in Figure 2.1 where the transmitter has 2 transmit antennas and the receiver has 2 receive antennas. There are 4 frequency bands available and each radio is assigned one of those bands. Figure 5.1 shows the original topology without TDD where the lines between the nodes indicate that the nodes can directly communicate with each other. Figure 5.2 shows the effective topology after TDD in which node 1 belongs to group 1, nodes 2,5,6,9 and 10 belong to group 2, nodes 3, 7 and 8 belong to group 3 and node 4 belongs to group 4. This topology has a total of 20 links. Each link is assumed to have its own M/M/1 queue. The nodes are assumed to operate at 2 GHz frequency. A total bandwidth of 200 MHz is assumed. This total bandwidth will be halved because of TDD operation. The spreading code is assumed to be a maximal length PN sequence with a length of 63. An inverse linear relationship is assumed between the channel coherence time and the channel estimation error variance where the error variance is assumed to be between .001 and .01. Quadrature-PSK modulation is assumed. The network performance is measured by the average end to end packet delay and delay jitter, the average end to end packet success rate and the average carried utilization of links. Each packet is assumed to contain 1000 bits.

The performance of the cross-layer algorithm and its comparisons to random routing and random channel assignment assuming uniform traffic with $\theta_c = 0.1$ are depicted in Figures (5.3-5.6). Figure 5.3 shows that our algorithm performs better than random routing in terms of average end to end delay especially for traffic loads greater than 750 packets/sec after which random routing floods some of the links with traffic more than what they can handle and causes their queues to be unstable which in turn introduces very large amount of delay. Figure 5.4 compares the average end to end packet success rate between our cross-layer algorithm and random routing with random channel assignment. The figure shows that the proposed algorithm outperforms the random algorithm by almost a factor of 2. Comparing Figures 5.3 and 5.4 shows that the optimized routing with random channel assignment algorithm performs slightly better than our cross-layer algorithm in terms of delay while our algorithm has a much higher packet success rate. This shows the tradeoff between delay and packet success rate that the cross-layer algorithm provides. Figure 5.5 compares the end to end delay jitter between the proposed cross-layer algorithm and random routing with random channel assignment and shows that the proposed algorithm has less delay jitter than the random one. Figure 5.6 shows the carried link utilization which takes into account the successful traffic that passes through each link. The proposed algorithm has higher average link utilization than random routing with or without optimized channel assignment. This is due to the fact that in random routing some links will be flooded with traffic more than they can handle and hence will not be utilized effectively. Figures 5.7-5.11 show the performance of the proposed cross-layer algorithm for non-uniform traffic. In Figures 5.7-5.8, it's assumed that the first nodes can call any other node with a probability of 1/3 while any other node can call any destination with a probability of 6/81. This means that node one generates 1/3 of the total traffic in the network. Figures 5.7 and 5.8 show that the cross-layer algorithm has a noticeable improvement in both average end to end delay and packet success rate when compared to random routing and random channel assignment. The cross-layer algorithm also has better carried link utilization as shown in Figure 5.9. Figures 5.10 and 5.11 show that as the polarization of traffic increases i.e. one node is generating most of the traffic, the cross-layer algorithm performs much better than the random routing with random channel assignment.

5.6 Conclusion

In this chapter, we have introduced a joint cross-layer routing and channel assignment algorithm for backbone wireless mesh networks. The cooperation between the physical, MAC and network layers as applied by the proposed algorithm improved the performance of the network. The results showed that the proposed algorithm improved the average end to end delay and average end to end packet success rate compared to those of random routing and random channel assignment (e.g. packet success rates were doubled when compared to those of random assignment). The results also indicated that sole optimal channel assignment or optimal routing alone cannot bring adequate quality of service measures i.e. delay, delay jitter and packet success values provided by the cross layer approach. It has been noticed from the results that the proposed algorithm is effective in defusing increased traffic flow polarization (e.g. packet delays have been reduced appreciably in such cases compared to those of random routing).

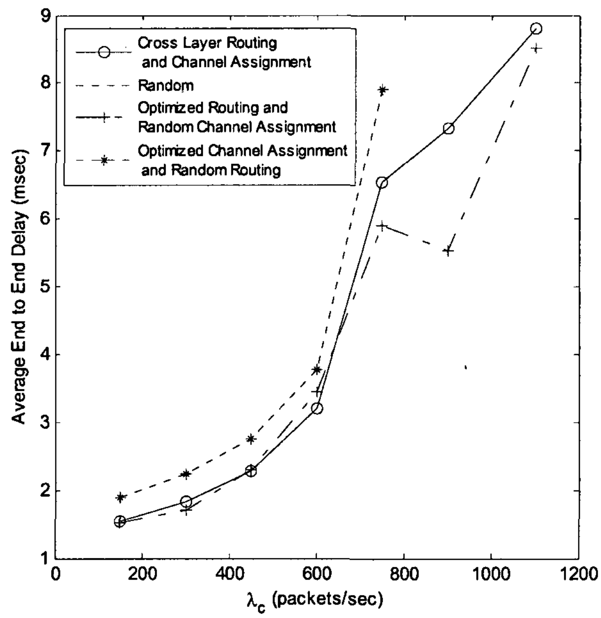

Figure 5.3 Average end to end delay

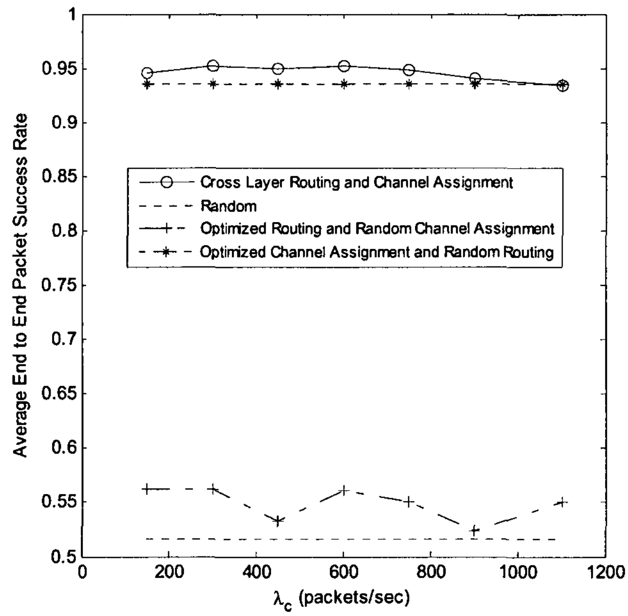

Figure 5.4 Average end to end packet success rate

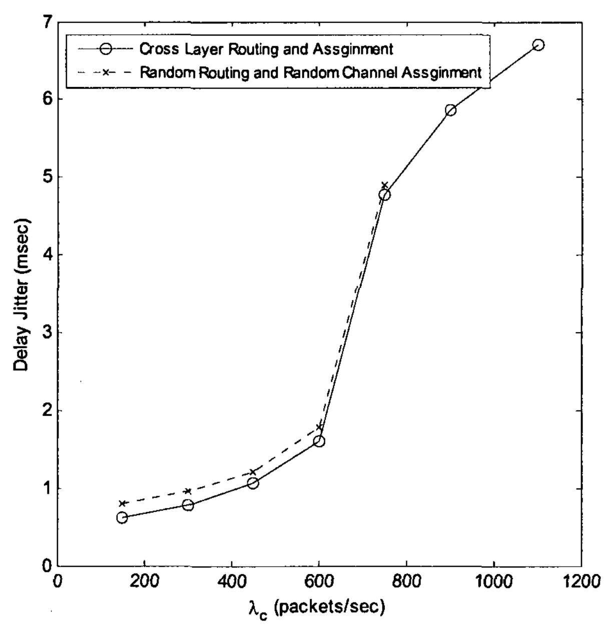

Figure 5.5 End to end delay jitter

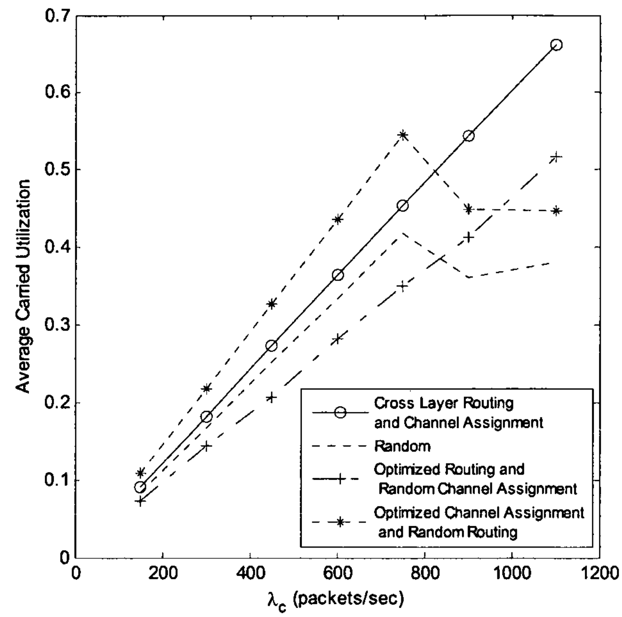

Figure 5.6 Average carried link utilization

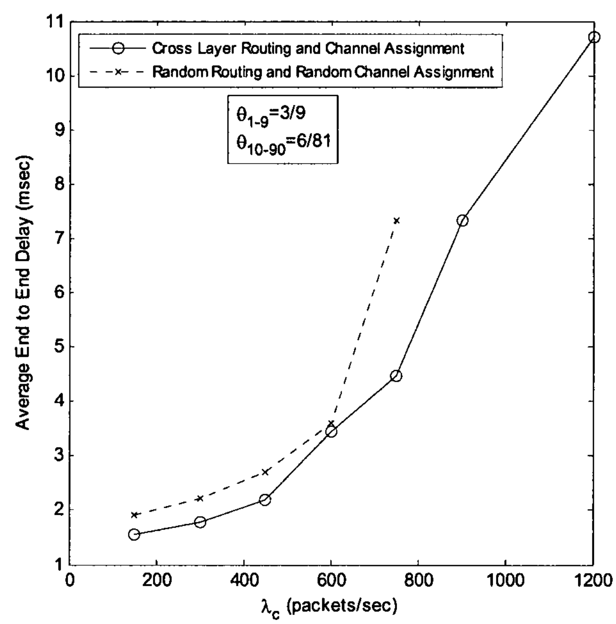

Figure 5.7 Average end to end delay of non uniform traffic

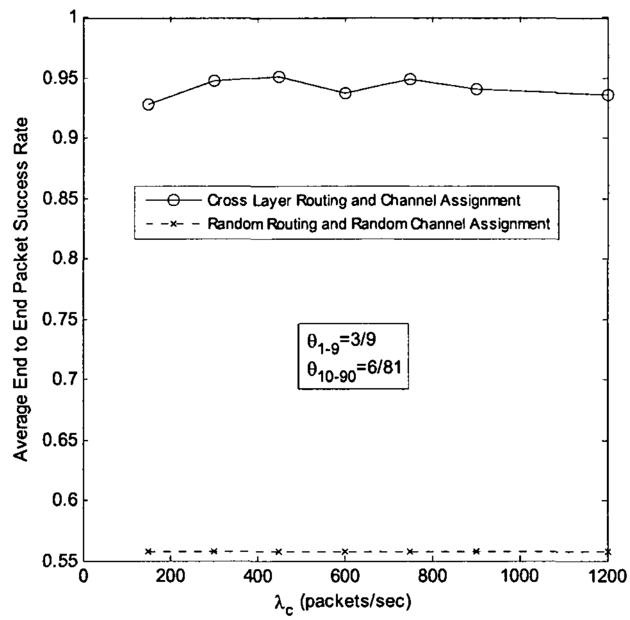

Figure 5.8 Average end to end packet success rate of non uniform traffic

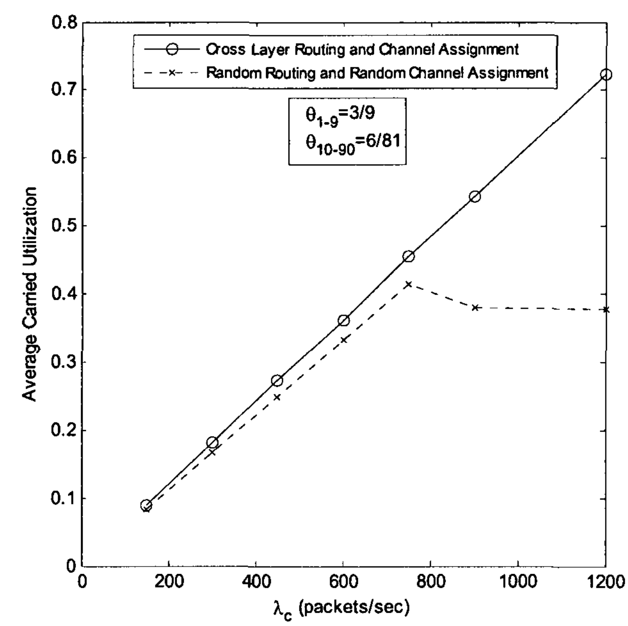

Figure 5.9 Average carried link utilization of non uniform traffic

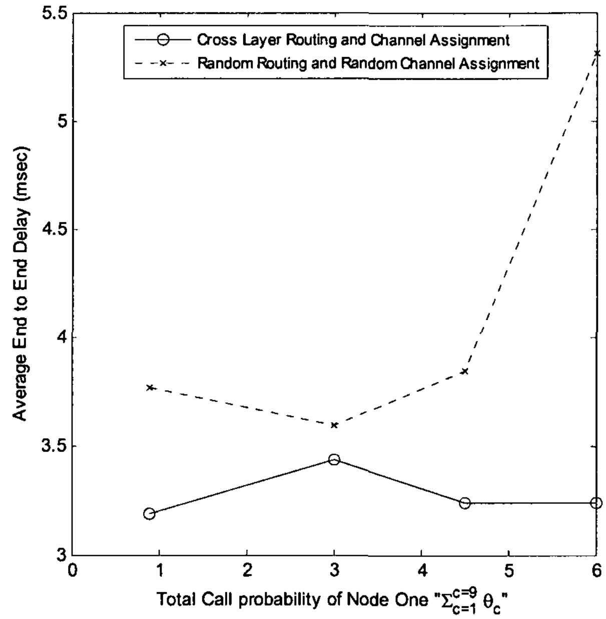

Figure 5.10 Call probability effect on delay

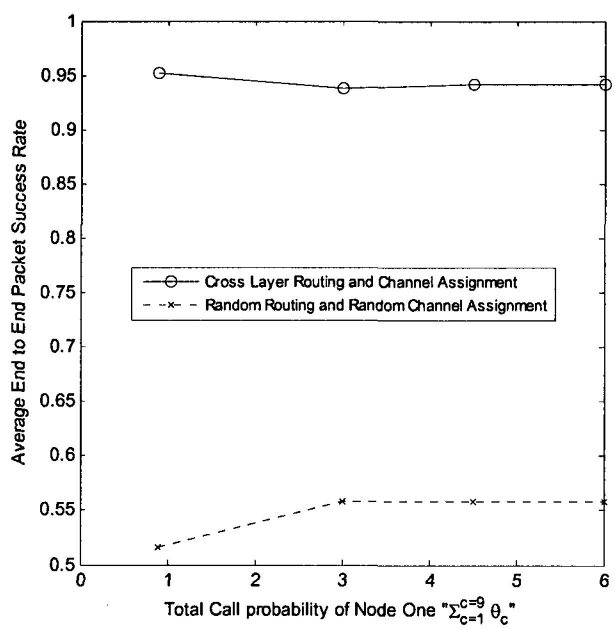

Figure 5.11 Call probability effect on packet success rate

Chapter 6: Conclusions and Future Work

6.1 Conclusions

In this thesis, we have introduced a CDMA-SFBC system for uplink transmission. The system exploits time, frequency, space and code diversities. Closed form expressions for the BER of the proposed system were derived. The expressions were derived for both MQAM and MPSK modulation schemes. The derived expressions were evaluated for a wide range of channel estimation error variance, normalized user channel cross correlation, number of users, spreading codes lengths and different MQAM/MPSK modulation schemes. The results have shed light on the effects of the various operating parameters. The results have also shown that the proposed system performs better at less channel estimation errors and user channel cross correlation.

We have also introduced a CDMA-SFBC system for downlink transmission. Closed form expressions for the BER of the proposed system were derived assuming quasi static Rayleigh fading channels. The expressions were derived for both MQAM and MPSK modulation schemes and for different STBCs.

In the proposed CDMA-SFBC systems, spreading was done after the STBC and the OFDM stages which increased the processing gain of the system since spreading was performed on a block of symbols rather than bits or individual symbols.

CDMA-SFBC systems did not only provide us with diversities, but also with a multiple access technique. Different users can be assigned the same sub channel in terms of frequency bands or antenna arrays, but they still can distinguish themselves from each other by different signature sequences.

Based on the closed form BER expressions for the uplink CDMA-SFBC system, we proposed a resource allocation algorithm for star wireless networks. The algorithm assigns the appropriate BTS, antenna array subsystem and OFDM tones to users such that the pair wise channel cross correlation between the users is minimized while each user is assigned channels with maximum coherence time. The results showed a noticeable improvement in the BER and the bandwidth efficiency of the system gained from the cross layer cooperation of the physical, MAC and higher layers (an instance of cross layer design). The algorithm can also be used to find the optimum number of users that the system can handle while maintaining the best bandwidth efficiency.

Finally, we introduced a joint cross-layer routing and channel assignment algorithm for backbone wireless mesh networks. The cooperation between the physical, MAC and network layers as applied by the proposed algorithm improved the performance of the network. The results showed that the proposed algorithm improved the average end to end delay and average end to end packet success rate compared to those of random routing and random channel assignment (e.g. packet success rates were doubled when compared to those of random assignment). The results also indicated that sole optimal channel assignment or optimal routing alone cannot bring adequate quality of service measures i.e. delay, delay jitter and packet success values provided by the cross layer approach. It has been noticed from the results that the proposed algorithm is effective in defusing increased traffic flow polarization (e.g. packet delays have been reduced appreciably in such cases compared to those of random routing).

6.2 Future Work

The work presented in this thesis gives rise to several issues that need to be addressed in future works. These future works can be summarized as follows:

- The BER results of the uplink CDMA-SFBC system obtained by numerically evaluating the derived closed form BER expressions are to be verified by system simulations.
- The BER results of the downlink CDMA-SFBC system obtained by numerically evaluating the derived closed form BER expressions are to be verified by system simulations.
- The computational complexity of the cross layer resource allocation algorithm for star CDMA-SFBC networks introduced in Chapter 4 is to be analyzed considering the number of users in the system and the number of available resources.
- The cross layer routing and resource allocation algorithm for CDMA-SFBC mesh networks assumed that each node has complete knowledge about all other nodes parameters. Future work is to investigate the development of a signaling protocol that shows what kind of messages are to be exchanged between the different nodes and how to exchange those messages.

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Appendix A

SNR and BER Analysis for CDMA-SFBC Uplink system with Three Transmit Antennas

For the three transmit antenna case we will use the g_c^3 STBC proposed by Tarokh in [2]. At the receiver, the received signal will be de-spread by being multiplied by the intended user's code, assuming perfect spreading code synchronization, and then it will be low pass filtered. OFDM demodulation of the received signal is then performed by the FFT block. The OFDM is assumed to have a cyclic prefix larger than the maximum delay spread of the channel to prevent ISI [8]. The demodulated received signal at the j-th receive antenna can be expressed as:

$$r_j(8k) = H_{j,1,1}(8k)s(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u(4k) + H_{j,2,1}(8k)s(4k+1) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u(4k+1) + H_{j,3,1}(8k)s(4k+2) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u(4k+2) + W_j(8k) \quad \text{(A1)}$$

$$r_j(8k+1) = -H_{j,1,1}(8k)s(4k+1) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u(4k+1) + H_{j,2,1}(8k)s(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u(4k) - H_{j,3,1}(8k)s(4k+3) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u(4k+3) + W_j(8k+1) \quad \text{(A2)}$$

$$r_j(8k+2) = -H_{j,1,1}(8k)s(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u(4k+2) + H_{j,2,1}(8k)s(4k+3) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u(4k+3) + H_{j,3,1}(8k)s(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u(4k) + W_j(8k+2) \quad \text{(A3)}$$

$r_j(8k+3) = -H_{j,1,1}(8k)s(4k+3) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u(4k+3) -$

$H_{j,2,1}(8k)s(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u(4k+2) + H_{j,3,1}(8k)s(4k+1) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u(4k+1) + W_j(8k+3)$ (A4)

$r_j(8k+4) = H_{j,1,1}(8k)s^*(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k) + H_{j,2,1}(8k)s^*(4k+$

$1) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k+1) + H_{j,3,1}(8k)s^*(4k+2) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k+2) + W_j(8k+4)$ (A5)

$r_j(8k+5) = -H_{j,1,1}(8k)s^*(4k+1) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k+1) +$

$H_{j,2,1}(8k)s^*(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k) - H_{j,3,1}(8k)s^*(4k+3) -$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k+3) + W_j(8k+5)$ (A6)

$r_j(8k+6) = -H_{j,1,1}(8k)s^*(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k+2) +$

$H_{j,2,1}(8k)s^*(4k+3) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k+3) + H_{j,3,1}(8k)s^*(4k) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k) + W_j(8k+6)$ (A7)

$r_j(8k+7) = -H_{j,1,1}(8k)s^*(4k+3) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k+3) -$

$H_{j,2,1}(8k)s^*(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k+2) + H_{j,3,1}(8k)s^*(4k+1) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k+1) + W_j(8k+7)$ (A8)

After ML detection the extracted signal can be expressed as:

$\tilde{s}(4k) =$

$\sum_{j=1}^{M_R} \left(\left(H_{j,1,1}^*(8k) + \epsilon_{j,1,1}^*(8k) \right) r_j(8k) + \left(H_{j,2,1}^*(8k) + \epsilon_{j,2,1}^*(8k) \right) r_j(8k+1) + \right.$

$$\left(H_{j,3,1}^{*}(8k)+\epsilon_{j,3,1}^{*}(8k)\right)r_j(8k+2)+\left(H_{j,1,1}(8k)+\epsilon_{j,1,1}(8k)\right)r_j^{*}(8k+4)+$$

$$\left(H_{j,2,1}(8k)+\epsilon_{j,2,1}(8k)\right)r_j^{*}(8k+5)+\left(H_{j,3,1}(8k)+\epsilon_{j,3,1}(8k)\right)r_j^{*}(8k+6)\Big) \quad \text{(A9)}$$

By analysis similar to the uplink with two transmit antennas we can find the SNR to be

$$SNR(8k)=\frac{4\left(\sum_{j=1}^{M_R}\left(|H_{j,1,1}(8k)|^2+|H_{j,2,1}(8k)|^2+|H_{j,3,1}(8k)|^2\right)\right)\eta_s}{M_T\left(2\eta_s\sigma_e^2+6\,\sigma_\zeta^2\rho\eta_s(U-1)M_R+2\,\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+2\right)} \quad \text{(A10)}$$

This can be rewritten in a more general format i.e.

$$SNR(8k)=\frac{\left(\sum_{i=1}^{M_T}\sum_{j=1}^{M_R}|H_{j,i,1}(8k)|^2\right)\eta_s}{M_TR_c\left(\eta_s\sigma_e^2+M_T\,\sigma_\zeta^2\rho\eta_s(U-1)M_R+\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)} \quad \text{(A11)}$$

such that $R_c=0.5$ and $M_T=3$.

Similar to the case of two transmit antennas, the BER of the MQAM system with three transmit antennas can be expressed as:

$$\overline{BER}_{MQAM}=0.2\left[1+\frac{6.4\eta_s}{M_T(2^b-1)\left(2\eta_s\sigma_e^2+6M_R\eta_s\rho\,\sigma_\zeta^2(U-1)+2\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+2\right)}\right]^{-3M_R} \quad \text{(A12)}$$

This can be rewritten in a more general format i.e.

$$\overline{BER}_{MQAM}=0.2\left[1+\frac{1.6\eta_s}{R_cM_T(2^b-1)\left(\eta_s\sigma_e^2+M_TM_R\eta_s\rho\,\sigma_\zeta^2(U-1)+\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)}\right]^{-M_TM_R} \quad \text{(A13)}$$

where $R_c=0.5$ and $M_T=3$.

Similarly we can find the BER of the MPSK to be:

$$\overline{BER}_{MPSK}=0.2\left[1+\frac{28\eta_s}{M_T(2^{1.9b}+1)\left(2\eta_s\sigma_e^2+6M_R\eta_s\rho\,\sigma_\zeta^2(U-1)+2\,\sigma_\zeta^2\sigma_e^2\eta_s(U-1)+2\right)}\right]^{-3M_R} \quad \text{(A14)}$$

This can be rewritten in a more general format i.e.

$$\overline{BER}_{MPSK} = 0.2\left[1 + \frac{7\eta_s}{R_c M_T(2^{1.9b}+1)\left(\eta_s\sigma_e^2 + M_T M_R \eta_s \rho\, \sigma_\zeta^2(U-1) + \sigma_\zeta^2\sigma_e^2\eta_s(U-1)+1\right)}\right]^{-M_T M_R} \quad \text{(A15)}$$

where $R_c = 0.5$ and $M_T = 3$.

Appendix B

SNR and BER Analysis for CDMA-SFBC Uplink system with Four Transmit Antennas

For the four transmit antenna case we will use the g_c^4 STBC proposed by Tarokh in [2]. At the receiver, the received signal will be de-spread by being multiplied by the intended user's code, assuming perfect spreading code synchronization, and then it will be low pass filtered. OFDM demodulation of the received signal is then performed by the FFT block. The OFDM is assumed to have a cyclic prefix larger than the maximum delay spread of the channel to prevent ISI [8]. The demodulated received signal at the j-th receive antenna can be expressed as:

$$r_j(8k) = H_{j,1,1}(8k)s(4k) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,1,u}(8k)s_u(4k) + H_{j,2,1}(8k)s(4k+1) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,u}(8k)s_u(4k+1) + H_{j,3,1}(8k)s(4k+2) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,3,u}(8k)s_u(4k+2) + H_{j,4,1}(8k)s(4k+3) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,4,u}(8k)s_u(4k+3) + W_j(8k) \quad \text{(B1)}$$

$$r_j(8k+1) = -H_{j,1,1}(8k)s(4k+1) - \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,1,u}(8k)s_u(4k+1) + H_{j,2,1}(8k)s(4k) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,u}(8k)s_u(4k) - H_{j,3,1}(8k)s(4k+3) - \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,3,u}(8k)s_u(4k+3) + H_{j,4,1}(8k)s(4k+2) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,4,u}(8k)s_u(4k+2) + W_j(8k+1) \quad \text{(B2)}$$

$$r_j(8k+2) = -H_{j,1,1}(8k)s(4k+2) - \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,1,u}(8k)s_u(4k+2) + H_{j,2,1}(8k)s(4k+3) + \sum_{u=2}^{U}\zeta_{1u}(t)H_{j,2,u}(8k)s_u(4k+3) + H_{j,3,1}(8k)s(4k) +$$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u(4k) - H_{j,4,1}(8k) s(4k+1) -$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,4,u}(8k) s_u(4k+1) + W_j(8k+2)$ (B3)

$r_j(8k+3) = -H_{j,1,1}(8k) s(4k+3) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u(4k+3) -$

$H_{j,2,1}(8k) s(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u(4k+2) + H_{j,3,1}(8k) s(4k+1) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u(4k+1) + H_{j,4,1}(8k) s(4k) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,4,u}(8k) s_u(4k) + W_j(8k+3)$ (B4)

$r_j(8k+4) = H_{j,1,1}(8k) s^*(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k) + H_{j,2,1}(8k) s^*(4k+$

$1) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k+1) + H_{j,3,1}(8k) s^*(4k+2) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k+2) + H_{j,4,1}(8k) s^*(4k+3) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,4,u}(8k) s_u^*(4k+3) + W_j(8k+4)$ (B5)

$r_j(8k+5) = -H_{j,1,1}(8k) s^*(4k+1) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k+1) +$

$H_{j,2,1}(8k) s^*(4k) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k) - H_{j,3,1}(8k) s^*(4k+3) -$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k+3) + H_{j,4,1}(8k) s^*(4k+2) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,4,u}(8k) s_u^*(4k+2) + W_j(8k+5)$ (B6)

$r_j(8k+6) = -H_{j,1,1}(8k) s^*(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k+2) +$

$H_{j,2,1}(8k) s^*(4k+3) + \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k+3) + H_{j,3,1}(8k) s^*(4k) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k) - H_{j,4,1}(8k) s^*(4k+1) -$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,4,u}(8k) s_u^*(4k+1) + W_j(8k+6)$ (B7)

$r_j(8k+7) = -H_{j,1,1}(8k) s^*(4k+3) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,1,u}(8k) s_u^*(4k+3) -$

$H_{j,2,1}(8k) s^*(4k+2) - \sum_{u=2}^{U} \zeta_{1u}(t) H_{j,2,u}(8k) s_u^*(4k+2) + H_{j,3,1}(8k) s^*(4k+1) +$

$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,3,u}(8k) s_u^*(4k+1) + H_{j,4,1}(8k) s^*(4k) +$

$$\sum_{u=2}^{U} \zeta_{1u}(t) H_{j,4,u}(8k) s_u^*(4k) + W_j(8k+7) \tag{B8}$$

After ML detection the extracted signal can be expressed as:

$\tilde{s}(4k) =$

$\sum_{j=1}^{M_R} \Big(\big(H_{j,1,1}^*(8k) + \epsilon_{j,1,1}^*(8k) \big) r_j(8k) + \big(H_{j,2,1}^*(8k) + \epsilon_{j,2,1}^*(8k) \big) r_j(8k+1) +$

$\big(H_{j,3,1}^*(8k) + \epsilon_{j,3,1}^*(8k) \big) r_j(8k+2) + \big(H_{j,4,1}^*(8k) + \epsilon_{j,4,1}^*(8k) \big) r_j(8k+3) +$

$\big(\quad {}_{j,1,1}(8k) + \epsilon_{j,1,1}(8k) \big) r_j^*(8k+4) + \big(H_{j,2,1}(8k) + \epsilon_{j,2,1}(8k) \big) r_j^*(8k+5) +$

$$\big(H_{j,3,1}(8k) + \epsilon_{j,3,1}(8k) \big) r_j^*(8k+6) + \big(H_{j,4,1}(8k) + \epsilon_{j,4,1}(8k) \big) r_j^*(8k+7) \Big) \tag{B9}$$

By analysis similar to the uplink with two transmit antennas we can find the SNR to be

$$SNR(8k) = \frac{4\left(\sum_{j=1}^{M_R}\left(|H_{j,1,1}(8k)|^2 + |H_{j,2,1}(8k)|^2 + |H_{j,3,1}(8k)|^2 + |H_{j,4,1}(8k)|^2\right)\right)\eta_s}{M_T\left(2\eta_s\sigma_e^2 + 8\,\sigma_\zeta^2\rho\eta_s(U-1)M_R + 2\,\sigma_\zeta^2\sigma_e^2\eta_s(U-1) + 2\right)} \tag{B10}$$

This can be rewritten in a more general format i.e.

$$SNR(8k) = \frac{\left(\sum_{i=1}^{M_T}\sum_{j=1}^{M_R}|H_{j,i,1}(8k)|^2\right)\eta_s}{M_T R_c\left(\eta_s\sigma_e^2 + M_T\,\sigma_\zeta^2\rho\eta_s(U-1)M_R + \sigma_\zeta^2\sigma_e^2\eta_s(U-1) + 1\right)} \tag{B11}$$

such that $R_c = 0.5$ and $M_T = 4$.

Similar to the case of two transmit antennas, the BER of the MQAM system with four transmit antennas can be expressed as:

$$\overline{BER}_{MQAM} = 0.2\left[1 + \frac{6.4\eta_s}{M_T(2^b-1)\left(2\eta_s\sigma_e^2 + 8M_R\eta_s\rho\,\sigma_\zeta^2(U-1) + 2\sigma_\zeta^2\sigma_e^2\eta_s(U-1) + 2\right)}\right]^{-4M_R} \tag{B12}$$

This can be rewritten in a more general format i.e.

$$\overline{BER}_{MQAM} = 0.2\left[1 + \frac{1.6\eta_s}{R_c M_T(2^b-1)\left(\eta_s\sigma_e^2 + M_T M_R \eta_s \rho\, \sigma_\zeta^2 (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)}\right]^{-M_T M_R} \quad \text{(B13)}$$

where $R_c = 0.5$ and $M_T = 4$.

Similarly we can find the BER of the MPSK to be:

$$\overline{BER}_{MPSK} = 0.2\left[1 + \frac{28\eta_s}{M_T(2^{1.9b}+1)\left(2\eta_s\sigma_e^2 + 8 M_R \eta_s \rho\, \sigma_\zeta^2 (U-1) + 2\, \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 2\right)}\right]^{-4M_R} \quad \text{(B14)}$$

This can be rewritten in a more general format i.e.

$$\overline{BER}_{MPSK} = 0.2\left[1 + \frac{7\eta_s}{R_c M_T(2^{1.9b}+1)\left(\eta_s\sigma_e^2 + M_T M_R \eta_s \rho\, \sigma_\zeta^2 (U-1) + \sigma_\zeta^2 \sigma_e^2 \eta_s (U-1) + 1\right)}\right]^{-M_T M_R} \quad \text{(B15)}$$

where $R_c = 0.5$ and $M_T = 4$.

Appendix C

SNR Evaluation and BER Analysis of the CDMA-SFBC Downlink System with Three Transmit Antennas

For the three transmit antenna case we will use the generalized complex orthogonal scheme g_c^3 introduced by Tarokh in [2]. At the receiver, the received signals will be de-spread by being multiplied by the corresponding Walsh code. After low pass filtering, OFDM demodulation is performed by FFT. Assuming perfect Walsh code orthogonality, the demodulated received signals at the *j-th* receive antenna can be expressed as:

$$r_j(8k) = \gamma_{j,1}(8k)s(4k) + \gamma_{j,2}(8k)s(4k+1) + \gamma_{j,3}(8k)s(4k+2) + W_j(8k) \quad \text{(C1)}$$

$$r_j(8k+1) = -\gamma_{j,1}(8k)s(4k+1) + \gamma_{j,2}(8k)s(4k) - \gamma_{j,3}(8k)s(4k+3) + W_j(8k+1) \quad \text{(C2)}$$

$$r_j(8k+2) = -\gamma_{j,1}(8k)s(4k+2) + \gamma_{j,2}(8k)s(4k+3) + \gamma_{j,3}(8k)s(4k) + W_j(8k+2) \quad \text{(C3)}$$

$$r_j(8k+3) = -\gamma_{j,1}(8k)s(4k+3) - \gamma_{j,2}(8k)s(4k+2) + \gamma_{j,3}(8k)s(4k+1) + W_j(8k+3) \quad \text{(C4)}$$

$$r_j(8k+4) = \gamma_{j,1}(8k)s^*(4k) + \gamma_{j,2}(8k)s^*(4k+1) + \gamma_{j,3}(8k)s^*(4k+2) + W_j(8k+4) \quad \text{(C5)}$$

$$r_j(8k+5) = -\gamma_{j,1}(8k)s^*(4k+1) + \gamma_{j,2}(8k)s^*(4k) - \gamma_{j,3}(8k)s^*(4k+3) + W_j(8k+5) \quad \text{(C6)}$$

$$r_j(8k+6) = -\gamma_{j,1}(8k)s^*(4k+2) + \gamma_{j,2}(8k)s^*(4k+3) + \gamma_{j,3}(8k)s^*(4k) +$$

$W_j(8k+6)$ (C7)

$r_j(8k+7) = -\gamma_{j,1}(8k)s^*(4k+3) - \gamma_{j,2}(8k)s^*(4k+2) + \gamma_{j,3}(8k)s^*(4k+1) +$

$W_j(8k+7)$ (C8)

Then ML detection can be used for the SFBC decoding of the received signal and the information can be extracted as:

$$\tilde{s}(4k) = \sum_{j=1}^{M_R}\Big(\big(\gamma_{j,1}^*(8k) + \epsilon_{j,1}^*(8k)\big)r_j(8k) + \big(\gamma_{j,2}^*(8k) + \epsilon_{j,2}^*(8k)\big)r_j(8k+1) +$$

$$\big(\gamma_{j,3}^*(8k) + \epsilon_{j,3}^*(8k)\big)r_j(8k+2) + \big(\gamma_{j,1}(8k) + \epsilon_{j,1}(8k)\big)r_j^*(8k+4) +$$

$$\big(\gamma_{j,2}(8k) + \epsilon_{j,2}(8k)\big)r_j^*(8k+5) + \big(\gamma_{j,3}(8k) + \epsilon_{j,3}(8k)\big)r_j^*(8k+6)\Big) \quad \text{(C9)}$$

and by further reduction (C9) can be rewritten as in the equation below.

$\tilde{s}(4k) =$

$\sum_{j=1}^{M_R}\Big(2\left(|\gamma_{j,1}(8k)|^2 + |\gamma_{j,2}(8k)|^2 + |\gamma_{j,3}(8k)|^2\right)s(4k) + \big(\epsilon_{j,1}^*(8k)\gamma_{j,1}(8k) +$

$\epsilon_{j,2}^*(8k)\gamma_{j,2}(8k) + \epsilon_{j,3}^*(8k)\gamma_{j,3}(8k) + \epsilon_{j,1}(8k)\gamma_{j,1}^*(8k) + \epsilon_{j,2}(8k)\gamma_{j,2}^*(8k) +$

$\epsilon_{j,3}(8k)\gamma_{j,3}^*(8k)\big)s(4k) +$

$\big(\epsilon_{j,1}^*(8k)\gamma_{j,2}(8k) - \epsilon_{j,2}^*(8k)\gamma_{j,1}(8k) + \epsilon_{j,1}(8k)\gamma_{j,2}^*(8k) -$

$\epsilon_{j,2}(8k)\gamma_{j,1}^*(8k)\big)s(4k+1) + \big(\epsilon_{j,1}^*(8k)\gamma_{j,3}(8k) - \epsilon_{j,3}^*(8k)\gamma_{j,1}(8k) +$

$\epsilon_{j,1}(8k)\gamma_{j,3}^*(8k) - \epsilon_{j,3}(8k)\gamma_{j,1}^*(8k)\big)s(4k+2) + \big(-\epsilon_{j,2}^*(8k)\gamma_{j,3}(8k) +$

$\epsilon_{j,3}^*(8k)\gamma_{j,2}(8k) - \epsilon_{j,2}(8k)\gamma_{j,3}^*(8k) - \epsilon_{j,3}(8k)\gamma_{j,1}^*(8k)\big)s(4k+3) +$

$\gamma_{j,1}^*(8k)W_j(8k) + \gamma_{j,2}^*(8k)W_j(8k+1) + \gamma_{j,3}^*(8k)W_j(8k+2) + \gamma_{j,1}(8k)W_j^*(8k +$

$4) + \gamma_{j,2}(8k)W_j^*(8k+5) + \gamma_{j,3}(8k)W_j^*(8k+6)\Big)$

and the SNR can be expressed as:

$$SNR = \frac{4\eta_s \sum_{j=1}^{M_R}\left(\left|\gamma_{j,1}(8k)\right|^2 + \left|\gamma_{j,2}(8k)\right|^2 + \left|\gamma_{j,3}(8k)\right|^2\right)}{M_T(2\eta_s\sigma_e^2+2)} \tag{C10}$$

which can be rewritten as:

$$SNR[8k] = \frac{\eta_s \sum_{i=1}^{M_T}\sum_{j=1}^{M_R}\left(\left|\gamma_{j,i}(8k)\right|^2\right)}{M_T R_c(\eta_s\sigma_e^2+1)} \tag{C11}$$

Similar to the case of two transmit antennas the BER of the MQAM system can be expressed as:

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{6.4\eta_s}{M_T(2^b-1)(2\eta_s\sigma_e^2+2)}\right)^{-M_T M_R} \tag{C12}$$

which can be written in a more general format as:

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{1.6\eta_s}{M_T R_c(2^b-1)(\eta_s\sigma_e^2+1)}\right)^{-M_T M_R} \tag{C13}$$

noting that $M_T = 3$ and $R_c = 0.5$.

For the MPSK the BER can be expressed as:

$$\overline{BER}_{MPSK} = 0.2\left(1 + \frac{28\eta_s}{M_T(2^{1.9b}+1)(2\eta_s\sigma_e^2+2)}\right)^{-M_T M_R} \tag{C14}$$

and in the general way by:

$$\overline{BER}_{MPSK} = 0.2\left(1 + \frac{7\eta_s}{M_T R_c(2^{1.9b}+1)(\eta_s\sigma_e^2+1)}\right)^{-M_T M_R} \tag{C15}$$

noting that $M_T = 3$ and $R_c = 0.5$.

Appendix D

SNR Evaluation and BER Analysis of the CDMA-SFBC Downlink System with Four Transmit Antennas

For the four transmit antenna case we will use the generalized complex orthogonal scheme g_c^4 introduced by Tarokh in [2]. At the receiver, the received signals will be de-spread by being multiplied by the corresponding Walsh code. After low pass filtering, OFDM demodulation is performed by FFT. Assuming perfect Walsh code orthogonality, the demodulated received signals at the *j-th* receive antenna can be expressed as:

$$r_j(8k) = \gamma_{j,1}(8k)s(4k) + \gamma_{j,2}(8k)s(4k+1) + \gamma_{j,3}(8k)s(4k+2) + \gamma_{j,4}(8k)s(4k+3) + W_j(8k) \tag{D1}$$

$$r_j(8k+1) = -\gamma_{j,1}(8k)s(4k+1) + \gamma_{j,2}(8k)s(4k) - \gamma_{j,3}(8k)s(4k+3) + \gamma_{j,4}(8k)s(4k+2) + W_j(8k+1) \tag{D2}$$

$$r_j(8k+2) = -\gamma_{j,1}(8k)s(4k+2) + \gamma_{j,2}(8k)s(4k+3) + \gamma_{j,3}(8k)s(4k) - \gamma_{j,4}(8k)s(4k+1) + W_j(8k+2) \tag{D3}$$

$$r_j(8k+3) = -\gamma_{j,1}(8k)s(4k+3) - \gamma_{j,2}(8k)s(4k+2) + \gamma_{j,3}(8k)s(4k+1) + \gamma_{j,4}(8k)s(4k) + W_j(8k+3) \tag{D4}$$

$$r_j(8k+4) = \gamma_{j,1}(8k)s^*(4k) + \gamma_{j,2}(8k)s^*(4k+1) + \gamma_{j,3}(8k)s^*(4k+2) + \gamma_{j,4}(8k)s^*(4k+3) + W_j(8k+4) \tag{D5}$$

$$r_j(8k+5) = -\gamma_{j,1}(8k)s^*(4k+1) + \gamma_{j,2}(8k)s^*(4k) - \gamma_{j,3}(8k)s^*(4k+3) + \gamma_{j,4}(8k)s^*(4k+2) + W_j(8k+5) \tag{D6}$$

$r_j(8k+6) = -\gamma_{j,1}(8k)s^*(4k+2) + \gamma_{j,2}(8k)s^*(4k+3) + \gamma_{j,3}(8k)s^*(4k) -$

$\gamma_{j,4}(8k)s^*(4k+1) + W_j(8k+6)$ (D7)

$r_j(8k+7) = -\gamma_{j,1}(8k)s^*(4k+3) - \gamma_{j,2}(8k)s^*(4k+2) + \gamma_{j,3}(8k)s^*(4k+1) +$

$\gamma_{j,4}(8k)s^*(4k) + W_j(8k+7)$ (D8)

Then ML detection can be used for the SFBC decoding of the received signal and the information can be extracted as:

$\tilde{s}(4k) = \sum_{j=1}^{M_R}\Big(\left(\gamma_{j,1}^*(8k) + \epsilon_{j,1}^*(8k)\right)r_j(8k) + \left(\gamma_{j,2}^*(8k) + \epsilon_{j,2}^*(8k)\right)r_j(8k+1) +$

$\left(\gamma_{j,3}^*(8k) + \epsilon_{j,3}^*(8k)\right)r_j(8k+2) + \left(\gamma_{j,4}^*(8k) + \epsilon_{j,4}^*(8k)\right)r_j(8k+3) +$

$\left(\gamma_{j,1}(8k) + \epsilon_{j,1}(8k)\right)r_j^*(8k+4) + \left(\gamma_{j,2}(8k) + \epsilon_{j,2}(8k)\right)r_j^*(8k+5) + \big(\gamma_{j,3}(8k) +$

$\epsilon_{j,3}(8k)\big)r_j^*(8k+6) + \left(\gamma_{j,4}(8k) + \epsilon_{j,4}(8k)\right)r_j^*(8k+7)\Big)$ (D9)

and by further reduction (D9) can be rewritten as in the equation below.

$\tilde{s}(4k) = \sum_{j=1}^{M_R}\Big(2\left(|\gamma_{j,1}(8k)|^2 + |\gamma_{j,2}(8k)|^2 + |\gamma_{j,3}(8k)|^2 + |\gamma_{j,4}(8k)|^2\right)s(4k) +$

$\big(\epsilon_{j,1}^*(8k)\gamma_{j,1}(8k) + \epsilon_{j,2}^*(8k)\gamma_{j,2}(8k) + \epsilon_{j,3}^*(8k)\gamma_{j,3}(8k) + \epsilon_{j,4}^*(8k)\gamma_{j,4}(8k) +$

$\epsilon_{j,1}(8k)\gamma_{j,1}^*(8k) + \epsilon_{j,2}(8k)\gamma_{j,2}^*(8k) + \epsilon_{j,3}(8k)\gamma_{j,3}^*(8k) +$

$\epsilon_{j,4}(8k)\gamma_{j,4}^*(8k)\big)s(4k) +$

$\big(\epsilon_{j,1}^*(8k)\gamma_{j,2}(8k) - \epsilon_{j,2}^*(8k)\gamma_{j,1}(8k) - \epsilon_{j,3}^*(8k)\gamma_{j,4}(8k) + \epsilon_{j,4}^*(8k)\gamma_{j,3}(8k) +$

$\epsilon_{j,1}(8k)\gamma_{j,2}^*(8k) - \epsilon_{j,2}(8k)\gamma_{j,1}^*(8k) - \epsilon_{j,3}(8k)\gamma_{j,4}^*(8k) +$

$\epsilon_{j,4}(8k)\gamma_{j,3}^*(8k)\big)s(4k+1) + \big(\epsilon_{j,1}^*(8k)\gamma_{j,3}(8k) + \epsilon_{j,2}^*(8k)\gamma_{j,4}(8k) -$

$\epsilon_{j,3}^*(8k)\gamma_{j,1}(8k) - \epsilon_{j,4}^*(8k)\gamma_{j,2}(8k) + \epsilon_{j,1}(8k)\gamma_{j,3}^*(8k) + \epsilon_{j,2}(8k)\gamma_{j,4}^*(8k) -$

$\epsilon_{j,3}(8k)\gamma_{j,1}^*(8k) - \epsilon_{j,4}(8k)\gamma_{j,2}^*(8k)\Big) s(4k+2) + \Big(\epsilon_{j,1}^*(8k)\gamma_{j,4}(8k) -$

$\epsilon_{j,2}^*(8k)\gamma_{j,3}(8k) + \epsilon_{j,3}^*(8k)\gamma_{j,2}(8k) - \epsilon_{j,4}^*(8k)\gamma_{j,1}(8k) + \epsilon_{j,1}(8k)\gamma_{j,4}^*(8k) -$

$\epsilon_{j,2}(8k)\gamma_{j,3}^*(8k) + \epsilon_{j,3}(8k)\gamma_{j,2}^*(8k) - \epsilon_{j,4}(8k)\gamma_{j,1}^*(8k)\Big) s(4k+3) +$

$\gamma_{j,1}^*(8k)W_j(8k) + \gamma_{j,2}^*(8k)W_j(8k+1) + \gamma_{j,3}^*(8k)W_j(8k+2) + \gamma_{j,4}^*(8k)W_j(8k+$

$3) + \gamma_{j,1}(8k)W_j^*(8k+4) + \gamma_{j,2}(8k)W_j^*(8k+5) + \gamma_{j,3}(8k)W_j^*(8k+6) +$

$\gamma_{j,4}(8k)W_j^*(8k+7)\Big)$ (D10)

and the SNR can be expressed as:

$$SNR = \frac{4\eta_s \sum_{j=1}^{M_R}\left(|\gamma_{j,1}(8k)|^2 + |\gamma_{j,2}(8k)|^2 + |\gamma_{j,3}(8k)|^2 + |\gamma_{j,4}(8k)|^2\right)}{M_T(2\eta_s\sigma_e^2 + 2)} \tag{D11}$$

which can be rewritten as:

$$SNR[8k] = \frac{\eta_s \sum_{i=1}^{M_T}\sum_{j=1}^{M_R}\left(|\gamma_{j,i}(8k)|^2\right)}{M_T R_c(\eta_s\sigma_e^2 + 1)} \tag{D12}$$

Similar to the case of two transmit antennas the BER of the MQAM system can be expressed as:

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{6.4\eta_s}{M_T(2^b - 1)(2\eta_s\sigma_e^2 + 2)}\right)^{-M_T M_R} \tag{D13}$$

which can be written in a more general format as:

$$\overline{BER}_{MQAM} = 0.2\left(1 + \frac{1.6\eta_s}{M_T R_c(2^b - 1)(\eta_s\sigma_e^2 + 1)}\right)^{-M_T M_R} \tag{D14}$$

noting that $M_T = 4$ and $R_c = 0.5$.

For the MPSK the BER can be expressed as:

$$\overline{BER}_{MPSK} = 0.2\left(1+\frac{28\eta_s}{M_T(2^{1.9b}+1)(2\eta_s\sigma_e^2+2)}\right)^{-M_T M_R} \tag{D15}$$

and in the general way:

$$\overline{BER}_{MPSK} = 0.2\left(1+\frac{7\eta_s}{M_T R_c(2^{1.9b}+1)(\eta_s\sigma_e^2+1)}\right)^{-M_T M_R} \tag{D16}$$

noting that $M_T = 4$ and $R_c = 0.5$.