OUTAGE CAPACITY ANALYSIS OF MC-CDMA BASED ON COGNITIVE RADIO NETWORK

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The thesis titled **“Outage Capacity Analysis of MC-CDMA based on Cognitive Radio Network”** submitted by **Md. Alomgir Kabir**, Student No: 1013160015 (P), Session: October 2013 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Science** in Electrical, Electronic and Communication Engineering on **30 September 2021.**

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I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

The thesis (fully or partially) has not been submitted for any degree or diploma in any university or institute previously.

Md. Alomgir Kabir
30 September 2021

DEDICATION

To my parents and family

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ABSTRACT

Cognitive Radio Networks (CRN) are aimed at efficiently utilizing the spectrum to solve the spectrum surge generated by large wireless node deployments. Such networks allow users to operate within the best frequency band available, ensuring smooth connectivity requirements during spectrum transitions. The spectrum can be used by both licensed (also called primary) and unlicensed (also called secondary) users. However, unlicensed users vacate the spectrum whenever demanded by the licensed users. This study presents the performance assessment of the Multi-Carrier Code Division Multiple Access (MC-CDMA) based cooperative CRN over Rayleigh fading channel. The proposed network scenario consists of Primary Transmitter (PT) and Primary Receiver (PR) pairs as well as a group of Secondary Transmitters (STs) and Secondary Receivers (SRs). A PT communicate with PR using inactive ST/SR and only one active ST may transmit data at the same time slot using the licensed channel of the PT, if the transmitted power of ST does not exceed predefined interference threshold. Analyses are carried out in order to obtain the expressions for the Signal to Noise plus Interference Ratio (SNIR) expressions of MC-CDMA systems. Based on the analytical models, a closed-form expression for the outage capacity as well as the outage probability over Rayleigh fading channel was derived. The analysis is further extended to derive SNIR of cooperative systems using Amplify and Forward (AF) or Decode and Forward (DF) relaying system. Finally, the performance of the proposed system is evaluated, showing changes in performance over state-of-the-art systems. In outage probability analysis, a close match has been found between simulation and numerical results and it depends primarily on the number of antennas being used in the PT/PR and ST/SR, and max interference temperature limit. The outage probability reduces (more than 3 dB) if the number of antennas increases (from 2x2 to 4x4) and interference temperature reduces. As selected ST/SR nodes are identified between PT and PR, the power analysis demonstrates efficiency improvement. If the active ST is situated farther away from the PR, the outage capacity of PU over Direct Link (DL) transmission as well as the cooperative relay link increases as a result.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 RELATED WORKS

CHAPTER 3 SYSTEM MODEL

CHAPTER 4 ANALYSIS OF OUTAGE CAPACITY

CHAPTER 5 ANALYSIS OF MIMO MC-CDMA BASED CCRN

CHAPTER 6 PERFORMANCE RESULTS AND DISCUSSION

CHAPTER 7 CONCLUSION AND FUTURE WORK

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AF	Amplify and Forward
ANC	Analog Network Coded
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BF	Block Coding
BPSK	Binary Phase Shift Keying
CR	Cognitive Radio
CRN	Cognitive Radio Network
CCN	Cognitive Cooperative Network
CDMA	Code Division Multiple Access
CSI	Channel State Information
CCI	Co-channel Interference
DS-CDMA	Direct Sequence CDMA
DF	Decode and Forward
DL	Direct Link
EGC	Equal Gain Combining
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
ICI	Inter Channel Interference
ISI	Inter Symbol Interference
MAI	Multi Access Interference
MISO	Multiple Input Single Output
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MC-DS-CDMA	Multicarrier DS-CDMA
MRC	Maximal Ratio Combining
MGF	Moment Generating Functions
NUM	Network Utility Maximization
NGN	Next Generation Network
NCCCN	Network Coded Cognitive Cooperative Network
OFDM	Orthogonal Frequency Division Multiplexing
PN	Pseudo Random Noise

PU	Primary User
PT	Primary Transmitter
PR	Primary Receiver
PDF	Probability Density Function
QoS	Quality of Service
QP	Quiet Period
QPSK	Quadrature Phase Shift Keying
SEP	Symbol Error Probability
SU	Secondary User
ST	Secondary Transmitter
SR	Secondary Receiver
SCRN	Single Hop CRN
SNIR	Signal to Noise plus Interference Ratio
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
STBC	Space Time Block Code
RCRN	Relay Assisted Cognitive Radio Network

LIST OF SYMBOLS

Symbol	**Description**
A_k	Amplitude of the modulated signal
a_k^j, b_p^j	Data bit for j^{th} users
c^j	Code sequence of j^{th} users
C_ϵ	Outage capacity
E_b/N_o	Signal to Noise Ratio
f_{N_c}	Subcarrier frequency
f_d	Subcarrier separation
$f_p(y)$	PDF of Rayleigh distribution functions for PU
$f_s(y)$	PDF of Rayleigh distribution functions for SU
$f_{\gamma_i}(y)$	Joint PDF
G_p	Processing Gain
g_{pi}	Rayleigh random variable
g_{si}	Rayleigh random variable
h_{PT-PR}	Channel coefficient between PT to PR
h_{PT-ST_j}	Channel coefficient between PT to in inactive ST
h_{ST_j-PR}	Channel coefficient between inactive ST to PR
h_{PT-ST_i}	Channel coefficient between PT to active ST
I	Interference
I_{TH}	Interference threshold or Interference temperature
i	Number of active SU
j	Number of inactive SU
K	Number of active STs for CCRN
M	Number of ST and SR pair
N_c	Number of subcarriers
N	Number of inactive STs for CCRN
N_{cp}	Number of cyclic prefix bit
p	Number of parallel paths
P_r	Received power
P_{out}	Outage probability

r	Received signal
r_{PT}	Received signal at cooperative relay network
R_{PT}	Achievable data rate of PT
R_{PT-PR}	Achievable data rate between PT to PR
R_{PT-ST_j}	Achievable data rate between PT to inactive ST
R_{ST_j-PR}	Achievable data rate between inactive ST to PR
S_{MC}^{j}	Transmitted symbols
T, T_b	Bit duration
T_s	Symbol duration
T_c	Chip duration
y_p	Signal strength of primary system
y_s	Signal strength of secondary system
$Z(n), \eta$	AWGN
λ_p	Rayleigh random variable with expected mean value of PU
λ_s	Rayleigh random variable with expected mean value of SU
λ_{PT-PR}	Link gain between PT to PR
λ_{PT-ST_j}	Link gain between PT to inactive ST
λ_{ST_j-PR}	Link gain between inactive ST to PR
λ_{PT-ST_i}	Link gain between PT to active ST
ρ	Probability
σ^2	Variance
ϵ	Given outage probability
φ	Phase shift
ω	Angular velocity

CHAPTER 1
INTRODUCTION

1.1 Background

Multi-carrier CDMA is one of the most promising multiple access techniques for next generation wireless network. MC-CDMA combines Orthogonal Frequency Division Multiplexing (OFDM) and Direct Sequence CDMA (DS-CDMA) where all users can access the entire frequency spectrum at any time. Upcoming high data rate demand of wireless networks has created radio frequency spectrum scarcity. Cognitive Radio Network (CRN) is defined as a system that detects an electromagnetic environment which is suitable for its operation. To be precised, the system which can dynamically and automatically adjust its operating parameters i.e., maximize throughput, minimize noise and interference, advancing interoperability, access secondary markets etc. in order to modify system performance. Firstly, with advanced digital signal processing techniques MC-CDMA has the strength to provide larger capacity than other multiple schemes. Use of orthogonal sub-carriers by OFDM technique in a MC-CDMA system provides higher data rate over multipath fading channels. It increases spectral efficiency to attain throughput of 1 Gbps or above and improves link reliability. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. Secondly, bandwidth of high data rate demand and capacity of wireless network has become crucial with increase of users and the Quality of Experience (QoE) especially reliability and throughput are the major concern for the users. Bandwidth scarcity becomes challenging to accommodate huge amount of traffic in limited spectrum. Thus, CRN has been introduced to solve bandwidth scarcity problem of wireless networks.

A great deal of next generation network (NGN) has been attracted to it in order to enhance the utilization of limited bandwidth resources [1-3]. There are limited number licensed bandwidths allocated into a number of wireless network nodes which are called primary users (PU). If the licensed user’s spectrum is used by any other users use that user is known as secondary user (SU). In cognitive radio user, the licensed bandwidth of PUs is used by a SU without creating any harmful interference to PU [4-6]. Recently, spreading spectrums based on MC-CDMA has drawn attention for the developing of cellular mobile communications. Outage capacity analysis for the SUs with optimal power allocation under different types of fading channel in CRNs and power constraints were investigated in [7].

The capacity is a vital parameter of a wireless network for determining the performance of fading channel. Originally there are two types of capacity in wireless network: Ergodic capacity and Outage capacity. Ergodic capacity is applicable only for fast fading channel because delay constrains is not considered here. On the contrary, outage capacity can be defined in terms of data rate when system outage is allowed to occur with given probability. It works in slow fading with interference limited environment. When signal travels to receiver in scattered way, it suffers from distortion which is called fading. Due to fading effect PU experiences signal outage. Outage probability is defined then power level of PR is below the achievable data rate i.e. receiver is out of the range due to multipath fading, interference from SU. Channel state information (CSI) is a term used in wireless communications to describe the known channel characteristics of a communication link. CSI indicates the condition of the channel where the transmitted signal is propagating. It is necessary to calculate CSI at the receiver for measuring the channel capacity of wireless communication system.

1.2 Literature Review

A detailed analysis of the work on possible Quality of Service (QoS) provisioning [8-10], channel assignment strategies [11-13], as well as alternative power management and control approaches of the CRN has been published by several researchers [14-16].

Spectrum sensing is the most challenging difficulty that CRN has faced. For SUs, the radio environment has spectrum gaps that must be identified as part of spectrum sensing. Although, it is possible for CR to measure the channel between the PT and PR directly, this is problematic. However, getting a direct measurement of the channel between the PT to PR is challenging for CRN [17]. CR can't broadcast and sense the radio environment at the same time. That's why fast spectrum sensing algorithms are required. Matched Filter Detection, Energy Detection and Cyclostationary Feature Detection are among the transmitter detection techniques investigated. Receiver uncertainty and the shadowing phenomenon are two constraints of transmitter detection [17].

In [18], Xie and Guo provide a comprehensive overview of the different channel fading models. Under average and peak interference power limits, secondary systems channel capacities in several fading scenarios such as Rayleigh fading, Nakagami fading and lognormal shadowing were investigated in [18]. Cooperative spectrum sensing [19–20] has been shown to increase performance. In [19], the authors looked at the optimum power loading issue in order to optimize transmission data throughput while keeping disturbance to primary users to a minimum. The authors of [21] developed a novel approach to sharing spectrum while avoiding certain problematic assumptions like full CSI at the secondary transmitter. He et al. [22] also talked about the challenges of choosing CRNs responsiveness, complexity, security, robustness and stability may all be improved by Intelligent Algorithms (AI). The present and future developments in CR are examined, as well as the applications for the smart grid [23-24], machine-to-machine (M2M) communications [25], and cloud computing.

Review of the previous works on MC-CDMA based CRN wireless network are summarized below in Table 1.1.

Table 1.1: Review of the previous works contributions and limitations

Reference	Contribution	Limitation
[33]	A protocol is proposed where secondary subscribers can share the licensed spectrum simultaneously with the primary subscriber. The proposed network scenario illustrates a single PTx-PRx pair and a group of M STx-SRx pairs and it is designed within the transmission range of the primary system. Spectrum efficiency and data speed can be significantly amended by CRNs with cooperative communications.	The impact of the access delay on the capacity in the two cooperative relay phases is not considered in the analysis.
[35]	It trails an underlay example to approve sharing the spectrum by SUs to the indoor devices. Searching a spatial opportunity, i.e., deciding its	The existing models have emphasized more on theoretical analysis rather than on the practical i.e. hardware

	transmission over the primary subscriber channels, CR represents its deployment scenario and the arrangements of the PRs and indoor devices.	deployment. Regarding this issue, because of the complexity of the underlying problem, these models have a tendency to oversee certain aspects. Noise uncertainty, channel knowledge, signal uncertainty, and hardware and model limitations e.t.c are fundamental to a hardware implementation which is overlooked. The deficiency of such imperfections in the system model reduces the overall analysis of performance of the CR system unfinished.
[37]	A new outage probability-based NUM formulation is suggested, and its solution method developed in an integrated fashion in order to solve the problem of privation of unambiguous cooperation between CR and PU systems which may cause difficulties for difficult for CRNs to acquire CR-to-PU and CR-to-CR channels accurately.	The proposed system is analyzed only for Rayleigh Fading channel and no comparison among other channel is shown. The power algorithms, effect of SNIR on outage probability are not studied here.
[39]	Here, a partial relay selection scheme is proposed and the analysis is based on an underlay cognitive network with fixed gain relays operating in the vicinity of a PU. A closed-form expressions are derived for the received Signal to Noise Ratio (SNR) distributions, system outage, and probability of BER and	The system is assumed to operate on direct link only. Therefore, the performance analyses don’t include any comparison between DF link and DL.

	average channel capacity of the system.	
[40]	Here, for a slow fading channel the outage capacity of a cooperative relaying based CRN has been analyzed in this study. It illustrates that performance of outage capacity of cooperative link increases with the increase of number of cooperative node as well as with that of ε.	The proposed system has not considered bit allocation and optimal power allocation based on outage probability analysis. It is anticipated that only one ST is active in parallel with the PU simultaneously.
[41]	In fading environment, the performance of a MIMO system is evaluated where correlated and uncorrelated MIMO channels are considered under the condition when CSI is not known at transmitter and CSI is known at receiver side.	Due to the correlation between channels the capacity loss is occurred. In order to gain high capacity, an amount of SNR has to be sacrificed.
[43]	Power allocation in OFDM based cognitive relay networks is investigated. Here, Relay-assisted cognitive radio network (RCRN) combines diversity gain with spectral sharing technique and thus improves the spectrum utilization efficiency compared to single hop CRN (SCRN).	The proposed system has not considered bit allocation and optimal power allocation based on outage probability analysis.
[45]	The capacity of MIMO systems in realistic propagation environments considering spatial fading correlation, double scattering, and keyhole effects are studied. A closed-form capacity bounds for constant correlation cases and the closed-form solution for the ergodic capacity of keyhole MIMO channels was	BER and Outage probability performance are not studied here.

	also analyzed.	
[46]	Here, the performance of several MIMO systems has been studied in terms of capacity and BER in Rayleigh fading channels with various STBCs which concluded that increasing the number of receiver antenna compared to that of transmitting one improves capacity.	The analysis has not showed outage probability, power allocation, and SINR performance for MIMO systems. The results were investigated only for BPSK scheme and not compared with any other modulation technique.
[47]	The effect of errors in the channel estimation on the transmit diversity based on Alamouti's STBC for a downlink MC-CDMA is examined using Moment Generating Functions (MGF) method. As the errors in the channel estimation degrades the system performance, the proposed closed BER expression can contribute significantly for computing performances.	The impacts on errors in the channel estimation only for the MIMO MC-CDMA system.
[48]	The performance of Alamouti's STBC for outdoor scheme with up to two transmitters and receiver's using realistic MIMO channel model is analyzed. It is found that spatial diversity significantly improves the performance of MC-CDMA systems including in outdoor scenarios, and presents a good trade-off between performance and complexity.	The system analysis is limited to Quadrature Phase Shift Keying (QPSK) modulation scheme. No comparison is shown among other modulation techniques.
[55]	The near-far problem in MC-CDMA system is studied and a new expression of BER in case of Nakagami fading	The BER is examined in terms of number of users, it does not consider other parameters

	channel is derived here. In this case, both Equal Gain Combining (EGC) and MRC are used and it is shown that MRC has better performance than that of EGC.	which can affect the system performance like SNIR, interference threshold etc.
[58]	In the proposed NCCCN, considering peak and average interference constraints, the problem of power allocation optimization is formed where interference temperature is taken into account. The proposed system performs better than the single hop CRN. Higher data rate is achieved by the proposed system for optimal power allocation than that of suboptimal power allocation.	The proposed system has not considered bit allocation and optimal power allocation based on outage probability analysis.

1.3 Research Gap

The research gaps retrieved from the literature are as follows: in wireless network, capacity is considered as one of the most vital metric for performance measurement in fading channels. The limitation regarding outage capacity as well as outage probability for MC-CDMA based CRN considering I_{TH} power limited system for the mentioned network has been found from the above discussion. Previously, just one active ST had been considered for theoretical analysis as well as simulation for system performance analysis.

Finally, the performance of the system is not evaluated considering CSI. As a result, these issues are being addressed in an attempt to resolve them.

1.4 Motivation

Now-a-days, high data rate speed is an inevitable metric in wireless communication. Besides, wireless spectrum is an important resource. Many of times, the spectrum of licensed users remains unoccupied. In addition, number of users has been increasing rapidly though scope of increasing spectrum is not possible to cope up with the number of users. As a result, spectrum scarcity has become a burning question. This problem can be solved by CRN. With the help of CRN based MC-CDMA technology, not only the unoccupied spectrum of licensed users can be utilized but also high-speed data rate can be achieved. Moreover, the interference can be limited using this technique.

1.5 Problem Statement

The problem has investigated in this thesis is as follows:

1. Closed form SNIR equation has been derived for some others systems [51] but to the best of author's knowledge, the closed form SNIR equation for MC-CDMA based CRN has not been analyzed yet.
2. In [27], closed form equation of joint Probability Density Function (PDF) has been expressed for different distribution as well as for several wireless channel. However, it was not derived considering two random variables with expected mean values for Rayleigh random distribution under CRN.
3. Several channels have been used for deducing a closed form equation of outage capacity and outage probability for different wireless network over Rayleigh fading channel [33], [59] but closed-form expression for the outage capacity as well as the outage probability for MC-CDMA based CRN has not been considered yet.

1.6 Scope of the Study

The performance of proposed system was analyzed using MATLAB simulation where known values of CSI were considered in this study. However, the proposed system has not yet been put into operation on a practical level. The value of Interference Temperature (I_{TH}) power is taken into consideration in this simulation, which is utilized in a real application. Though simulation work does not consider some conditions, they are taken into account in case of practical work.

1.7 Objectives

The main objectives of this work are to evaluate the Outage Capacity Analysis of MC-CDMA Based CRN. The specific objectives are as follows:

1. To propose a MC-CDMA based CRN.
2. To derive a closed-form SNIR equation of MC-CDMA system.

3. To acquire a closed-form expression for the outage capacity as well as the outage probability over Rayleigh fading channel.
4. To simulate the proposed system in MATLAB and evaluate the performance of the system.
5. To compare the performance between the proposed system and the existing system.

1.8 Methodology

All nodes use Binary Phase Shift Keying (BPSK) modulator MC-CDMA based transmission using single antenna and all the links are considered to follow Rayleigh flat fading plus additive white Gaussian Noise (AWGN) as OFDM converge frequency selective flat fading. The numerical results of the outage capacity as well as the probability for the performance evaluation of cooperative relaying cognitive wireless network scheme are presented in this work. The results are simulated using MATLAB for MC-CDMA under Rayleigh channel considering with AWGN. Walsh-Hadamard spreading codes (N=256) are used in this system. Channel condition does not change during phase of transmission. The outage capacity of the cooperative relay links for the different values of ε. I have considered three cases of ε where ε=0.1, ε= 0.01 and ε= 0.001.

1.9 Organization of the Thesis

The remainder of the paper describes the layout of the thesis which is organized into seven chapters.

Chapter 2 includes related works on CRN, outage capacity for MC-CDMA, Space-Time Block Coding (STBC) MC-CDMA systems, modeling of system and interference effect on MC-CDMA based CRN system.

Chapter 3 presents MC-CDMA system model and channel fading characteristics. The system model consists of transmitter, receiver with OFDM sub-carriers and MC-CDMA based CRN with direct link transmission and decode and forward transmission model. Here, the system scenario of cognitive cooperative relay with MC-CDMA is also represented. Multipath propagation for Rayleigh fading distribution is considered as a channel model.

Chapter 4 introduces an analytical approach to evaluate outage capacity performance of a MC-CDMA based CRN. The closed form expressions are derived for SNIR, joint PDF, outage probability and finally outage capacity for both direct transmission and decode and forward transmission of CRN with MC-CDMA considering Rayleigh fading channel.

In chapter 5, the analysis is further extended to multiple input multiple output (MIMO) MC-CDMA of cognitive cooperative relay network (CCRN) to evaluate system performance based on the analytical equations of outage capacity and outage probability.

Chapter 6 covers the results of the numerical analysis. The system performance is presented for different set of system parameters such as number of receiving antenna, OFDM sub-carrier, spreading code, modulation system for a given SNIR and the outage probability. The results are presented in terms of outage capacity vs SNIR and outage probability vs SNIR.

Chapter 7 concludes the thesis and summarizes the results of the work. Areas for future work are also indicated.

CHAPTER 2

RELATED WORKS

2.1 Review of Previous Research on CRN

A powerful and promising spectrum sharing technology which is the solution to bandwidth limitation problems is CRN technology [28-29]. It has provided a lucrative deal of NGN to make it more efficacious the utilization of limited bandwidth resources which was described by [30]. In [5], authors describe the information theoretic limits, models, and design of CRN. A study of wireless communications and Cognitive Radio (CR) transmissions under quality of service (QoS) constraints and channel uncertainty has been carried out in [31]. A time-varying Rayleigh fading channel assuming no prior channel is available at the transmitter and the receiver it was investigated the performance of pilot-assisted wireless transmission strategies. They analyzed different channel estimation techniques, including single-pilot minimum mean-square-error (MMSE) estimation, and causal and noncausal Wiener filters, and analyze efficient resource allocation strategies. The PU is demonstrated in [32] as a number of wireless network nodes into which limited number licensed bandwidth are assigned. The licensed spectrum may be used by any other user that is known as SU. In CRNs, SUs can use the licensed bandwidth of PUs without creating any harmful interference to PU. Another research in this regard has been carried out in [33]. They proposed a protocol where SUs are permitted to share the licensed spectrum of the PU. The proposed network scenario illustrates a single primary transmitter-receiver (PTx-PRx) pair and a group of M secondary transmitter-receiver (STx-SRx) pairs and it is designed within the transmission range of the primary system. Spectrum efficiency and data rate can be significantly improved by CRNs with cooperative communications. In [34] authors proposed a scenario where three possible transmission modes are described. They are: direct transmission mode, multi-hop transmission mode and cooperative communication mode. Here, the authors optimize the outage capacity for CRNs with cooperative communications in order to solve the problems jointly. The proposed algorithm has some advantages of gaining fast convergence rate and computation easiness. In addition, the time-varying radio environment scenario is also considered, and it is shown that the algorithm has good tracking capability for it. Finally, the performance of the scheme is proved by simulation. An extension of CR network has been idealized in [35]. It trails an underlay example to approve sharing the spectrum by SUs to the indoor devices. Searching a spatial opportunity, i.e., deciding its transmission over the primary subscriber channels, CR represents its deployment scenario and the arrangements of the PRs and indoor devices.

There is privation of unambiguous cooperation between CR and PU systems; hence it is sometimes challenging for CRNs to acquire CR-to-PU and CR-to-CR channels accurately. To solve this uncertainty a novel outage probability-based Network Utility Maximization (NUM) formulation is appeared, and the method of solution is developed in a combined fashion in [36].

2.2 Outage Capacity for MC-CDMA

The achievable data rate R_{PT} at receiver is less than the prescribed or target data rate then the CRN abandons the transmission. So, the system can be defined as outage and outage is allowed to occur with probability is known as outage capacity. For advancing the cellular mobile communication, spreading spectrums are used which is based on MC-CDMA recently. A system is proposed in [37] where outage capacity for the SUs with optimal power allocation under several types of fading channel in CRNs and power restrictions are investigated. It has been evaluated that the outage probability and outage capacity for selective relaying basis and without direct link (DL) combining which was illustrated in [38]. For best relay selection with decode and forward relay networks under Rayleigh fading channel, outage capacity has been evaluated which is studied from the research [39]. Outage probability is also analyzed in [58] where the system is based on cooperative relay with and without network coding. Here, a comparison is performed between the proposed system's spectral efficiency and previous existing systems, thereafter a relative improvement is determined. In fading environment, the performance of a MIMO system is evaluated in [41], where correlated and uncorrelated MIMO channels are considered under a specific condition. The condition is without knowing CSI at transmitter and knowing at receiver side. The Ergodic Capacity, the delay-limited capacity, and the outage capacity of SU block-fading (BF) channels under spectrum sharing has been studied by some authors. They derived the optimal power allocation stratagems for SU to attain aforementioned capacities. The interference power constraint to protect PU, the transmit power constraint of SU transmitter was also reflected [42].

Now-a-days, MC-CDMA over Rayleigh fading channel and cooperative relay selection CRN have become most concerned topic for researchers. Research has been performed where cognitive network partial relay selection is investigated in the impact of interference temperature threshold on the AF model [43]. A study has been carried in order to investigate cooperative diversity performance in this system with orthogonal and non-orthogonal spreading codes [44]. Here, it was shown that the orthogonal spreading code cancels Multiple Access Interference (MAI) and the performance does not depend on the size of the spreading code.

To enhance the performance of the wireless communication system, the transmitter and receiver coding scheme should be changed such as applying the code block in multi antenna systems, known as MIMO. The capacity of MIMO system is analyzed in [45].

2.3 STBC MC-CDMA Systems

One of MIMO transmission techniques often used is STBC found in [46]. The effect of errors in the channel estimation on the transmit diversity based on Alamouti’s STBC for an uplink MC-CDMA is also studied [47].

In [48], the performance of Alamouti’s STBC for outdoor scheme with up to two transmitters and receiver’s using realistic MIMO channel model is analyzed.

A research [49] concluded the expressions of closed-form for the single-user capacity of maximal ratio combining diversity systems. Here, a Rayleigh fading channel with two types of correlation was taken into account.

2.4 Modeling of MC-CDMA System

In [50], the authors evaluated the capacities of CDMA systems for multimedia services in a single cell and a multiple cell environment. They designed a model assuming N user groups described in section 2.2 where a group is for voice service, and rest of them are for various data services. The users in a group have the same quality and information data rate constraint.

To find the outage capacity and SNIR performance of proposed system and to establish the system model several studies are performed. Basic principle of MC-CDMA and MC-DS-CDMA system modeling is described in [51]. An article [52] also presents three kinds of MC-CDMA schemes and their benefits and drawbacks in terms of transmitter and receiver arrangements, the spectral effectiveness and the downlink Bit Error Rate (BER) performance in a frequency selective low Rayleigh fading channel. Those three schemes are DS-CDMA, MC-CDMA and modified MC-CDMA scheme. The CDMA signal and the fading channel models presentation followed by optimal joint detection and channel estimation and the suboptimal channel estimation methods are described in [53].

A research [54] focused on some computational analysis on the down-link BER performance in a frequency selective slow Rayleigh fading channel. A new expression of BER in case of Nakagami fading channel is derived in [55]. The near-far problem in MC-CDMA system was considered here. Considering the same channel another theory of error rate was established where MC DS-CDMA system in conjunction with Maximal Ratio Combining (MRC) was used [56].

The Symbol Error Probability (SEP) of cooperative systems considering AF or DF relaying has been studied in [57]. This research combines the signals received from all relays and the source using MRC strategy. The outage capacity of a cooperative relaying-based CRN in slow fading channel has been analyzed in [40].

2.5 Interference effect on MC-CDMA based CRN system

The outage capacity of MIMO channel is studied where interference power to the receiver is taken to consideration [59]. They investigated the impact of the MIMO diversity on such multi constraint CR-MIMO systems. They peak interference power constraint is taken into consideration at the PR and peak transmits power constraint at the CR transmitter. Both of the authors conducted another study on same perception considering a multiple input single output (MISO) channel [59]. An article [58] emphasized on the radio resource allocation where interference temperature constraints for the network coded cognitive cooperative network (NCCCN) is considered. Analog network coded (ANC) OFDM progresses the capacity of the cognitive cooperative network (CCN). A better system performance than that of the conventional DS-CDMA system is analyzed where they derived and new expression of the signal-to-interference-noise ratio (SINR) for single cell MC-CDMA (MC- link of a MC-CDMA) wireless system in a frequency-selective Rayleigh fading channel [60].

MC-CDMA based direct link (DL) as well as cooperative relaying CRNs is proposed in this paper. The main objective in this paper is to derive a closed form SNIR equation of MC-CDMA system. Thereafter, the contents from the derived equation are used to closely derive the outage probability and outage capacity under Rayleigh fading channel through DL as well as cooperative relay with consideration of active and inactive SUs [64]. The derived results are exposed of the analysis on the parameters of outage capacity as well as probability of PUs. The proposed numerical analysis is also proven by simulations. An article [59] proposed a novel spectrum sensing method established on the instantaneous SINR of the received data. This scheme permits the terminals of a CRN to momentarily sense the presence of Co-Channel Interference (CCI), whether PUs or other CR users without the need to roster a Quiet Period (QP). To achieve the virtues of cooperation, several cooperative sensing protocols are projected. The first protocol is a centralized majority-voting protocol while the other two protocols are distributed protocols that are assimilated with multi hop techniques, namely AF and DF. The proposed method and protocols were demonstrated to accomplish good detection performance over a varied range of conditions.

2.6 Chapter Summary

This chapter gives an idea of several spectrum sharing techniques of CRN and their evolution over the different fading channel. This chapter also provides a comprehensive review on system designing with different coding techniques, interference effect and capacity for MC-CDMA wireless network. At the end of the chapter, a thorough discussion on the current research on the designing of MC-CDMA based CRN under Rayleigh fading channel has been presented.

CHAPTER 3

SYSTEM MODEL

3.1 Introduction

MC-CDMA is a raising technology for next generation wireless network that can solve higher data rate user demand and it improves the performance over multipath links [50-52]. [52] MC-CDMA system works together in combination of DS-CDMA and OFDM where all users can access the entire frequency spectrum at a time. Wireless communication performance is degraded due to multipath fading, Inter Symbol Interference (ISI) and MAI [54]. It assembles the facilities of CDMA with natural strength to frequency selectivity offered by OFDM and in MC-CDMA, the processing as well as spectrum sharing takes place in frequency domain [64]. Due to high data rate demand of wireless networks, there is a possibility of scarcity of radio frequency spectrum. CRN is a powerful spectrum sharing technology to solve this bandwidth limitation problem.

3.2 Channel Model of CRN based MC-CDMA System

In this model, it is assumed that signal passing through the wireless medium then it varies randomly according to Rayleigh fading. In addition, AWGN is a channel model in which the only white noise with a constant spectral density with equal amplitude. Therefore, the channel co-efficient can be denoted by, h_{PT-PR}, h_{PT-STj}, h_{STj-PR}, h_{PT-STi} and interference channel co-efficient $h_{STi-STj}$. Where, i is the active SU and j is the inactive SU which gains are distributed with Rayleigh random variables with the mean values of λ_{PT-PR}, λ_{PT-STj}, λ_{STj-PR}, λ_{PT-STi} and $\lambda_{STi-STj}$ respectively.

3.3 Transmitter Model of MC-CDMA

Figure 3.1 shows the transmitter block diagram of a MC-CDMA with OFDM modulator. In this, input data stream with bit duration T_b of the j^{th} user is converted into Nc parallel data streams. The new symbol duration of each stream becomes, $T_s = Nc * T_b$. Parallel data symbols at each data stream of j^{th} user are coded by the particular Pseudo Random Noise (PN) code having chip duration Tc, processing gain Gp. Thereafter, each data symbol is spread in the time domain.

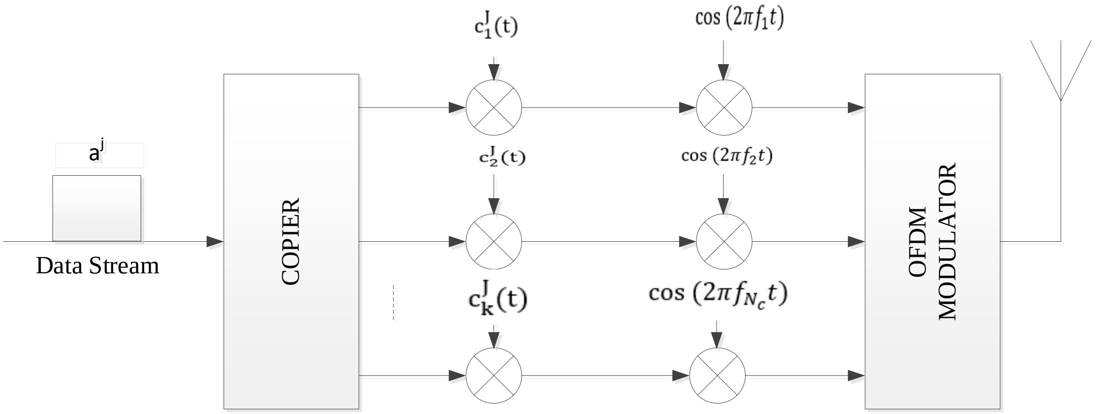

Figure 3.1 Block diagram of MC-CDMA transmitter

The coded symbol of every parallel data is being modulated by sub-carrier of respective channel using OFDM modulator.

Sub-carriers are produced after taking Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) at transmitter and receiver sides respectively. Finally, all symbols are combined and transmitted through the transmitting antenna.

3.4 Receiver Model of MC-CDMA

Let, there are K-number of users is received data in frequency domain where l^{th} subcarrier data is converted into N_c parallel data stream by serial to parallel conversion. l^{th} subcarrier is multiplied by PN code sequence, c^j and then it is demodulated. The frequency of subcarrier is f_{NC}. The parallel data in time domain is converted into serial data by parallel to serial converter. The design is illustrated with figure 3.2.

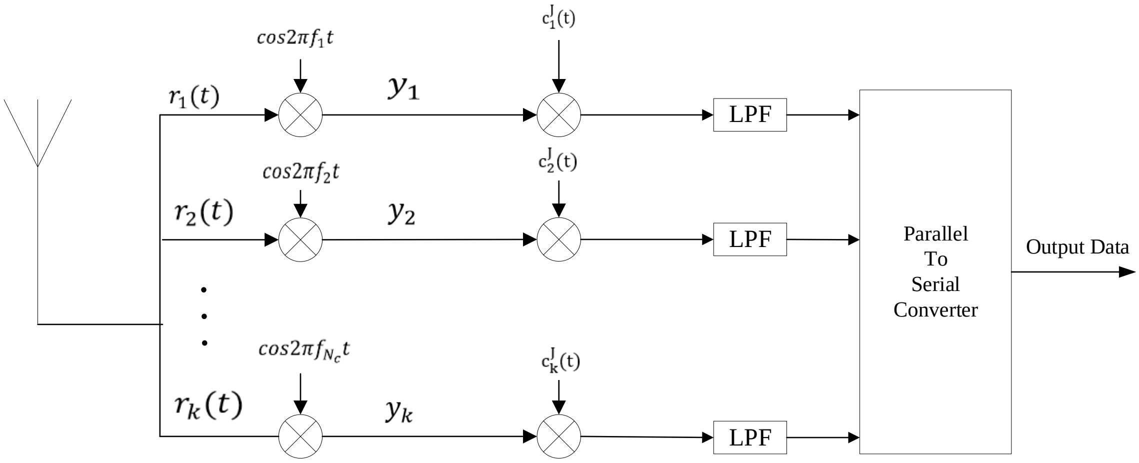

Figure 3.2 Block diagram of MC-CDMA receiver

3.5 CRN with MC-CDMA

All the links are considered as Rayleigh flat fading plus AWGN as OFDM converge frequency selective flat fading. It is also assumed that channel condition does not change during phase of transmission. Here, a CRN scenario which is shown in figure 3.3. The primary communication system consists of a PT and PR which have been considered in the figure 3.3 (a). When the direct transmission link is failed to transmit the data to destination due to long distance or interference. Then we have been proposed another system that is shown in the figure 3.3 (b). It is assumed that in proposed network scenario only one active SU may transmit data simultaneously with the co-existence of PU below a certain I_{TH} to the PR at the same time slot when PU is active.

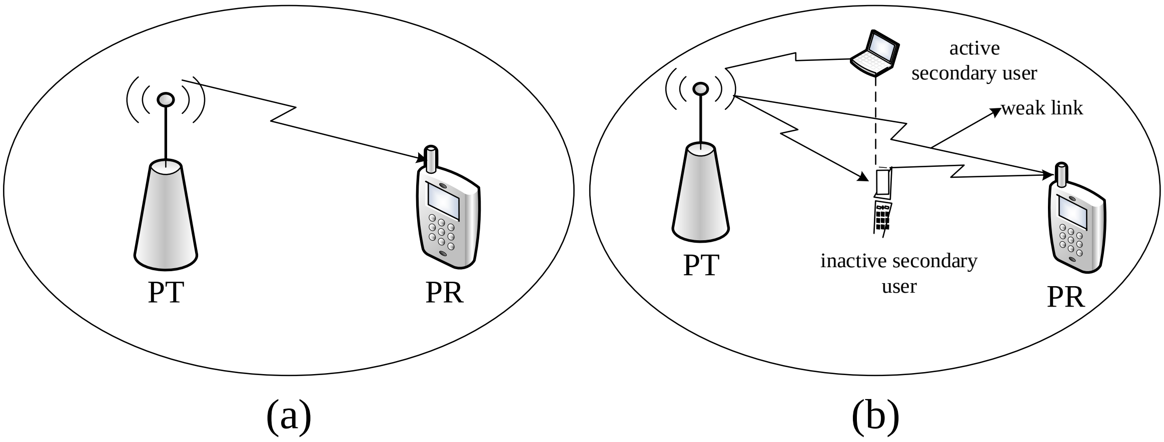

Figure 3.3 (a) Direct link transmission and (b) Decode and forward transmission

3.6 MC-CDMA based Cognitive Cooperative Relay Network

3.6.1 System scenario

Figure 3.4 illustrates a scenario for cooperative relay based CRN. It is assumed that there are M pairs of ST and SR where two types of secondary transmitters (STs) are considered as active ST and inactive ST. There are K ($K \in M$) numbers of active STs and the N number of inactive STs where, $N = M - K$. The active ST group is marked as ST_x ($x = 1, 2, \ldots, K$) and inactive ST group as ST_y ($y = 1, 2, \ldots, N$). When the PT transmits data using direct link to the PR, if the data rate falls below R_{PT} then the N numbers of inactive STs are used as relay through which the PT can communicate with PR. This method is called AF or DF. While inactive STs are acting as relays, both relays and PRs are affected by the interference from active STs. If the interference is below the I_{TH} level, the inactive

STs and PT can transmit data to PR simultaneously otherwise, the STs cannot be used as relay to communicate with PR.

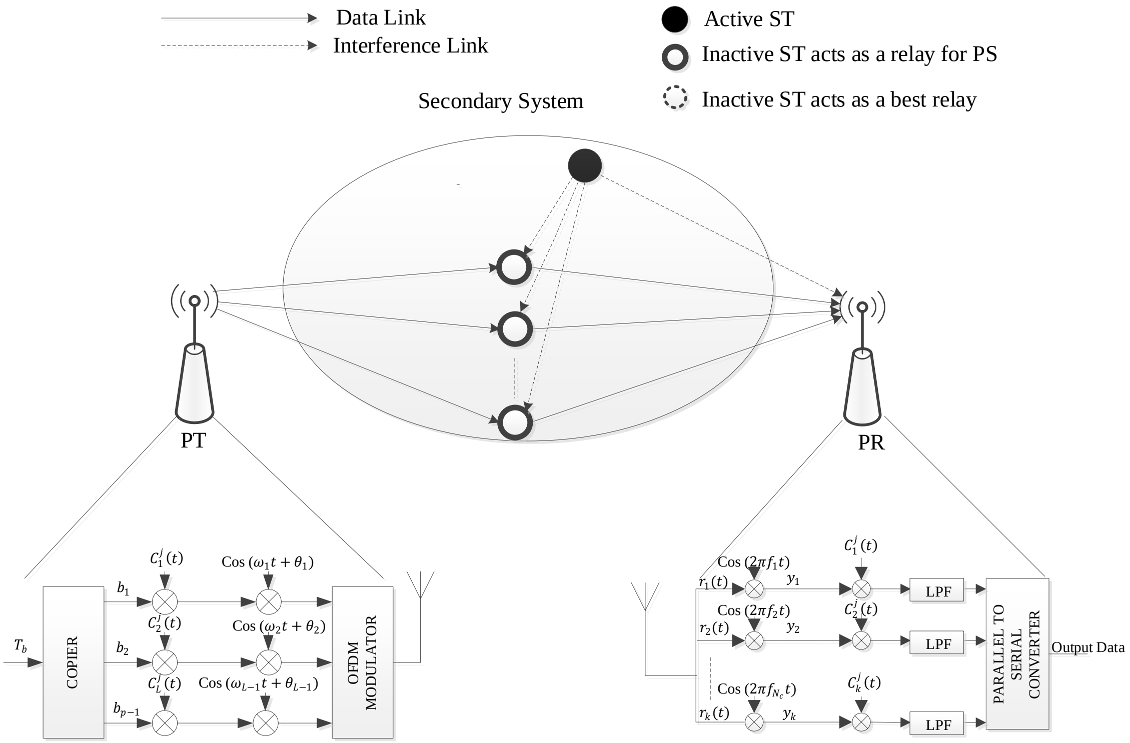

Figure 3.4 Proposed scenario of MC-CDMA based cooperative relaying CRN

3.6.2 Channel model of MC-CDMA based CCRN

When the transmitter transmits data through Rayleigh fading channel, the magnitude of transmitted signals varies randomly according to Rayleigh distribution. In case of long transmission, fading remains almost constant for Rayleigh flat fading with AWGN while it varies in case of short transmission. The fading channel coefficients for the link, PT to cooperative relay are assumed to be α_{PT-ST_1}, $\alpha_{PT-ST_2} \ldots \alpha_{PT-STy}$ respectively for *N* number of inactive SUs. Similarly, those coefficients for the link cooperative relay to PRs and the interference link between active STs to inactive STs are considered as α_{ST_1-PR}, $\alpha_{ST_2-PR} \ldots \alpha_{STy-PR}$ and $\alpha_{STx-ST_1}, \alpha_{STx-ST_2} \ldots \alpha_{STx-STy}$ for *K* number of active STs respectively. The channel co-efficient for PT→ inactive STs are h_{PT-ST_1}, $h_{PT-ST_2} \ldots h_{PT-STy}$ and for anactive STs → PR are h_{ST_1-PR}, ,$h_{ST_1-PR} \ldots h_{STy-PR}$ which are exponentially distributed with mean values λ_{PT-ST_1}, $\lambda_{PT-ST_2} \ldots \lambda_{PT-STy}$, λ_{ST_1-PR}, $\lambda_{ST_2-PR} \ldots \lambda_{STy-PR}$ [55].

At the receiver, multiple antennas are used for improvement of receiver diversity and each of them is arrayed with MC-CDMA receivers. MRC combining technique is used to combine the outputs of MC-CDMA receivers. Finally, the outputs of all the receiving antennas are again combined with OFDM demodulator. The destination coherently combines the signals that are received from the source. All the relays use MRC combining technique.

A cooperative hybrid spectrum sharing model is proposed in [33] where ergodic capacity and outage probability analysis has been performed but no specific modulation scheme was considered. However, in this proposed system MC-CDMA based CRN is adopted. Moreover, at the receiver multiple antennas are used for the improvement of receiver diversity and MRC technique is used to combine the outputs of the receivers. On the other hand, such techniques are not deployed in proposed system of [33].

While comparing new proposed system model with that of [33] it is found that interference from SU and inactive SU have been considered in the referred work. On the other hand, interference from active ST is also taken into account along with interference from PU and inactive SU in the proposed scenario.

3.7 Chapter Summary

In this chapter, a transmitter and receiver model of MC-CDMA wireless communication has been proposed. In order to solve the bandwidth scarcity as well as effective allocation of spectrum resources and also provide higher demand of bandwidth, a MC-CDMA based CRN scenario is proposed where two transmission systems are considered for communication such as direct link transmission and DAF transmission. Subsequently, this chapter also illustrates the cooperative relay based CRN as well as also describes link gain and channel coefficient for Rayleigh fading channel.

CHAPTER 4

ANALYSIS OF OUTAGE CAPACITY

4.1 Transmitter Analysis of MC-CDMA System

Let, the subcarrier k of the j^{th} user the combined MC-CDMA transmitted signals can be written as [62],

$$S_{MC}^{j}(t) =$$

$$A_0 a_0^j c_0^j(t)\cos(2\pi f_0 t) + A_1 a_1^j c_1^j(t)\cos(2\pi f_1 t) + \ldots + A_{N-1} a_{N-1}^j c_{N-1}^j(t)\cos(2\pi f_k t)$$

$$= \sum_{k=0}^{N-1} A_k a_k^j p(t-kT) c_k^j(t)\cos[\![(2\pi(f_k + kf_d)t]\!]) \qquad (4.1)$$

Where, A_k is the amplitude of the carrier signal a_k^j is the data bit for j^{th} user of subcarrier k. c_k^j represents the k^{th} chip of the spreading sequence of the j^{th} user. Where, k= 0, 1, 2, ... N-*1*, T is the symbol bit period, f_d is the subcarrier separation, $S_{MC}^{j}(t)$ is the Multi-carrier transmitted symbol and p is the number of parallel paths. After performing N point IFFT operation equation (4.1) expressed by [62],

$$S_{MC}^{j}(t) = \frac{1}{N}\sum_{n=0}^{N-1} A_k a_k^j p(t-kT) c_k^j(t)\exp\left(j\frac{2\pi}{N}k_n + (f_k + kf_d)\right) \qquad (4.2)$$

By sampling the modulated signal N times during an OFDM symbols represents as:

$$S(m) = \frac{1}{N}\sum_{m=0}^{\infty}\sum_{n=0}^{N-1} A_k a_k^j p(t-kT) c_k^j(t)\exp\left(j\frac{2\pi}{N}k_n + (f_k + kf_d)\right) \qquad (4.3)$$

Where, *S(0)* = [*S*0*; S*1*; S*2*::: SN*-1]*T.*

Adding cyclic prefix equation (4.3) can be derived as,

$$\sum_{m=0}^{\infty} S_m(n) = \sum_{m=0}^{\infty} S_m\{n - m(N + N_{cp})\} \qquad (4.4)$$

Where, N_{cp} is the number of cyclic prefix bit.

4.2 Receiver Analysis of MC-CDMA System

At the MC-CDMA receiver, the reverse action takes place. The down-converted received signal was sampled and converted into a parallel stream of k^{th} subcarrier. So, the received signal can be written as,

$$r(n)=\sum_{k}^{N-1} h(k)S_m(n-k)+Z(n) \tag{4.5}$$

Where, $Z(n)$ is the AWGN noise for projected network scenario. The FFT is applied in order to recover the desired frequency components. Then the equation (4.5) can be derived as,

$$y_{k,m}^{j}=\sum_{n=0}^{N-1} r(\eta_m+n)\exp\left(-j\frac{2\pi}{N}k_n\right)+Z_n$$

Where,

$$r(m)=[r(\eta_m), r(\eta_m+1) \ldots r(\eta_m+N-1)]^T$$

And

$$\eta_m == m(N+N_{cp})+N_{cp}$$

Finally derived a closed-form of MC-CDMA received signal,

$$y_{k,m}^{j}=\frac{A_k^2}{2}h_{k,m}a_k^j c_k^j(t)+Z_{k,m}$$

$$=\mathrm{P}h_{k,m}a_k^j c_k^j(t)+Z_{k,m} \tag{4.6}$$

Where, the receiver power P,

$$P=\sum_{k=0}^{N-1}\frac{A_k^2}{2}$$

And h is the channel co-efficient for this system.

4.3 Joint PDF of Rayleigh Fading Channel

When the transmission power of the ST is P_S, which is the same for every antenna, the signal strength of PR and SR is y_p and y_s respectively.

$$y_p=\alpha P_s$$

$$y_s=\beta P_s$$

A SU can use in the PUs bandwidth, if the PU satisfies an interference temperature constrains as follows:

$$y_p=\alpha P_s \le I_{Th} \tag{4.7}$$

Where, I_{Th} is the interference threshold power. Then the maximum transmitted power can be written as follows:

$$PS_{max} = \frac{I_{Th}}{\alpha}$$

Received signal strength at the SR is:

$$y_s = \beta P_s$$

$$= \frac{\beta}{\alpha} I_{Th}$$

$$= \gamma_i I_{Th} \tag{4.8}$$

Where, α and β are two Rayleigh random variables. Here the Rayleigh distribution function is considered, which is a continuous probability distribution for position-valued random variables. Then the PDF of Rayleigh distribution functions for the PU and SU respectively,

$$f_p(y) = \frac{y}{\lambda_p^2} e^{(-\frac{y^2}{2\lambda_p^2})} \tag{4.9}$$

$$f_s(y) = \frac{y}{\lambda_s^2} e^{(-\frac{y^2}{2\lambda_s^2})} \tag{4.10}$$

The joint PDF equation for the Rayleigh random variables formula,

$$f_{\gamma i} = \int_0^\infty y f_s(yz) f_p(y) dy \tag{4.11}$$

From equation (4.11),

$$f_{\gamma i}(y) = \int_0^\infty y \frac{y}{\lambda_s^2} e^{(-\frac{y^2}{2\lambda_s^2})} \frac{y}{\lambda_p^2} e^{(-\frac{y^2}{2\lambda_p^2})} dy \tag{4.12}$$

The results of (4.12) can be obtained as a closed form joint PDF expression for the Rayleigh random distribution,

$$f(x) = f_{\gamma i}(y) = \frac{4\lambda_s^2 \lambda_p^2}{(\lambda_s^2 + \lambda_p^2 x)^2} \tag{4.13}$$

The detail derivation of (4.13) is shown in the section of the Annex-A.

4.4 Outage Capacity Analysis

In this section, outage capacity as well as the outage probability are focused for the proposed MC-CDMA when the direct link has been failed to communicate with the destination then the proposed network scenario in figure 3.3 (b) has been considered.

4.4.1 Direct link transmission

The achievable data rate can be written as,

$$R_{PT-PR} = \log_2(1 + SNIR) \tag{4.14}$$

Where,

$$SNIR = \frac{\alpha_{PT-PR}\sum_{k=1}^{N-1}\frac{A_k^2}{2}}{\alpha_{ST_i-PR}\sum_{k=1}^{N-1}\frac{A_k^2}{2}\, a_{k-1}^{j} P(t-kT_b) C_k^{j^2}(t) + N_{on}}$$

$$= \frac{\alpha_{PT-PR} \times P_R}{\alpha_{ST_i-PR}(\sigma^2+I)} = \rho \frac{P_R}{(\sigma^2+I)} \tag{4.15}$$

Where,

$$P_R = \sum_{k=1}^{N} \frac{A_k^2}{2}$$

$$I = \alpha_{ST_i-PR}\sum_{k=1}^{N-1}\frac{A_k^2}{2}\, a_{k-1}^{j} P(t-kT_b) C_k^{j^2}(t)$$

$$\sigma^2 = N_{on}$$

From equation (4.14),

$$R_{PT-PR} = \log_2\left(1 + \rho\frac{P_R}{(\sigma^2+I)}\right)$$

$$\Rightarrow 2^{R_{PT-PR}} = \left(1 + \rho\frac{P_R}{(\sigma^2+I)}\right)$$

$$\Rightarrow \rho\frac{P_R}{(\sigma^2+I)} = 2^{R_{PT-PR}} - 1$$

$$\Rightarrow \rho = \left(2^{R_{PT-PR}} - 1\right)\left(\frac{(\sigma^2+I)}{P_R}\right) \tag{4.16}$$

All the link gains assumed in this research are exponentially distributed random variables with their mean values are shown in section 3.6. The outage probability for the direct link,

$$P_r(R_{PT-PR} < R_{PT}) = P_r\{\frac{\alpha_{PT-PR}}{\alpha_{ST_i-PR}} < \rho\} \tag{4.17}$$

Outage probability [64],

$$P_{out} = \int_0^{\rho} \frac{4\lambda_{PT-PR}^2 \lambda_{ST_i-PR}^2}{(\lambda_{PT-PR}^2 + \lambda_{ST_i-PR}^2 x)^2} dx = \int_0^{\rho} \frac{4\lambda_1^2\lambda_2^2}{(\lambda_1^2+\lambda_2^2 x)^2} dx$$

Let,

$$\lambda_1 = \lambda_{PT-PR}$$

$$\lambda_2 = \lambda_{ST_i-PR}$$

$$p = \lambda_1^2+\lambda_2^2 x$$

$$\lambda_2^2 dx = dp$$

$$x = 0, p = \lambda_1^2$$

$$x = \rho, p = \lambda_1^2+\lambda_2^2\rho$$

Hence,

$$P_{out} = 4\lambda_1^2\lambda_2^2 \int_0^{\rho} \frac{1}{(\lambda_1^2+\lambda_2^2 x)^2} dx$$

$$= \frac{4\lambda_1^2\lambda_2^2}{\lambda_2^2} \int_{\lambda_1^2}^{\lambda_1^2+\lambda_2^2\rho} \frac{1}{p^2} dp$$

$$= -4\lambda_1^2 \left(\frac{1}{\lambda_1^2+\lambda_2^2\rho} - \frac{1}{\lambda_1^2}\right)$$

$$= 4 - \frac{4\lambda_1^2}{\lambda_1^2+\lambda_2^2\rho}$$

$$= \frac{4\lambda_2^2\rho}{\lambda_1^2+\lambda_2^2\rho} = \frac{4\lambda_{ST_i-PR}^2\rho}{\lambda_{PT-PR}^2+\lambda_{ST_i-PR}^2\rho} \tag{4.18}$$

The outage capacity with the given outage probability,

$$C_\varepsilon = \log_2(1 + SNIR)\,(1-\varepsilon)$$

$$= \log_2\left(1 + \rho' \frac{P_R}{\sigma^2+I}\right)(1-\varepsilon) \text{ [59]} \tag{4.19}$$

Where,

$$\varepsilon = \frac{4\lambda_{ST_i-PR}^2\rho'}{\lambda_{PT-PR}^2+\lambda_{ST_i-PR}^2\rho'} \tag{4.20}$$

$$\Rightarrow 4\lambda_{ST_i-PR}^2\rho' = \varepsilon\lambda_{PT-PR}^2 + \varepsilon\lambda_{ST_i-PR}^2\rho'$$

$$\Rightarrow 4\lambda_{ST_i-PR}^2\rho' - \varepsilon\lambda_{ST_i-PR}^2\rho' = \varepsilon\lambda_{PT-PR}^2$$

$$\Rightarrow \rho' = \frac{\varepsilon\lambda_{PT-PR}^2}{4\lambda_{ST_i-PR}^2 - \varepsilon\lambda_{ST_i-PR}^2}$$

$$\Rightarrow \rho' = \frac{\lambda_{PT-PR}^2}{\lambda_{ST_i-PR}^2}\left(\frac{\varepsilon}{4-\varepsilon}\right) \tag{4.21}$$

4.4.2 Decode and forward transmission

The achievable data rate can be written as,

$$R_{PT-PR} = log_2(1 + SNIR) \tag{4.22}$$

Where,

$$SNIR = \frac{\sum_{k=0}^{N-1}|\alpha_k|^2P^2}{\sum_{k=0}^{N-1}|\alpha_k|^2MAI+\sum_{k=0}^{N-1}|\beta_k|^2P_{ST_i-PR}+\sigma^2} \tag{4.23}$$

From equation (4.22) data rate can be written as corresponding CRN scenario in figure 3.3 (b).

$$R_{PT-ST_j} = \frac{1}{2}\log_2(1 + SNIR_{PT-ST_j}) \tag{4.24}$$

$$R_{ST_j-PR} = \frac{1}{2}\log_2(1 + SNIR_{ST_j-PR}) \tag{4.25}$$

SNIR in equation of (4.24) and (4.25) approximated as follows:

$$SNIR_{PT-ST_j} = \frac{\alpha P}{\sigma^2+I} \tag{4.26}$$

$$SNIR_{ST_j-PR} = \frac{\beta P}{\sigma^2+I} \tag{4.27}$$

Where σ^2 is the variance and I is the interference of the MC-CDMA system. From equation (4.25) and (4.26),

$$R_{PT-ST_j} = \frac{1}{2}\log_2\left(1 + \alpha_{PT-ST_j}\frac{P}{\sigma^2+I}\right)$$

$$\alpha_{PT-ST_j} = \left(2^{2R_{PT-ST_j}} - 1\right)\frac{\sigma^2+I}{P} \tag{4.28}$$

Similarly,

$$\beta_{ST_j-PR} = \left(2^{2R_{ST_j-PR}} - 1\right)\frac{\sigma^2+I}{P} \tag{4.29}$$

Outage Probability can be written as,

$$P_{out} = \int_0^{\alpha} \frac{4\lambda_s^2\lambda_p^2}{(\lambda_s^2+\lambda_p^2 x)^2} dx \tag{4.30}$$

Now the outage probability is according to equation (4.30) for the two link of *PT-ST$_j$* and *ST$_j$-PR* corresponding [64].

$$P_r\left\{R_{PT-ST_j} < R_{PT}\right\} = \frac{4\alpha_{PT-ST_j}\lambda^2_{ST_i-ST_j}}{\lambda^2_{PT-ST_j}+\alpha_{PT-ST_j}\lambda^2_{ST_i-ST_j}} \tag{4.31}$$

$$P_r\left\{R_{ST_j-PR} < R_{PT}\right\} = \frac{4\alpha_{ST_j-PR}\lambda^2_{ST_i-PR}}{\lambda^2_{ST_j-PR}+\alpha_{ST_j-PR}\lambda^2_{ST_i-PR}} \tag{4.32}$$

Two hop co-operative relay link is minimum one of the hop for transmit end to end data. ***S*** is denoted as the set of relays that can be considered for relay selection as [65],

$$S = j^{min(R_{PT\text{-}ST j};R_{ST j\text{-}PR})}$$

If the inactive SUs does not achieves the data rate of R_{PT} i.e. $|\mathbf{S} = 0|$the outage Probability [59],

$$P_{out} = P_r\{||s|| = 0\}$$

$$P_{out} = P_r\{max_{m\in X}\left(\min\{R_{PT-ST_m}, R_{ST_m-PR}\}\right) < R_{PT}\}$$

$$P_{out} = \prod_{m=0}^{N-1}\{P_r\{(\min\{R_{PT-ST_m}, R_{ST_m-PR}\})\} < R_{PT}\}$$

$$P_{out} = \prod_{m=0}^{N-1}\left[1 - \left(1 - P_r\{R_{PT-ST_m} < R_{PT}\}\right)\left(1 - P_r\{R_{ST_m-PR} < R_{PT}\}\right)\right] \tag{4.33}$$

Therefore, the outage capacity can be written from given outage probability, ∈ equation (4.33) as,

$$C_{\in} = \log_2\left(1 + \alpha_{PT-ST_m-PR}\frac{P}{\sigma^2+I}\right)(1-\epsilon)\ [59] \tag{4.34}$$

Where, the value of α_{PT-ST_m-PR} can be calculated as follows:

$$\in = \prod_{m=0}^{N-1}\left[1-\left(1-P_r\left\{R_{PT-ST_m} < R_{PT}\right\}\right)\left(1-P_r\left\{R_{ST_m-PR} < R_{PT}\right\}\right)\right]$$

$\sqrt[n]{\in} =\ 1-\left(1-P_r\left\{R_{PT-ST_m} < R_{PT}\right\}\right)\left(1-P_r\left\{R_{ST_m-PR} < R_{PT}\right\}\right)$ [Let, $\sqrt[n]{\in} = \in'$]

$$\in' = 1-\left(1-\frac{4\alpha_{PT-ST_m}\lambda^2_{ST_i-ST_m}}{\lambda^2_{PT-ST_m}+\alpha_{PT-ST_m}\lambda^2_{ST_i-ST_m}}\right)\left(1-\frac{4\alpha_{ST_m-PR}\lambda^2_{ST_i-PR}}{\lambda^2_{ST_m-PR}+\alpha_{PT-ST_m}\lambda^2_{ST_i-PR}}\right) \tag{4.36}$$

Now equation (4.36) replaced by,

$$\alpha' = \alpha_{PT\,-\,STm} = \alpha_{STm-PR} = \alpha_{PT\,-\,STm-PR}$$
$$\lambda_{SO} = \lambda^2_{ST_i-ST_m}$$

$$\lambda_{PO} = \lambda^2_{PT-ST_m}$$
$$\lambda_{S1} = \lambda^2_{ST_i-PR}$$
$$\lambda_{P1} = \lambda^2_{ST_m-PR}$$

$$\epsilon' = 1-\left(1-\frac{4\alpha'\lambda_{S0}}{\lambda_{P0}+\alpha'\lambda_{S0}}\right)\left(1-\frac{4\alpha'\lambda_{S1}}{\lambda_{P1}+\alpha'\lambda_{S1}}\right)$$

$$\epsilon' = \frac{4\alpha'\lambda_{S1}}{\lambda_{P1}+\alpha'\lambda_{S1}}+\frac{4\alpha'\lambda_{S0}}{\lambda_{P0}+\alpha'\lambda_{S0}}-\frac{4\alpha'\lambda_{S0}\lambda_{S1}}{(\lambda_{P0}+\alpha'\lambda_{S0})(\lambda_{P1}+\alpha'\lambda_{S1})}$$

$$\epsilon' = \frac{Q}{(\lambda_{P0}+\alpha'\lambda_{S0})(\lambda_{P1}+\alpha'\lambda_{S1})} \tag{4.37}$$

Where,

$$Q = 4\alpha'\lambda_{S1}\lambda_{P0} + 4\alpha'^2\lambda_{S0}\lambda_{S1} + 4\alpha'\lambda_{S0}\lambda_{P1} + 4\alpha'^2\lambda_{S0}\lambda_{S1} - 16\alpha'^2\lambda_{S0}$$

$$\Rightarrow 4\alpha'\lambda_{S1}\lambda_{P0} + 4\alpha'\lambda_{S0}\lambda_{P1} - 8\alpha'^2\lambda_{S0}\lambda_{S1}$$
$$= \epsilon'\lambda_{P0}\lambda_{P1} + \epsilon'\alpha'\lambda_{S1}\lambda_{P0} + \epsilon'\alpha'\lambda_{S0}\lambda_{P1} + \epsilon'\alpha'^2\lambda_{S0}\lambda_{S1}$$

$$\Rightarrow 4\alpha'\lambda_{S1}\lambda_{P0} - \epsilon'\alpha'\lambda_{S1}\lambda_{P0} + 4\alpha'\lambda_{S0}\lambda_{P1} - \epsilon'\alpha'\lambda_{S0}\lambda_{P1} - 8\alpha'^2\lambda_{S0}\lambda_{S1}$$
$$- \epsilon'\alpha'^2\lambda_{S0}\lambda_{S1} = \epsilon'\lambda_{P0}\lambda_{P1}$$

$$\Rightarrow (4\lambda_{S1}\lambda_{P0} - \epsilon'\lambda_{S1}\lambda_{P0} + 4\lambda_{S0}\lambda_{P1} - \epsilon'\lambda_{S0}\lambda_{P1})\alpha' - (8+\epsilon')\alpha'^2\lambda_{S0}\lambda_{S1} = \epsilon'\lambda_{P0}\lambda_{P1}$$

$$\Rightarrow \epsilon'\lambda_{P0}\lambda_{P1} = \alpha'\{\lambda_{S1}\lambda_{P0}(4-\epsilon') + \lambda_{S0}\lambda_{P1}(4-\epsilon')\} - (8+\epsilon')\alpha'^2\lambda_{S0}\lambda_{S1}$$

$$\Rightarrow \alpha'^2\lambda_{S0}\lambda_{S1}(8+\epsilon') - \alpha'(4-\epsilon')(\lambda_{S1}\lambda_{P0} + \lambda_{S0}\lambda_{P1}) + \epsilon'\lambda_{P0}\lambda_{P1} = 0$$

$$\Rightarrow A\alpha'^2 + B\alpha' + C = 0$$

$$\alpha' = \frac{-B \pm \sqrt{B^2-4AC}}{2A} \tag{4.38}$$

Therefore, outage capacity cannot be negative. So, equation (4.38) can be expressed as,

$$\alpha' = \frac{-B + \sqrt{B^2-4AC}}{2A} \tag{4.39}$$

Where,

$$A = \lambda_{S0}\lambda_{S1}(8+\epsilon')$$

$$B = (\epsilon' - 4)(\lambda_{S1}\lambda_{P0} + \lambda_{S0}\lambda_{P1})$$

$$C = \epsilon'\lambda_{P0}\lambda_{P1}$$

Now putting the value of λ_{S0}, λ_{P0}, λ_{S1}, λ_{P1} and ϵ' then the equation of *A*, *B* and *C* can be derived as,

$$A = \lambda^2_{ST_i-ST_m}\lambda^2_{ST_i-PR}\left(8+\sqrt[n]{\epsilon}\right)$$

$$B = \left(\sqrt[n]{\epsilon} - 4\right)\left\{\lambda^2_{PT-ST_m}\lambda^2_{ST_i-PR} + \lambda^2_{ST_i-ST_m}\lambda^2_{ST_m-PR}\right\}$$

$$C = \sqrt[n]{\epsilon}\lambda^2_{PT-ST_m}\lambda^2_{ST_m-PR}$$

4.5 Chapter Summary

In this chapter, the transmitted and received signals of MC-CDMA wireless network are derived by numerical equations. The analysis is extended to find the closed form SNIR equation of MC-CDMA system. Thereafter, a joint PDF of Rayleigh fading channel is analyzed. Finally, closed-form expressions of the outage probability and outage capacity are derived for direct link transmission as well as decode and forward transmission based CRN.

CHAPTER 5

ANALYSIS OF MIMO MC-CDMA BASED CCRN

5.1 Primary Transmitter

According to the block diagram of MC-CDMA transmitter shown in figure 3.4, the transmitted signals are modulated by BPSK modulation systems. The proposed MC-CDMA transmitted signals can be expressed as [62],

$$S_{MC}^{J}(t)=\sum_{n=-\infty}^{\infty}\sum_{p=1}^{L}\sum_{l=1}^{L}\sqrt{2P_T}\;b_P^J(n)C_l^J(n)P(t-nT_s)\cos(\omega_l n+\theta_l) \tag{5.40}$$

Here, P_T, b_P^J , θ and Ts are defines the transmitted power per symbol, transmitted bit symbol of J^{th} user in P^{th} sub-channel being modulated by the L sub-carrier, the instantaneous phase angle of each sub-carrier which are assumed to be uniformly distributed over [0:2π], the symbol duration for the projected MC-CDMA respectively.

5.2 Primary Receiver

The signals transmitted by K number of users are received by the receiver of the J^{th} user. After combining all the transmitted signals at the receiver end and expressed as [62],

$$r(t)=\sum_{n=-\infty}^{\infty}\sum_{J=1}^{K}\sum_{l=1}^{L}\sqrt{2P_r}\,\beta_l^J b_l^J(n)c_l^J(n)P(t-nT_s)\cos(\omega_l n+\theta_l+\emptyset_l)+\eta(\mathrm{t}) \tag{5.41}$$

Where, P_r is the received power, φ is the phase shift and β^J is the amplitude attenuation. The received signal at the output of the Coherent Demodulator corresponding to 1^{st} path is derived and so on.

$$y_1=\sum_{J=1}^{K}\sqrt{2P_r}\beta_l^J\,b_1^J c_1^J(n)P(t-nT_s)\cos(\omega_1 n+\theta_1+\varphi_1)\times c_1^J\alpha_1^J\cos(\omega_l n+\theta_l+\varphi_1) \tag{5.42}$$

$$y_2=\sum_{J=1}^{K}\sqrt{2P_r}\beta_l^J\,b_2^J c_2^J(n)P(t-nT_s)\cos(\omega_2 n+\theta_2+\varphi_2)\times c_2^J\alpha_2^J\cos(\omega_2 n+\theta_2+\varphi_2) \tag{5.43}$$

$$y_K=\sum_{J=K}^{K}\sqrt{2P_r}\beta_l^J\,b_L^J c_L^J(n)P(t-nT_s)\cos(\omega_L n+\theta_L+\varphi_L)\times c_L^J\alpha_L^J\cos(\omega_L n+\theta_L+\varphi_L) \tag{5.44}$$

After passing through the low pass filter of the MC-CDMA systems, the output signal can be written as-

$$Y = \sum_{J=1}^{K}\sum_{l=1}^{L}\sqrt{\frac{P_r}{2}}\beta_l^J\, b_L^J c_L^J(n)P(t-nT_s)\cos(\omega_L n+\theta_L+\varphi_L)\times c_L^J\alpha_L^J\cos(\omega_L n+\theta_L+\varphi_L)+\eta \tag{5.45}$$

Now, Signal power for the MC-CDMA systems is defined as-

$$P_s = \sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2 \tag{5.46}$$

$$P_s = P\sum_{l=1}^{L-1}\alpha_l^2 \tag{5.47}$$

Where, σ_n^2 is the variance and $P = \sqrt{\frac{P_r}{2}}$.

5.3 MIMO MC-CDMA

Finally, a close form SNIR equation of MIMO MC-CDMA systems is derived-

$$SNIR = \frac{|H|^2\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2}{\sigma_n^2} \tag{5.48}$$

CAUSE: Consider the wireless communication scenario shown in figure 3.4. Here, MC-CDMA transmitter is communicating with MC-CDMA receiver through a cooperative relay network which is inactive ST for the designed system. Assume that MC-CDMA is transmitting a signal $\boldsymbol{S_{MC}^{j}}(t)$ which has an average power normalized to one. The received signal at cooperative relay network can be written as,

$$r_{ST} = \alpha_{PT-ST_y}\{S_{MC}^{j}(t)+\eta_1\}+\eta_2 \tag{5.49}$$

The received signal at the end of the relay is then multiplied by the gain of the relay and then re-transmitted to the MC-CDMA receiver. The received signal at receiver can be written as,

$$r_{PT} = \alpha_{ST_y-PR}G\{\alpha_1 S_{MC}^{j}(t)+\eta_1\}+\eta_2 \tag{5.50}$$

Where, amplification gain,

$$G = \frac{1}{\frac{P_r}{2}\sum_{l=1}^{L-1}\alpha_l^2\left|h_{PT-ST_y}^2\right|d_{PT-ST_y}^{-\alpha}+\sigma_n^2} \tag{5.51}$$

The destination of the projected system combines the received signals using a MRC and the overall SNIR for MC-CDMA cooperative relay network at the receiver end can be written as,

$$\gamma_{MRC} = \gamma_{PT-PR} + \gamma_{PT-ST_y-PR} \text{ [57]}$$

$$\gamma_{MRC} = \gamma_{PT-PR} + \frac{\gamma_{PT-ST_y}\gamma_{ST_y-PR}}{\gamma_{PT-ST_y}+\gamma_{ST_y-PR}+1} \tag{5.52}$$

$$\gamma_{MRC} =$$

$$\frac{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2}{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2\sum_{j=2}^{J-1}\beta_l^j b_l^j+\sigma_n^2} + \frac{\left(\frac{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2}{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2\sum_{j=2}^{J-1}\beta_l^j b_l^j+\sigma_n^2}\right)^2\left|h_{PT-ST_y}^2\right|d_{PT-ST_y}^{-\alpha}\left|h_{ST_y-PR}^2\right|d_{ST_y-PR}^{-\alpha}}{\frac{\left|h_{PT-ST_y}^2\right|d_{PT-ST_y}^{-\alpha}\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2}{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2\sum_{j=2}^{J-1}\beta_l^j b_l^j+\sigma_n^2}+\frac{\left|h_{ST_y-PR}^2\right|d_{ST_y-PR}^{-\alpha}\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2}{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2\sum_{j=2}^{J-1}\beta_l^j b_l^j+\sigma_n^2}} \tag{5.53}$$

Data rate corresponding the cooperative relay nodes are,

$$R_{PT-ST_y} = \frac{1}{2}log_2(1+SNIR_{PT-ST_y}) \tag{5.54}$$

$$R_{ST_y-PR} = \frac{1}{2}log_2(1+SNIR_{ST_y-PR}) \tag{5.55}$$

Where, SNIR in equation of (5.54) and (5.55) approximated as follows:

$$SNIR_{PT-ST_y} = \left|h_{PT-ST_y}^2\right|\frac{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2}{\sqrt{\frac{P_r}{2}}\sum_{l=1}^{L-1}\alpha_l^2\sum_{j=2}^{J-1}\beta_l^j b_l^j+\sigma_n^2} \tag{5.56}$$

$$SNIR_{PT-ST_y} = \frac{\rho_{PT-ST_y}P_S}{\mathrm{I}+\sigma^2} \tag{5.57}$$

$$SNIR_{ST_y-PR} = \frac{\rho_{ST_y-PR}P_S}{\mathrm{I}+\sigma^2} \tag{5.58}$$

Where, I define the interference of the MC-CDMA system. $\left|h_{PT-ST_y}\right|, \left|h_{ST_y-PR}\right|$ are assume that the channel coefficient and link path gain to the corresponding channels are $\rho_{PT-ST_y} = \left|h_{PT-ST_y}\right|^2$ and $\rho_{ST_y-PR} = \left|h_{ST_y-PR}\right|^2$ [63]. From equation (5.54) and (5.55),

$$R_{PT-ST_y} = \frac{1}{2}\log_2\left(1 + \frac{\rho_{PT-ST_y} P_S}{I+\sigma^2}\right) \tag{5.59}$$

$$\rho_{PT-ST_y} = \left(2^{2R_{PT-ST_y}} - 1\right)\frac{I+\sigma^2}{P_S} \tag{5.60}$$

Similarly,

$$\rho_{ST_y-PR} = \left(2^{2R_{ST_y-PR}} - 1\right)\frac{I+\sigma^2}{P_S} \tag{5.61}$$

Outage Probability can be expressed as [40],

$$P_{out} = \int_0^{\rho} \frac{4\lambda_S^2\lambda_P^2}{(\lambda_S^2+\lambda_P^2 z)^2} dz \tag{5.61}$$

Where, λ_S, λ_P are expected random variables and z is expressed as random variable of PDF for Rayleigh fading channel. The outage probability follows equation (5.62) for the two links of $PT - ST_y$ and $ST_y - PR$ respectively.

$$P_r(R_{PT-ST_y} < R_{PT-PR}) = \frac{4\rho_{PT-ST_y}\,\lambda^2_{ST_x-ST_y}}{\lambda^2_{PT-ST_y}+\rho_{PT-ST_y}\lambda^2_{ST_x-ST_y}} \tag{5.63}$$

$$P_r(R_{ST_y-PR} < R_{PT-PR}) = \frac{4\rho_{ST_y-PR}\lambda^2_{STx-PR}}{\lambda^2_{STj-PR}+\rho_{SR}\lambda^2_{ST_x-PR}} \tag{5.64}$$

Where, λ is the exponential random variables with mean value. Dual hop cooperative relay link is a useful method in reducing channel scarcity where minimum one of the hop is involved to transmit end to end data. $\boldsymbol{S}$ is denoted as the set of relays that can be expressed for relay selection as [65],

$$S = x^{\min\,(R_{ST_y-PR}, R_{ST_y-PR})} \tag{5.65}$$

When, $|\boldsymbol{S} = 0|$, that is the inactive SUs do not attain the data rate of R_{PT-ST_y} the Outage Probability is expressed as [64],

$$P_{out} = P_r\{\|s\| = 0\} \tag{5.66}$$

$$P_{out} = P_r\{max_{m\in N}\left(\min\{R_{PT-ST_m}, R_{ST_m-PR}\}\right) < R_{PT}\}$$

$$P_{out} = \prod_{m=1}^{N-1}\{P_r\left(\min\left\{R_{PT-ST_y}, R_{ST_y-PR}\right\}\right) < R_{PT}\}$$

$$P_{out} = \prod_{m=1}^{N-1}\left[1-\left(1-P_r\{R_{PT-ST_m} < R_{PT}\}\right)\left(1-P_r\{R_{ST_m-PR} < R_{PT}\}\right)\right]$$

(5.67)

5.4 Chapter Summary

This chapter provides the theoretical analysis of MIMO MC-CDMA based CCRN under Rayleigh fading channel. The analysis is also carried out for SNIR equation of MC-CDMA based CCRN considering MRC at the receiver and applying transmit and receive diversity. In the end, total system’s outage probability is derived for cooperative relay based network.

CHAPTER 6

PERFORMANCE RESULTS AND DISCUSSION

6.1 Results and Discussion

This section shows the numerical results of all nodes use BPSK modulator MC-CDMA based transmission using single antenna. The numerical results of the outage capacity as well as the probability for the performance evaluation of cooperative relaying cognitive wireless network scheme is presented in this work. The results are simulated using MATLAB for MC-CDMA under Rayleigh channel considering with AWGN. The SNIR performance results of a MC-CDMA cooperative relay system with diverse system parameters and order of Rayleigh fading with and without receive interference are evaluated. To end, the optimum values of system parameters like number of OFDM sub-carrier, spreading code, modulation system for a given SNIR and the outage probability are determined from the simulation results. The parameters are used for the numerical simulations are shown in table 6.1 below.

Table 6.1: Table of System Parameters

Parameter	Attributes
Spreading codes, *C*	Walsh-Hadamard Code (256)
Channel	Rayleigh fading
Modulation	BPSK
Antennas	SISO, SIMO, MISO, MIMO
Interference temperature power	0, 0.2, 10 dB
Equalization technique	MRC
Cooperative relay, *N*	1, 2, 3, 4
Outage probability, ϵ	0.1, 0.01, 0.001

6.2 SNIR vs Outage Probability of Primary Network Analysis

Figure 6.1 illustrates that the outage probability decreases with increase of SNIR as well as increase number of cooperative relay. It can be observed that the proposed cooperative relaying scheme shows better outage probability performance than the direct link transmission system. Moreover, analytic and simulation results clearly indicate the improvement of the proposed transmission scenario as increasing number of cooperative relay.

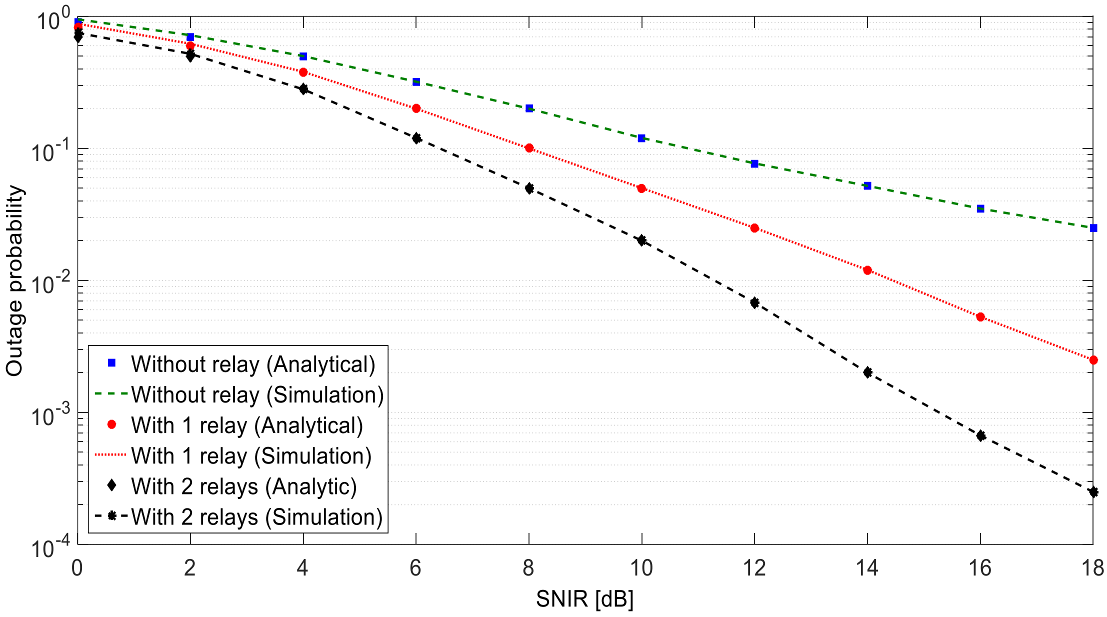

Figure 6.1 SNIR vs Outage probability of the primary network with or without cooperative relaying.

In figure 6.2 shows the effect of SNIR on the outage probability when the I_{TH} 10 dB. In proposed scenario all active ST have same transmit power and each ST satisfy equation (4.7). For that reason, if increases the SNIR as well as decreases outage probability and after 10 dB figure 6.2 becomes flat.

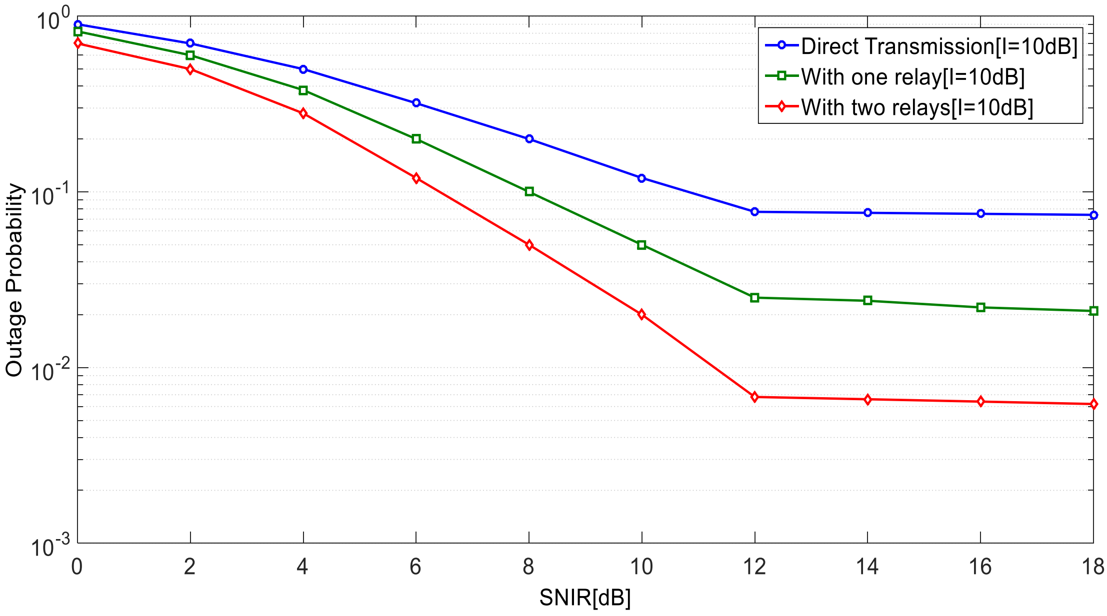

Figure 6.2 SNIR vs Outage probability through direct transmission and also varying relay.

6.3 SNIR vs Outage Capacity Analysis of CRN

In figure 6.3, it is seen that the outage capacity of the cooperative relaying links for the different values of ϵ. Here, three cases of ϵ are considered where ϵ= 0.1, 0.01and 0.001 respectively.

From the figure, it is observed clearly that outage capacity decreases by varying the position of active ST for the given outage probability. It can be observed that the outage capacity decreases at the outage probability of ϵ=0.001 when active ST closer to PR. For the simulation it has been considered that SUs are located with the range of PT and PR.

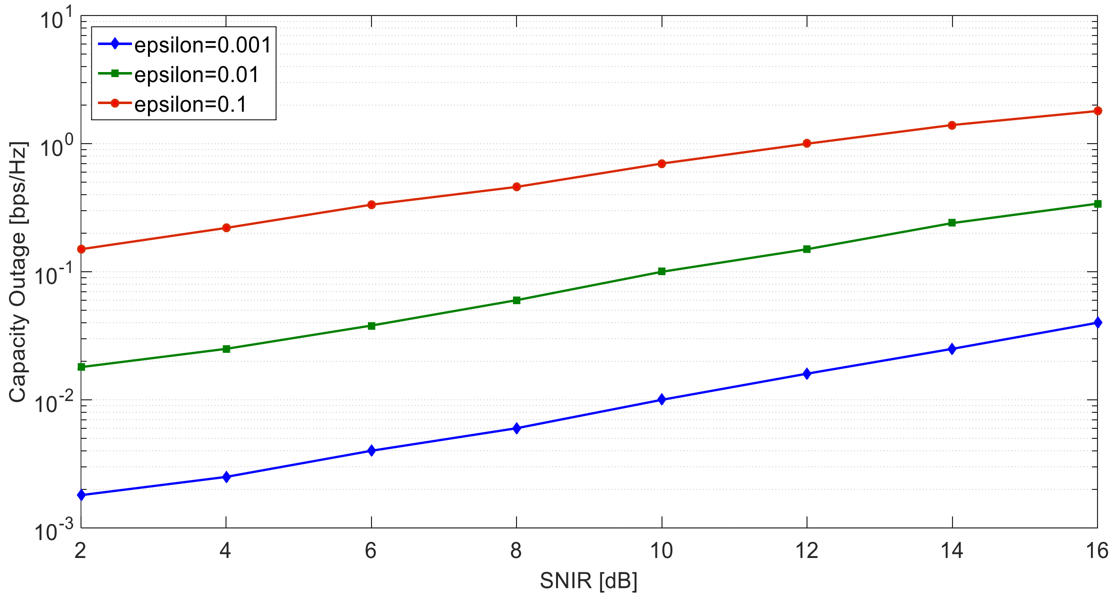

Figure 6.3 SNIR vs Outage capacity with varying epsilon.

6.4 SNIR vs Outage Capacity for SIMO and MISO Systems

The channel capacities of OFDM and MC-CDMA for SISO and MIMO system are compared in figure 6.4. For all systems, channel capacity increases with the increase of SNIR.

Moreover, MC-CDMA always provides higher channel capacity than OFDM irrespective of the number of received antennas.

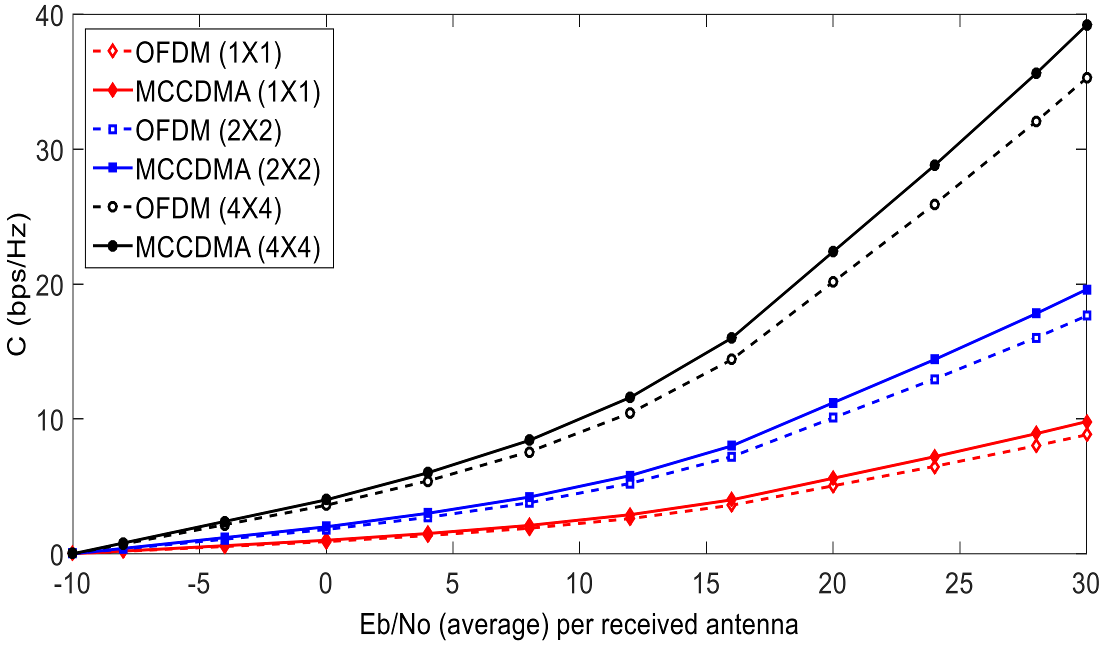

Figure 6.4 SNIR vs Outage capacity for SIMO and MISO systems without interference.

From the analysis, it can be seen from figure 6.5 that for 10 dB SNIR per antenna channel capacity of OFDM and MC-CDMA are about 1.5 bps/Hz for SISO system. However, for MIMO system the performance of channel is improved with the increase of received antenna.

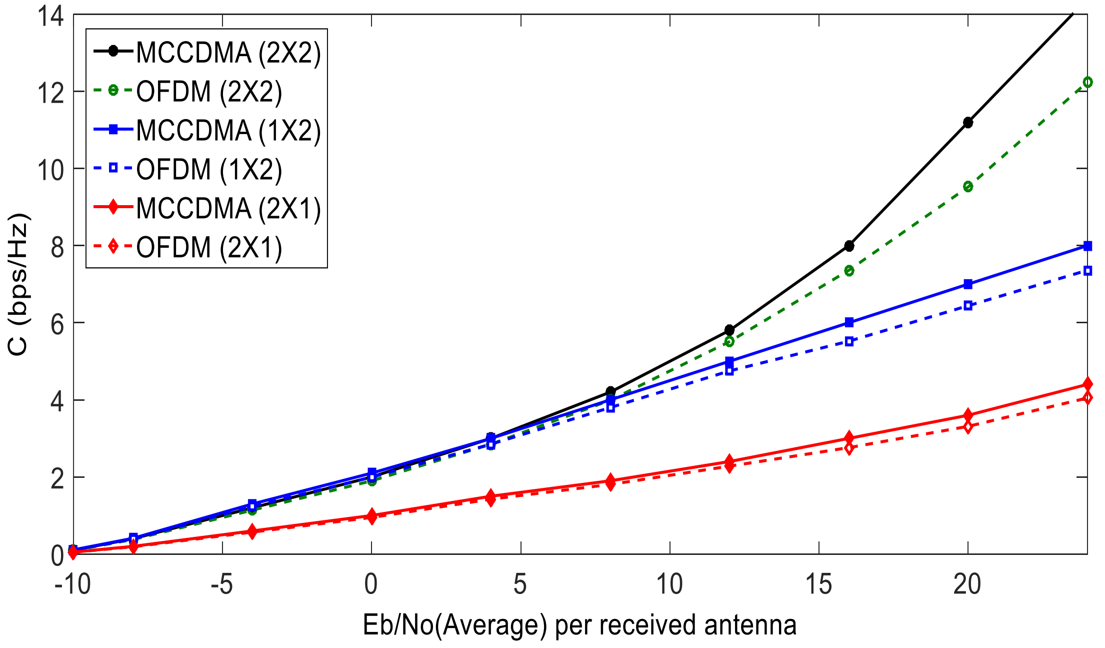

Figure 6.5 SNIR vs Outage capacity for MIMO systems without interference.

The best performance is observed for MC-CDMA, 4×4 MIMO system where channel capacity is 10 bps/Hz for the same value of SNIR. Here, the comparison is shown for the channel capacity of MC-CDMA and OFDM for MISO, SIMO and MIMO multiplexing in figure 6.6. For same SNIR (10 dB), MC-CDMA shows the most improvement for MIMO (almost 4.8 bps/Hz) than all other multiplexing where OFDM with MISO multiplexing shows the least value of channel capacity (slightly more than 2 bps/Hz).

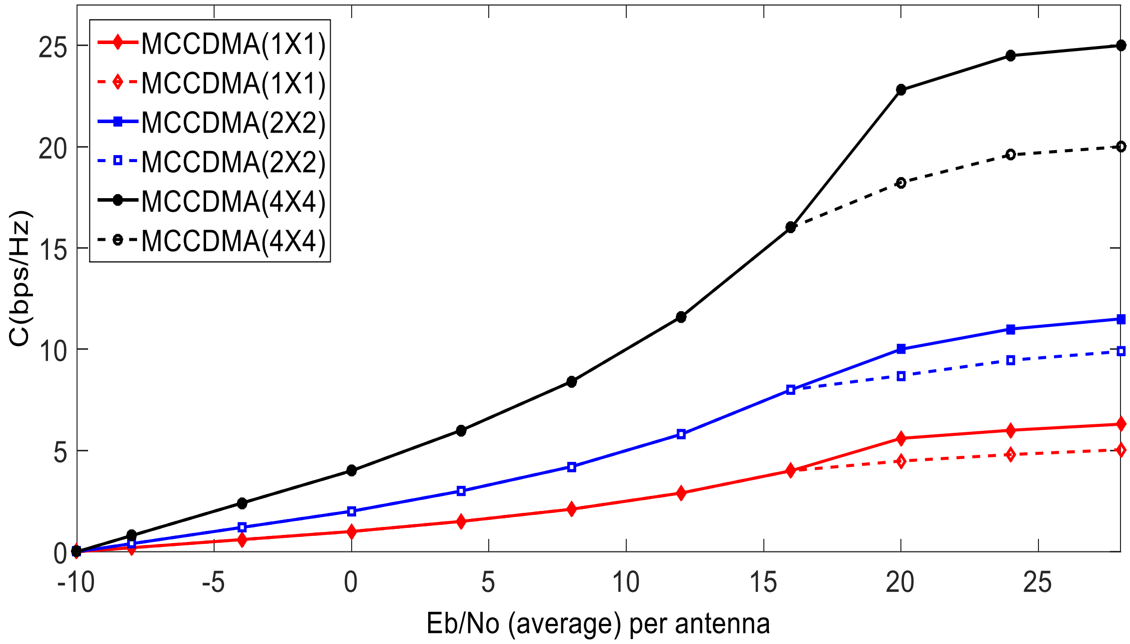

Figure 6.6 Effect on SNIR on the link capacity.

6.5 SNIR vs Outage Probability for MIMO Systems with P_{max}

In figure 6.7 and figure 6.8, the SNIR varies from -8 dB to 2 dB. In figure 6.7, the outage probability is analyzed with SNIR for MIMO multiplexing.

Here, the outage probability P_{out} for 4x4 and 2x2 antenna for -2 dB SNIR is 0.0001 and 0.28 respectively, which indicates that P_{out} performance is dependent on MIMO system. Therefore, P_{out} improves for 4x4 MIMO system compared to 2x2 MIMO system. Interference temperature power has an impact on MIMO system outage probability performance, as shown in figure 6.8.

When MRC combining methods are employed at the receivers, the outage probability for a 4x4 antenna is better than 2x2 antenna system. The I_{TH} limit increases the Pout compared to no interference limit case.

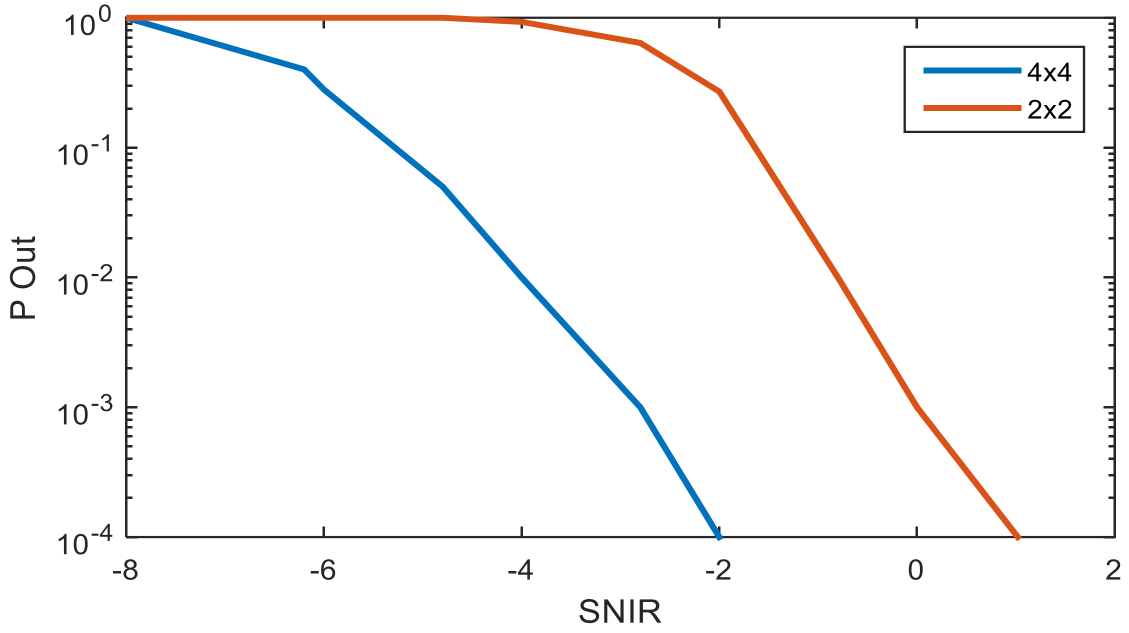

Figure 6.7 The effect of SNIR on the Outage probability for MIMO systems.

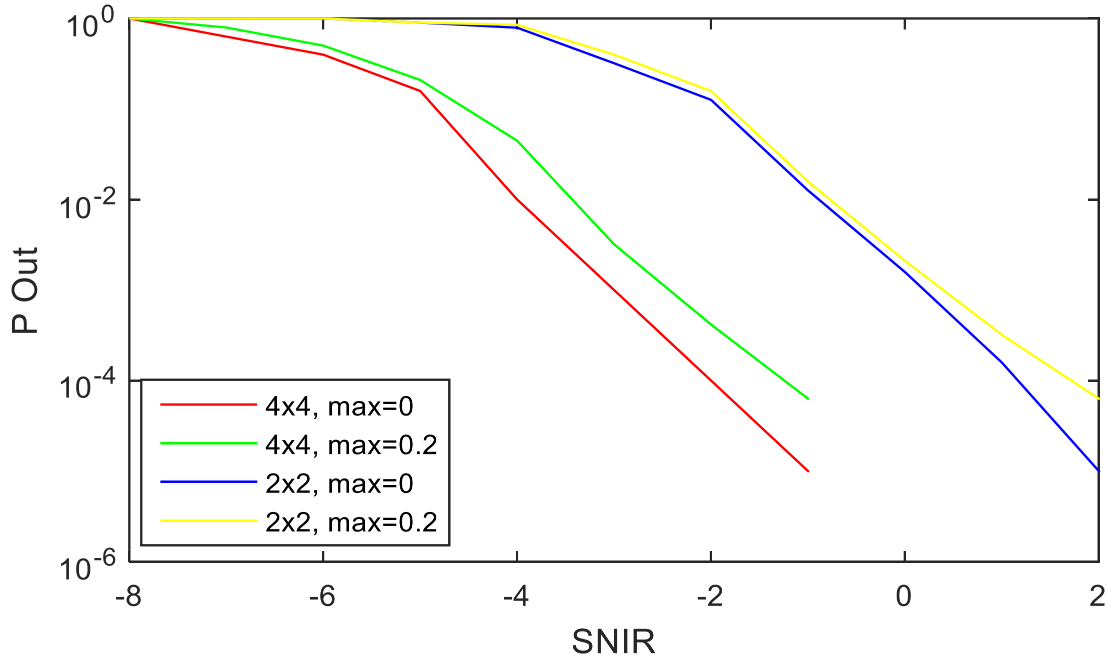

Figure 6.8 The effect of SNIR on the Outage Probability for MIMO systems with varying max values.

Moreover, the probability decreases for all MIMO multiplexing with the rise of SNIR. Hence, the outage probability of cooperative relay is better than that of non-cooperative relay. Both the simulation result and numerical analysis clearly indicates that the proposed system provides better performance due to the increase of cooperative relays.

6.6 Comparison with Previous Research

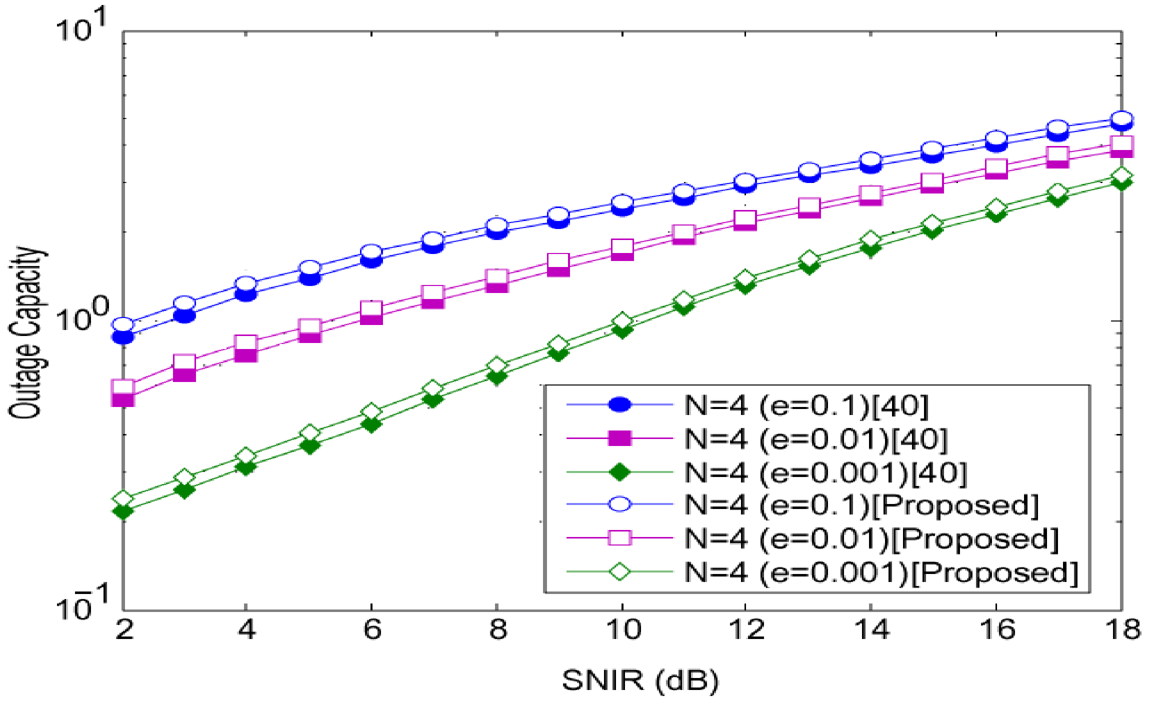

Figure 6.9 SNIR vs outage capacity for different values of ε and with N=4 number of ST (cooperative relays).

The outage capacity has been observed considering SNIR from 2 to 18 dB and varying the given probability ∈=0.1, 0.01, 0.001 for N=4 relays.

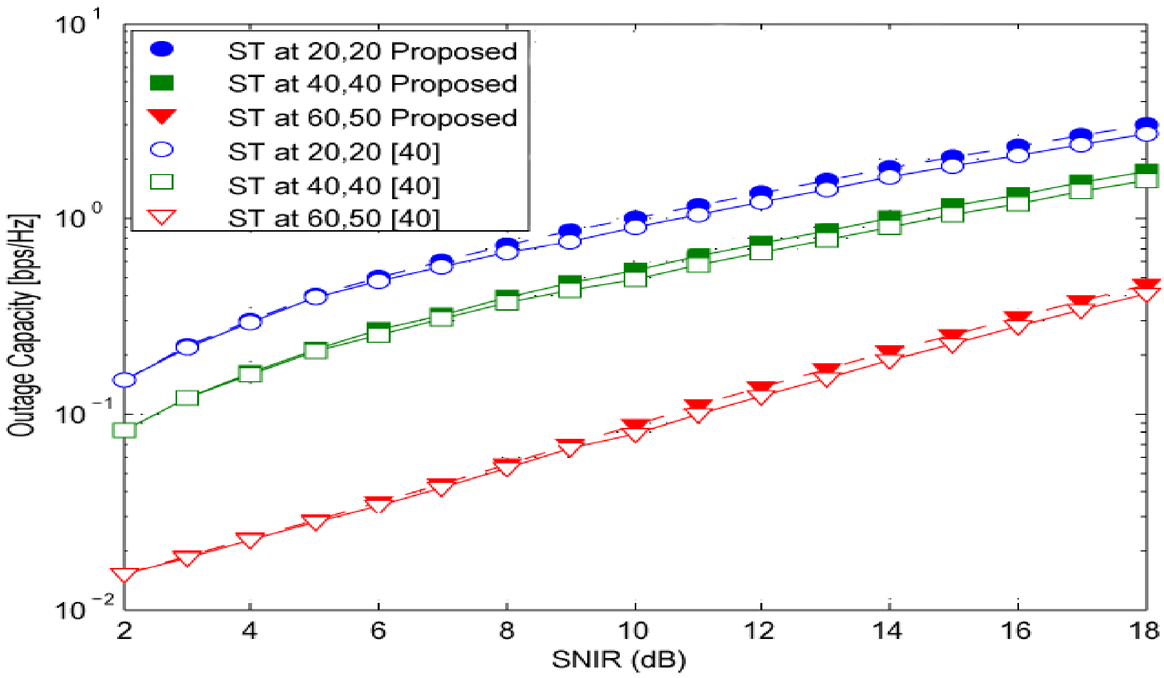

Figure 6.10 SNIR vs outage capacity with varying position of ST where relay position is fixed.

However, outage capacity of the proposed system with existing system is also analyzed considering same number of relays for same SNIR shown in figure 6.9. Comparing this figure, it is noticed in figure 6.9 that the suggested system's outage capacity is 1, 0.6, 0.25 at 12 dB SNIR, while these values are approximately 0.9, 0.54, 0.23 in the referenced study for outage probability, ϵ =0.1, 0.01, 0.001 correspondingly. Hence, it is concluded that the suggested system increases outage capacity by increasing SNIR.

On the contrary, figure 6.10 shows the outage capacity with varying position of active ST for a given outage probability.

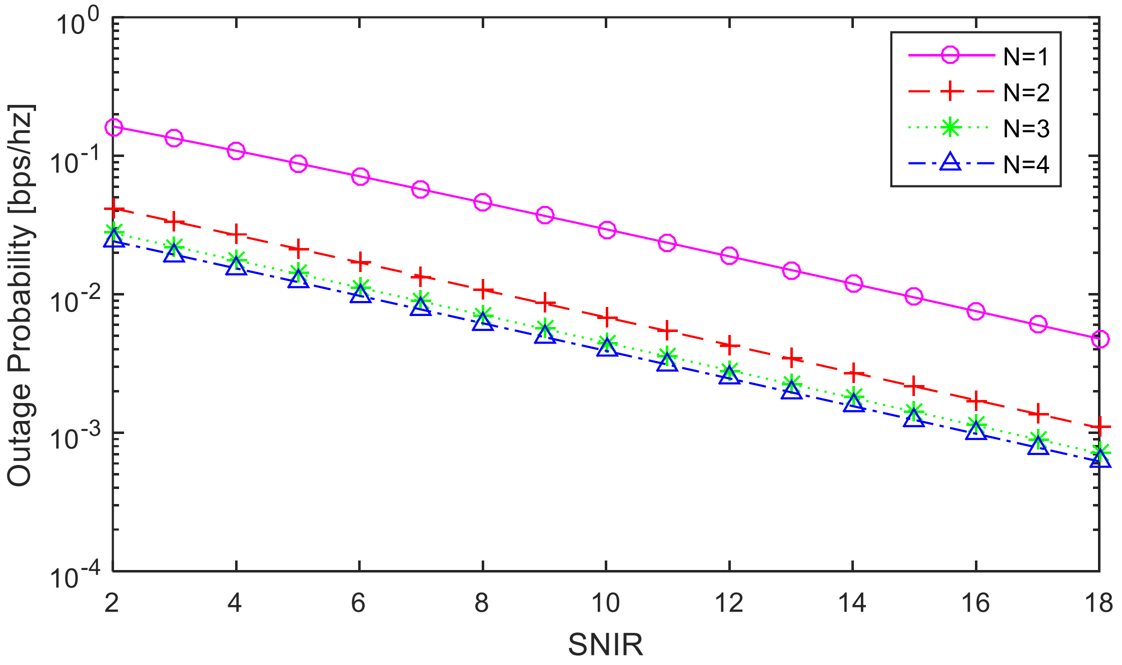

Figure 6.11 SNIR vs outage probability for different values of nodes (cooperative relays).

When the active ST is located far away from the PR, as shown in Figure 6.10, the outage capacity increases as the interference effect decreases. For the nearest location of ST (20, 20) to PR, the outage capacity of a research [40] has been found almost 0.9 at 10 dB SNIR while for new proposed system it has been evaluated to be about 1 for the same location and same SNIR. Hence, new designed model shows better performance in terms of outage capacity compared to [40].

Observing the simulation results, it is found that better outage probability has been investigated in new proposed system shown in figure 6.11. For instance, at 8 dB SNIR, [40] outage probability of the previous research is approximately 0.013 for four relays while for the same condition, the outage probability is 0.004 in our proposed network shown in figure 6.11. Hence, the proposed scheme can be considered as improved version in terms of outage probability.

6.7 Chapter Summary

This chapter shows the behavior of some important user parameters for the implementation of proposed MC-CDMA based CRN under Rayleigh fading channel. Performance of the proposed system model has been evaluated using MATLAB simulations. This chapter provides the results of outage probability as well as outage capacity with SNIR and cooperative relay. The results analysis clearly shows the better system performance for proposed model of the CRN. In the end, the outage capacity and outage probability by increasing SNIR of proposed system with existing system is investigated.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

In this paper the outage probability and outage capacity expression have been deduced for cooperative relaying link of a least temperature constraint CRN. A closed form equation of the outage probability as well as the outage capacity and joint PDF has also been derived. The establishment of a cooperative relay network is the cost of this enhancement which includes primary and secondary systems. The primary networks are divided into two phases, where the first phase is from PT to inactive SU (relay) and the second phase is from relay to PR. It involves dividing STs into active and inactive groups, using a better relay selection procedure, as well as coordination and synchronization between PT, PR, and relays during the first phase and the second phase. Numerical results show that the performance of the proposed system is better for cooperative relay nodes and when the number of nodes N increases to two or more, we observed that the cooperative link outperforms the DL transmission in terms of outage capacity. It has also been found that the theoretical and numerical results matched properly.

To share the spectrum of other mobile it is necessary to analyze the performance of the proposed MC-CDMA cooperative relay communication system. The performance of SNIR for Rayleigh fading channel with MRC technique for different systems like SIMO, MISO and MIMO with and without interference are determined and also the derived expression of outage probability matched with the simulation result.

7.2 Major Contribution of this Thesis

In this thesis, the research is different from other previous works. Some distinguishable contributions of this research are given below:

1. The closed form SNIR equation of MC-CDMA system-based CRN is analyzed where pair of SUs has been considered in the proposed system scenario.
2. The closed from joint probability equation is derived in order to evaluate the outage probability as well as outage capacity of cooperative relay based CRN under satisfying interference temperature I_{TH} for MC-CDMA primary system where inactive STs act as a cooperative relay.

3. The outage capacity is shown to be improved when the number of relays increase and better outage probability has been found in proposed network.

7.3 Scope of Future Work

Thesis paper developed the framework for a MC-CDMA system-based CRN technique. Although several features were investigated, few of the issues were not considered due to the work required and complexity of analytical analysis. Higher order modulation scheme such as QPSK can be used in future for further analysis. In addition, some, forward error correction coding techniques can be used for further increasing the system performance i.e., convolution coding, turbo coding etc. Further works can be carried out for MC-DS-CDMA with cooperative relay-based CRN technique and also applying MIMO transmit and receive diversity for this system. It is assumed that CSI is known in this analysis. Determining capacity for unknown CSI will be a problem in the future.

LIST OF PUBLICATIONS

The contributions of this thesis have been published in international conferences as listed below:

International Conferences

1. M. A. Kabir and M. S. Kaiser, "Outage capacity analysis of MC-CDMA based on cognitive radio network," 2015 *International Conference on Electrical Engineering and Information Communication Technology (ICEEICT)*, Dhaka, 2015, pp. 1-5, doi: 10.1109/ICEEICT.2015.7307463.
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ANNEX-A

A. Derivation of equation (4.13)

Let λ_p and λ_s are the two expected mean value of Rayleigh random variable. The joint PDF equation (13) can be derived as follows:

$$\begin{aligned}
f_{\gamma_i}(y) &= \frac{1}{\lambda_s^2\lambda_p^2}\int_0^\infty y^3 e^{(-\frac{y^2 z}{2\lambda_s^2})} e^{(-\frac{y^2}{2\lambda_p^2})}\, dy \\
&= \frac{1}{\lambda_s^2\lambda_p^2}\int_0^\infty y^3 e^{-y^2(\frac{z}{2\lambda_s^2}+\frac{1}{2\lambda_p^2})}\, dy \\
&= \frac{4}{ab}\int_0^\infty y^3 e^{-y^2(\frac{z}{a}+\frac{1}{b})}\, dy \text{ [Let, } 2\lambda_s^2 = a, 2\lambda_p^2 = b] \\
&= \frac{4}{ab}\int_0^\infty y^2 e^{-y^2(\frac{z}{a}+\frac{1}{b})}\, y dy \\
&= \frac{4}{2ab}\int_0^\infty x e^{-x(\frac{bz+a}{ab})}\, dx \\
&= \frac{2}{ab}[x\int_0^\infty e^{-x\left(\frac{bz+a}{ab}\right)}\, dx \\
&\qquad - \int_0^\infty (\frac{d}{dx}x(\int e^{-x\left(\frac{bz+a}{ab}\right)}\, dx)dx] \\
&= \frac{2}{ab}\frac{a^2b^2}{(bz+a)^2} \\
&= \frac{1}{2\lambda_s^2\lambda_p^2}\frac{16\lambda_s^4\lambda_p^4}{(2\lambda_p^2 z+2\lambda_s^2)^2} \\
f_{\gamma_i}(y) &= \frac{4\lambda_s^2\lambda_p^2}{(\lambda_p^2 z+\lambda_s^2)^2}
\end{aligned}$$