Performance Evaluation and Analysis of Power Limited Cognitive Radios

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Submitted By

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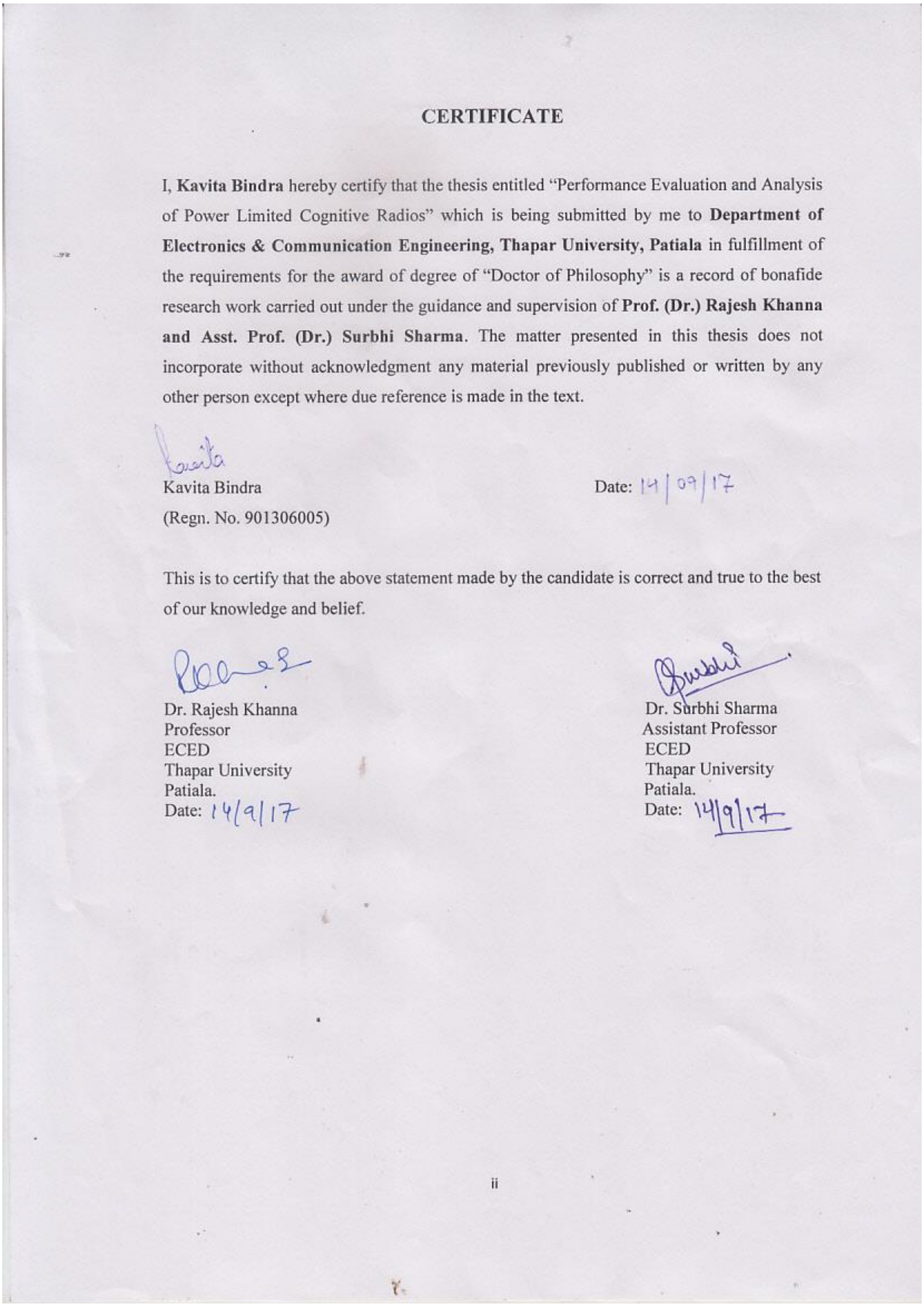

CERTIFICATE

I, **Kavita Bindra** hereby certify that the thesis entitled "Performance Evaluation and Analysis of Power Limited Cognitive Radios" which is being submitted by me to **Department of Electronics & Communication Engineering, Thapar University, Patiala** in fulfillment of the requirements for the award of degree of "Doctor of Philosophy" is a record of bonafide research work carried out under the guidance and supervision of **Prof. (Dr.) Rajesh Khanna and Asst. Prof. (Dr.) Surbhi Sharma**. The matter presented in this thesis does not incorporate without acknowledgment any material previously published or written by any other person except where due reference is made in the text.

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This is to certify that the above statement made by the candidate is correct and true to the best of our knowledge and belief.

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Abstract

Due to ever increasing demand of higher data rate, improved spectral efficiency, lower latency rate and reduced bit error rate, there is a need to develop an efficient communication system that skilfully utilizing the scarce spectrum resources and is capable of meeting above requirements. By taking this into consideration, the formulated objectives of the thesis lead to an improved communication system which incorporates underlay spectrum sharing cognitive radios, an improved diversity combining technique i.e. Generalized Selection Combining and transmit diversity, obtained through Transmit Antenna Selection as well as Space Time Block Coding in multiuser environment. First of all, this thesis discusses an underlay cognitive radio where the cognitive user and the primary user share the same spectrum bandwidth. The proposed system is analyzed by employing transmit antenna selection and generalized selection combining in multiuser scenario in context of average post processing signal-to-noise-ratio (SNR) and ergodic capacity. In scheduled multiuser environment, the $'K'$ active users are competing for the spectrum resources. The results attained thus shows that all the performance metrics improve as the number of best combined receiver branches increases. Also enhanced performance is achieved when one best transmit antenna and the one best cognitive user is chosen on the basis of highest post processed SNR at the output of CR receiver.

Likewise, another very effective transmit diversity scheme is applied i.e. space time coding with generalized selection combining in underlay cognitive radios. This system is investigated with average post processed SNR, ergodic capacity and the average bit error rate, when the transmit power of cognitive transmitter is constrained by the outage probability of the primary network. The improved results are obtained for all the performance metrics when the number of best combined branches increases from 1 (Selection combining) to 4 (Maximal ratio combining), respectively. This section concludes with the performance comparison of shared spectrum cognitive radios with transmit antenna selection and space time block coding with generalized selection combining in multiuser multi-input-multi-output (MIMO) system. The average post processed SNR, ergodic capacity and the average bit error rate is analyzed for both the proposed systems. The achieved outcomes reveals that the system employing transmit antenna selection provides better and improved performance as compared to the MIMO counterpart. Also it is shown that performance gains become even more when one best cognitive user is chosen out of all competing users. This thesis also focuses on the interference environment which is studied and analyzed with the optimal combining scheme i.e. Optimum Combining. The underlay cognitive radios is studied and analyzed with the average post processed SNR, ergodic capacity, outage probability and the average bit error rate, when the proposed system is constrained of interference temperature limit as defined by the primary network. The proposed work is also analyzed with the varying number of primary interferers and the number of receiver branches. All the achieved simulation results are well corroborated with their analytical counterpart.

Keywords:

Average post processed signal-to-noise-ratio, Average bit error rate, Cognitive radio, Ergodic capacity, Generalised selection combining, Multiuser diversity, Optimum combining, Space time block coding, Transmit antenna selection.

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(Kavita Bindra)

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List of Acronyms

ABER	Average Bit Error Rate
AIP	Average Interference Power
AMPS	Advanced Mobile Phone systems
AS	Antenna Selection
AWGN	Additive White Gaussian Noise
BLAST	Bell labs space time architecture
CA	Convex Approximation
CCI	Co-Channel Interference
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CR	Cognitive Radio
CSI	Channel State Information
DOFs	Degree of Freedoms
DPC	Dirty Paper Coding
DPSK	Differential Phase shift Keying
DSS	Dynamic Spectrum Sharing
ECC	Electronic Communications Committee
EDGE	Enhanced data for GSM evolution
EGC	Equal Gain Combining
EH	Energy Harvesting
EVDO	Evolution Data Optimized
FCC	Federal Communications Commission
FSK	Frequency shift Keying
GPRS	General Packet radio services
GSC	Generalized Selection Combining
GSM	Global System for Mobile communication
GSTSOM	Generalized Space time Sum of Magnitudes
GSTSOS	Generalized Space time Sum of Squares
HDTV	High Definition Television
HSPA	High Speed Packet Access

I I D	Independent and Identically Distributed
I T	Interference Temperature
IoTs	Internet of Things
ISM	Industrial Scientific and Medical
ITU	International Telecommunication Union
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Multiple Access
MATLAB	Matrix Laboratory
MC-CDMA	Multi Carrier- Code Division Multiple Access
MCS-TM-NI	MIMO cognitive system-TAS/MRC-No Interference
MGF	Moment Generating Function
MIMO	Multiple Input and Multiple Output
MISO	Multiple Input Single Output
mmW	Millimeter Wave
MRC	Maximal Ratio Combining
MRRC	Maximal Ratio Receive Combining
MS-GSC	Minimum Selection Generalized Selection Combining
MUD	Multiuser Diversity
NMT	Nordic Mobile Telephone
OC	Optimum Combining
OFDM	Orthogonal Frequency Division Multiplexing
OSTBC	Orthogonal Space Time Block Coding
PAM	Pulse Amplitude Modulation
PDF	Probability Density Function
PSK	Phase Shift Keying
PTP	Peak Transmit Power
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAS	Receive Antenna Selection
RF	Radio Frequency
Rx	Receiver
SC	Selection Combining
SD	Spatial Diversity

SDMA	Space Division Multiple Access
SDR	Software Defined Radio
SER	Symbol Error Rate
SIMO	Single Input and Multiple Output
SINR	Signal-to-Noise and Interference Ratio
SM	Spatial Multiplexing
SNR	Signal-to-Noise-Ratio
STBC	Space Time Block coding
STC	Space Time Coding
STTC	Space Time Trellis Coding
SU	Secondary User
TAS	Transmit Antenna Selection
Tx	Transmitter
U-NII	Unlicensed Information Infrastructure
UWB	Ultra Wide-Band
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide interoperability for Microwave Access
WLANs	Wireless Local Area Networks
WPC	Wireless Planning and Coordination
WRANs	Wireless Regional Area Networks
ZF	Zero Forcing

List of Symbols

$(.)^{T}$	The transpose of a vector
$(\,.\,)^{H}$	The Hermitian (Complex conjugate) transpose of a vector
${}_2F_1$	Hyper geometric function
$\log_2$	Log with the base 2
Ω_y	Mean value of random variable y
L_t	Number of interferers
N_{PR}	Number of primary user receive antennas for STBC/GSC system
N_c	Best combined receiver branches
N_r	Number of receive antennas at the CR-Rx
N_t	Number of transmit antennas at the CR-Tx
P_{crmax}	Maximum transmit power for the STBC/GSC system
$P_{p,out}$	Outage probability constraint of the primary network
P_p	Peak transmit power of CR-Tx for the S-TAS/GSC system
P_{pu}	Transmit power of primary network for STBC/GSC system
P_r	Probability
P_t	Transmit power of CR-Tx for CR-OC system
R_{CR}	Transmission rate of the CR network for the STBC/GSC system
R_{PU}	Transmission rate of the primary network for STBC/GSC system
γ_{PUth}	Outage probability threshold of the primary network
γ_t	SIR threshold value
ϵ_{PU}	Desired outage probability of the primary network
$\sim, \approx$	Approximately
$<$	Less than
$<<$	Much less than
$\leq$	Less than equal to
$\geq$	Greater than equal to
argmax( )	Returns the largest value from a vector
B	Signal bandwidth

Q	Interference temperature limit
CN(mean,variance)	circularly symmetric and complex random values
$Q(x)$	Gaussian Q- function
Γ	Gamma function
K	Number of CR users
L	Primary user receive antenna for S-TAS/GSC system
N	Total number of uncoded bits transmitted for the STBC/GSC system
No	Noise power spectral density
P	Transmit power of interferer
Pe	Probability of error
R	Interference covariance matrix
$\mathbb{E}[.]$	An expectation operator
ε	Covariance matrix for CR-OC system
ξ	Mean interference power received at the primary receiver
ς	Neper’s number

List of SCI publications

- Kavita Vij Bindra, Surbhi Sharma and Rajesh Khanna, “Performance Analysis of Scheduled TAS Cognitive Radio system with Generalized Selection Combining”, Wireless Personal Communications, Vol. 95, No. 2, pp. 1567-1582, July 2017. **(Impact Factor: 0.1.200)**
- Kavita Vij Bindra, Surbhi Sharma and Rajesh Khanna, “Performance Analysis of Combined Space Time Block Coding with Generalized Selection Combining in Underlay Cognitive Radio”, Wireless Personal Communications, Vol. 95, No. 3, pp. 2561-2573, Aug. 2017. **(Impact Factor: 1.200)**
- Kavita Vij Bindra, Rajesh Khanna and Surbhi Sharma, “Performance Analysis of Optimum Combiner in Power Limited Cognitive Radios with multiple primary interferers”, Electronika ir Electrotechnika, Vol. 24, No.1, 2018. **(Impact Factor: 0.859).**

Chapter 1

Introduction to Cognitive Radio

1.1 Introduction

Wireless technology is a backbone of all aspects of communication and computing. Over the last decade, there is increasing demand for higher data rate and improved spectral efficiency. In wireless communication, the numbers of users are rising exponentially. In order to cope up with these demands, the researchers have to meet two contradictory goals i.e. improved data rate and interference reduction with slight increase in bandwidth and power. Thus a reliable and efficient spectrum utilization policy [1-2] will be a vital aspect for the exponential growth of demand and innovation in wireless world. The radio spectrum is becoming limited due to aggressing new technologies. Thus let us brief some wireless technologies [5] which cater the thrust of high data rate and regional coverage. e.g. GSM (Global system for mobile communication), CDMA (Code division multiple access), GPRS (General packet radio services) and EDGE (Enhanced data for GSM evolution) etc. are 2G (second generation) wireless systems which are capable of providing high speed data exchange and voice calling. The 3G & 4G (third and fourth generation) technologies support voice calling, video calling and conferencing, online gaming and high definition television (HDTV). Some of the 3G and 4G technologies are WCDMA (wideband code division multiple access), CDMA 2000 and LTE (Long term evolution), WiMAX (Worldwide interoperability for microwave access). Due to unprecedented rise in wireless data traffic and mobile users, there is a need to accommodate this enormous thrust for higher data rate and unlimited bandwidth. So the wireless researchers initiated a changeover from 4G to 5G. 5G technology aims at providing higher data rate with low latency and efficient utilization of energy and spectrum resources. Examples of some 5G aspects are: cognitive radios, millimeterWave (mmW) communication, Internet of Things (IoTs), massive MIMO and smart antennas etc. The evolution of all wireless technologies is summarized in Table-1.1

To support compatibility among standards, hardware set ups, interference free and seamless communication, the electromagnetic spectrum is shared and used among all the nations worldwide. The International Telecommunication Union (ITU) [2] allocates the frequency spectrum to different countries and also holds their right or its efficient and unlimited usage. The wireless planning and coordination (WPC) wing of ministry of communication in India is responsible for spectrum licensing its associated management in order to fulfill the demands of wireless users. In ITU, the working party (WP) 1B is managing the relationship between software defined radio (SDR) and cognitive radio (CR) in context of technical and operational recommendations. Also WP 5A is developing the application of cognitive radio system for mobile services.

Table-1.1: Evolution of wireless technology [5].

Generation	Time Period	Technology	Data Rate	Features
1 G	1981-1990	AMPS (Advanced Mobile Phone System) NMT (Nordic Mobile Telephone)	~ 14.4 Kbps	Supports analog signal which provides voice calling.
2G	1991-2000	GSM (Gobal System for Mobile Communication) CDMA (Code Division Multiple Access)	~ 10 Kbps	Supports digital data exchange and voice calling
2.5 G	2001-2004	GPRS (General Packet Radio Service)	~ 50 Kbps	Supports packet data using internet over cellular network
3 G	2004-2005	WCDMA (Wideband Code Division Multiple Access), CDMA 2000	~ 384 Kbps	Provides data exchange, voice and video calling, multimedia services with streaming.
		EVDO (evolution Data Optimized)	~ 5-30 Mbps	
4 G	2010	LTE (Long Term Evolution), WiMax (Worldwide Interoperability for microwave access)	~ 100-200 Mbps	Video Conferencing, online gaming, HDTV (High Definition Television)
5G	Come into existence probably by 2020	CR (Cognitive Radios), OFDM (Orthogonal Frequency Division Multiplexing Access), MC-CDMA (Multi Carrier- Code Division Multiple Access), UWB (Ultra Wide Band)	~ 1Gbps	Currently there is no 5G technology in use. Upcoming 5G is aiming at providing higher data rate with efficient utilisation of spectrum resources.

The Electromagnetic emissions and the usage of radio spectrum is regulated and coordinated by the International regulatory agencies such as Federal Communications Commission FCC (United States) and Electronic Communications Committee (ECC Europe). The radio spectrum is divided into several frequency bands which are further separated into licensed and unlicensed bands. *Unlicensed frequency bands* are those part of radio spectrum in which any type of radio service is allowed. The unlicensed user also known as cognitive or secondary user (SU) which occupies the unlicensed bands, has to meet some predefined set of regulatory requirements such as transmit power, modulation type and antenna characteristics etc. Some examples of unlicensed frequency bands are Industrial Scientific and Medical (ISM) such as 2.4 GHz band and Unlicensed Information Infrastructure (U-NII) band in US, such as 5 GHz. The *licensed frequency bands* are being assigned to the licensed user also known as primary users (PU) which exhibits the exclusive rights to utilize these bands for radio communication. Some of the examples of licensed radio communication are radio navigation, television broadcasting and cellular services etc.

Static spectrum allocation i.e. to assign licensed frequency band to PU is favorable and have many benefits. The significant advantage is its simple implementation for apportioning specific spectrum as there is no ambiguity that who can use the spectrum. Also there is no predefined regulation to be followed. The licensed spectrum can be allocated statically or dynamically. As for static spectrum allocation, the functional devices are fixed and substantial infrastructure investment makes sense only when, one has acquired the assured access to the given spectrum band. The equipments deployed to transmit on the dedicated frequency band is designed simpler and does not require any interference management because the dedicated user is not bothered about arbitrary competing users.

The static spectrum allocation scheme has many benefits and also played an essential role in the past but it lead to very inefficient and under utilization of the scarce radio spectrum. According to FCC, it is found that most of the spectrum is left under utilized in accordance with temporal and geographical variations [13]. The rapid increase in new innovative technologies is straining the efficiency of conventional spectrum allocation policies. As a result, this inefficiency in the usage of limited available spectrum necessitates exploiting a new communication paradigm which aims at improving the spectrum usage and allocation so as to nurture innovation. The only solution is to migrate from current spectrum allocation policy to Dynamic Spectrum Sharing scheme (DSS) [3-5]. DSS is a set of techniques that focuses at better utilization of radio spectrum as a function of space, time and frequency.

Thus, Cognitive Radio (CR) [4] has been proposed which significantly improves the radio spectrum utilization by its flexible spectrum management schemes. A cognitive radio is defined as an intelligent communication system, which is aware of its surrounding and adapts its parameters such as transmit power, modulation type and carrier frequency etc. by keeping two contrary aims to be achieved:

(a) Highly reliable communication link to be established while maintaining interference below some threshold limit.

(b) Efficient utilization of spectrum by taking into consideration the predefined set of protocols.

Apart from interference regulation and management [6], another basic point for the cognitive radio technology is the standardization process. It will take the evolution to next generation CR technology, which definitely provides enhanced functionalities and improved services by utilizing the scarce radio spectrum in a gainful manner [5]. Also it will ensure significant benefits and provide interoperability among wireless networks. There are several IEEE standard coordinated groups which are working on CR standardization process for instance

- IEEE 802.22 is aiming to develop Wireless Regional Area Networks (WRANs) [7-8] for the cognitive transmission by utilizing TV white space (TVWS). TVWS is the under utilized portion or the temporal spectrum holes in the allocated television frequency spectrum which can be exploited by the unlicensed users. The under utilization of white spaces in television spectrum and an easy monitoring of PU activity invokes TVWS usage in WRANs for CR [2,8].
- IEEE 802.16h is working on the interference management as interference poses a major issue in spectrum sharing.
- IEEE 802.11y aims at developing a protocol for efficient resource utilization to allocate resources in a gainful way which leads to overall system improvement.

A CR, first of all senses the unoccupied part of spectrum, which is also called as 'holes'. The holes are that portion of spectrum which are currently not being utilized by PU or incubent user. After finding a vacant frequency band, the CR adapts its parameter in accordance with statistical variations on the pretext that it should not cause harmful effects of cross interference to the PU.

Even after the communication starts, the CR has to predict the appearance of PU so that a SU or CR user can vacate an occupied band to the PU. A CR technology incorporate four functionalities [9] as illustrated in Figure 1.1 and given below in steps (a) to (d):

a) To determine the vacant part of spectrum which is not currently being used by PU *(SPECTRUM SENSING).*

b) To choose the best available channel for communication *(SPECTRUM DECISION).*

c) To share the spectrum simultaneously with PU on some specified criteria and also allocate the available resources to one best user among all contending users. *(SPECTRUM SHARING).*

d) To leave an occupied channel and migrate to new one whenever the PU appears for transmission *(SPECTRUM MOBILITY).*

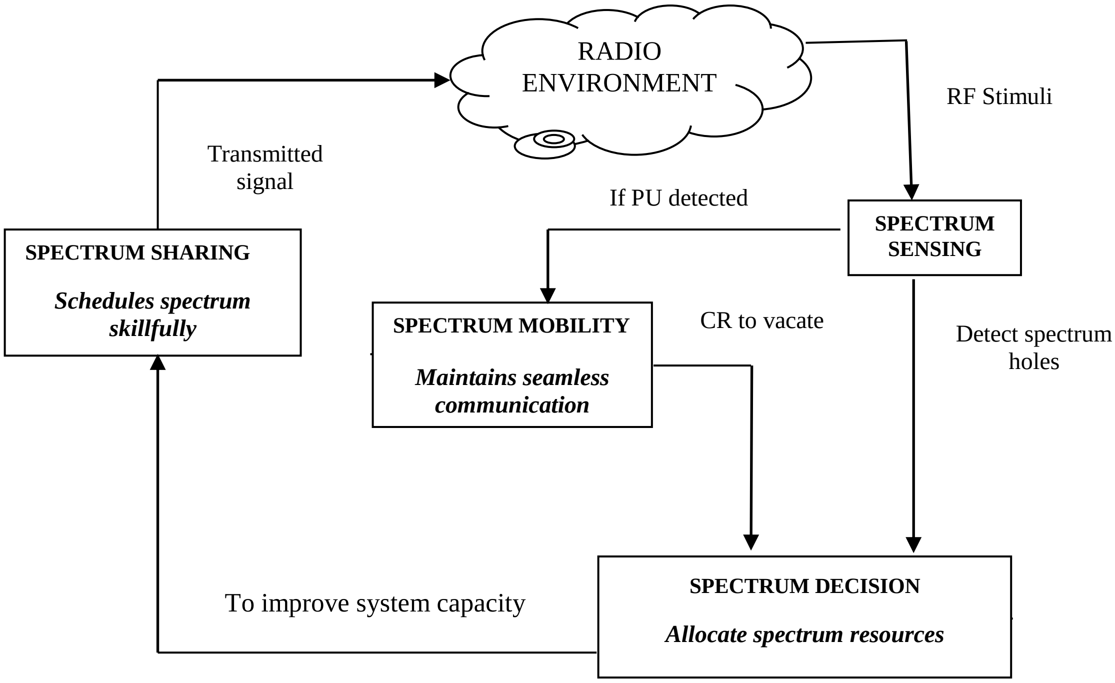

Fig. 1.1 Block diagram of a Cognitive radio.

A CR has three main network paradigms [9-11] such as underlay, overlay and interweave. The underlay paradigm aims at simultaneous transmission of PU and SU but on the pretext that cognitive user should keep its interference to PU below some acceptable threshold [12-14]. In overlay paradigm, the cognitive user have access to over hear the signal processing and coding of primary network and also transmits PU data in order to improve the performance of primary network. In interweave paradigm, the cognitive user has to search for vacant spectrum and exploit the detected holes for its transmission. Chapter 2 describes each type of spectrum access method in detail.

1.2 Aim and objectives of the thesis

The proposed system is designed in such a way that it should meet the following requirements:

- To proficiently utilize the available scarce radio spectrum thus enhances the spectral efficiency of the proposed system.
- To reduce the probability of error and simultaneously increases the data rate of the designed system.
- To reduce the signal processing and the overall system complexity.

Besides the above defined requirements, the proposed CR system is also capable of achieving the following aims:

(a) Interference Management

By taking into context, the better utilization of spectrum, we adopted underlay spectrum access scheme in which PU and CR users communicate concurrently over the same channel and CR user regulates its transmit power in order to protect PU from interference. To achieve this, we have studied and analyzed the effects of various transmit power strategies by considering interference temperature constraint (Q), PU outage probability constraint, peak transmit power constraint and average interference power constraint.

(b) Throughput enhancement

In order to improve system capacity, we have employed transmitter and receiver diversity. The proposed system is improved through TAS and STBC schemes at the transmitter whereas receive diversity is obtained by deploying GSC, MRC and OC combining at the dedicated Rx. By implementing TAS and GSC at transmitter and receiver simultaneously reduces system complexity and provides improved spectral efficiency.

(c) Efficient Resource allocation

The efficient resource allocation is another key idea in CR technology. CR scheme also ensure that all the available resources will be provided to best CR user on the basis of instantaneous channel conditions. This feature is defined by one of the four functionalities of CR i.e. spectrum management which have potential to achieve multi-user diversity gain. Keeping above defined aims in our mind, the following objectives are formulated in this research work.

Objectives

1. To evaluate and analyze an improved combining technique in power limited Cognitive Radios.
2. Performance analysis of proposed technique in different fading environments.
3. Performance evaluation of proposed scheme with antenna selection in scheduled underlay cognitive radios.
4. Performance evaluation and analysis in MIMO systems.

1.3 Contribution of the Thesis

Based on the motivations, the main contribution of the thesis is the implementation of CR by deploying underlay spectrum access method. In order to reduce the complexity of the proposed system, GSC combining technique with TAS and STC schemes is well studied and analyzed. The proposed system deals with transmitter and receiver diversity simultaneously. The system under consideration is analyzed for the effect of multiuser diversity when the multiple users are trying to compete for the spectrum resources. Also the impact of interference is demonstrated by employing OC in underlay CR system. The contributions of the thesis are listed below:

Contribution 1:

(a) To evaluate and analyze an improved combining technique in power limited Cognitive Radios.

(b) Performance evaluation of proposed scheme with antenna selection in scheduled underlay cognitive radios.

This contribution is achieved by studying and analyzing an improved diversity combining i.e. GSC in underlay cognitive radios, when the transmitted signal undergoes Rayleigh as well as Rician fading. Its improvement has been demonstrated in terms of average post processing SNR at the receiver output and ergodic capacity. The results obtained show that both the performance metrics are a function of number of best chosen branches on the basis of largest effective SNR.

Additionally, the transmit diversity is attained by applying TAS and receive diversity is obtained by equipping Rx with GSC technique. In this contribution, the cognitive transmitter is limiting its transmit power below the interference temperature limit (Q) as defined by primary network. The effect of joint transmit and receive diversity in multiuser scenario has been studied. We have derived approximate expressions for the probability density function (PDF) of TAS/GSC CR system, average post processing SNR and ergodic capacity for the proposed system. Finally, the obtained results for scheduled system are compared with conventional non-scheduled system.

Contribution 2:

Performance evaluation and analysis in MIMO or STBC/GSC systems

In this contribution, the transmit diversity is achieved by a very popular technique i.e. space time coding. The transmit power of CR-Tx is restricted by fulfilling the outage probability constraint as defined by primary network. This contribution is analyzed for average post processed SNR at the receiver output, ergodic capacity and average bit error rate (ABER).

We have derived expressions for the PDF of the proposed STBC/GSC CR system, average post processed SNR and ABER, by using moment generating function (MGF). Analytical outcomes are validated by computer simulations performed by MATLAB software.

Contribution 3:

Performance comparison between scheduled TAS/GSC and scheduled STBC/GSC in power limited cognitive radios

This contribution is achieved by performing the comparison between scheduled TAS/GSC and scheduled STBC/GSC in underlay CR under PU outage probability constraint. This contribution is analyzed with average post processed SNR, ergodic capacity and ABER for both the scheduled as well as non-scheduled system. The achieved results show that TAS outperforms STBC in terms of system performance but STBC has simpler implementation and reduced signal processing.

Contribution 4:

Performance Analysis of optimum combiner in power limited cognitive radios with multiple primary interferers

In this contribution, the underlay cognitive radio has been analyzed with OC at the CR-Rx under the influence of interference from multiple primary interferers. The transmit power of CR-Tx is restricted by the AIP constraint as given by PU. This part of research work is analyzed in terms of average signal-to-interference-ratio (SIR) at the CR-Rx, ergodic capacity, outage probability and ABER. The achieved results show that all the above said performance metrics are function of number of interferers.

1.4 Thesis Organization

The thesis is organized in six chapters. The detailed content of each chapter of the thesis are as follows:

CHAPTER I discusses the need of cognitive radios and presents static and dynamic spectrum allocation in CR. Also it presents motivation for research, aims, objectives and organization of the thesis.

CHAPTER II describes cognitive radios paradigms, diversity combining techniques, transmit antenna selection, space time block coding and multiuser scheduling in detail. After describing above defined parameters, their associated literature review is presented.

CHAPTER III introduces GSC in Rician and Rayleigh fading environment. It also deals with the design and analysis of TAS with GSC in multiuser environment. It analyzes the proposed system model both analytically and with Monte Carlo simulations performed through MATLAB. In addition, it also discusses the advantages of employing transmit and receive diversity simultaneously.

CHAPTER IV deals with the design and analysis of MIMO system in power limited cognitive radios. It describes the proposed system model which includes the STBC transmission technique with GSC combining at the CR-Rx. The proposed system is analyzed with the new transmit power policy which is based on the primary user outage constraint. It also includes the performance analysis and simulations of the system with its complexity considerations. Also it deals with the comparative analysis between TAS/GSC and STBC/GSC in power limited cognitive radios. Both the scheduled and non-scheduled TAS/GSC and STBC/GSC have been compared.

CHAPTER V introduces underlay cognitive radios in interference limited environment. It discusses the system model for the proposed system with OC at the CR-Rx under the impact of multiple PU interferers. This chapter also includes the performance analysis and simulations of the proposed system under consideration.

CHAPTER VI concludes the research work and presents future scope for further research.

Chapter 2

Implementing Cognitive radio with various spatial diversity schemes and its related literature Review

This chapter is divided into five sections. Section 2.1, presents introduction and available literature on the evolution of Cognitive radios, various spectrum access techniques and transmit power control strategies to avoid interference to the PU network. Section 2.2 encompasses different diversity combining techniques and its associated literature in MIMO and CR. Section 2.3, discusses transmit diversity and its related literature in terms of TAS and STBC. Section 2.4 focuses at MUD environment with appropriate scheduling techniques and finally this chapter concluded with section 2.5, which embraced co-channel interference scenario.

2.1 Introduction to various spectrum access techniques in Cognitive Radios

As discussed in preceding chapter that cognitive radio is an effective means to utilise the radio spectrum resources in a gainful manner. Its features and various spectrum access strategies lead to the better and skilful utilization of the limited spectrum in an efficient way. In this thesis, we have incorporated one of the spectrum access policy i.e. underlay spectrum sharing. This type of spectrum access technique, allows secondary user to share primary user spectrum on some predefined protocols such as received interference power constraint (Q). To meet this condition, the CR-Tx has to restrict its power to be transmitted. The following section discusses the various spectrum access policies in detail.

(a) Underlay Spectrum Access

Underlay paradigm is a type of spectrum access technique which allows both the primary and cognitive user to communicate concurrently over the same frequency band only if the interference caused by a cognitive user to PU is below some predefined threshold margins, also known as *interference temperature (IT)* [6] as shown in Fig. 2.1. This type of spectrum access technique assumes that the SU-Transmitter (Tx) is equipped with channel state information (CSI) of interference link i.e. from SU-Tx to PU-Receiver (Rx), which can be gathered by a spectrum manager. Interference temperature (Q) can be defined as the maximum interference noise power that a PU-Rx can tolerate [15-17]. The interference temperature constraint can be fulfilled by employing multiple antennas at the SU-Tx which are used to take away the effect of SU transmissions from PU-Rx.

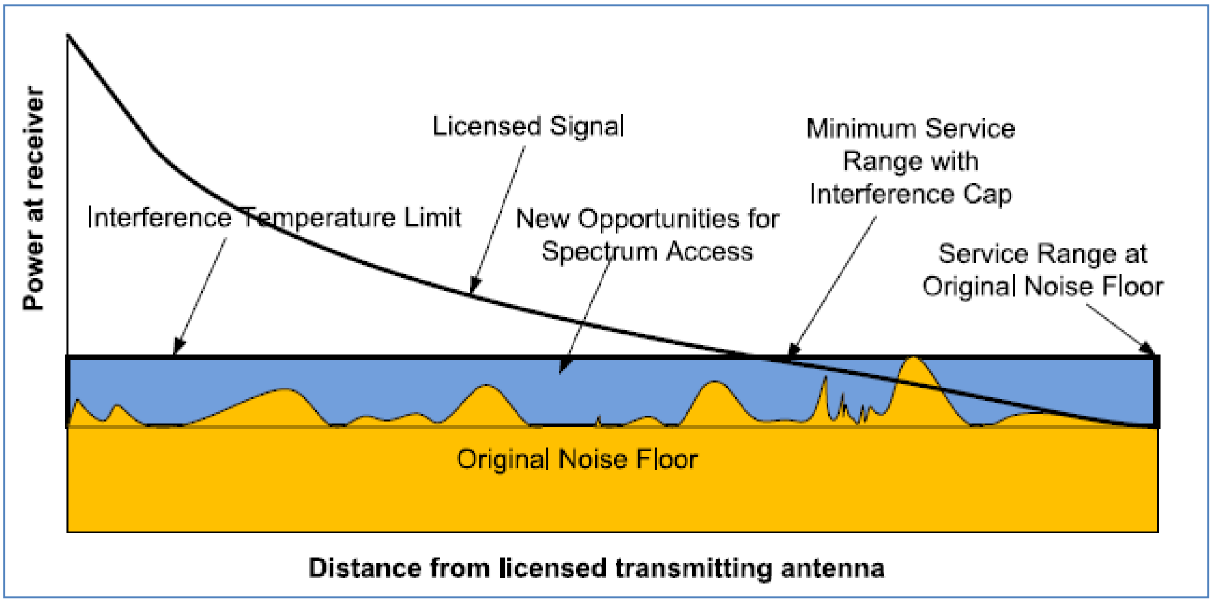

Fig. 2.1 Interference temperature defined by FCC 2003a [11]

This can also be achieved by spreading signal below the noise floor bandwidth (i.e. spread spectrum or ultra wide band (UWB)) at the SU-Tx and then get despread at the intended Rx. Apart from conventional interference temperature constraint, other constraints have also been proposed in the literature such as Average Interference Power (AIP), Peak Transmit Power (PTP), outage probability constraint etc [18-23] are outlined by primary network. The cognitive transmitter should be very conservative so that its transmit power is optimized below a defined threshold. In this type of spectrum access technique, the interference power threshold constraints are very strict, which drives a cognitive network to communicate over short range.

(b) Overlay Spectrum Access

In this type of spectrum sharing access, the SU-Tx is equipped with the knowledge of PU message and codebooks [15-16]. This information can be made available through spectrum manager or PU may broadcast its messages periodically. Alternately, the PU can send its message to be transmitted to SU, prior to its communication. Thus, knowledge of PU codebook message can be exploited in number of ways in order to minimize the effect of interference at SU and PU-Rx. On the other hand, the determinate impact of interference at SU-Rx from PU transmission can be mitigated through dirty paper coding (DPC) technique. On the basis of acquired knowledge about PU transmissions, the SU-Tx can split it’s transmit power into two halves, firstly for its own transmission and remaining half power is used to relay the PU transmissions. The transmit power which optimally divide reveals that increase in Signal-to-Noise- Ratio (SNR) of PU output, due to SU relaying can be balanced if output SNR of PU, decreases because of interference caused by SU-Tx using half power for its transmissions. Hence, it can be concluded that transmission rate of PU remains unchanged even if SU uses half power for its communication. Both the licensed and unlicensed band communication can exploit benefits of overlay paradigm. In licensed band transmission, the SU is allowed to share available bandwidth with PU but it should restrict its transmit power below some margins and simultaneously aims to improve its throughput. In unlicensed band communication, SU has to use the codebook and messages of PU to reduce cross link interference and aim to enhance its spectral efficiency [23-25].

(c) *Interweave Spectrum Access*

This spectrum access method is the ultimate idea that led to the birth of CR technology which is based on opportunistic transmission [13-15]. The research conducted by FCC shows that large part of the spectrum is under utilized. It can be said that there exist a temporary space, time and frequency voids, which can be referred as spectrum holes that are not in regular use by both the licensed and unlicensed bands. These spectrum holes are not permanent and vary according to time and geographical location. Hence, this type of spectrum access policy leads to the better utilization of spectrum holes by cognitive users. All the users who are exploiting the spectrum holes in an unlicensed band are secondary or cognitive users and they have to keep watch on PU activity such that if a PU become active then SU has to vacate current spectrum, thus occupying new available band. It can be concluded that interweave spectrum access method is an intelligent CR which constantly monitors PU behavior to detect the spectrum holes and then opportunistically occupies it, without producing interference to the active users. The concept of CR technology enables us to study the co-existence of primary and cognitive users by exploiting different spectrum access schemes in order to improve the utilization of scarce spectrum. It is clear from the above discussion that the main issue in the deployment of CR is to minimize the effect of cross interference [16-17] and simultaneously improves the overall system capacity. Hence the following section discusses the literature review on the evolution of CR, its features, functionalities, various spectrum access methods and different transmit power control policies.

Literature review on cognitive radios

J Mitola [1] has made a maiden attempt to define cognitive radio as an efficient and flexible way to use the scarce spectrum by employing spectrum leasing protocols. The purpose of cognitive radio research is to develop an efficient software agent which exhibits high level of excellence in radio domains that may be called as "cognitive".

C I Badoi et al. [5] have presented and discussed 5G and CR technologies. The proposed technology identifies CR as the primary step to obtain the interoperability between the different networks. Finally they concluded that the 5G based on CR is a fruitful combination which will render us the real 5G scenario.

B Wang and K J Ray Liu [13] have presented the functionalities, features, network architecture and its applications in cognitive radios. They thoroughly discussed the fundamental requirements for deploying a cognitive radio network i.e. spectrum sensing, cooperative spectrum sensing and different types of detection techniques. In addition they also proposed the dynamic spectrum sharing and management techniques such as spectrum mobility, power control strategy, routing and medium access control.

S Srinivasa and S A Jafar [14] have given the overview of different spectrum sharing techniques i.e. underlay, overlay and interweave, when secondary transmission takes place simultaneously with primary. They have studied the radio links models based upon these techniques. The results achieved by comparing these techniques in terms of throughput show that the overlay scheme has the ability to improve the overall secondary network output, as compared to interweave. The achieved improvement holds true when the secondary transmitter is provided with the channel knowledge of interference link and disappears as the distance between the primary and secondary network increases.

M G Khoshkholgh et al. [15] have analyzed throughput of CR network in terms of capacity for secondary network services in underlay and overlay schemes. They achieved a vital parameter which eliminates the interference constraint and thus results in reduced system complexity by making secondary network independent of obtaining channel state information of interference link. They also proposed a mixed strategy in contrast to overlay scheme in which the secondary user transmits during busy period, with some probability threshold, subject to satisfy the interference constraint. In addition they also proposed a power allocation strategy that when applied, achieves optimal channel capacity by adjusting probability threshold.

A Ghasemi and E S Sousa [16] have investigated the CR scenario in terms of capacity gains when the fading channels are subjected to the constraints like interference power at the primary receiver. They analyzed the proposed system with multiple secondary users. The channel capacity in Rayleigh fading is higher than AWGN counterpart, when each secondary user is scheduled on the basis of largest channel path gain known as multiuser diversity gain (MUD).

Charles Kabiri et al. [18] have studied a cognitive radio network employing multiple secondary users communicating with secondary base station and a primary user. The impact of interference link from SU to PU has been analyzed in terms of ergodic capacity and outage probability. The achieved results show that severe faded interference link makes SU to transmit more power.

H Tran et al. [19] have studied a cognitive radio network under the impact of joint outage probability of multiple primary transmitters and peak transmit power constraint of SU network. They have obtained the closed form expression of outage probability for secondary network under the adaptive transmit power scheme. They concluded that the proposed system performance degrades when number of PU increases. It can be further improved by utilizing the bandwidth of more number of licensed bands.

X Kang et al. [20] have proposed a new transmit power scheme which exploited the fact that primary transmission may result in non-zero outage probability margin thus allowing SU-Tx to transmit more power. Based upon this, they have studied optimal power allocation policies, subject to outage probability constraint of PU along with average/peak transmit power constraint of SU-Tx. Results achieved show that the significant capacity gains are obtained by proposed transmit power schemes over the conventional interference temperature constraints.

In this paper [21], **R Duan and M S Elmusrati** focused on generalized selection combining in shared cognitive radio under block Rayleigh fading channel. They have derived the closed form expressions for ergodic capacity and symbol error rate under the impact of primary user outage probability. The achieved result shows that the channel link from CR-Tx to PR-Rx is of prime importance for the performance of cognitive network.

In this paper, **X Kang et al.** [22] have analyzed the CR network in which CR user shares the spectrum of PU for transmission over block fading channels. They have studied the new type of constraint imposed on the SU in order to protect PU by limiting the maximum transmission outage probability of the PU below a desired target. They have framed optimal transmit power policies for the SU to maximize the ergodic and outage capacity under PTP constraint along with the proposed PU outage probability constraint. It is thus shown that the derived and transmit power strategies achieves significant capacity gains as compared to conventional interference temperature (IT) constraints.

H Tran et al. [23] have studied and analyzed the performance of CR SIMO network under the influence of PU outage constraint as well as PTP constraint of CR-Tx. They have also derived closed form expression for the outage probability and ergodic capacity by taking into consideration an adaptive power allocation strategy.

In this paper, the **L Sibomama et al.** [24] have studied and analyzed simultaneous wireless information and power transfer (SWIPT) system under PU peak interference power constraint. They derived the analytical expressions of ergodic capacity for the information decoding and energy harvest models. The results achieved show that the parameters affecting the performance of secondary network are the number of SU-Rxs and the target outage probability. The proposed SWIPT policy achieves acceptable quality of service for the user and also responsible for energy harvesting (EH).

L Sboui et al. [25] have presented channel state estimations with both desired as well as interference links in spectrum sharing environment under the average transmit power and interference outage constraints. They have derived the expressions for optimal power allocation scheme and ergodic capacity. They have done the asymptotic analysis of ergodic capacity which shows that at low SNR the capacity depends upon the perfect secondary channel state information. At high SNR the capacity has horizontal asymptotes that are tighten by knowledge of interference link channel state information. They have also applied a practical power control policy which applied without CSI's (i.e. of CR network and CR network to PU network). The result achieves the same outcomes as actual capacity obtained at both the low and high SNR regimes.

It is to be concluded that cognitive radio technology and its associated spectrum access schemes result in an efficient, reliable and improved communication system which utilises the scarce spectrum resources in a skilful manner. By taken this into consideration the usefulness of CR technology, we attempt to design an efficient wireless communication system by incorporating underlay spectrum access and various transmit power schemes.

2.2 Introduction to receive diversity

To avoid deleterious effect of interference away from primary receivers, CR-Tx can be equipped with multiple antennas in order to improve overall system performance [26-28]. The deployment of multiple antennas at the transmitter [26] or receiver [28-32] combats the malicious effect of fading through spatial diversity (SD) [32-33]. A brief discussion about receiver diversity is described in the following section.

- ***Receive diversity***

Receive diversity also known as Single-Input-Multiple-Output (SIMO) system, employs multiple antennas at the receiver thus make it a highly reliable system in terms of array as well as diversity gain [34-38]. The receive diversity is incurred by employing combining technique. The basic idea is that if several independent paths are sufficiently separated in space, time and frequency and their channel coefficient are statically independent, then the probability that all the channel paths will undergo deep fade simultaneously becomes very less [39-43].

Receive diversity is obtained by performing some post processing [44-45] on the signals received on different antennas elements which undergoes independent fading. Let us consider a generalized receiver reception having total *'N'* branches as shown in Figure 2.2 The Rx accepts various versions of transmitted signals. Each i^{th} signal experience a different complex channel path coefficient $h_i\ (t)$ due to random nature of wireless medium and noise $n_i(t)$. These received signals are combined in a gainful manner in order to exploit different diversity schemes [46-47].

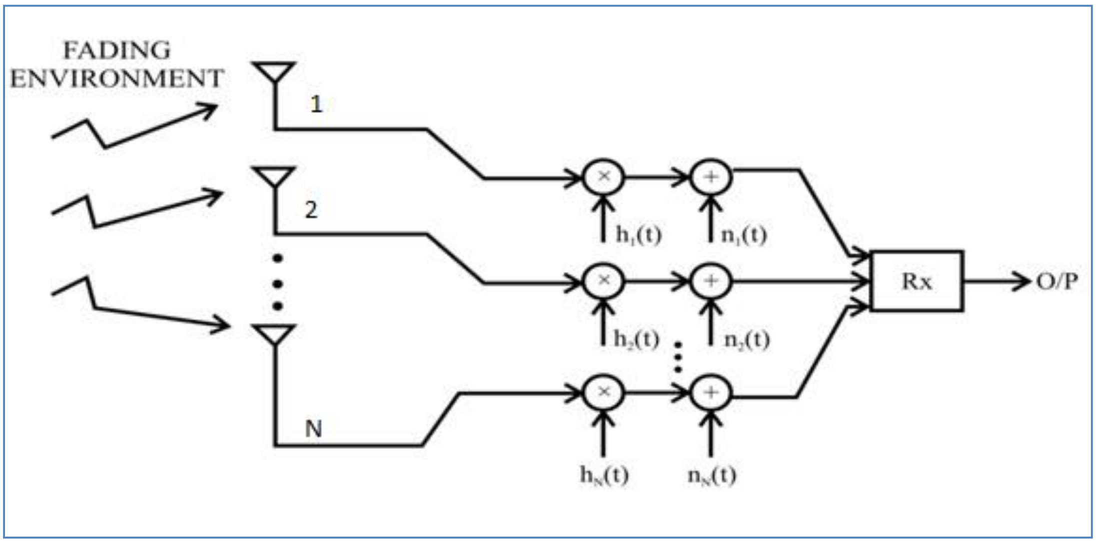

Fig. 2.2 An illustration of receive diversity [57]

There are different diversity combining techniques [47] such as SC *(Selection Combining),* EGC *(Equal Gain Combining)* [48], MRC *(Maximal Ratio Combining)* [49-50], GSC *(Generalized Selection Combining)* [51-53] etc. In SC, the Rx chooses the one of the best path out of all available channels on the basis of maximum received SNR. EGC can be achieved by adding all the received signals after they are properly co-phased. Whereas in MRC the received signals are weighted i.e. each branch is weighted according to its channel coefficient and then coherently added in order to achieve maximum SNR at the output of combiner.

In SC, only one RF (Radio frequency) chain is required by the receiver as discussed above. It is also possible that the Rx can be equipped with more than one RF chain or less RF chains than *N*. In this case, the subset of receiver antenna elements is selected out of all available paths on the basis of maximum instantaneous signal-to-noise-ratio (SNR) and then combined by employing MRC technique. This type of combining is called as *Generalized Selection Combining* (GSC) [52]. The MRC diversity combining scheme is the optimal choice when the each receiver element is under the influence of additive white Gaussian noise (AWGN) and also outperforms the other available combining schemes. But it becomes the sub-optimal choice in the presence of Co-Channel Interference (CCI).

The diversity reception obtained by employing adaptive antenna arrays is a key candidate which can mitigate the effect of multiple fading and interference at each receiver antenna. *Optimum Combining (OC)* [53] technique is a powerful array processing diversity reception scheme which is capable of providing increased degree of freedoms (DOFs) or diversity paths and simultaneously palliate the deleterious impact of CCI. In OC, the received signal at each antenna element is properly weighted and then combined to increase Signal-to-noise and interference ratio (SINR) at the output of combiner. OC provides larger SINR as compared to MRC technique and it is beneficial to employ OC scheme in interference limited scenarios.

To reduce the deleterious effect of fading, diversity combining at the intended receiver is an effective way to deal with it. The subsequent section provide insight to all available diversity combining schemes such as selection combining, equal gain combining, maximal ratio combining and generalised selection combining. The following section discusses the performance comparison between different diversity combining schemes in MIMO as well as with CR, available in literature.

Literature review on receive diversity

In this paper [46], **T Eng et al.** have presented the performance of different diversity combining techniques in terms of bit error rate probability. The achieved outcomes indicate that by combining two or three best branches bring results very close to that of MRC in case of coherent combining. Consequently it achieves significant improvement when only one best branch is selected (i.e. SC) out of all available branches. In case of non coherent combining, two or three best paths give performance comparable to that of EGC and if number of best paths and power decay becomes large, then the performance becomes better than EGC.

In this paper [51], **Y Ma and S Pasupathy** have derived an expression of moment generating function (MGF) for the SNR at the output of generalized selection combiner over the generalized fading channels. The derived expression is further used to analyze the performance of the considered system in terms of probability of error, outage probability. They have derived the statistics of the output SNR, when both the total available branches *'N'* and best chosen path *'L'* are large.

In this paper [52], **M S Alouini and M K Simon** have studied and analyzed the performance of GSC and compared the achieved results with conventional diversity combining techniques such as SC and MRC. They have derived the expression of MGF of the output SNR. By using the derived MGF, they obtained closed form expressions for average combined SNR at the GSC combiner output, probability of outage and average BER for the various modulation schemes. Achieved results show that diversity gain increases as the number of combined strongest paths increases and reduces as that number increases further.

A Annamalai et al. [30] have analyzed the performance of generalized selection combining (GSC) for both the coherent and non coherent receivers under the Rician fading environment. They derived the expressions for the MGF, Cumulative Distribution Function (CDF) and PDF of the output SNR at the GSC receiver. They have also derived the expression for the MGF under the influence of Nakagami-m fading channel. The derived expressions for the MGF and PDF are utilized for calculating the average SER for the various modulation schemes. The derived CDF is used for deriving the outage probability of the considered system.

In this paper [31], **Q Wu et al.** have investigated the performance of spectrum sharing system employing generalized selection combining under the influence of imperfect channel estimation. They have derived the closed form expression of effective capacity under the impact of imperfect channel knowledge. The results obtained show that the capacity degrades when the number of receiver antenna increases. It has been shown that imperfect channel knowledge does not produce any loss in performance of the system but selection combining is incorporated under stringent delay QoS necessities.

This section deals with the receiver diversity expeditiously removes malicious effect of fading. We have studied literature available on various diversity combining schemes such as *selection combining, maximal ratio combining, generalised selection combining. GSC is an improved diversity combining technique which is trade-off between the performance of SC and MRC. It aims at reducing system complexity, power consumption and overall implementation cost. Hence we analyzed and compared CR environment by employing GSC and MRC at the CR-Rx.*

2.3 Introduction to spatial diversity schemes

Like receive diversity, we can also deploy multiple antennas at the transmitter i.e. *transmit diversity* which makes it Multiple-Input-Single-Output (MISO) system. Spatial diversity can be attained by utilizing the concept of transmit diversity. To use multiple antenna at transmitter or receiver side result in a wireless communication system, which is known as *Multiple-Input-Multiple-Output (MIMO)* [53-54]. MIMO scheme is used for 3G communication i.e. in Wideband- Code Division Multiple Access (W-CDMA) and is considered for the highly reliable systems based on IEEE 802.11 standards for WLANS. The multiple antennas can be used for the creation of highly effective antenna diversity systems through which transmission of various parallel data streams can take place in order to increase the spectral efficiency of the system. Apart from 3G applications, MIMO scheme is an attractive candidate for 4G technology as it provides better link reliability i.e. diversity gain and improved data rate in terms of multiplexing gain [55]. Some of the 4G MIMO solutions are discussed below:

In 4G applications such as, cellular networks, satellite based communications etc., the transmission model consists of 'K' active users those want to communicate with the base station. The nature of independent channel fluctuations from different users in a multiuser scenario provides multiuser diversity gain (MUD). This kind of system is known as Multiuser MIMO (MU-MIMO). MU-MIMO systems exploits diversity by selecting the best user out of 'K' active users for a particular time slot, depends upon the instantaneous output power at each user. MIMO systems capably separates transmitted signal from multiple users which results in space division multiple access (SDMA) method. OFDM (Orthogonal Frequency Division Multiplexing) is an another attractive choice which results less multipath fades, higher spectral efficiency and lower interference as all sub carriers are orthogonal to each other. Apart from this, High Speed Packet Access (HSPA) with MIMO boosts uplink and downlink data rates. Hence, in this research work, diversity and multiplexing gains with MU-MIMO are explored as they enhance data rate with different QoS requirements.

The properties of MIMO system can be exploited using Spatial Multiplexing (SM) and Spatial Diversity (SD) [56]. The spatial multiplexing (SM) scheme results in transmitting parallel and independent data streams to be transmitted from multiple antennas. The communication system exhibit spatial multiplexing may scale overall capacity as *min (M, N).* The examples of SM system include Bell labs space time architecture (BLAST).

Another multiple antenna technique is the Spatial Diversity in wireless communication system which minimizes the effects of fading. The multiple and independent replicas of transmitted signal is received at the intended receiver, then they can be combined effectively even if one or more copies exhibits deep fade. These different copies are linearly weighted and combined on the basis of average SNR at the output of combiner. If a receiver is equipped with *N* receive antennas, then the efficacy of the system to avoid deep fades is *'N'* which represent its diversity order. One of the key candidates of SD is an efficient transmission technique known as space time coding (STC) [38]. The space time coding scheme has capability of delivering diversity order of *MN*, where *M* and *N* represents the number of transmit and receive antennas, respectively. Diversity scheme is an attractive choice to combat the malicious effect of multipath fading, co-channel interference and the environmental errors. Diversity can be achieved at the transmitter (transmit diversity) or at the receiver (receive diversity) by employing multiple antennas at both the ends.

One of the key candidate to obtain transmit diversity is through transmit antenna selection. TAS aims at selecting one best transmit antenna out of all available antennas on the basis of maximum SNR at the dedicated receiver. By employing TAS at the transmitter and GSC at the receiver, overall system complexity gets reduced in terms of less RF chains, lower power consumption and less implementation cost. Hence TAS with various diversity combining techniques have been thoroughly studied in the following section.

➢ ***Antenna Selection***

Apart from the usefulness of MIMO systems, there are some drawbacks also. The primary drawback of any MIMO communication system is its increased complexity [57]. As the number of antenna elements increases, RF chains also increase which result in more complexity, implementation cost, power consumption and signal processing. If a MIMO system is equipped with *'M'* transmit antennas known as *transmit diversity* and *'N'* receive antennas called as *receive diversity*, then the considered system needs *'MN'* complete RF chains. This drawback of MIMO led to evolution of *Antenna Selection (AS)* scheme [58]. Every communication system require some sort of post processing in order to recover the original transmitted signal (i.e. receive diversity) which may be corrupted by random channel behavior.

The SD is powerful technique to obtain diversity enhancement and it can be accomplished by employing TAS (Transmit Antenna Selection) [59-67] and space time block coding (STBC) [68-77] at the transmitter side. TAS scheme aims for selecting one best antenna out of all available transmit antennas, to maximize the SNR at the receiver. This process reduces the required number of RF chains and thus leads to substantial savings in terms of reduced complexity, signal processing, power and cost etc. These savings come at a cost of very negligible performance loss. Unlike Receive Antenna Selection (RAS) which aims at selecting one or subset of best receiver branches [27], TAS scheme require feedback from receiver to transmitter. This feedback rate is small if only one antenna is chosen. Figure 2.3 shows that TAS is similar to RAS, where the one best antenna is chosen on the basis of highest received instantaneous SNR at the Rx.

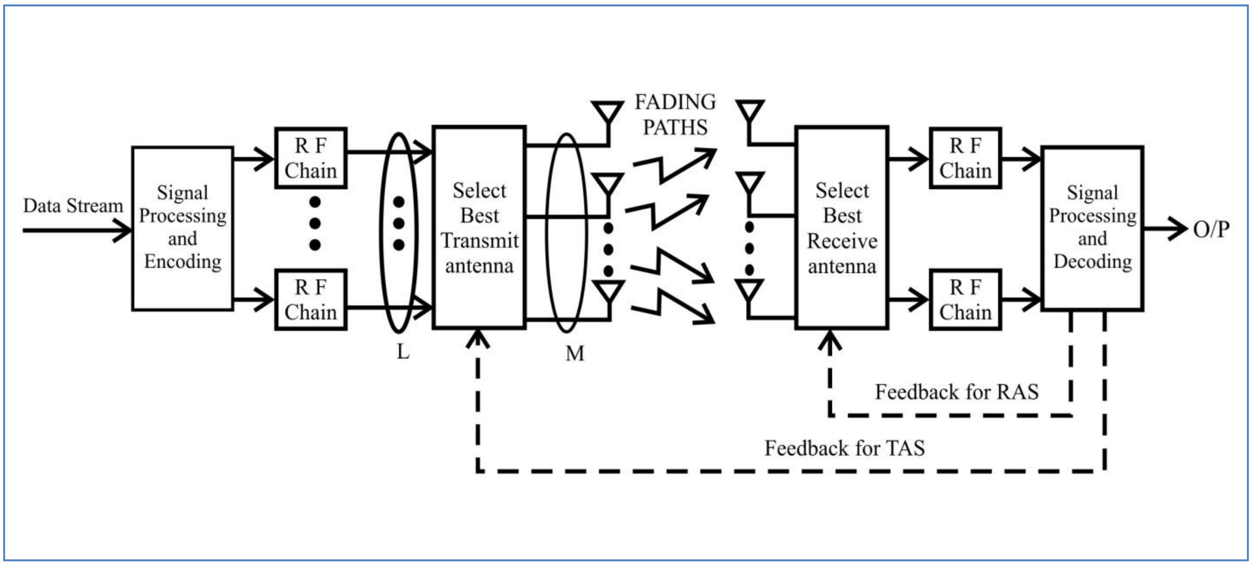

Fig. 2.3 Block diagram of Transmit and Receive Antenna Selection system. [57]

Literature review on Transmit Antenna Selection scheme

In this paper [26], **X Cai and G B Giankkis** have analyzed the closed form expressions for symbol error symbol (SER) with TAS and receive GSC with M-PSK and M-QAM modulation techniques. They concluded that with receive GSC, the number of best branches *'I'* to be chosen exhibits better performance as compared to TAS at the transmitterand GSC at Rx or receive MRC without TAS at transmitter. With proper selection of L (i.e. best branches chosen at the transmitter), the performance gap between GSC and MRC with transmit spatial diversity becomes very negligible.

S Kim et al. [58] have studied the mutual information for the iterative receivers by employing transmit antenna selection (TAS) scheme. From the achieved results, it has been shown that the proposed TAS scheme has significantly improved performance as compared to the conventional counterpart.

S Choi et al. [59] have presented the useful statistics such as CDF, PDF and MGF for TAS/MRC system with generalised receiver selection over the Nakagami-*m* faded channel. They derived the closed form expressions for the average SNR at the receiver output and average BER for the multi antenna system. Results thus obtained shows that the performance of the considered system is influenced by the fading channel behaviour.

In this paper [60], TAS with generalised selection combining over Rayleigh fading under output threshold has been analyzed by **B S Tan et al.** They have derived the expressions for outage probability, average output SNR and symbol error rate for different modulation schemes. The results obtained show that TAS/GSC with output threshold performs similar to the conventional TAS/GSC.

In this paper, **M F Hanif et al.** [61] have proposed joint transmit and receive antenna selection for satisfying the constraints imposed by primary network as well as achieving satisfactory capacity gains for the CR network. They have presented three schemes viz. optimal search approach, convex approximation and norm based transmit and receive antenna selection approach. The optimal search approach was most computational demanding while CA (Convex Approximation) approach solves the problem iteratively in small steps. They also presented norm based approach which results in significant complexity reduction and achieves accurate outputs. Their analysis proved that antenna selection with MIMO is having potential of achieving higher gains for denser PU environments.

X Zhang et al. [62] have investigated outage capacity and symbol error rate for TAS/MRC system in multiuser environment. The obtained results revealed that outage capacity increases with rise in mean effective SNR among K users and decreases with increase in variance of effective SNR. They also showed from the output of SER that diversity order of the TAS/MRC multiuser system is approximately equals to ($KNtNr - KNt + 1$), where Nt and Nr represents the number of Tx and Rx antennas.

V Blagojevic and P Ivanis [63] have studied and analyzed shared spectrum CR system by employing TAS/MRC with an arbitrary number of receive and transmit antennas. They have derived the expression for capacity by taking into consideration the transmit power constraint. The results obtained thus show that the derived capacity depends upon the product of average channel path gain and peak interference to noise ratio.

In this paper [64], **D Li** has analyzed the effect of channel estimation errors on the effective capacity of MISO CR system. They have derived new closed form expressions of capacity under perfect channel estimation. The achieved results indicate that the considered system remain robust against the fluctuations in channel estimations, particularly when the delay Quality of Service (QoS) of the secondary network is restricted.

In this paper, **F A Khan et al.** [65] have analyzed the MIMO CR system in both the scenarios i.e. with interference and without interference. The system under consideration employed TAS at SU-Tx and MRC at the PU-Rx, respectively. They derived the closed form expression of MGF, Symbol Error Rate (SER) and ergodic capacity for MCS-TM-NI system (MIMO Cognitive System-TAS/MRC-No Interference). They have also derived the closed form expression of outage probability for both the systems i.e. MCS-TM-NI and MCS-TM-WI (MIMO Cognitive System-TAS/MRC-With Interference) under Rayleigh fading.

In this paper, **F A Khan et al.** [66] have analyzed the MIMO CR system by considering TAS at the SU-Tx and MRC at the PU-Rx. They have derived the closed form expressions for the Outage Probability, MGF and SER under the impact of peak interference power constant in addition to peak transmit power of each SU. Also the performance of the system under consideration shows that MIMO-CR with TAS/MRC obtains a diversity order of Nt Nr.

Space time block coding is another efficient method of transmit diversity. It aims at developing highly reliable communication with reduced decoding complexity. Following section focuses at the available literature on STBC and also its performance comparison with TAS.

➢ *Space Time Block Coding scheme*

Another most important transmit diversity technique is space time coding (STC). Transmit diversity obtained STC require proper pre-coding before transmission. Tarokh et al. [69] made a maiden attempt by proposing space time trellis coding (STTC). The performance given by STTC scheme is extremely well but at the cost of increased decoding complexity. By taking this issue into consideration i.e. complex decoding, Alamouti [68] proposed a remarkable scheme of transmit diversity which employs two transmit antennas and one receive antenna. His idea was further for large number of transmit antennas which lead to the concept of space time block coding (STBC). Since, Alamouti's scheme does not provide any coding gain but its main attraction is its less complexity and improved performance. STBC scheme transmits data stream over multiple transmit antennas in different time slots. STBC deployed system does not require CSI at the transmitter like in TAS, which further leads to its sophisticated implementation.

Literature review on Space time block coding scheme

S M Alamouti [68] has proposed a new transmit diversity method which employs two transmit antennas and one receive antenna which provides same diversity gain as MRRC (Maximal Ratio Receive Combining). It is also shown that this scheme can be generalized to two transmit and *N* number of Rx antennas which renders the diversity order of 2N. This novel transmit diversity method does not need feedback from Rx to Tx and its system complexity stays same as the MRRC. This proposed scheme results in 3 dB performance loss because of transmitting two symbols from the two transmit antennas. But if the transmit power becomes doubled, then its performance become similar to that of MRRC.

In this paper, **V Tarokh et al**. [69] have brought insight to the very attractive method for transmission through multiple transmit antenna i.e. space time block coding over Rayleigh and Rician fading environment. The proposed codes exploits full diversity being offered by transmit and receive antennas. These codes exhibit very simple maximum likelihood decoding. They have designed codes for the arbitrary real constellation like PAM (Pulse Amplitude Modulation) achieves maximum transmission rate for any number of transmit antennas. For complex constellation, particularly for n = 2, 3 and 4, the designed STBC achieves as 1, ¾ and ¾ of highest possible transmission rate.

B S Tan et al. [72] have proposed and analyzed minimum selection generalized selection combining receiver (MS-GSC) over Rayleigh fading environment. They have computed the MGF of the proposed system. By utilizing the derived MGF, the SER of the considered system is obtained. It is also shown that the proposed system i.e. OSTBC/MS-GSC performs similar to OSTBC/GSC system with reduced complexity and power saving when predetermined threshold value is properly optimized.

Asaduzzaman and H Y Kong [73] have studied MIMO CR system under the effect of peak interference power (PIP) constraint along with peak transmit power (PTP) constraint. They have investigated the performance by employing transmit antenna selection (TAS) as well as with space time coding (STC). They studied the proposed system in terms of outage capacity and ergodic capacity. Achieved results showed that the ergodic capacity is dependent on transmission power policy in case of STC system. The TAS scheme bears much less system complexity than STC. By applying optimal power allocation scheme, both the proposed TAS and STC systems achieve same capacity.

X N Zeng and Ali Ghrayeb [74] have investigated the performance of receiver selection and TAS by employing STBC. They derived and studied the impact of upper bounds for any number of transmit and receive antennas on the BER performance. They showed that by employing antenna selection, the diversity order of the system under consideration is maintained but the SNR degrades by a value upper bounded by 10 $\log_{10}$ (M/L) dB, where M and L denotes the best combined branches of transmitter and receiver, respectively.

S A Zummo [75] has investigated the performance of bit error probability by applying union bounds on STBC coded system with receiver selection using MRC and GSC. The results thus achieved reveal that the applied union bounds obtain broad range of diversity orders.

W Li and N C Beaulieu [76] have derived SER for GSC conventional system using Alamouti scheme with MPSK over flat Rayleigh fading channel. They have proposed two new schemes of generalized receiver selection viz. GSTSOS (Generalized space time sum of squares) and GSTSOM (Generalized space time sum of magnitudes) which proved to be simpler than the conventional GSC scheme. They have also illustrated the effects of channel estimation error on GSC, GSTSOS, GSTSOM and MRC systems.

By aiming to reduce system complexity, antenna selection scheme at both the transmitter and the receiver has been taken into consideration. Joint diversity is obtained through the powerful spatial diversity techniques such as TAS and STBC at the transmitter while GSC at the receiver. Thus we designed and analyzed TAS/GSC and STBC/GSC CR system which is very less explored.

2.4 Multiuser Scheduling with joint Transmit and Receive diversity

- ***Multiuser Diversity***

Another effective way to achieve diversity gain is opportunistic scheduling in multiuser environment. It aims at selecting one best candidate user on the basis of channel conditions. Multiuser diversity [78-83] is a promising technique to improve diversity by scheduling multiple users [78-79] in a multiuser MIMO environment [49]. The multiuser diversity aims at selecting one of the best user out of all available active users on the basis of maximum instantaneous post processed output at the receiver as shown in Figure 2.4.

After selecting one best user, all the available resources required for communication will be apportioned to the selected user and all other users which are competing for the communication resources, will be quiet. Following are some advantages of scheduled multiuser scenario:

- It has been shown in the literature [89-91] that scheduled system provides performance improvement than non scheduled system by MUD (Multiuser diversity) gain.
- It also aims at reducing overall impact of mutual interference between all the contending users by choosing one best user out of all available users.

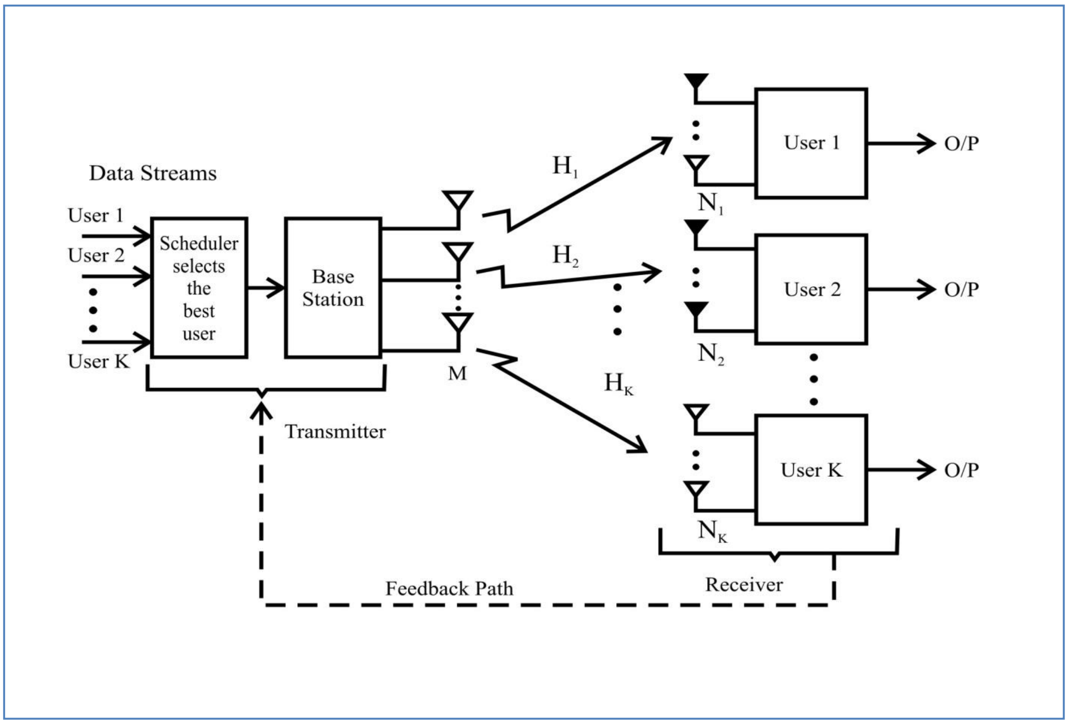

Fig. 2.4 Block diagram of scheduled multiuser system. [89]

After choosing the best user, all other users will remain idle which results in substantial energy savings. Available literature is thoroughly studied on multiuser scheduling in MIMO as well as in CR in subsequent section.

Literature review on multiuser diversity

P Mitran [78] has investigated the performance of cognitive network under Rician fading that if one user is scheduled to transmit by simultaneously reducing interference to the primary users, then the considered secondary network becomes useful. They concluded that moderate to large secondary networks with low duty cycle and simultaneous faded transmissions are viable. The achieved results show that restricted outage probabilities are independent of asymptotic conduct of network size, interference threshold limit and fading scenario.

Y Li and A Nosratinia [80] have proposed hybrid opportunistic scheduling scheme in CR-MAC (Multiple access) network aims at maximizing the overall capacity and reducing interference. This type of scheduling opportunistically provides all the available spectrum resources to the secondary transmitter with largest secondary channel path gain. They have also demonstrated a tradeoff between interference reduction and throughput enhancement by characterizing number of active secondary transmitters. Additionally, they also studied user scheduling with non-i.i.d (independent and identically distributed) channel path coefficients.

M Torabi and D Haccoun [81] have presented the outcomes of user scheduling with antenna selection and orthogonal space tome block coding (OSTBC) in MIMO systems, in homogeneous as well as heterogeneous networks over Rayleigh fading channels. They concluded that in independent and non-identical distributed values of average SNR degrades the diversity order of the considered system but simultaneously improves capacity.

T W Ban et al. [82] have studied multiuser diversity gain in a spectrum sharing environment when secondary network transmission power is restricted by the interference temperature constraint given by the primary network. They showed that in high power regions, when transmit power P becomes larger than Q (i.e. interference temperature threshold), the capacity gains grows significantly.

D Lee [83] has analyzed the scheduling scheme which chooses a best user on the basis of maximum effective SNR by employing Zero forcing (ZF) precoder in multiuser MIMO systems. The SER and the ergodic capacity illustrates that the diversity order is a function of best chosen user for the effective SNR. From the numerical analysis, they concluded that system performance of scheduled system improves by MUD over its conventional non-scheduled system counterpart.

D Lee and Y T Noh [84] have presented the impact of channel estimation error on Gaussian distributed channel with joint diversity offered by multiuser scheduling and STBC. They have derived the closed form expression for the outage probability. The results reveal that achievable rate in terms of system throughput improves by MUD, as the number of user increases. They also concluded that the SNR gain from joint diversity remains unaffected as the number of user increases and the performance remains same as conventional non-scheduled system.

X Zhang et al. [85] have analyzed the MUD gain in MIMO Rayleigh flat faded system with antenna selection. They derived closed form expression as well as tight approximation of outage probability in terms of MUD gain. The achieved outcomes shows that MIMO antenna selection system in multiuser diversity scenario obtains a diversity order equals to the product of the number of transmit, number of receive antennas and the number of users.

M Torabi et al. [86] have analyzed the MIMO-MRC system with different user scheduling policies. They have studied both the diversities, multiuser diversity as well as antenna diversities, by employing SNR based and normalized SNR based scheduling schemes. They presented that antenna selection improves system performance and reduces channel hardening. The normalized SNR based user scheduling scheme provides fairness among all available active users at the expense of very negligible throughput loss.

D Lee and K Kim [87] have studied the joint diversity policy combining space time block coding (STBC) with user scheduling environment where the best user is adaptively selected on the basis of maximum effective signal-to-noise ratio. They have derived the closed form expression for symbol error rate (SER) for M-ary QAM (Quadrature Amplitude Modulation) and M-ary PSK (Phase Shift Keying) modulation schemes. From the results, it can be concluded that the diversity order of joint diversity MIMO system increases in proportion to MUD as well as spatial diversity. On the other hand, SNR gain falls as spatial diversity increase.

In this paper the **D Li and B J Jeong** [89] have analyzed the MIMO CR systems with scheduled TAS and scheduled STBC with MRC at the CR-Rx. They have derived the approximate PDFs for both the systems. Using the derived PDFs, the closed form expressions for average post processing SNR and ergodic capacity for both the systems have been derived. Achieved results show that the scheduled systems have the capability to provide SNR as well as capacity gain over non-scheduled system by MUD. In addition they have also analyzed that the ergodic capacity degrades for imperfect CSI in comparison to perfect CSI scenario.

In this paper, **M Kulkarni et al.** [90] have studied and analyzed the performance comparison between TAS and OSTBC transmit diversity schemes in equi-correlated Rayleigh faded MIMO system. They have derived a novel series based expression of BER for TAS/MRC. They have also derived closed form expression of BER for OSTBC MIMO system. They observed that, in general TAS/MRC outperforms OSTBC for equi-correlated scenarios. But numerical results show that OSTBC is an attractive choice for MIMO CR systems. The strict interference constraints result in improved gain as compared to the conventional MIMO.

In this paper [91], **D Lee et al.** have presented the both TAS and STBC with MUD in MIMO system. They analyzed the proposed system in terms of effective SNR and the outage probability. The achieved outcome shows that as the number of transmit antennas increases the outage probability improves by the array gain, for both the schemes. On the other hand, outage probability for the STBC with MUD gets worse if number of transmit antennas increases. Finally it can be concluded that both proposed schemes have their own benefits in terms of system throughput without extra burden.

To further improve system throughput and spectral efficiency, we incorporate scheduling scheme which aims at selecting one CR user at a time. By choosing one best user out of all available CR users achieves MUD gain. We also analyzed and compared the behaviour of multiuser MIMO environment for both the proposed TAS/GSC and STBC/GSC systems.

2.5 Literature review on Co-channel Interference environment

Optimum diversity combining is the fundamental solution to combat the detrimental effects of co-channel interference. OC improves the SINR by efficiently suppresses the effect of fading and interference at the receiver output. Following section deals with the literature review of different diversity combining schemes in interference dominant scenario.

K S Ahn [93] has analyzed the performance of MIMO links with transmit beam forming and noise under the impact of multiple interferers in Rayleigh fading environment. They have derived the expression for distribution of SINR and outage probability. They have also derived an upper bound of an average symbol error rate for PSK, PAM and QAM modulation techniques.

V A Aalo and J Zhang [94] have analyzed the performance of MRC in the presence of CCI (Co-Channel Interference) and noise when both the desired and interfering signal undergo Nakagami fading. They have derived closed form expressions for average error and outage probability for both the coherent and non-coherent FSK (Frequency shift Keying) and PSK systems. The achieved results show that the MRC performs well even in interference limited scenario and its performance further improves as the diversity order enhances.

V A Aalo and C Chayawan [95] have studied and analyzed the effect of CCI on the cellular radio communication system. They have derived the closed form expression for outage probability of m-element antenna array with MRC which aims at maximizing the SINR at the receiver output.

X W Cui et al. [96] have analyzed MRC with unequal power co-channel interferers. They have obtained the closed form expression of outage probability for Rician and Rayleigh channel models. They have concluded that the outage performance improves as diversity order increases. They have also observed that at a given value of average SIR, the outage performance deteriorates in the presence of a dominant interferer.

Y Huang et al. [97] have studied the outage probability of spectrum sharing with MRC diversity under the influence of multiple primary trans-receivers. The results revealed that the outage probability saturates to an outage floor. They also showed that higher outage probability results due to stringent interference temperature constraints. However, the outage probability further improves by increasing antennas at the secondary user.

In this paper, **M A Doghfous et al.** [98] have analyzed the performance of adaptive Minimum Selection Generalised Selection Combining (MS-GSC) under the effect of co-channel interference over multipath fading scenario. The adaptive thresholds have been set without the knowledge of instantaneous power associated with the interfering signals, in order to enhance the spectral efficiency of discrete time rectangular constellation system. They have found the analytical formulations for ABER, average spectral efficiency and average outage probability.

Y Akyiddiz and B D Rao [99] have studied the distribution of SINR of OC in the presence of co-channel interference. They obtained a decomposition of SINR into two independent components by considering the system with more antenna array elements than the number of interferers. They also derived the upper and lower bounds on the distribution of SINR and compared with MRC by considering the system when number of antenna elements is less than the number of interferers.

J Lui et al. [100] have derived the analytical expressions for OC with two interferers and MRC with arbitrary number of interferers for DPSK (Differential Phase shift Keying) signals over flat faded channel. They also derived the BER expression for OC and MRC with correlated channels for dual antenna systems. Results achieved showed that OC performs significantly better than MRC as far as co-channel interference rejection is concerned. They also demonstrated that BERs of OC and MRC significantly degrades if the channel correlation of the desired signal approaches to unity.

N I Miridakis and D D Vergados [101] have studied and derived the outage probability expressions for both SINR and SNR with GSC combining. They considered the interfering signal undergoes Nakagami-m fading conditions and the desired user suffers from i.i.d Rayleigh fading. Also the asymptotic outage analysis in high average SNR conditions, provide insight to the GSC combining in interference scenario.

A shah and A M Haimovich [102] have studied and compared the performance of a system employing different diversity combining techniques. They have derived the expressions for density function of SIR, outage probability and average bit error rate for the MRC and OC for Rayleigh as well as Rician fading under the influence of equal co-channel interferers. They have shown that the results of MRC hold for an arbitrary number of interferers but OC outperforms MRC when the number of interferer sources are larger or equal to the number of receive antennas. It is also concluded that if the degrees of freedom (DOF) of an antenna array is not sufficient enough to cancel the interference, then the impact of interference is realised on the system performance. This paper also demonstrates the advantage of OC even when the number of CCI exceeds the number of array antenna.

In this paper [103], **C Chayawan and V A Aalo** have studied and analyzed the system in which the desired signal has the line of sight (LOS) component in the presence of multiple equal CCI under the Rayleigh faded environment. They derived a PDF of output SIR (signal-to-interference ratio) and an expression for the outage probability. They have concluded that when the number of interferes is close to the antenna diversity order, then OC provides better diversity gain than MRC. However, as the number of interferer increases beyond the diversity order, OC performs almost same as MRC with reduced diversity gain.

A Shah and A M Haimovich [104] have studied and analyzed OC with multiple CCI under Rayleigh fading and have derived the expression for maximum SIR. They have also derived the closed form formulas for outage probability and average bit error rate in the presence of equal power interferers.

In this paper [109], **V Hendre et al.** have analyzed the CR-adhoc network with multiple primary transmitters communicating in underlay mode. The performance of the system is enhanced by employing TAS and OC in order to maximize signal-to-interference-ratio (SINR) at the receiver. They analyzed the considered system in terms of bit error rate probability by considering aggregate interference from multiple primary transmitters under the impact of Rician fading.

This section gives insight into the interference limited scenario for various diversity schemes. Literature review concluded that the maximal ratio combining is the best combining *technique in AWGN limited environment but it becomes sub optimal choice when co-channel interference comes into existence. To combat the harmful effect of the interference, Optimum combining is the optimal choice. Motivated by this fact, we design and analyze cognitive radios with optimum combining at the CR-Rx.*

Chapter 3

Performance Evaluation and Analysis of Generalised selection combining scheme in scheduled TAS multiuser CR System under Interference temperature constraint

The primary contribution of this chapter is the performance analysis of a multiuser MIMO system with transmit antenna selection at CR-Tx and GSC at each CR user Rx. MUD gain is obtained by choosing best CR user on the basis of instantaneous post processing SNR at the output of CR-Rx. The proposed system is a function of best chosen Rx branches in order to obtain improved performance metrics viz. average post processing SNR and ergodic capacity. The S-TAS-GSC system is investigated for the two cases

- *(i)* *When the number of transmit antennas are fixed and number of CR users are varying.*
- *(ii)* *When both the number of transmit antennas and the CR users are varying.*

For both the cases, the peak transmit power (P_p) *of CR-Tx is assumed to be very less than the interference temperature limit 'Q' that is predefined by the PU network. If this constraint is violated, it will worsen overall throughput of the proposed CR system.*

3.1 Introduction

The radio spectrum is a scarce natural resource coordinated by the government agencies. The CR technology enables utilizing the limited available spectrum in a more proficient manner using spectrum access policies [1-4]. The spectrum sharing CR systems have been appealing to the researchers that the conventional study of fading environment is under transmitter focussed constraints, while it is not suitable for CR, since we have to protect the PU from receiving harmful interference from the CR network. The received signal constraints can lead to substantially different results as compared to transmitted signal constraints [16-17]. Spatial diversity obtained from multi antenna system is an important aspect to effectively combat the malicious effects of multipath fading in wireless communication [38-39]. This issue can be effectively resolved by deploying diversity combining techniques [46-47]. However transmit and receive diversity contributes to substantial improvement in overall system throughput.

The CR system implementing MIMO becomes an attractive choice for the research community as it provides enriched diversity, rate and also capable of extenuating the harmful effect of interference at the PU-Rx. However, MIMO comes up with increased complexity at the radio front end due to additional antennas consisting of transistors, down convertors, low noise amplifiers and analog-to-digital convertors that scale with number of RF chains. Thus antenna selection [54] becomes a fruitful solution to all such problems. In this chapter, we deployed multiuser MIMO CR system with TAS at the transmitter and GSC at the receiver, respectively. It is evident from the literature that the GSC (N_r, N_c) is a trade off between the performance and complexity of MRC and SC as it recursively combines N_c best branches out of N_r resolvable branches, where $N_c \leq N_r$ [51-52]. The GSC is an improved diversity combining scheme which provides almost similar performance as MRC with extremely little throughput loss. Also, SD obtained by implementing TAS is a key prospect for diversity improvement [58-67]. It selects one best transmit antenna out of all available antennas on the pretext of largest post processing SNR at the output of CR-Rx. In [58], the performance of TAS with conventional diversity combiners at the Rx has been analyzed. TAS with GSC (TAS/GSC) is examined in [67] and it shows that performance gap between TAS/GSC and TAS/MRC is very small. It also revealed that TAS/GSC also performs better than receive MRC without TAS. It is demonstrated that antenna selection alleviates the effect of channel hardening and thus increases the system performance in multiuser MIMO systems [81-82]. The product of SD and MUD provides joint diversity by employing TAS and user scheduling. Result in [89-91], shows that the CR scheduled system has improved capacity over non-scheduled CR system by MUD.

Now available literature provides insight into an improved diversity combining scheme, i.e. Generalised selection combining which is a performance trade off between the selection combining and maximal ratio combining. The capacity gains achieved by incorporating GSC are very much closer to that of MRC, which consider as an optimal diversity combining scheme. Also by conceptualizing the benefits of GSC over MRC and TAS in terms of less cost, low power consumption, improved channel estimation and reduced number of RF chains, the contributions of this chapter are listed below:

- The improved diversity combining technique i.e. GSC has been studied and analyzed under the influence of Rayleigh as well as Rician faded environment.
- Derived PDF of scheduled TAS/GSC CR system in multiuser environment.
- By utilizing the derived PDF, the performance of the considered system has been analyzed for metrics viz. Average post processing SNR, ergodic capacity with ‘K’ CR users.
- Lastly, the performance comparison of S-TAS-GSC CR system has been done with conventional TAS-GSC system in order to find MUD gain.

The system model for the analysis of the proposed S-TAS/GSC CR system is discussed in the following section.

3.2 System Model

A proposed underlay spectrum sharing network has been demonstrated for multiuser environment is shown in figure 3.1 which chooses the best CR user on the context of highest instantaneous post processing SNR.

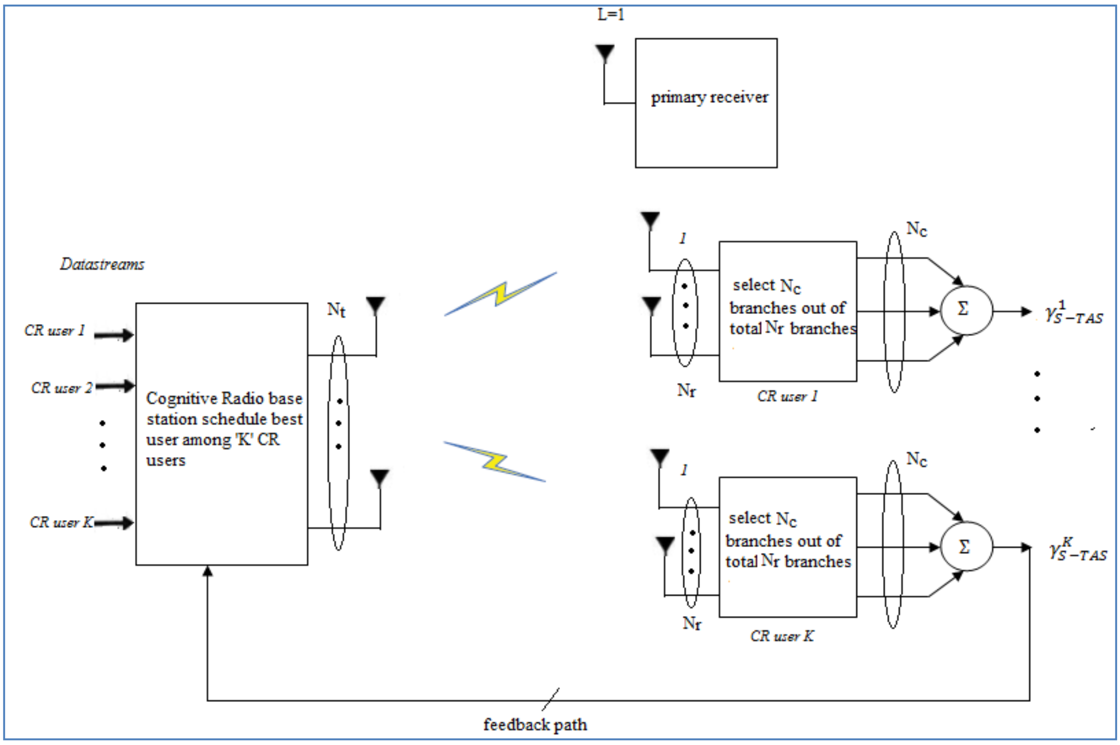

Fig. 3.1: Block diagram of scheduled-TAS-GSC underlay CR system.

The S-TAS-GSC system is equipped with a CR-Tx having N_t $(l = 1 \dots N_t)$ transmitting antennas and K $(k = 1 \dots K)$ number of CR users and each user is equipped with N_r receive antennas. Each CR user is equipped with GSC (N_r, N_c), where N_c best receiver branches are adaptively combined. The PU-Rx is communicating with single receive antenna i.e. $L = 1$. The channel coefficients matrix between CR-Tx and the $k^{t□}$ CR user is denoted by $\boldsymbol{Z}_{CR}^{K}$ which is $(N_r \times N_t)$ dimensional matrix. The channel path coefficients between CR-Tx and *'K'* users are assumed to be independent and identically distributed (i.i.d) random variables having Rayleigh distribution. In order to protect PU from malign interference of CR base station, we restrict transmit power of CR-Tx to be very less than the interference power tolerate limit i.e. P_p<< Q defined at the primary network, [19]. In this research work, it is assumed that the signal bandwidth is denoted as B and variance of AWGN as $'N_0'$. Our study assumed that the CR-Tx is equipped with perfect CSI through reliable feedback path. The instantaneous SNR of each CR user corresponding to each transmitting antenna is fed back to the transmitter in order to select best user and best transmit antenna. In S-TAS-GSC CR system, the post processing SNR [89] at the output of k^{th} CR user is written as

$$\boldsymbol{\gamma}_{S-TAS-GSC} = \frac{P_p}{NoB}\boldsymbol{z}_{max}\,; \tag{3.4}$$

where $\boldsymbol{z}_{max}$ can be obtained by selecting best transmit antenna and best user amongst N_t transmitting antennas and $'K'$ CR users, respectively and is given by

$$\boldsymbol{z}_{max} = \underbrace{max}_{(N_t,K)} \boldsymbol{z}_{GSC}{}^{K}_{N_t} \,. \tag{3.5}$$

The $\boldsymbol{z}_{GSC}$ can be determined by aligning the channel path gains from CR-Tx to each competent CR user i.e. $\{z_{i:N_r}\}_{i=1}^{N_c}$ in descending order such that $z_{1:N_r} \geq z_{2:N_r} \geq \; z_{N_r:N_r}$.

$$\boldsymbol{z}_{GSC}{}^{K}_{N_t} = \sum_{n=1}^{N_c} \boldsymbol{z}_{GSC}{}^{K}_{n,N_t} \times \left(\boldsymbol{z}_{GSC}{}^{K}_{n,N_t}\right)^{H}, \tag{3.6}$$

where $(\,.\,)^{H}$ depicts complex conjugate transpose and post processed by MRC combiner $\boldsymbol{z}_{GSC}{}^{K}_{N_t}$ becomes a chi-square random variable bearing $2N_c$ degree of freedoms (DOFs). The complex path gains $\boldsymbol{z}_{k,l}$ of k^{th} CR user corresponding to l^{th} transmitting antenna and is given as

$$\boldsymbol{z}_{max} = max\{\boldsymbol{z}_{k,l}\}\,, \;\; k = \{1,2, \ldots K\}\,; \;\; l = \{1 \ldots \ldots N_t\} \tag{3.7}$$

3.3 Performance Analysis of S-TAS/GSC System under Interference temperature constraint

In this section, TAS and user scheduling are examined for the proposed S-TAS-GSC CR system under the influence of interference temperature constraint as defined by PU. In order to fulfil this constraint, the peak transmit power of CR-Tx (P_p) is kept below the interference temperature limit (Q). To perform *Transmit Antenna Selection* among all available N_t transmit antennas, the CR-Tx must be provided with the index of the chosen transmit antenna on the basis of largest post processing SNR from all the K active CR users which are contending for the spectrum resources. Each CR user evaluates its post processing SNR by adaptively combining best N_c branches corresponding to each transmit antenna.

From Eq. (3.5), $\boldsymbol{z}_{max}$ can be evaluated by considering ($K \times N_t$) dimensional matrix of all CR users having KN_t elements. The largest element is selected and its corresponding transmit antenna is chosen out of KN_t elements. Then out of total k rows, the column vector corresponding to the largest element can be given as $(\boldsymbol{z}_{1,l}, \boldsymbol{z}_{2,l} \dots \boldsymbol{z}_{k,l})^{\boldsymbol{T}}$, where $(.)^{\boldsymbol{T}}$ represents the transpose of the given vector. While performing TAS, only the index of best transmitting antenna is required by each CR user for feedback to the CR-Tx, instead of transmitting full CSI given by $K \times N_t$ matrix, which thereby reduces bandwidth of the feedback channel. Following are the steps involved for deriving the PDF of the S-TAS/GSC CR system:

- By using order statistics [87], the PDF of the proposed system for TAS is obtained by incorporating the density function of GSC as given in [53].
- Then for the selected best transmit antenna, the best CR user is chosen.
- Finally after getting the PDF of the S-TAS/GSC CR system, average post processing SNR and the ergodic capacity of the proposed model are evaluated.

Step:1 PDF of TAS for the proposed system

Using the theory of order statistics, the CDF $F_{z_{GSC}}(z)$ of $\boldsymbol{z}_{GSC}$ to perform TAS for the k^{th} CR user can be expressed as

$$F_{z_{(k,l)}}(z) = \left[F_{z_{GSC}}(z)\right]^{N_t} \tag{3.8}$$

PDF can be found by differentiating CDF equation (3.8), we get

$$f_{z_{(k,l)}}(z) = N_t\, f_{z_{GSC}}(z)\left[F_{z_{GSC}}(z)\right]^{N_t-1} \tag{3.9}$$

The PDF and CDF of $\boldsymbol{z}_{GSC}$ are given by (3.10) and (3.11), respectively [53] where μ_z denotes the mean value of random variable 'z'.

$$f_{z_{GSC}}(z) = \binom{N_r}{Nc}\left(\frac{z^{\mathrm{Nc}-1}\mathrm{e}^{\frac{-z}{\mu_z}}}{\mu_z{}^{\mathrm{Nc}}(\mathrm{Nc}-1)!} + \frac{\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\mu_z}\left(\mathrm{e}^{\frac{-z\left(1+\frac{l}{N_c}\right)}{\mu_z}} - \mathrm{e}^{\frac{-z}{\mu_z}}\sum_{m=0}^{Nc-2}\frac{\left(\frac{-l}{Nc}\right)^m z^m}{\mu_z{}^m m!}\right)\right) \tag{3.10}$$

$$F_{z_{GSC}}(z) = \binom{N_r}{Nc}\left(1 - e^{\frac{-z}{\mu_z}}\sum_{l=0}^{Nc-1}\frac{\left(\frac{z}{\mu_z}\right)^l}{l!} + \right.$$

$$\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r - N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(\left(\frac{1}{\left(1+\frac{l}{N_c}\right)}\left(1 - e^{\frac{-z\left(1+\frac{l}{N_c}\right)}{\mu_z}}\right)\right)-\right.$$

$$\left.\sum_{m=0}^{Nc-2}\left(\frac{-l}{Nc}\right)^m + \sum_{m=0}^{Nc-2}\left(\frac{-l}{Nc}\right)^m e^{\frac{-z}{\mu_z}}\sum_{k=0}^{m}\frac{\left(\frac{z}{\mu_z}\right)^k}{k!}\right)\right) \tag{3.11}$$

Step:2 PDF of the best user for the proposed system

After performing TAS, user selection will be done by the scheduler at the CR-Tx which chooses one best active CR user on the basis of maximum channel power gain which is already obtained for the l^{th} best transmit antenna out of all transmit antennas and can be represented as

$$j = \arg\underbrace{max}_{k\in K}\left(z_{1,l}, z_{2,l} \ldots z_{k,l}\right) \tag{3.12}$$

Hence the best CR user is selected amongst $k = \{1 \ldots \ldots K\}$ CR users. The CDF and PDF of the best user chosen from all K CR users are obtained through the study of order statistics [87]

$$F_{z_{(j,l)}}(z) = \left[F_{z(_{k,l})}(z)\right]^K \tag{3.13}$$

The PDF can be achieved by differentiating Eq. (3.13), we get

$$f_{z_{(j,l)}}(z) = K\, f_{z_{(k,l)}}(z)\left[F_{z_{(k,l)}}(z)\right]^{K-1} \tag{3.14}$$

Now proceeding for evaluating the final PDF of the S-TAS/GSC CR system substitute $F_{z_{(k,l)}}(z)$ and $f_{z_{(k,l)}}(z)$ from (3.8) and (3.9) in (3.13) and (3.14), yields

$$F_{z_{(j,l)}}(z) = \left[F_{z_{GSC}}(z)\right]^{KN_t} \tag{3.15}$$

$$f_{z_{(j,l)}}(z) = KN_t\, f_{z_{GSC}}(z)\left[F_{z_{GSC}}(z)\right]^{KN_t-1} \tag{3.16}$$

By putting the PDF ($f_{GSC}(z)$) from Eq. (3.10), CDF ($F_{GSC}(z)$) from Eq. (3.11) into (3.15), the final PDF ($f_{z_{S-TAS/GSC}}(z)$) for the best transmit antenna and the best CR user for the proposed S-TAS/GSC CR network is obtained and is given by

$$f_{z_{S-TAS/GSC}}(z) = KN_t \binom{N_r}{Nc}^{KN_t} \left[1 - e^{\frac{-z}{\mu_z}} \sum_{l=0}^{Nc-1} \frac{\left(\frac{z}{\mu_z}\right)^l}{l!} \right.$$

$$+ \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1} \left(\left(\frac{1}{\left(1+\frac{l}{N_c}\right)} \left(1 - e^{\frac{-z\left(1+\frac{l}{N_c}\right)}{\mu_z}}\right) \right)\right.$$

$$\left.\left. - \sum_{m=0}^{Nc-2} \left(\frac{-l}{Nc}\right)^m + \sum_{m=0}^{Nc-2} \left(\frac{-l}{Nc}\right)^m e^{\frac{-z}{\mu_z}} \sum_{k=0}^{m} \frac{\left(\frac{z}{\mu_z}\right)^k}{k!} \right) \right]^{KN_t-1}$$

$$\left(\frac{z^{Nc-1} e^{\frac{-z}{\mu_z}}}{\mu_z{}^{Nc}(Nc-1)!} + \frac{\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\mu_z} \left(e^{\frac{-z\left(1+\frac{l}{N_c}\right)}{\mu_z}} - e^{\frac{-z}{\mu_z}} \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m z^m}{\mu_z{}^m m!} \right) \right), \tag{3.17}$$

where μ_z defines the mean value of random variable *'z'*.
Approximating $[.]^{KN_t-1}$ by binomial expansion [105] in (3.17), we get

$$[F_{GSC}(z)]^{KN_t-1} = \sum_{i=0}^{KN_t-1}(-1)^i \binom{KN_t-1}{i} \left(1-F_{GSC}(z)\right)^i f_{GSC}(z) \tag{3.18}$$

By putting (3.18) into (3.17), we obtain the PDF of S-TAS/GSC CR system as

$$f_{z_{S-TAS/GSC}}(z) = KN_t \binom{N_r}{Nc}^{KN_t} \sum_{i=0}^{KN_t-1}(-1)^i \binom{KN_t-1}{i} \left\{ 1 - e^{\frac{-z}{\mu_h}} \sum_{b=0}^{Nc-1} \frac{\left(\frac{z}{\mu_z}\right)^b}{b!} + \right.$$

$$\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} \left(\left(\left(1+\frac{l}{Nc}\right)^{-1} e^{-\frac{z}{\mu_z}\left(1+\frac{l}{Nc}\right)} \right) - \sum_{m=0}^{Nc-2} \left(\frac{-l}{Nc}\right)^m \left(1 - \right.\right.$$

$$e^{\frac{-z}{\mu_z}} \sum_{k=0}^{m} \frac{\left(\frac{z}{\mu_z}\right)^{k}}{k!} \Bigg)\Bigg)\Bigg\}^{i} \left\{\frac{z^{Nc-1} e^{-\frac{z}{\mu_z}}}{z^{Nc-1}(Nc-1)!} + \frac{1}{\mu_z} \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} e^{-\frac{z}{\mu_z}} - \right.$$

$$\left. \frac{1}{\mu_z} \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} e^{-\frac{z}{\mu_z}\left(1+\frac{l}{Nc}\right)} \sum_{m=0}^{Nc-2} \left(\frac{-lz}{Nc\mu_z}\right)^{m} \frac{1}{m!}\right\} \tag{3.19}$$

By applying trinomial expansion in (3.19) and some manipulations, we get

$$f_{z_{S-TAS/GSC}}(h)$$

$$= KN_t \binom{N_r}{Nc}^{KN_t} \sum_{i=0}^{KN_t-1} (-1)^{i} \binom{KN_t-1}{i} \sum_{p=0}^{i} \sum_{k=0}^{p} \binom{i}{p} \binom{p}{k} \left\{\sum_{b=0}^{Nc-1} \frac{(b+1)\Gamma\left(b+1, \frac{z}{\mu_z}\right)}{\Gamma(b+2)}\right\}^{(i-p)}$$

$$\Bigg\{- \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} \Bigg(\left(1+\frac{l}{Nc}\right)^{-1} \Bigg(1 -$$

$$e^{-\frac{z}{\mu_z}\left(1+\frac{l}{Nc}\right)}\Bigg)\Bigg)\Bigg\}^{(p-k)} \Bigg\{\sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} \sum_{m=0}^{Nc-2} \left(\frac{-l}{Nc}\right)^{m} \Bigg(1 -$$

$$e^{\frac{-z}{\mu_z}} \sum_{k=0}^{m} \frac{\left(\frac{z}{\mu_z}\right)^{k}}{k!} \Bigg)\Bigg\}^{k} \left\{\frac{z^{Nc-1} e^{-\frac{z}{\mu_z}}}{\mu_z{}^{Nc-1}(Nc-1)!} + \frac{1}{\mu_z} \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} e^{-\frac{z}{\mu_z}} - \right.$$

$$\left. \frac{1}{\mu_z} \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} e^{-\frac{z}{\mu_z}\left(1+\frac{l}{Nc}\right)} \sum_{m=0}^{Nc-2} \left(\frac{-lz}{Nc\mu_z}\right)^{m} \frac{1}{m!}\right\} \tag{3.20}$$

Simplifying further, the PDF of S-TAS-GSC CR system can be derived as

$$f_{z_{S-TAS/GSC}}(z)$$

$$= KN_t \binom{N_r}{Nc}^{KN_t} \sum_{i=0}^{KN_t-1} (-1)^{i} \binom{KN_t-1}{i} \sum_{p=0}^{i} \sum_{k=0}^{p} \binom{i}{p} \binom{p}{k} \left\{\sum_{b=0}^{Nc-1} \frac{(b+1)\Gamma\left(b+1, \frac{z}{\mu_z}\right)}{\Gamma(b+2)}\right\}^{(i-p)}$$

$$\Bigg\{\sum_{a=0}^{p-k} \binom{p-k}{a} \Bigg[- \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} \Bigg(1$$

$$+ \frac{l}{Nc}\Bigg)^{-1}\Bigg]^{(p-k-a)} \Bigg[\sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-Nc}{l} \left(\frac{Nc}{l}\right)^{Nc-1} \Bigg(1$$

$$+ \frac{l}{Nc}\Bigg)^{-1} e^{-\frac{z}{\mu_z}\left(1+\frac{l}{Nc}\right)}\Bigg]^{a}\Bigg\}$$

$$\left\{\begin{array}{c}\sum_{f=0}^{k}\binom{k}{f}\left[\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-Nc}{l}\left(\frac{Nc}{l}\right)^{Nc-1}\sum_{m=0}^{Nc-2}\left(\frac{-l}{Nc}\right)^{m}\right]^{(k-f)} \\ \left[-\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-Nc}{l}\left(\frac{Nc}{l}\right)^{Nc-1}\sum_{m=0}^{Nc-2}\left(\frac{-l}{Nc}\right)^{m}\frac{(m+1)\Gamma\left(m+1,\frac{z}{\mu_z}\right)}{\Gamma(m+2)}\right]^{f}\end{array}\right\}$$

$$\left\{\frac{z^{Nc-1}e^{-\frac{z}{\mu_z}}}{{\mu_h}^{Nc-1}(Nc-1)!}+\frac{1}{\mu_z}\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-Nc}{l}\left(\frac{Nc}{l}\right)^{Nc-1}e^{-\frac{z}{\mu_z}}-\right.$$

$$\left.\frac{1}{\mu_z}\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-Nc}{l}\left(\frac{Nc}{l}\right)^{Nc-1}e^{-\frac{z}{\mu_z}\left(1+\frac{l}{Nc}\right)}\sum_{m=0}^{Nc-2}\left(\frac{-lz}{Nc\mu_z}\right)^{m}\frac{1}{m!}\right\} \qquad (3.21)$$

After deriving the PDF of the S-TAS/GSC CR system, the performance metrics in terms of average post processing SNR and ergodic capacity have been derived in the subsequent section.

(a) Average Post Processing SNR

Average post processing SNR i.e. $\left(\boldsymbol{\gamma_{S-TAS/GSC}}\right)$ of the S-TAS/GSC CR system at the output of GSC combiner is found out by calculating the first moment of $z_{S-TAS/GSC}$ and is written as

$$\gamma_{S-TAS/GSC}=\frac{P_p}{NoB}\,\mathbb{E}\{z_{S-TAS/GSC}\}, \qquad (3.22)$$

where, $\mathbb{E}[.]$ and P_p denotes an expectation function and the peak transmit power of CR-Tx. Now the first moment of $z_{S-TAS/GSC}$ is given as

$$\mathbb{E}\{z_{S-TAS/GSC}\}=\int_0^{\infty}z\,f_{z_{S-TAS/GSC}}(z)d(z). \qquad (3.23)$$

$$\gamma_{S-TAS/GSC}=\frac{P_p}{NoB}\int_0^{\infty}z\,f_{z_{S-TAS/GSC}}(z)d(z), \qquad (3.24)$$

Equation (3.24) is evaluated using Wolfram Mathematica software. One best transmit antenna is assigned to the best user which maximizes average post processing SNR $(\gamma_{S-TAS/GSC})$ at the output of CR-Rx.

(b) Ergodic Capacity

The Ergodic capacity ($C_{S-TAS/GSC}$) of S-TAS/GSC CR network is defined as the maximum long term achievable rate and can be evaluated by performing average of all the fading states of a channel. It can be approximated using Taylor's series expansion of logarithm function [106] and is given by

$$C_{S-TAS/GSC} \approx \log_2\left(1 + \frac{P_p}{N0B}\mathbb{E}\{z_{S-TAS/GSC}\}\right) - \frac{\varsigma\left(\frac{P_p}{N0B}\right)^2 \sigma^2_{z_{S-TAS/GSC}}}{2\left(1+\frac{P_p}{N0B}\mathbb{E}\{z_{S-TAS/GSC}\}\right)^2}, \qquad (3.25)$$

where $\varsigma = log_2 e$ and e denotes the Neper's number and the variance $\sigma^2_{z_{S-TAS/GSC}}$ of $S-TAS/GSC$ and can be written as

$$\sigma^2_{z_{S-TAS/GSC}} \;=\; \mathbb{E}\{z_{S-TAS/GSC}\}^2 - \mathbb{E}^2\{z_{S-TAS/GSC}\}, \qquad (3.26)$$

where $\mathbb{E}^2\{z_{S-TAS/GSC}\}$ represents the second moment of random variable $f_{S-TAS/GSC}$ and can be written as

$$\mathbb{E}^2\{z_{S-TAS/GSC}\} = \int_0^\infty z^2 \, f_{z_{S-TAS/GSC}}\ (z)\mathrm{d}(z) \qquad (3.27)$$

3.4 Results and Discussion

The achieved results are demonstrated in three parts viz. first part discusses the conventional GSC scheme in Rayleigh and Rician fading scenario. The second part elaborates the proposed system with varying number of best chosen receiver branches and the CR users. Lastly the results are shown with different combinations of number of transmit antennas and the number of CR users.

(a) Performance analysis of conventional GSC scheme in different fading environments

- *Under the influence of Rayleigh fading*

Figure 3.2 and figure 3.3 shows the analytical as well as simulation results for average post processing SNR and ergodic capacity for the CR system with GSC at the CR-Rx. Here it is assumed that the CR-Tx is having $N_t = 1$ transmit antenna, GSC (N_r, N_c) employed CR-Rx is equipped with $N_r = 4$ and N_c adaptively changes from 1 to 4. From the figure 3.2, it is deduced that average post processing SNR increases from 7.49 dB,9.40 dB, 10.16 dB to

10.39 dB as number of best branches to be combined increases from $N_c = 1$ (SC) to $N_c = 4$ (MRC).

Similarly figure 3.3 shows the results achieved for the ergodic capacity for the GSC CR system. It is shown that ergodic capacity is 2.75, 3.30, 3.52 and 3.61 Bits/Sec/Hz when the number of best branches combined at the CR-Rx increases from $N_c = 1,2,3$ & 4, respectively. It is thus noted that SNR gain of ~ 0.29 dB and capacity gain of merely ~ 2% is obtained when N_c goes from 3 to 4, i.e. GSC (4,3) to GSC (4,4) or MRC. Hence it is concluded that very negligible gain is achieved at the cost of overall system complexity.

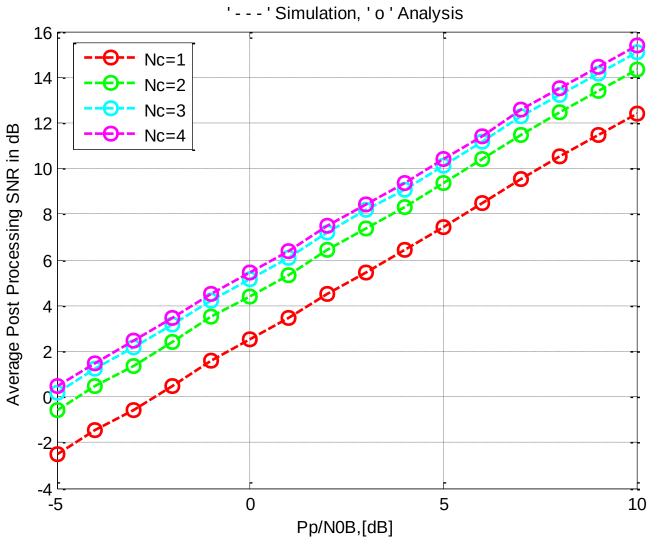

Fig.3.2 Average post processing SNR of GSC in power limited CR system

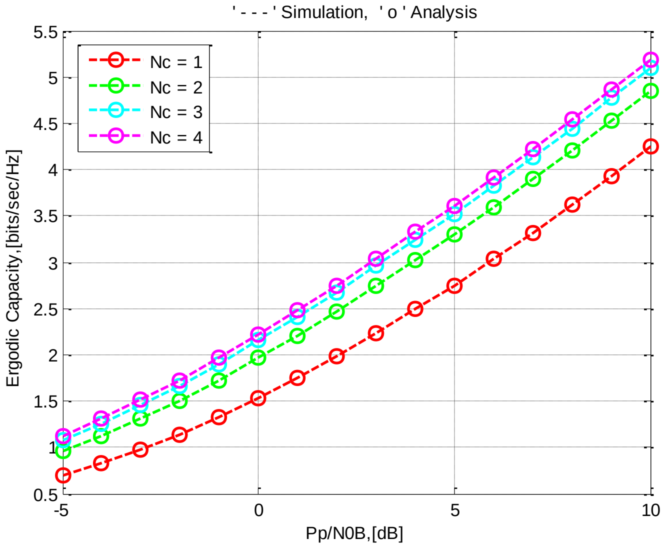

Fig.3.3 Ergodic capacity of GSC in power limited CR system.

- *Under the influence of Rician fading*

This section discusses the simulation result for the underlay cognitive radio under the influence of Rician fading with GSC at the CR-Rx. The achieved outcome shows that the system under consideration is the function of the number of best receiver branches to be combined. Figure 3.4 demonstrate the simulation results of average post processing SNR at CR-Rx with GSC in underlay cognitive radios at Q=5 dB. From the figure 3.4, we deduced that, average post processing SNR increases as the number of best to be chosen goes from $N_c = 1$ to $N_c = 4$, respectively. It shows that at $N_c = 1$, average SNR is 5.81 dB, at $N_c = 2$ it is 10.17 dB, at $N_c = 3$ it is 13.56 and at $N_c = 4$ it is 15.96 dB.

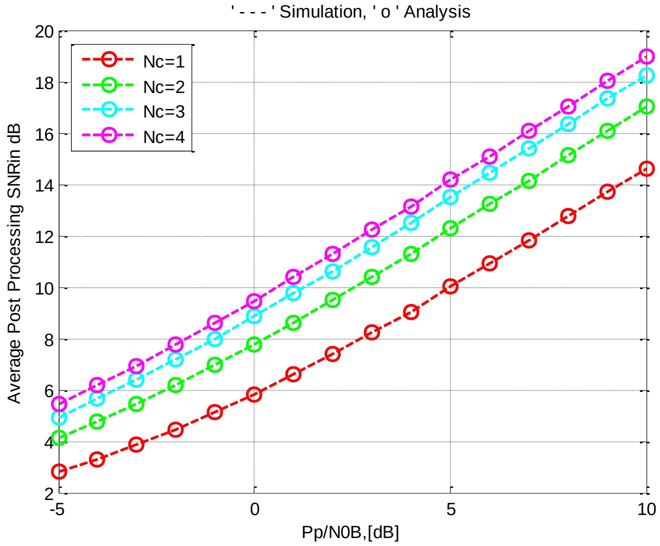

Fig. 3.4 Average post processing SNR of GSC CR system in Rician fading environment

Similarly figure 3.5, shows the results for ergodic capacity for GSC cognitive radios under the Rician fading scenario. It is found out that ergodic capacity increases from 3.32 bits/sec/Hz to 4.72 bits/sec/Hz as the number of best branches to be combined at the CR-Rx increases from $N_c = 1$ to $N_c = 4$.

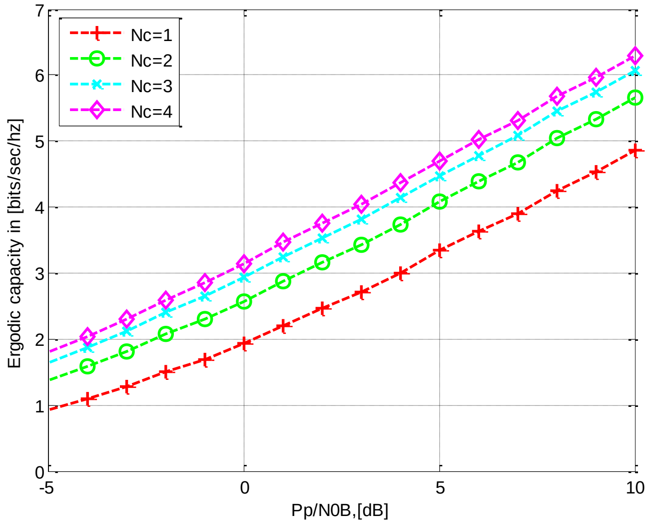

Fig. 3.5 Ergodic capacity of GSC CR system in Rician fading environment

Table-3.1 depicts the performance evaluation of GSC technique under the influence of various fading environments viz. Rayleigh and Rician. It is clear from Table-3.1, that as the number of best combined branches increases both the performance metrics improve, respectively. Also, it is demonstrated that the performance of the considered system depends upon the fading environment. It can be seen that the average post processing SNR in Rayleigh and Rician scenarios goes from 7.49 to 10.39dB and 10.03 to 14.16 dB as N_c increases from 1 to 4, respectively. Whereas ergodic capacity increases from 2.75 to 3.61 and 3.32 to 4.68 when N_c goes from 1 to 4. It can be concluded that Rician fading model provides better output as compared to Rayleigh counterpart. As Rician fading is a phasor addition of two dominant paths i.e. direct link and ground reflected link and the combined outcome is completely predictable at the dedicated Rx. Whereas Rayleigh scenario is more realistic model as the transmitted signal suffers many amplitude and phase fluctuations due to stochastic behaviour of the wireless medium.

Table –3.1 Performance Evaluation of GSC scheme in shared spectrum CR system for varying number of best Rx branches under the impact of different fading scenarios

Parameters Best combined Branches	Average post processing SNR in dB of conventional GSC CR systems at Q=5dB for different fading environments		Ergodic capacity in Bits/Sec/Hz of conventional GSC CR systems at Q=5dB for different fading environments	
	Rayleigh Fading	**Rician Fading**	**Rayleigh Fading**	**Rician Fading**
$N_c = 1$	7.49	10.03	2.75	3.32
$N_c = 2$	9.40	12.29	3.30	4.07
$N_c = 3$	10.16	13.49	3.52	4.46
$N_c = 4$	10.39	14.16	3.61	4.68

In the next section the performance of the proposed GSC system with TAS and S-TAS is analyzed with fixed number of transmit antennas (N_t).

(b) Performance analysis of TAS/GSC and S-TAS/GSC systems with fixed N_t and fixed K

The analytical performance of S-TAS/GSC has been discussed in section 3.3. Now the performance analysis is done on the basis of Monte Carlo simulations. The various parameters required for the simulation are given below:

The proposed multiuser CR network consists of two transmit antennas i.e. $N_c = 2$ at CR-Tx and four CR users where each CR-Rx is assumed to be equipped with four receive antennas i.e. $N_r = 4$. The channel is modelled as flat Rayleigh faded with complex Gaussian distribution with mean = 0, variance = 1 and is denoted as $CN(0,1)$. The noise is considered white and is modelled as $CN(0,1)$. For finding average post processing SNR and ergodic capacity, a block consisting of 200 random bits is sent from transmitter with all the bits having values 0 or 1. The bits are transmitted using BPSK modulation as ± 1. The peak power P_p of each block transmission is varied from -5 dB to 10 dB.

At the receiver end, the bits received at the input of GSC combiner are processed on the basis of maximum instantaneous channel gain. Based on the sorted values of channel gain, the best N_c branches are combined, where $N_c = 1,2,3,4$. For the chosen number of best combined branches, the instantaneous post processing SNR is obtained at the output of each CR-Rx corresponding to each transmit antenna. Now each CR user feedback the index of best antenna to the scheduler at the CR-Tx. Further for best selected transmitter antenna, the best CR user is selected on the basis of maximum post processing SNR. The performance metrics in terms of average post processing SNR and ergodic capacity for the best selected CR user and the best transmitting antenna have been found using Monte Carlo simulations. For each value of P_p, the achieved results are averaged over 10000 channel iterations.

In this part of results, we demonstrated that the analytical results obtained using Eq. (3.24) for average post processing SNR and Eq. (3.25) for ergodic capacity are fully corroborated with the simulation counterpart for the proposed S-TAS/GSC system with $K = 1$ (TAS/GSC) and $K = 4$ (S-TAS/GSC) under the impact of Rayleigh fading channel. Figure 3.6 depicts the analytical as well as simulated results for average post processing SNR for the TAS-GSC CR system. From the figure 3.6, it can be deduced that as the number of best chosen Rx branches increases, the Average post processing SNR rises for $Nc = 1$(i.e. SC) increases from 9.34 dB to 12.07 dB at $Nc = 4$ (i.e. MRC) at $P_p = 5$ dB. It is demonstrated that very small SNR gain of ~ 0.28 dB is achieved when Nc goes from 3 to 4.

Figure 3.7 is plotted for the simulated and analytical results of ergodic capacity of TAS/GSC system with varying number of best combined N_c antennas. It is shown that the ergodic capacity improves as Nc goes from 1 to 4. Results shows that overall increase in ergodic capacity is 27.38% when number of best branches increases from $Nc = 1$ i.e. SC to Nc=4 i.e. MRC at $P_p = 5dB$. It is also seen that negligible increase of 2.3% in ergodic capacity is achieved at GSC (4,3) system over GSC(4,4).

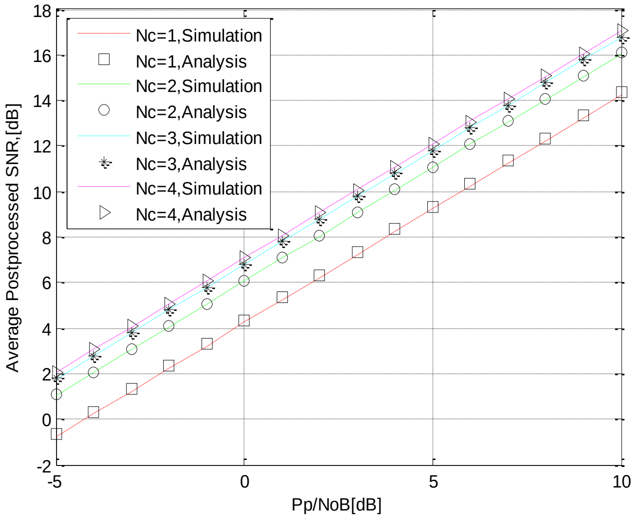

Figure 3.6: Performance evaluation of conventional TAS/GSC CR system for average post processing SNR with K=1

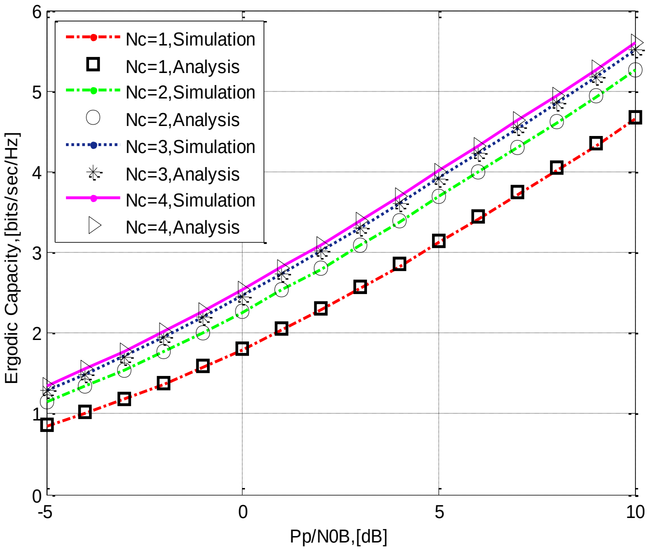

Figure 3.7: Performance evaluation of conventional TAS/GSC CR system for ergodic capacity with K=1

In figure 3.8, the average post processing SNR of S-TAS/GSC system is plotted for the simulated and analytical results, when $K = 4$ and number of best receive (Nc) antennas are recursively varying. It is illustrated that average post processing SNR for TAS-GSC CR system increases by 2.5 dB when Nc increases from 1 to 4 at $P_p = 5$ dB. From Table-3.1, it's verified that there is a slight SNR gain enhancement of i.e. 0.27 dB for $Nc = 3$ i.e. GSC (4,3) over MRC i.e. GSC(4,4).

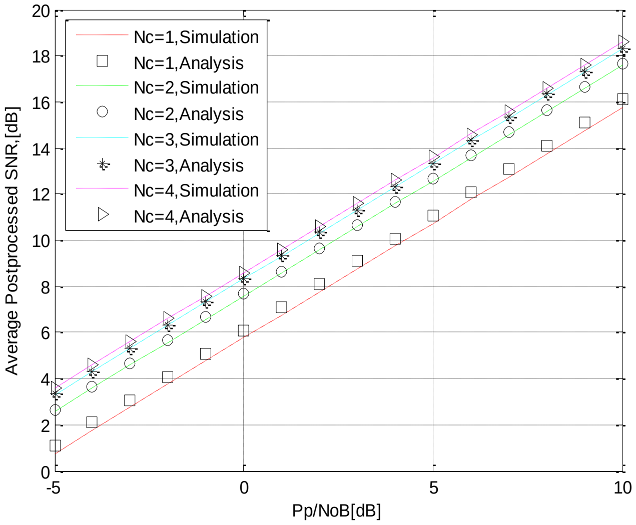

Figure 3.8: Performance evaluation of S – TAS/GSC CR system for Average post processing SNR with K=4

Figure 3.9 demonstrate both the analytical and simulation outcomes for the ergodic capacity of S-TAS/GSC CR system with $K = 4$ CR users. Attained results shows that ergodic capacity improves by 22% when number of best branches increases from $Nc = 1$ (i.e. SC) to $Nc = 4$ (i.e. MRC) at $P_p = 5dB$. It is also seen that very slight increase of 2% in ergodic capacity is achieved at GSC(4,3) system over GSC(4,4).

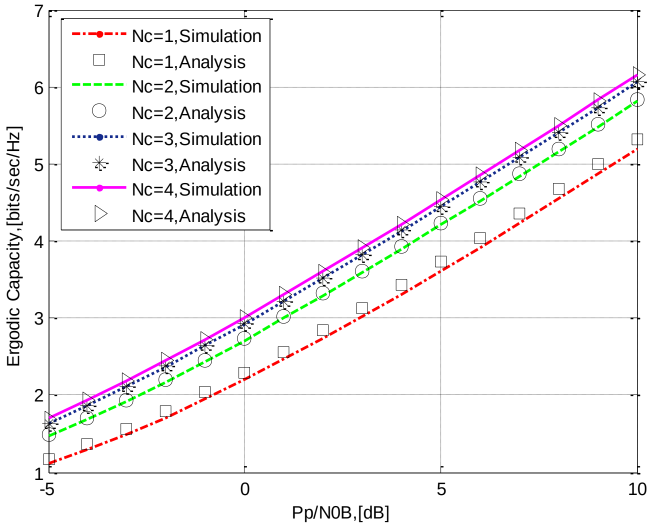

Fig. 3.9: Performance evaluation of S – TAS/GSC CR system for ergodic capacity with K=4

Figures 3.10 and 3.11 compare simulated as well as analytical results of conventional TAS/GSC with $K = 1$ and S-TAS/GSC with $K = 4$ systems in context of Average post processing SNR and ergodic capacity. MUD gain of ≈1.5 dB is obtained at $P_p = 5dB$ by S-

TAS/GSC system over TAS/GSC system for Nc = 3 has been shown in figure 3.10. Capacity improvement of ≈ 13% is achieved by S-TAS/GSC system over TAS/GSC system at $P_p = 5dB$ is inferred from the figure 3.11. Finally it can be inculcated that overall system throughput enhancement is obtained from S-TAS/GSC system as compared to the conventional TAS/GSC system.

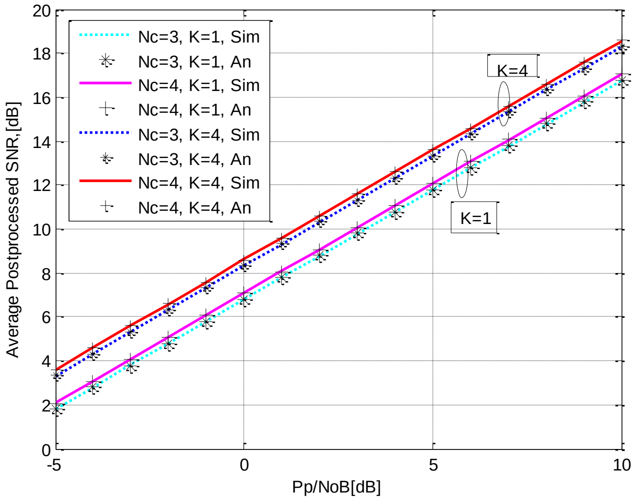

Figure 3.10: Performance comparison between S – TAS/GSC and conventional TAS/GSC CR system in terms of average post processing SNR

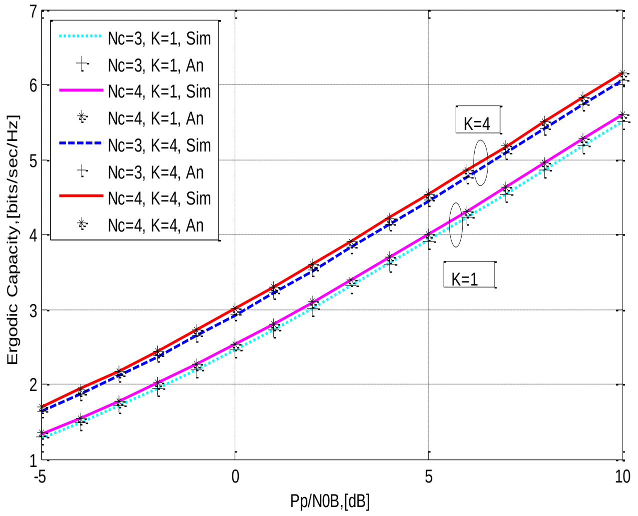

Figure 3.11: Performance comparison between S – TAS/GSC and conventional TAS/GSC CR systems in terms of ergodic capacity.

Table 3.2 shows the performance comparison between the two proposed schemes i.e. S-TAS/GSC and conventional TAS/GSC with varying number of combined Rx chains and CR users, respectively. It can be seen that the Average post processing SNR for $K = 1$ and 4 for GSC (4,3) is 11.79 dB and 13.32 dB respectively and with MRC or GSC (4,4) is 12.07 dB and 13.59 dB respectively. Likewise the ergodic capacity for $K = 1$ *and* 4 for GSC(4,3) is

4.53 bits/s/Hz and 5.08 bits/s/Hz respectively and with MRC or GSC (4,4) enhances to 4.62 bits/s/Hz and 5.17 bits/s/Hz respectively. Thus it can be resolved that SNR gain of S-TAS/GSC with $K = 4$ at GSC$(4,3)$ and GSC$(4,4)$ is ~ 1.5 dB over their counterpart i.e. conventional TAS/GSC CR system with $K = 1$.

TABLE-3.2: Performance comparison between the conventional TAS/GSC and S- TAS/GSC

PROPOSED MODELS	**TAS/GSC** $P_p = 5\ dB$, Q =15 dB, $N_t = 2$, $N_r = 4, L = 1, K = 1$		**S-TAS/GSC** $P_p = 5\ dB$, Q=15 dB, $N_t = 2$, $N_r = 4, L = 1, K = 4$	
Metrics **Best Combined Rx branches**	**AVERAGE POST PROCESSING SNR (in dB)**	**ERGODIC CAPACITY (in Bits/Sec/Hz)**	**AVERAGE POST PROCESSING SNR (in dB)**	**ERGODIC CAPACITY (in Bits/Sec/Hz)**
N_c= 1	9.34	3.14	11.08	3.72
N_c= 2	11.08	3.68	12.66	4.23
N_c= 3	11.79	3.91	13.32	4.44
N_c= 4	12.07	4.0	13.59	4.53

Additionally, the gain in ergodic capacity for S-TAS/GSC with $K = 4$ at GSC$(4,3)$ and GSC$(4,4)$ is ~ 12% over their similitude i.e. conventional TAS/GSC CR system with $K = 1$. Finally it can be said that the GSC$(4,3)$ achieves almost same results as MRC or GSC $(4,4)$ with very little loss in overall system throughput. It's concluded that by employing GSC combining, overall system complexity gets reduced and performance equivalent to an optimal diversity combining technique i.e. MRC can be obtained.

(c) Performance evaluation of S-TAS/GSC with varying number of transmit antennas (N_t) and CR users (K)

In this section, the previous work is generalised for varying number of transmitting antennas and CR users. The performance of conventional TAS/GSC (i.e. single user system) and S-TAS/GSC cognitive systems is analyzed in terms of average post processing SNR and ergodic capacity in Rayleigh fading environment.

Figure 3.12 depicts the average post processing SNR of S-TAS/GSC CR system with different N_t and K configurations for $N_c = 3\ and\ 4$. The achieved result shows that at ($N_t =$

$1, K = 1)$ i.e. with no TAS and no user scheduling done, the SNR at the CR-Rx is obtained as 10.14 dB and10.43 dB $N_c = 3\ and\ 4$, respectively. Whereas for the case when $(N_t = 1, K = 8)$ i.e. no TAS but with user scheduling done out of 8 available and active CR users, the SNR attained is 13.17 dB and 13.45 dB at $N_c = 3\ and\ 4$ respectively. Thus CR user scheduling without TAS offers SNR improvement of ~ 3dB for both $N_c = 3\ and\ 4$. Alternatively, when both TAS and scheduling are considered for $N_t =\ 4$ and $K = 4$, the Average post processing SNR increases from 13.78 dB to 14.06 dB at $N_c = 3\ \&\ 4$ respectively. Also when $N_t >\ N_r$ i.e. $(N_t = 6, K = 8)$ the SNR at the CR-Rx rises from 14.56 dB to 14.85 dB.

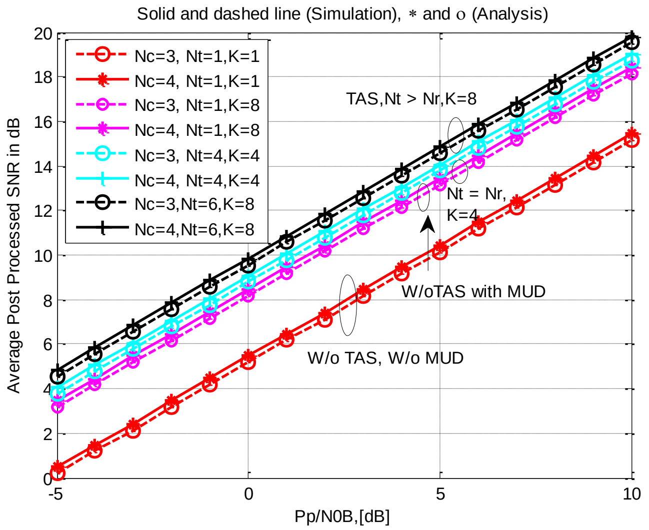

Fig. 3.12: Performance evaluation of CR network with changing configurations of transmit antennas and CR users in terms of average post processing SNR

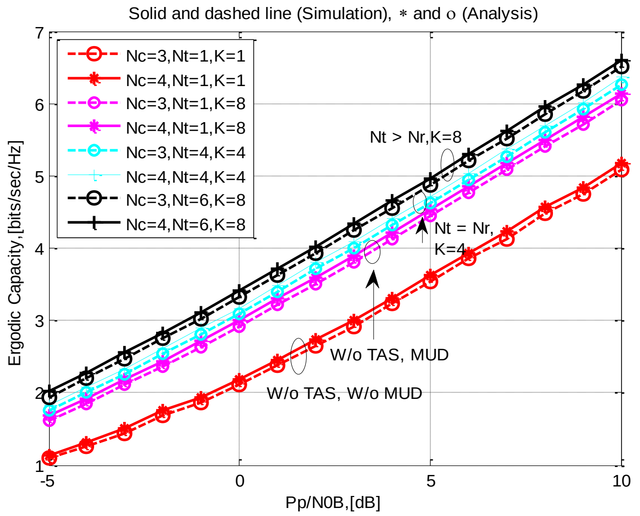

Figure 3.13: Performance evaluation of CR network with changing configurations of transmit antennas and CR users in terms of ergodic capacity

Figure 3.13 indicates the outcomes of S-TAS/GSC CR system in terms of ergodic capacity with changing number of transmit antennas and the CR users under the effect when when N_c

changes from 3 to 4. It can be noted that without TAS and scheduling i.e. $N_t = 1, K = 1$, the ergodic capacity obtained as 3.53 and 3.62 bits/Sec/Hz at $N_c = 3\ and\ 4$ respectively. The ergodic capacity increases from 4.44 and 4.53 bits/Sec/Hz at $N_t = 1\ and\ K = 8$ for $N_c = 3\ \&\ 4$ respectively. Also when considering $N_t = N_r$ i.e. ($N_t = 4, K = 4$) the capacity rises from 4.62 bits/sec/Hz to 4.71 bits/sec/Hz at $N_c = 3\ and\ 4$. On the contrary, when $N_t > N_r$ i.e. ($N_t = 6, K = 8$) the ergodic capacity enhances from 4.88 to 4.97 bits/sec/Hz, at $N_c = 3\ and\ 4$ respectively.

Table-3.3 demonstrates the SNR gain as well as capacity gain for S-TAS/GSC CR system for varying number of transmit antenna and CR users at $N_c = 3\ and\ 4$. It is clear from the Table-3.3 that for scheduled CR system without TAS with $N_t = 1, K = 8$, the SNR gain of ~ 3dB and ergodic capacity gain of ~ 25% is achieved as compared to non-scheduled CR system i.e. without TAS and user scheduling with $N_t = 1, K = 1$.By considering, S-TAS/GSC CR system employing TAS as well as user scheduling i.e. $N_t = 4, K = 4$ then SNR gain and capacity gains of approximately 3.64 dB and 30% are incurred as compared with non-scheduled system i.e. ($N_t = 1, K = 1$). Now by taken into consideration $N_t > N_r$ i.e. ($N_t = 6, K = 8$) CR system and comparing it with three different combinations of $N_t, K = (1,1)$, (1,8) & (4,4) system, the SNR gain of ~ 4.4 dB, 1.4 dB and 0.8 dB is obtained respectively. Also for ($N_t = 6, K = 8$) CR system, capacity gain of ~ 38%, 10% and 6%, is achieved as compared to $N_t, K = (1,1)$, (1,8) & (4,4) systems, respectively.

Table-3.3 Performance evaluation of S-TAS/GSC CR system for different combinations of transmit antennas and CR users.

Parameters / **Best combined Branches**	**Average post processing SNR of S-TAS/GSC CR systems for different configurations of transmit antenna (N_t) and CR users (K) in dB.**				**Ergodic capacity of S-TAS/GSC CR systems for different configurations of transmit antenna (N_t) and CR users (K) in Bits/Sec/Hz.**			
	(N_t, K) $(1,1)$	(N_t, K) $(1,8)$	(N_t, K) $(4,4)$	(N_t, K) $(6,8)$	(N_t, K) $(1,1)$	(N_t, K) $(1,8)$	(N_t, K) $(4,4)$	(N_t, K) $(6,8)$
$N_c = 3$	10.14	13.17	13.78	14.56	3.53	4.44	4.62	4.88
$N_c = 4$	10.43	13.45	14.06	14.85	3.62	4.53	4.71	4.97

3.5 Conclusions

From the available research work, we analyze an efficient communication system which incorporates spectrum sharing CR network with TAS and GSC at the transmitter and receiver, respectively. Then we derived the PDF of S-TAS/GSC CR system which is a function of number of best combined receiver branches and the number of active $'K'$ CR users which are competing or the spectrum resources. By utilizing the derived PDF, the approximate expressions for average post processing SNR and the ergodic capacity for the considered CR system with $K = 1\ and\ 4$ are obtained. The derived analytical as well as simulated result shows that average post processing SNR gain and ergodic capacity gain of S-TAS/GSC with $K = 4$ users is higher than TAS/GSC with $K = 1$ user by MUD. The proposed system is also studied and analyzed with various combinations of (N_t, K), i.e. CR users and the number of transmit antennas, respectively. Hence it indicates that GSC (4,3) gives almost the same outcomes as MRC, which ultimately reduces transmitter complexity and signal processing by reducing the number of RF chains.

After studying and thoroughly analyzed the one of the best spatial diversity scheme i.e. TAS, where one best transmit antenna is selected out of all available antennas. Hence the proposed system was communicating with single best antenna. Now we are going to study the impact of MIMO system with another very efficient SD scheme i.e. space time coding. The subsequent chapter discusses STBC at the CR-Tx with GSC at the CR-Rx in underlay spectrum sharing scheme. It also demonstrates the performance comparison of both the SD schemes i.e. TAS and STBC in multiuser scenario.

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Chapter 4

Performance Analysis of multiuser MIMO with Transmit Antenna Selection and Space Time Block Coding with Generalized Selection Combining in Underlay CR system with primary user outage constraint

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In this chapter, the TAS/GSC has been extended to STBC/GSC in cognitive radios under primary user outage constraint which is considered as the tighter constraint as compared to the conventional interference temperature constraint. The proposed transmit power policy enforces CR -Tx to adapt its power to be transmitted so as to protect primary network from harmful interference from the CR network in order to satisfy PU outage probability constraint. Further the proposed systems S-TAS/GSC and S-STBC/GSC have extended to scheduled multiuser environment. It is demonstrated that S-TAS system have potential to improve system throughput in terms of average post processed SNR, ergodic capacity and ABER as compared to S-STBC CR system.

This chapter is divided into two parts; the first part introduces GSC with STBC transmission at the CR base station in underlay spectrum sharing. The second part demonstrates the multiuser CR system by implementing TAS/GSC and STBC/GSC at the CR-Tx. In the last section, the performances of both the scheduled CR systems have been compared and outcomes are plotted as well as tabulated.

4.1 Introduction

Orthogonal Space Time Block Coding (OSTBC) is a simple transmit diversity technique with low decoding complexity. This was first proposed by Alamouti for two transmit antennas [68]. His idea was further studied for generalized number of antennas [69] by Tarokh et al. The joint transmit and receive diversity significantly improves overall system capacity. Conventionally, OSTBC uses MRC at the receiver (Rx) side for scalar detection of signal. As number of receive branches increases, the implementation and signal processing with MRC becomes more complex. To reduce system complexity, OSTBC with GSC is proposed in [73]. The main advantage of OSTBC/GSC over OSTBC/MRC [74] is reduced hardware complexity, implementation cost, power consumption and signal processing with almost similar performance. Furthermore STBC/GSC can attain power savings as compared with STBC/MRC [75-77]. The performance bounds for generalized selection combining with space time codes are provided in [75]. Considering the advantage of GSC over MRC in terms of less cost, low power consumption, improved channel estimation [51-53] and reduced number of RF chains, we have studied STBC/GSC in underlay cognitive radios.

Second part of this chapter, shows the performance comparison of both the spatial diversity schemes viz. TAS and STBC. SD obtain through both the techniques is a fundamental aspect for efficaciously combating malign effects of multipath fading. In TAS [58-67], single transmit antenna is selected out of 'N_t' transmit antennas at CR-Tx on the basis of CSI available through error free feedback path, whereas STBC [70-71] requires all transmitting antennas for the communication process. It transmits multiple replicas of data to be transmitted among all available transmit antennas in different time slots. In [89], authors have analyzed TAS and STBC in terms of ergodic and outage capacity in MIMO CR systems. Unlike TAS, STBC does not require feedback path to a CR-Tx, which result in overall reduced complexity. The ergodic capacity of CR scheduled system is improved by MUD gain over non-scheduled i.e. with single user system and is studied in [81-83]. In [88], the authors have analyzed scheduled TAS/MRC and scheduled STBC/MRC in CR and concluded that S-TAS achieves better performance than S-STBC by MUD. Thus by exploiting both multiuser MIMO and antenna diversities at the same time, higher system capacity and reduced bit error rate performance is achieved over fading scenario [89-91]. Section 4.2 discusses the system model of STBC transmit diversity in underlay CR with GSC at the CR-Rx.

4.2. Performance evaluation of STBC scheme in underlay Cognitive radios with generalized selection combining under PU outage probability constraint

4.2.1 System Model

An underlay STBC/GSC CR system model is shown in Figure 4.1. The CR network of proposed system consists of a CR-Tx employing STBC transmission [103-104] and a CR-Rx equipped with GSC combiner. The PU network consists of a PU-Tx communicating with a PU-Rx. Here the CR-Tx and CR-Rx are equipped with $N_t(j = 1,2)$ and $N_r(i = 1 \dots N_r)$ antennas, respectively. The PU-Tx is assumed to be located far away from CR network receiver hence its impact i.e. cross interference on from PU-Tx to CR-Rx is not taken into consideration. The PU-Rx is having $N_{PR}(k = 1 \dots N_{PR})$ antennas. Let $\boldsymbol{H}_{CR}$ be $(N_r \times N_t)$ dimensional channel matrix between CR-Tx and CR-Rx. In addition there is an interference link $\boldsymbol{H}_{\alpha}$ of dimension $(N_{PR} \times N_t)$ from CR-Tx to PU-Rx. The channel path gain from PU-Tx to PU-Rx is denoted by h_β. The entries h_{ij} of matrix $\boldsymbol{H}_{CR}$, h_{kj} of matrix $\boldsymbol{H}_\alpha$ and h_β are independent and identically distributed exponential random variable.

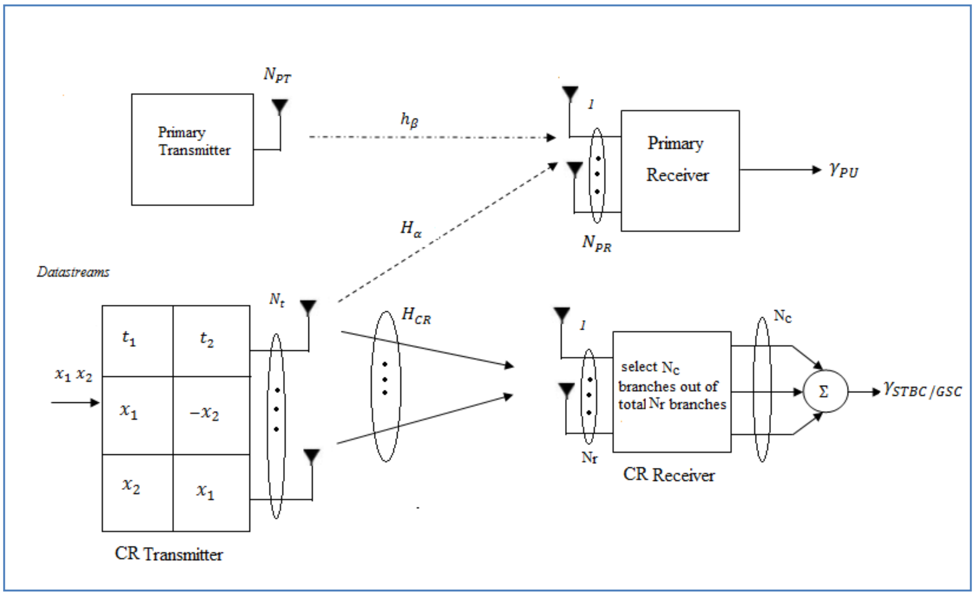


Figure 4.1: System model of shared spectrum STBC/GSC cognitive radio system

It is considered that CR-Tx is transmitting via orthogonal space time block coding scheme and the CR-Rx is equipped with GSC combining having N_r receive antennas. In GSC combining, out of N_r resolvable paths, best N_c branches are combined adaptively. The perfect channel state information from CR-Tx to PU-Rx and CR-Tx to CR-Rx is available to CR-Tx through reliable feedback path. We represent the signal bandwidth B and additive white Gaussian noise $'N_0'$. Let $\boldsymbol{\Omega_h}$, $\boldsymbol{\Omega_\alpha}$ and $\boldsymbol{\Omega_\beta}$ denote the mean values of random variables $\boldsymbol{h}$, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, respectively. Using Alamouti scheme at the CR-Tx, out of total 'N' bits to be transmitted, two bits i.e. x_1 *and* x_2 are being transmitting in two consecutive time slots. The received signal ($\boldsymbol{r}_{N_t,N_c}$) in these two time slots at the i^{th} branch of CR-Rx can be written as

$$\boldsymbol{r}_{1,i} = \boldsymbol{h}_{1,i}x_1 + \boldsymbol{h}_{2,i}x_2 + \boldsymbol{n}_{1,i} \tag{4.1}$$

$$\boldsymbol{r}_{2,i} = -\,\boldsymbol{h}_{1,i}{x_2}^* + \boldsymbol{h}_{2,i}{x_1}^* + \boldsymbol{n}_{2,i} \tag{4.2}$$

Where $\boldsymbol{h}_{j,i}$ denotes $j = 1,2$ and $i = 1,2 \ldots N_r$ is the complex channel path gain between j^{th} transmitting antenna and i^{th} receive antenna and $\boldsymbol{n}_{j,i}$ is the additive white Gaussian noise. At the SU-Rx, the received signal is first processed by space time combiner, which computes the decision variables denoted by ($\boldsymbol{y}_{N_t,N_c}$) as

$$\boldsymbol{y}_{1,i} = {\boldsymbol{h}_{1,i}}^*\boldsymbol{r}_{1,i} + \boldsymbol{h}_{2,i}{\boldsymbol{r}_{2,i}}^* \tag{4.3}$$

$$\boldsymbol{y}_{2,i} = \boldsymbol{h}_{2,i}{}^{*}\boldsymbol{r}_{1,i} - \boldsymbol{h}_{1,i}\boldsymbol{r}_{2,i}{}^{*} \tag{4.4}$$

For a generalized selection combining GSC ($N_{r,}N_{c}$), the best N_c branches are combined on the basis of highest instantaneous SNR, out of total N_r available branches. Hence the signal-to-noise ratio at the output of GSC combiner ($\boldsymbol{\gamma}_{stbc_{gsc}}$) of the CR-Rx can be written as [76]

$$\boldsymbol{\gamma}_{stbc_{gsc}} = \frac{P_{crmax}}{N_o B R_{CR} N_t} \sum_{i=1}^{N_c} \boldsymbol{y}_{ji}, \;\; j = 1,2 \qquad , \tag{4.5}$$

where, P_{crmax} denotes the maximum transmit power which is derived later in the following section and R_{CR} defines the transmission rate of the CR network.

4.2.2 Performance Analysis of STBC/GSC system

- ***Transmit Power Scheme for CR-Tx under PU Outage constraint***

In this section, we deduce the transmit power policy for the CR-Tx in order to enhance the system throughput under the PU outage constraint at PU-Rx, along with the PTP (peak transmit Power) constraint at CR-Tx. It is thus shown that proposed transmit power strategy is adopted from [19] having advantage of incurring substantial increase in capacity gain as compared to conventional IT (Interference Temperature) constraint. To fulfill IT constraint, the CR-Tx has to limit its power in order to protect PU from malicious interference from CR network. It should be taken into consideration that PU allows the secondary user to access its licensed spectrum as long as quality of service of PU is not compromised by the interference power received from the CR-Tx [18-21].

In [106], the author has proposed the use of outage capacity parameter instead of using Interference Temperature constraint as new criteria to regulate transmit power of CR-Tx. This new method is directly related to PU transmissions and thus leads to improved system throughput of cognitive network. We assume that instantaneous channel state information is not available at PU-Tx, hence it is communicating with constant transmit power P_{pu} and transmission rate R_{PU}. The QoS is maintained if the outage probability of PU is kept below a specified threshold. Let ϵ_{PU} and γ_{PUth} denote the desired outage probability and outage threshold of PU network can be referred as $\gamma_{PUth} = 2^{r_{PU}} - 1$ at the PU-Rx, respectively. By taken into consideration, the effect of CR transmissions to Primary User radio link, the PU network outage constraint ($P_{p,out}$) can be written as [23]

$$P_{p,out} = P_r\{\{\gamma_{PU}\} \leq \gamma_{PUth}\} \leq \epsilon_{PU}, \tag{4.6}$$

where γ_{PU} denotes instantaneous signal-to-noise plus interference ratio at PU-Rx [53] and can be written as

$$\gamma_{PU} = \frac{P_{pu}\, h_\beta}{P_{cr}\sum_{j=1}^{N_t}\sum_{k=1}^{N_{PR}} h_{kj} + N_o B} \ , \tag{4.7}$$

where, $P_{pu}\ and\ P_{cr}$ denote the power transmitted by PU-Tx and CR-Tx, respectively. By putting $\boldsymbol{z} = \sum_{j=1}^{N_t}\sum_{k=1}^{N_{PR}} \boldsymbol{h}_{kj}$ which is a chi square random variable with $2N_t N_{PR}$ degrees of freedom. Rewriting (4.7) as

$$\gamma_{PU} = \frac{P_{pu}\, h_\beta}{P_{cr} z + N_o B} \ , \tag{4.8}$$

To calculate outage probability of PU network, let us substitute (4.8) into (4.6) and integrating it over the PDF of $\boldsymbol{z}$, we get

$$P_{p,out} = \int_0^\infty P_r\left[P_{pu}\, h_\beta \leq (P_{cr} z + N_o B)\gamma_{PUth}\right] f_{\boldsymbol{H}_\alpha} d(z) \leq \epsilon_{pu} \ , \tag{4.9}$$

where, $f_{\boldsymbol{H}_\alpha}(z) = \frac{z^{N_t N_{PR}-1}}{{\Omega_\alpha}^{N_t N_{PR}} \Gamma(N_t N_{PR})} exp\left(\frac{-z}{\Omega_\alpha}\right)$ is the PDF of channel path gain from CR-Tx to PU-Rx.

Integrating (4.9) w.r.t z, we get

$$1 - \left(\frac{P_{pu}\,\Omega_\beta}{\gamma_{PUth} P_{cr} \Omega_\alpha + P_{pu}\,\Omega_\beta}\right)^{N_t N_{PR}} exp\left(-\frac{N_0 B \gamma_{PUth}}{P_{pu}\,\Omega_\beta}\right) \leq \epsilon_{PU} \tag{4.10}$$

Calculating P_{cr} from (4.10), we obtain

$$P_{cr} \leq \frac{P_{pu}\,\Omega_\beta}{\gamma_{PUth}\Omega_\alpha}\left[\frac{1}{\left(\sqrt[N_t N_{PR}]{1-\epsilon_{PU}}\right)} exp\left(-\frac{N_0 B \gamma_{PUth}}{P_{pu}\,\Omega_\beta}\right) - 1\right] \tag{4.11}$$

Thus the maximum transmit power of CR-Tx (P_{crmax}) under the outage probability constraint of PU can be given as

$$P_{crmax} = min\left(\frac{P_{pu}\,\Omega_{\beta}}{\gamma_{PUth}\Omega_{\alpha}} \left[\frac{1}{\left(^{N_t N_{PR}}\sqrt{1-\epsilon_{PU}} \right)} exp\left(-\frac{N_0 B \gamma_{PUth}}{P_{pu}\,\Omega_{\beta}} \right) - 1 \right], P_{CR-peak} \right), \tag{4.12}$$

where, $\Omega_{\alpha} = \xi$ and $P_{CR-peak}$ is the average interference power received at the PU and the peak power that CR-Tx can impart from N_t transmit antennas during a symbol period, respectively. This derived expression renders the maximum allowable transmit power by the CR-Tx in order to satisfy the outage probability constraint defined by the primary network and PTP constraint specified at the CR-Tx, respectively. Based upon the derived transmit power in Eq. (4.12), performance of the proposed system is examined in terms of average post processed SNR, ergodic capacity and ABER.

(a) Average Post Processed SNR

The combined signal after being processed by the space time combiner is fed to MRC which finally provides the post processed output at the CR-Rx. Now, the performance of the proposed system is examined in terms of average post processed SNR which can be obtained by calculating the first moment of the random variable '$\boldsymbol{y}$' over all the fading states of the Rayleigh channel. The PDF of the STBC/GSC CR system can be written as

$$f_{y_{GSC}}(y) = \binom{N_r}{N_c} \left(\frac{y^{Nc-1} \mathrm{e}^{\frac{-yN_t}{\Omega_y}} {N_t}^{\mathrm{Nc}}}{{\Omega_y}^{Nc}(Nc-1)!} + \frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_y} \left(\mathrm{e}^{\frac{-yN_t\left(1+\frac{l}{N_c}\right)}{\Omega_y}} - \mathrm{e}^{\frac{-yN_t}{\Omega_y}} \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m (yN_t)^m}{{\Omega_y}^m m!} \right) \right) \tag{4.13}$$

where, $f_{y_{GSC}}$ and Ω_y is the PDF [53] and average value of random variable $\boldsymbol{y}$.The first moment of y_{GSC} can be written as

$$\mathbb{E}\{y_{GSC}\} = \int_0^{\infty} y \; f_{y_{GSC}}(y) dy \tag{4.14}$$

$$= \binom{N_r}{N_c} \int_0^{\infty} y \left(\frac{y^{\mathrm{Nc}-1} \mathrm{e}^{\frac{-yN_t}{\Omega_y}} {N_t}^{\mathrm{Nc}}}{{\Omega_y}^{\mathrm{Nc}} (\mathrm{Nc}-1)!} + \frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_y} \left(\mathrm{e}^{\frac{-yN_t\left(1+\frac{l}{N_c}\right)}{\Omega_y}} - \mathrm{e}^{\frac{-yN_t}{\Omega_y}} \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m (yN_t)^m}{{\Omega_y}^m m!} \right) \right) dy$$

(4.15)

After solving (4.15), the average post processed SNR ($\gamma_{STBC/GSC}$) of STBC/GSC CR system is obtained as

$$\gamma_{STBC/GSC} = \frac{P_{crmax}}{N_o B R_{CR} N_t} \binom{N_r}{N_c} \left[\frac{\left(\frac{N_t}{\Omega_y}\right)^{-Nc-1} \Gamma(1+Nc) {N_t}^{\mathrm{Nc}}}{{\Omega_y}^{\mathrm{Nc}} (\mathrm{Nc}-1)!} + \frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_y} \left\{ \frac{(\Omega_y)^2 (Nc)^2}{(1+Nc)^2 {N_t}^2} - \left(\frac{N_t}{\Omega_y}\right)^{-m-2} \Gamma(m+2) \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m {N_t}^m}{{\Omega_y}^m m!} \right\} \right] \tag{4.16}$$

(b) Ergodic Capacity

The Ergodic Capacity ($\boldsymbol{C_{STBC/GSC}}$) of a proposed CR network under probability outage constraint of the primary network is defined as the maximum long term achievable rate and can be determined by performing average over all the channel fading states of a channel. The $C_{STBC/GSC}$ of the STBC/GSC CR can be expressed as [89]

$$C_{STBC/GSC} = \mathbb{E}\left\{\log_2\left(1 + \frac{P_{crmax}}{R_{CR} N_o B N_t} f_{GSC}\right)\right\} \tag{4.17}$$

To analyze the performance of the proposed system, ergodic capacity can be approximated using Taylor's series expansion of logarithm function and is represented in [106] as

$$C_{STBC/GSC} \approx \log_2\left(1 + \frac{P_{crmax}}{R_{CR} N_o B N_t} \mathbb{E}\{y_{GSC}\}\right) - \frac{\varsigma \left(\frac{P_{crmax}}{N_o B R_{CR} N_t}\right)^2 \sigma^2_{y_{GSC}}}{2\left(1 + \frac{P_{crmax}}{R_{CR} N_o B N_t} \mathbb{E}\{y_{GSC}\}\right)^2},$$

(4.18)

where, R_{CR} is the transmission rate of CR network, $\varsigma = log_2 e$ and e denotes the Neper's number.

Since the variance $\sigma^2_{y_{GSC}}$ of y_{GSC} is

$$\sigma_{y_{GSC}}^2 = \mathbb{E}\{{y_{GSC}}^2\} - \mathbb{E}^2\{y_{GSC}\}$$

(4.19)

To find variance, the second moment of y_{GSC} can be calculated as

$$\mathbb{E}\{{y_{GSC}}^2\} = \int_0^\infty y^2 \; f_{GSC}(y)dy$$

(4.20)

$$= \binom{N_r}{N_c} \int_0^\infty y^2 \left(\frac{y^{\mathrm{Nc}-1} \mathrm{e}^{\frac{-yN_t}{\Omega_y}} {N_t}^{\mathrm{Nc}}}{{\Omega_y}^{\mathrm{Nc}} (\mathrm{Nc}-1)!} + \frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_x} \left(\mathrm{e}^{\frac{-yN_t\left(1+\frac{l}{N_c}\right)}{\Omega_y}} - \right.\right.$$

$$\left.\left. \mathrm{e}^{\frac{-yN_t}{\Omega_y}} \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m (yN_t)^m}{{\Omega_y}^m m!} \right)\right) dy$$

(4.21)

By solving (4.21), we obtain

$$= \binom{N_r}{N_c} \left[\frac{\left(\frac{N_t}{\Omega_y}\right)^{-Nc-2} \Gamma(Nc+2) {N_t}^{\mathrm{Nc}}}{{\Omega_y}^{\mathrm{Nc}} (\mathrm{Nc}-1)!} + \frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_y} \left\{ \frac{2\left(\Omega_y\right)^3 (Nc)^3}{(1+N_c)^3 {N_t}^3} \right\} - \right.$$

$$\left. \left(\frac{N_t}{\Omega_y}\right)^{-m-3} \Gamma(m+3) \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m (y)^{m+2} {N_t}^m}{{\Omega_y}^m m!} \right] \tag{4.22}$$

(c) Average Bit Error Rate

An average bit error rate (ABER) can be termed as the erroneous bits received at the intended Rx due to random behaviour of the fading channel, noise and interference etc. It is considered as the rough estimate of the probability of error and can be determined by calculating moment generating function (MGF) of the given PDF. The MGF of the proposed system is obtained by applying the following relationship [72]

$$M_{GSC}(s) = \int_0^\infty \exp(s\gamma) \; p(\gamma)d(\gamma) \tag{4.23}$$

$$= \binom{N_r}{N_c} \int_0^{\infty} exp(s\gamma) \Bigg\{ \Bigg(\frac{\gamma^{\mathrm{Nc}-1} \mathrm{e}^{\frac{-\gamma N_t}{\bar{\gamma}}} {N_t}^{\mathrm{Nc}}}{\bar{\gamma}^{\mathrm{Nc}} (\mathrm{Nc}-1)!} + \frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\bar{\gamma}} \Bigg(\mathrm{e}^{\frac{-\gamma N_t \left(1+\frac{l}{N_c}\right)}{\bar{\gamma}}} -$$

$$\mathrm{e}^{\frac{-\gamma N_t}{\bar{\gamma}}} \sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m (\gamma N_t)^m}{\bar{\gamma}^m m!} \Bigg) \Bigg) \Bigg\} d(\gamma), \qquad (4.24)$$

where $\bar{\gamma} = \frac{P_{crmax}}{R_{CR} N0B}$ and

$p(\gamma)$ is obtained by expressing (4.13) in terms of γ.

$$M_{GSC}(s) = \binom{N_r}{N_c} \int_0^{\infty} \Bigg\{ \frac{\gamma^{Nc-1} {N_t}^{Nc}}{\bar{\gamma}^{Nc} (Nc-1)!} exp\left[-\gamma \left(\frac{N_t}{\bar{\gamma}} - s\right)\right] +$$

$$\frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\bar{\gamma}} \Bigg\{ exp\left[-\gamma \left[\frac{N_t}{\bar{\gamma}} \left(\frac{l}{N_c} + 1\right) - s\right]\right] -$$

$$\sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m (\gamma N_t)^m}{\bar{\gamma}^m m!} exp\left[-\gamma \left(\left(\frac{N_t}{\bar{\gamma}} - s\right)\right)\right] \Bigg\} \Bigg\} \qquad (4.25)$$

Hence MGF can be evaluated by using following identity [105, Eq. 2.321.2]

$$\int_0^{\infty} x^n e^{ax} \; dx = e^{ax} \left(\sum_{k=0}^{n} \frac{(-1)^k k! \binom{n}{k}}{a^{k+1}} x^{n-k} \right)$$

(4.26)

Using (4.26) in (4.25), MGF for the proposed STBC/GSC CR system can be written as

$$M_{GSC}(s) =$$

$$\binom{N_r}{N_c} \int_0^{\infty} \Bigg\{ \frac{{N_t}^{Nc}}{\bar{\gamma}^{Nc} (Nc-1)!} exp\left[-\gamma \left(\frac{N_t - s\bar{\gamma}}{\bar{\gamma}}\right)\right] \left(\sum_{i=0}^{Nc-1} (-1)^i i! \binom{Nc-1}{i} \left(\frac{\bar{\gamma}}{N_t - s\bar{\gamma}}\right)^{i+1} \gamma^{Nc-1+i} \right) +$$

$$\frac{N_t \sum_{l=1}^{N_r-Nc} (-1)^{Nc+l-1} \binom{N_r-N_c}{l} \left(\frac{N_c}{l}\right)^{N_c-1}}{\bar{\gamma}} \Bigg\{ exp\left[-\gamma \left(\frac{N_t i + N_t Nc - sNc\bar{\gamma}}{Nc\bar{\gamma}}\right)\right] -$$

$$\sum_{m=0}^{Nc-2} \frac{\left(\frac{-l}{Nc}\right)^m {N_t}^m}{\bar{\gamma}^m m!} \left[exp\left[-\gamma \left(\frac{N_t - s\bar{\gamma}}{\bar{\gamma}}\right)\right] \left(\sum_{k=0}^{j} (-1)^k K! \binom{j}{k} \left(\frac{\bar{\gamma}}{N_t - s\bar{\gamma}}\right)^{k+1} \gamma^{j-k} \right) \right] \Bigg\} \Bigg\} d\gamma \qquad (4.27)$$

Since the MGF of received average SNR at the GSC combiner over Rayleigh fading channel is assumed to be independent and identical for each transmit antenna 'N_t'. Hence the MGF of the considered STBC/GSC CR system can be obtained by raising Eq. (4.27) to the power equals to the number of transmit antenna i.e. N_t and we get $M_{STBC/GSC} = (M_{GSC})^{N_t}$. With this obtained MGF, the ABER of the STBC/GSC system can be achieved from [72] as

$$Pe_{STBC/GSC} = \frac{1}{\pi}\int_0^{\frac{(N_t-1)\pi}{N_t}} M_{STBC/GSC}\left(\frac{-g}{sin^2\phi}\right)\, d(\phi)\,, \tag{4.28}$$

where $g = sin^2\left(\frac{\pi}{N_t}\right)$, represents the modulation constant.

4.2.3 Results and Discussion

The proposed STBC/GSC CR network consists of two transmit antennas i.e. $N_t = 2$ at CR-Tx and four receive antennas i.e. $N_r = 2$ at the intended CR-Rx. The channel is modelled as flat Rayleigh faded with complex Gaussian distribution with mean = 0, variance = 1 and is denoted as $CN(0,1)$. The noise is considered white and is modelled as $CN(0,1)$. To find average post processed SNR, ergodic capacity and ABER, a block consisting of 100 random bits is sent from transmitter with all the bits having values 0 or 1. The bits are transmitted using BPSK modulation as ± 1. All bits are transmitted using STBC scheme i.e. two bits are transmitted from N_t antennas in two consecutive time slots. The desired outage probability constraint of PU (ϵ_{PU}) upon which the transmit power of CR-Tx depends is varied from 0 to 0.7 for each block transmission. The simulation details for the receiver part is same as discussed in section 3.4. At a given value of desired outage probability constraint of PU i.e. ϵ_{PU}, the achieved outcomes are averaged over 1000 channel realizations.

The attained results show that as the desired outage probability (ϵ_{PU}) of the primary network increases, with increase in the transmit power (P_{crmax}) of CR base station as seen from Eq. (4.12). The results obtained for the STBC/GSC CR system under Rayleigh fading scenario assumed $N_t = 2$, $N_r = 4$, N_c varies from 1 to 4, $R_{SU} = 1$, $R_{PU} = 0.2$, $\xi = 0.1$ and $\epsilon_{PU} = 0.4$.

The analytical results such as average post processed SNR from Eq. (4.16), ergodic capacity from Eq. (4.18) and ABER from Eq. (4.28) are achieved for the STBC/GSC CR system under the influence of outage probability constraint defined by the primary network.

It is shown in figure 4.2 to figure 4.3 that as the number of best combined branches at the GSC employed receiver increases from $N_c = 1$ (SC) to $N_c = 4$ (MRC), the average post processed SNR and the ergodic capacity improves from 4.12 to 7.85 dB and 1.84 to 2.77 Bits/Sec/Hz at $\epsilon_{PU} = 0.4$, respectively. It has been evidenced that the SNR gain and capacity gain for the proposed system is nearly 0.49 dB and ~4% is obtained when N_c goes from 3 to 4.

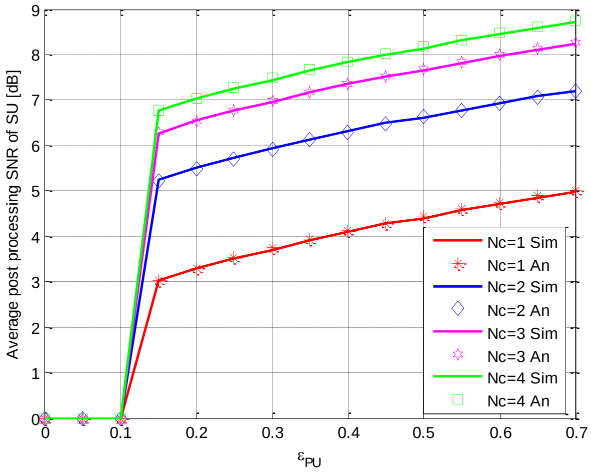


Fig. 4.2: Performance evaluation of STBC/GSC in terms of average post processed SNR under primary outage ϵ_{PU} at $\xi = 0.1$

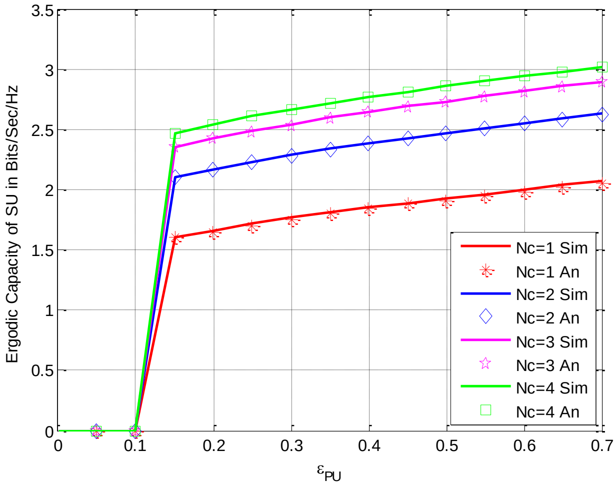


Fig. 4.3: Performance evaluation of STBC/GSC in terms of Ergodic capacity under primary outage ϵ_{PU} at $\xi = 0.1$.

For ABER, the analytical results are compared for two values of interferences as $\xi = 0.1$ *and* $\xi = 0.05$. The analytical results obtained are under the primary network outage constraint for the STBC/GSC CR system utilizing BPSK with modulation constant $g = 1$ in (4.28) has been depicted in Figure 4.4. It is thus shown that when number of best combined branches changes from 3 (i.e. GSC) to 4 (i.e. MRC), the average error rate drops from 0.00365 to 0.00020 at $\epsilon_{PU} = 0.4$ and at $\xi = 0.1$. It is also shown that ABER falls for $\xi = 0.05$, when the interference link from CR-Tx to PU-Rx suffers severe fading.

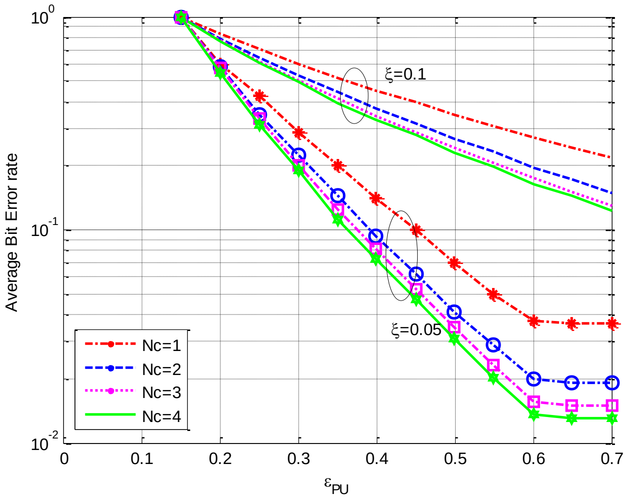


Fig. 4.4: Performance evaluation of STBC/GSC in terms of Average Bit Error Rate under primary outage ϵ_{PU} at $\xi = 0.1$ and $\xi = 0.05$, respectively.

Table-4.1 Performance Evaluation of STBC/GSC CR System at $\xi = 0.1$

Metrics / Best chosen branches	Average Post Processed SNR [dB]	Ergodic Capacity in [Bits/Sec/z]	Average Bit Error Rate *Pe*	Simulation parameters
$N_c = 1$	4.12	1.84	0.00365	$N_t = 2$ $N_r = 4$ $R_{CR} = 1$ $R_{PU} = 0.2$ $P_{CR-peak} =$ 5 dB $\epsilon_{PU} = 0.4$ $\xi = \frac{\Omega_\alpha}{\Omega_h} = 0.1$ $\Omega_h = 1$ $\Omega_\beta = 1$
$N_c = 2$	6.30	2.38	0.00062	
$N_c = 3$	7.36	2.64	0.00028	
$N_c = 4$	7.85	2.77	0.00020	

Table 4.1 shows the results of spectrum sharing STBC/GSC system in context of average post processed SNR, ergodic capacity and ABER under the impact of PU outage probability constraint. It can be seen from the table 4.1, that when number of best chosen receiver paths increases from 3 to 4, then average post processed SNR and ergodic capacity increases from 7.36 dB to 7.85 dB and 2.66 Bits/Sec/Hz to 2.77 Bits/Sec/Hz at $\epsilon_{PU} = 0.4$, respectively. Thus it can be resolved that negligible SNR and capacity gains of ~ 0.49 dB and ~4% are achieved. Likewise the ABER for the same system falls from 0.00028 to 0.00020 which results in very little increase in probability of error is incurred. The outcomes thus attained

shows that GSC (4,3) obtains nearly same results as compared to GSC (4,4) (i.e. MRC) with very less throughput loss at the cost of reduced system complexity and overall signal processing of the whole communication system. After discussing TAS/GSC in chapter 3 and STBC/GSC in underlay CR scenario in section 4.2, now the performance of both the proposed systems is analyzed in multiuser scheduled environment in following section.

4.3 Performance Comparison of S-TAS/GSC with S-STBC/GSC CR under the PU outage probability constraint

In this section the performance of scheduled TAS and the scheduled STBC CR system in multiuser MIMO system have been compared. The proposed systems are analyzed under the impact of primary network outage probability constraint which is discussed in preceding section 4.2. The main contributions of this section are listed below:

- Analysis of joint diversity scheme comprising Scheduled TAS and Scheduled STBC with GSC at CR-Rx, in terms of average post processed SNR, ergodic capacity and ABER.
- Improvement in system throughput in terms of average post processed SNR, ergodic capacity and ABER.
- Realization of multiuser diversity (MUD) gain for proposed systems by selecting one best user out of *'K'* active CR users.

4.3.1 Performance Analysis of S-TAS/GSC System

In chapter-3, the performance analysis of S-TAS/GSC CR system has been done under interference temperature constraint in terms of average post processing SNR and ergodic capacity. Now in this section, the performance analysis of the same S-TAS/GSC CR system is done under PU outage probability constraint in terms of same parameters. Additionally one more parameter ABER is also analyzed.

4.3.1.1 S-TAS/GSC under primary user outage probability constraint

In the **S-TAS/GSC** CR system, joint diversity obtained through TAS and user scheduling is implemented with GSC. We have already derived the PDF for the S-TAS/GSC CR system in Eq. (3.21) as discussed in chapter-3. Hence from Eq. (3.4) and (3.5) post processed SNR at K^{th} CR-Rx can be written as

$$\gamma_{S-TAS/GSC} = \frac{P_{cr}}{N_0 B} h_{x-max} \; ; \tag{4.29}$$

where $h_{x-max} = \underbrace{max}_{(N_t,K)} H_{CR}^{K}$.

The PDF $f_{h_{x-max}}(x)$ of S-TAS/GSC CR system at each CR-Rx can be approximated as follows

$$\begin{aligned}
f_{h_{x-max}}(x) = {} & N_tK\binom{N_r}{N_c}^{N_tK}\sum_{i=0}^{N_tK-1}(-1)^i\binom{N_tK-1}{i}\sum_{p=0}^{i}\sum_{k=0}^{p}\binom{i}{p}\binom{p}{k}\left\{\sum_{b=0}^{Nc-1}\frac{(b+1)\Gamma\left(b+1,\frac{x}{\Omega_x}\right)}{\Gamma(b+2)}\right\}^{(i-p)} \\
& \left\{\sum_{a=0}^{p-k}\binom{p-k}{a}\left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_cc-1}\left(1+\frac{l}{N_c}\right)^{-1}\right]^{(p-k-a)}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}e^{-\frac{x}{\Omega_x}\left(1+\frac{l}{N_c}\right)}\right]^{a}\right\} \\
& \left\{\begin{matrix}\sum_{f=0}^{k}\binom{k}{f}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\right]^{(k-f)} \\ \left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\frac{(m+1)\Gamma\left(m+1,\frac{x}{\Omega_x}\right)}{\Gamma(m+2)}\right]^{f}\end{matrix}\right\}\left(\frac{x^{N_c-1}e^{\frac{-x}{\Omega x}}}{\bar{x}^{Lc}(N_c-1)!}+\right. \\
& \left.\frac{\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_x}\left(e^{\frac{-x\left(1+\frac{l}{N_c}\right)}{\Omega_x}}-e^{\frac{-x}{\Omega x}}\sum_{m=0}^{N_c-2}\frac{\left(\frac{-l}{N_c}\right)^{m}x^{m}}{\Omega_x{}^{m}m!}\right)\right)
\end{aligned}\tag{4.30}$$

By using derived PDF of the S-TAS/GSC CR system, performance metrics viz. Average post processed SNR, ergodic capacity and ABER have been found.

(a) Average Post Processed SNR

Average post processed SNR ($\gamma_{S-TAS/GSC}$) can be calculated by obtaining by obtaining first moment of $f_{h_{x-max}}(x)$ and is given as

$$\varepsilon\{h_{x-max}\} = \int_0^{\infty} x\, f_{h_{x-max}}(x)\,\mathrm{d}(x) \ . \tag{4.31}$$

The final expression for average post processed SNR of S-TAS CR system at the output of GSC combiner is obtained using Eq. (4.30) and (4.31) as

$$\gamma_{S-TAS/GSC} = \frac{P_{cr}}{N_o\,B}\int_0^{\infty} x\, f_{h_{x-max}}(x)\,\mathrm{d}(x) \tag{4.32}$$

(b) Ergodic Capacity

The ergodic capacity, $C_{S-TAS/GSC}$ for the S-TAS/GSC CR system can be derived using Eq. (4.17) and can be written as

$$C_{S-TAS/GSC} = \mathbb{E}\left\{\log_2\left(1 + \frac{P_{cr}}{N_o\, B} f_{h_{x-max}}\right)\right\} \tag{4.33}$$

$C_{S-TAS/GSC}$ for the proposed CR system can be approximated as [89]

$$C_{S-TAS/GSC} \approx \log_2\left(1 + \frac{P_{cr}}{N_o\, B}\, \varepsilon\{h_{x-max}\}\right) - \frac{\varsigma\left(\frac{P_{cr}}{N_o\, B}\right)^2 \sigma^2_{h_{x-max}}}{2\left(1+\frac{P_{cr}}{N_o\, B}\varepsilon\{h_{x-max}\}\right)^2}\,, \tag{4.34}$$

where, the variance $\sigma^2_{h_{x-max}}$ [113] of h_{x-max} is

$$\sigma^2_{h_{x-max}} = \varepsilon\left\{{h_{x-max}}^2\right\} - \varepsilon^2\{h_{x-max}\}\,. \tag{4.35}$$

The second moment of h_{x-max} can be formulated as

$$\varepsilon\left\{{h_{x-max}}^2\right\}=\int_0^\infty x^2\, f_{h_{x-max}}(x)\mathrm{d}(x) \tag{4.36}$$

(c) Average Bit Error Rate

The ABER can be obtained by integrating bit error probability for the best transmit antenna as well as the best user over the PDF of random variable $\boldsymbol{f_{h_{x-max}}}$. The MGF approach can be used to find ABER as discussed below [72]

$$M_{S-TAS/GSC}(s) = \int_0^\infty exp(s\gamma)\ p(\gamma)d(\gamma) \tag{4.37}$$

$$= \int_0^\infty N_t K \binom{N_r}{N_c}^{N_t K} \sum_{i=0}^{N_t K-1} (-1)^i \binom{N_t K - 1}{i} \sum_{p=0}^{i} \sum_{k=0}^{p} \binom{i}{p} \binom{p}{k} \left\{\sum_{b=0}^{Nc-1} \frac{(b+1)\Gamma\left(b+1,\frac{\gamma}{\bar{\gamma}}\right)}{\Gamma(b+2)}\right\}^{(i-p)}$$

$$\left\{\sum_{a=0}^{p-k}\binom{p-k}{a}\left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}\right]^{(p-k-a)}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}e^{-\frac{\gamma}{\bar{\gamma}}\left(1+\frac{l}{N_c}\right)}\right]^{a}\right\}$$

$$\left\{\begin{matrix}\sum_{f=0}^{k}\binom{k}{f}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\right]^{(k-f)}\\ \left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\frac{(m+1)\Gamma\left(m+1,\frac{\gamma}{\bar{\gamma}}\right)}{\Gamma(m+2)}\right]^{f}\end{matrix}\right\}\left(\frac{\gamma^{N_c-1}\mathrm{e}^{\frac{-\gamma}{\bar{\gamma}}(1-s\bar{\gamma})}}{\bar{\gamma}^{\mathrm{Lc}}(N_c-1)!}+\right.$$

$$\left.\frac{\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\bar{\gamma}}\left(\mathrm{e}^{\frac{-\gamma\left(1+\frac{l}{N_c}-s\bar{\gamma}\right)}{\bar{\gamma}}}-\mathrm{e}^{\mathrm{e}^{\frac{-\gamma}{\bar{\gamma}}(1-s\bar{\gamma})}}\sum_{\mathrm{m}=0}^{N_c-2}\frac{\left(\frac{-\mathrm{l}}{\mathrm{Nc}}\right)^{\mathrm{m}}\gamma^{\mathrm{m}}}{\bar{\gamma}^{\mathrm{m}}\mathrm{m}!}\right)\right)d(\gamma)\,, \qquad (4.38)$$

where, $\bar{\gamma}=\frac{P_{cr}}{N_o\,B}$ and substituting $p(\gamma)$ from (4.13) in terms of γ. (4.39)

Thus the MGF for S-TAS/GSC CR system can be written as

$$M_{S-TAS/GSC}(s=$$

$$\int_0^\infty N_tK\binom{N_r}{N_c}^{N_tK}\sum_{i=0}^{N_tK-1}(-1)^i\binom{N_tK-1}{i}\sum_{p=0}^{i}\sum_{k=0}^{p}\binom{i}{p}\binom{p}{k}\left\{\sum_{b=0}^{Nc-1}\frac{(b+1)\Gamma\left(b+1,\frac{\gamma}{\bar{\gamma}}\right)}{\Gamma(b+2)}\right\}^{(i-p)}$$

$$\left\{\sum_{a=0}^{p-k}\binom{p-k}{a}\left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}\right]^{(p-k-a)}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}e^{-\frac{\gamma}{\bar{\gamma}}\left(1+\frac{l}{N_c}\right)}\right]^{a}\right\}$$

$$\left\{\sum_{f=0}^{k}\binom{k}{f}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\right]^{(k-f)}\left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right.\right.\right.$$

$$\left(\frac{\mathrm{e}^{\frac{-\gamma}{\bar{\gamma}}(1-s\bar{\gamma})}\left(\sum_{k=0}^{N_c-1}(-1)^k k!\binom{N_c-1}{k}\bar{\gamma}^{\,K+1-N_c}\,\gamma^{N_c-1-k}\right)}{(N_c-1)!\,(s\bar{\gamma}-1)^{\mathrm{k}+1}}\right.$$

$$+\frac{\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\bar{\gamma}}\left(\mathrm{e}^{\frac{-\gamma\left(1+\frac{l}{N_c}-s\bar{\gamma}\right)}{\bar{\gamma}}}\right.$$

$$\left.\left.-\sum_{m=0}^{N_c-2}\frac{\left(\frac{-\mathrm{l}}{\mathrm{Nc}}\right)^{\mathrm{m}}\mathrm{e}^{\frac{\gamma}{\bar{\gamma}}(s\bar{\gamma}-1)}\left(\sum_{j=0}^{m}(-1)^j j!\binom{m}{j}\,\bar{\gamma}^{j+1-m}\,\gamma^{m-j}\right)}{m!}\right)\right) \tag{4.40}$$

With this obtained MGF, the ABER of the S-TAS/GSC system can be achieved as

$$P_{e_{S-TAS/GSC}}=\frac{1}{\pi}\int_0^{\frac{(N_t-1)\pi}{N_t}} M_{S-TAS/GSC}\left(\frac{-g}{sin^2\phi}\right)\,d(\phi) \quad . \tag{4.41}$$

An underlay CR system with TAS/GSC in multiuser scenario has been analyzed in context of average post processed SNR, ergodic capacity and ABER. The considered system is constrained of desired outage probability defined by primary network. Now the following section describes STBC/GSC scheme in multiuser environment.

4.3.1.2 Performance Analysis of S-STBC/GSC under primary user outage constraint

Similar to S-TAS/GSC, S-STBC/GSC chooses one best CR user out of all active users on the basis of maximum instantaneous SNR at the output of GSC combiner of each CR-Rx. From Eq. (4.5), the post processed SNR at K^{th} CR-Rx can be written as

$$\gamma_{S-STBC/GSC}=\frac{P_{cr}}{N_0 B R_{CR} N_t}\boldsymbol{h}_{y-max}\,; \tag{4.42}$$

where, $h_{y-max}=\underbrace{max}_{K}\ \boldsymbol{H}_{CR}^{K}$.

The PDF of S-STBC/GSC CR system can be obtained by selecting one maximum out of total $'K'$ random variables and can be written as

$$f_{h_{y-max}}(y)=K\binom{N_r}{N_c}^{K}\sum_{i=0}^{K-1}(-1)^i\binom{K-1}{i}\sum_{p=0}^{i}\sum_{k=0}^{p}\binom{i}{p}\binom{p}{k}\left\{\sum_{b=0}^{Nc-1}\frac{(b+1)\Gamma\left(b+1,\frac{yN_t}{\Omega_y}\right)}{\Gamma(b+2)}\right\}^{(i-p)}$$

$$\left\{\sum_{a=0}^{p-k}\binom{p-k}{a}\left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1\right.\right.\right.$$

$$\left.\left.+\frac{l}{N_c}\right)^{-1}\right]^{(p-k-a)}\left.\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}e^{-\frac{yN_t}{\Omega_y}\left(1+\frac{l}{N_c}\right)}\right]^{a}\right\}$$

$$\left\{\begin{matrix}\sum_{f=0}^{k}\binom{k}{f}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\right]^{(k-f)}\\ \left(\left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\frac{(m+1)\Gamma\left(m+1,\frac{yM}{\Omega_y}\right)}{\Gamma(m+2)}\right]^{f}\right.\end{matrix}\right\}\left(\frac{\mathrm{y}^{N_c-1}\mathrm{e}^{\frac{-\mathrm{y}N_t}{\Omega_y}}\mathrm{M}^{\mathrm{Nc}}}{\bar{\mathrm{y}}^{\mathrm{Lc}}(N_c-1)!}+\right.$$

$$\left.\frac{N_t\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\Omega_y}\left(\mathrm{e}^{\frac{-\mathrm{y}N_t\left(1+\frac{l}{N_c}\right)}{\Omega_y}}-\mathrm{e}^{\frac{-\mathrm{y}N_t}{\Omega_y}}\sum_{\mathrm{m}=0}^{N_c-2}\frac{\left(\frac{-\mathrm{l}}{\mathrm{Nc}}\right)^{\mathrm{m}}\mathrm{y}^{\mathrm{m}}{N_t}^{\mathrm{m}}}{{\Omega_y}^{m}\mathrm{m}!}\right)\right) \qquad (4.43)$$

After calculating first moment or **average post processed SNR ($\gamma_{S-STBC/GSC}$)** and second moment ($\varepsilon\{{h_{y-max}}^2\}$) of random variable y, the **ergodic Capacity** ($C_{S-STBC/GSC}$) of S-STBC/GSC CR system can be approximated using Taylor's series and can be written as

$$C_{S-STBC/GSC}\approx\log_2\left(1+\frac{P_{cr}}{N0BR_{CR}\,N_t}\varepsilon\{h_{y-max}\}\right)-\frac{\varsigma\left(\frac{P_{cr}}{N0BR_{CR}\,N_t}\right)^2\sigma_{y-max}^2}{2\left(1+\frac{P_{cr}}{N0BR_{CR}\,N_t}\varepsilon\{h_{y-max}\}\right)^2}\quad, \qquad (4.45)$$

where the variance $\sigma_{h_{y-max}}^2$ of h_{y-max} is

$$\sigma_{h_{y-max}}^2=\ \varepsilon\{{h_{y-max}}^2\}-\varepsilon^2\{h_{y-max}\} \qquad (4.46)$$

ABER for S-STBC/GSC CR system can be found by calculating MGF of the S-STBC/GSC system PDF. The MGF of the proposed system is obtained as

$$M_{S-STBC/GSC}(s)=$$

$$\int_0^\infty K\binom{N_r}{N_c}^{K}\sum_{i=0}^{K-1}(-1)^i\binom{K-1}{i}\sum_{p=0}^{i}\sum_{k=0}^{p}\binom{i}{p}\binom{p}{k}\left\{\sum_{b=0}^{Nc-1}\frac{(b+1)\Gamma\left(b+1,\frac{yN_t}{\bar{\mathrm{y}}}\right)}{\Gamma(b+2)}\right\}^{(i-p)}$$

$$\Bigg\{\sum_{a=0}^{p-k}\binom{p-k}{a}\Bigg[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_cc-1}\Bigg(1$$

$$+\frac{l}{N_c}\Bigg)^{-1}\Bigg]^{(p-k-a)}\Bigg[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\left(1+\frac{l}{N_c}\right)^{-1}e^{-\frac{yN_t}{\overline{\mathrm{y}}}\left(1+\frac{l}{N_c}\right)}\Bigg]^{a}\Bigg\}$$

$$\left\{\begin{matrix}\displaystyle\sum_{f=0}^{k}\binom{k}{f}\Bigg[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\Bigg]^{(k-f)}\\ \displaystyle\Bigg[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\frac{(m+1)\Gamma\left(m+1,\frac{yN_t}{\overline{\gamma}}\right)}{\Gamma(m+2)}\Bigg]^{f}\end{matrix}\right\}$$

$$\Bigg\{\frac{\gamma^{Nc-1}{N_t}^{Nc}}{\overline{\gamma}^{Nc}(Nc-1)!}exp\left[-\gamma\left(\frac{N_t}{\overline{\gamma}}-s\right)\right]+\frac{N_t\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\overline{\gamma}}\Bigg\{exp\left[-\gamma\left[\frac{N_t}{\overline{\gamma}}\left(\frac{l}{N_c}+1\right)-s\right]\right]-$$

$$\sum_{m=0}^{Nc-2}\frac{\left(\frac{-l}{Nc}\right)^{m}(\gamma N_t)^m}{\overline{\gamma}^m m!}exp\left[-\gamma\left(\left(\frac{N_t}{\overline{\gamma}}-s\right)\right)\right]\Bigg\}\Bigg\}\,d\gamma \qquad (4.47)$$

After some manipulations the final expression for MGF of S-STBC/GSC CR system can be achieved as

$$=$$

$$\int_0^\infty K\binom{N_r}{N_c}^{K}\sum_{i=0}^{K-1}(-1)^i\binom{K-1}{i}\sum_{p=0}^{i}\sum_{k=0}^{p}\binom{i}{p}\binom{p}{k}\left\{\sum_{b=0}^{Nc-1}\frac{(b+1)\Gamma\left(b+1,\frac{yN_t}{\overline{\mathrm{y}}}\right)}{\Gamma(b+2)}\right\}^{(i-p)}\Bigg\{\sum_{a=0}^{p-k}\binom{p-k}{a}\Bigg[-\sum_{l=}^{N_r}$$

$$\frac{l}{N_c}\Bigg)^{-1}\Bigg]^{(p-k-a)}\Bigg[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\Bigg(1+$$

$$\frac{l}{N_c}\Bigg)^{-1}e^{-\frac{yN_t}{\overline{\mathrm{y}}}\left(1+\frac{l}{N_c}\right)}\Bigg]^{a}\Bigg\}\left\{\begin{matrix}\sum_{f=0}^{k}\binom{k}{f}\left[\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\right]^{(k-f)}\\ \left[-\sum_{l=1}^{N_r-N_c}(-1)^{N_c+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}\sum_{m=0}^{N_c-2}\left(\frac{-l}{N_c}\right)^{m}\frac{(m+1)\Gamma\left(m+1,\frac{yN_t}{\overline{\overline{\mathrm{y}}}}\right)}{\Gamma(m+2)}\right]^{f}\end{matrix}\right\}\Bigg\{\frac{}{\overline{\gamma}^{Nc}}$$

$$\frac{N_t\sum_{l=1}^{N_r-Nc}(-1)^{Nc+l-1}\binom{N_r-N_c}{l}\left(\frac{N_c}{l}\right)^{N_c-1}}{\overline{\gamma}}\Bigg\{exp\left[-\gamma\left(\frac{N_ti+N_tNc-sNc\overline{\gamma}}{Nc\overline{\gamma}}\right)\right]-\sum_{m=0}^{Nc-2}\frac{\left(\frac{-l}{Nc}\right)^{m}{N_t}^{m}}{\overline{\gamma}^m m!}-$$

$$exp\left[-\gamma\left(\frac{N_t-s\overline{\gamma}}{\overline{\gamma}}\right)\right]\left(\sum_{k=0}^{m}(-1)^k K!\binom{j}{k}\left(\frac{\overline{\gamma}}{M-s\overline{\gamma}}\right)^{k+1}\gamma^{m-k}\right)\Bigg\}\Bigg\} \qquad (4.48)$$

Hence the MGF of complete S-STBC/ GSC CR system can be obtained as $M_{(S-STBC/GSC)total} = (M_{S-STBC/GSC})^{N_t}$. With this obtained MGF, the ABER for the S-STBC/GSC system can be achieved as

$$P_{e_{S-STBC/GSC}} = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} M_{(S-STBC/GSC)total}\left(\frac{-g}{sin^2\phi}\right) d(\phi). \tag{4.49}$$

4.4 Results and Discussion

In this section, we compare analytical as well as simulation results for S-TAS/GSC and S-STBC/GSC CR system under PU outage constraint for BPSK modulation over flat Rayleigh fading channel. We represented obtained outcomes in three parts viz. First part discusses S-TAS/GSC CR system, second part demonstrated S-STBC/GSC CR system and third part shows the comparison between S-TAS/GSC and S-STBC/GSC CR systems. All the results are plotted and tabulated with varying number of CR users in context of average post processed SNR, ergodic capacity and ABER, respectively.

(a) Performance Analysis of S-TAS/GSC system under the impact of PU outage constraint

The simulation details for S-TAS/GSC CR system are same as discussed in section 3.4.The results obtained for the S-TAS/GSC CR system under Rayleigh fading scenario assumed $N_t = 2$, $N_r = 4$, N_c varies from 1 to 4, $K = 1, 4$, $R_{PU} = 0.2$, $\xi = 0.1$ and $\epsilon_{PU} = 0.4$. The analytical result of average post processed SNR for S-TAS/GSC CR system is obtained from Eq. (4.32). It is shown in figure 4.5, that for given number of CR users i.e. $K = 1$ and 4, the average post processed SNR for S-TAS/GSC CR system enhances from 12.60 to 12.87 dB and 14.36 to 14.64 dB with increase in number of combined branches from $N_c = 3$ to $N_c = 4$, respectively at $\epsilon_{PU} = 0.4$. It is thus resolved that multiuser diversity gain of ~1.7 dB is achieved at $N_c = 3$ and 4, respectively. Hence it can be seen that almost same performance is achieved at GSC (4,3) and GSC (4,4) i.e. MRC.

The numerical result of ergodic capacity for S-TAS/GSC CR system is obtained from Eq. (4.34) and is shown in Figure 4.6. It is demonstrated that ergodic capacity improves from 3.79 to 3.87 Bits/Sec/Hz and increases from 4.16 to 4.28 Bits/Sec/Hz for $K = 1$, 4 as number of best branches to be combined increases from $N_c = 3$ to $N_c = 4$, respectively at $\epsilon_{PU} = 0.4$. It is thus resolved that multiuser diversity gain of nearly 10% is achieved at $N_c = 3$ and 4 as well.

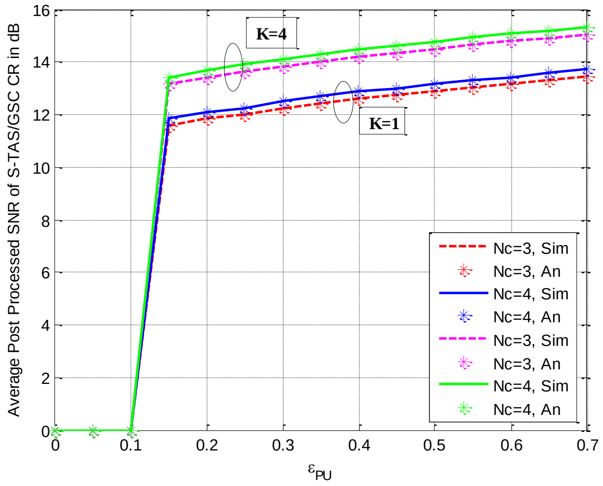


Fig. 4.5: Average Post Processed SNR of S-TAS/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

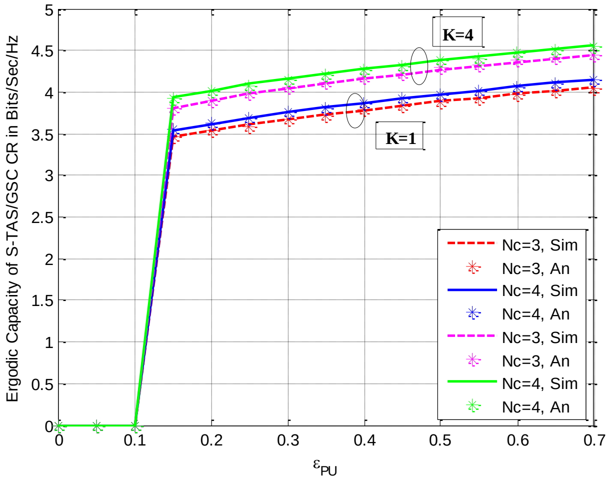


Fig. 4.6: Ergodic Capacity of S-TAS/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

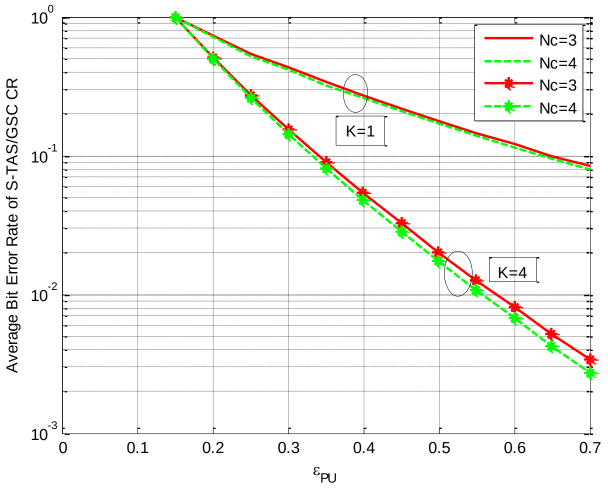


Fig. 4.7: Average Bit Error Rate of S-TAS/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

Figure 4.7, demonstrates only analytical results of average bit error rate obtained from Eq. (4.41) for S-TAS/GSC CR system. It is shown that ABER improves from 0.000011 to 8.09 ×

10^{-9} and further drops from 3.47×10^{-9} to 1.47×10^{-9} for $K = 1, 4$ as number of best branches to be combined increases from $N_c = 3$ to $N_c = 4$, respectively at $\epsilon_{PU} = 0.4$.

Table 4.2 demonstrates the outcomes viz. Average post processed signal to noise ratio, ergodic capacity and average bit error rate for scheduled TAS/GSC CR system. It is seen that MUD gain is achieved when one best CR user is chosen out of K active users which are competing for spectrum access. It can be concluded that 1.7 dB SNR gain and approximately 10% ergodic capacity gain is achieved for S-TAS/GSC system when number of best branches to be combined increase from $N_c = 3$ to $N_c = 4$, respectively.

Table-4.2 Performance Analysis of S-TAS/GSC CR system at $\xi = 0.1$

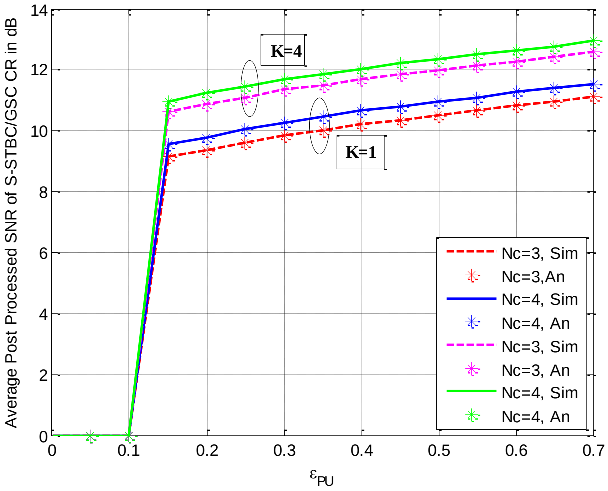
Metrics **Best Combined branches**	**Selection Criteria**	**Average post processed SNR [dB]**	**Ergodic Capacity [bits/Sec/Hz]**	**Average Bit Error Rate**	**MUD gain in terms of SNR [dB]**	**MUD gain in terms of ergodic capacity**	**Notes and assumptions**
$N_c = 3, (K = 1)$	**CR user And Transmit Antenna**	12.60	3.79	0.000011	1.7	10%	$N_t = 2$ $N_r = 4$ $R_{PU} = 0.2$ $P_{CR-peak} =$ 5 dB $\epsilon_{PU} = 0.4$ $\xi = \frac{\Omega_\alpha}{\Omega_h} = 0.1$ $\Omega_h = 1$ $\Omega_\beta = 1$
$N_c = 3, (K = 4)$		14.36	4.16	3.47×10^{-9}			
$N_c = 4, (K = 1)$		12.87	3.87	8.09×10^{-9}	1.7	~10%	
$N_c = 4, (K = 4)$		14.64	4.28	1.47×10^{-9}			

After analyzing the performance of S-TAS/GSC CR system, now we are in a position to examine the performance of S-STBC/GSC CR system under PU outage probability constraint.

(b) Performance Analysis of S-STBC/GSC CR system under PU outage constraint

The simulation details of transmitter side are same as discussed in section (4.2.3). At the receiver side, the signal received at the input of GSC combiner is processed by space time combiner on the basis of maximum instantaneous channel gain. Based on the aligned values of channel gain, the best N_c branches have been combined, where $N_c = 1,2,3,4$. Each CR user will feedback the instantaneous post processing SNR to the CR-Tx. Further on the basis of received CSI, the best CR user is selected out of all active users. Now the performance metrics in terms of average post processed SNR, ergodic capacity and ABER for the best selected CR user have been found using Monte Carlo simulations. The achieved results are averaged over 1000 channel iterations for each value of PU outage probability which varies from 0 to 0.7.

The results achieved for the S-STBC/GSC CR system under Rayleigh fading scenario assumed $N_t = 2$, $N_r = 4$, N_c varies from 1 to 4, $K = 1, 4$, $R_{PU} = 0.2$, $\xi = 0.1$ and $\epsilon_{PU} = 0.4$. It is shown in figure 4.8, that Average Post Processed SNR for S-STBC/GSC CR system enhance from 10.21 to 10.65 dB and raises from 11.67 to 12.03 dB for $K = 1 , 4$ as number of best branches to be combined increases from $N_c = 3$ to $N_c = 4$, respectively at $\epsilon_{PU} = 0.4$. It is thus concluded that multiuser diversity gain of ~1.4 dB is achieved at $N_c = 3$ *and* 4, respectively.



Fig, 4.8: Average Post Processed SNR of S-STBC/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

The analytical result of ergodic capacity for S-STBC/GSC CR system is obtained from Eq. (4.45) and is demonstrated in figure 4.9. It is shown that ergodic capacity increases from 2.64 to 2.77 Bits/Sec/Hz and enhance from 3.05 to 3.16 Bits/Sec/Hz for $K = 1 , 4$ as number of best branches to be combined increases from $N_c = 3$ to $N_c = 4$, respectively at $\epsilon_{PU} = 0.4$. Thus MUD gain of ~14% and 15% is achieved at $N_c = 3$ *and* 4, respectively.

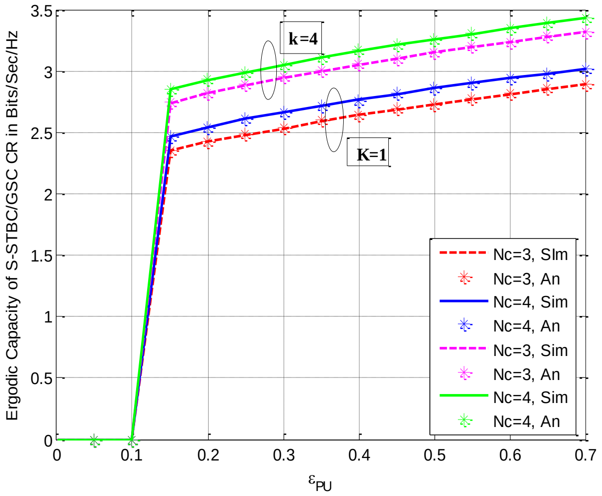


Fig. 4.9: Ergodic Capacity of S-STBC/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

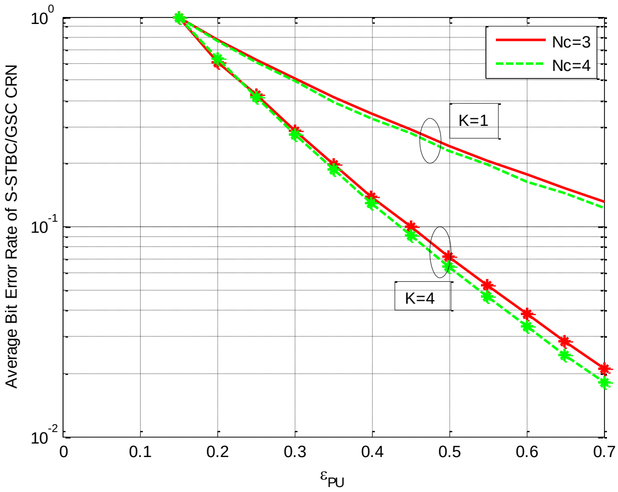


Figure 4.10: Average Bit Error Rate of S-STBC/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

Table-4.3 depict the performance evaluation of parameters namely average post processed SNR, ergodic capacity and ABER for scheduled STBC/GSC CR system. It is interpreted that MUD gain is achieved when one best CR user is chosen out of K active users. Thus it can be resolved that ~ 1.4 dB SNR gain and approximately 15% ergodic capacity gain is achieved for S-STBC/GSC system when number of best branches to be combined increase from $N_c = 3$ to $N_c = 4$, respectively.

Table-4.3 Performance Analysis of S-STBC/GSC CR System at $\xi = 0.1$

Metric Best chosen branches	Selection Criteria	Average post processed SNR [dB]	Ergodic Capacity [bits/Sec/Hz]	Average Bit Error Rate	MUD gain in terms of SNR	MUD gain in terms of ergodic capacity	Notes and assumptions
$N_c = 3, (K = 1)$	CR user	10.21	2.64	0.00028	1.4	14%	$N_t = 2$ $N_r = 4$ $R_{SU} = 1$ $R_{PU} = 0.2$ $P_{CR-peak} =$ 5 dB $\epsilon_{PU} = 0.4$ $\xi = \frac{\Omega_\alpha}{\Omega_h} = 0.1$ $\Omega_h = 1$ $\Omega_\beta = 1$
$N_c = 3, (K = 4)$		11.67	3.05	4.56×10^{-6}			
$N_c = 4, (K = 1)$		10.65	2.77	0.00020	1.38	15%	
$N_c = 4, (K = 4)$		12.03	3.16	1.81×10^{-6}			

The following section demonstrates the performance comparison between both the S-TAS/GSC and S-STBC/GSC CR systems under the PU outage probability constraint.

(c) Performance comparison between S-TAS/GSC and S-STBC/GSC CR systems under PU outage constraint

From Fig. 4.11, we can see that average post processed SNR for S-TAS/GSC CR system increase from 12.60 to 12.87 dB at $K = 1$ and it varies from 14.36 to 14.64 dB at $K = 4$, when number of best branches to be combined raises from $N_c = 3$ to 4. Also average post processed SNR for S-STBC/GSC CR increase from 10.21 to 10.65 dB at $K = 1$ and 11.07 to 12.03 dB for $K = 4$, when N_c goes from 3 to 4 at $\epsilon_{PU} = 0.4$. It can be seen that MUD gain of nearly 1.7 dB and 1.4 dB is achieved for S-TAS/GSC and S-STBC/GSC CR systems for $N_c = 3$ as well as 4, respectively.

We can show from figure 4.12 that ergodic capacity for S-TAS/GSC CR system improves from 3.79 to 3.87 Bits/Sec/Hz at $K = 1$ and 4.16 to 4.28 Bits/Sec/Hz at $K = 4$ when number of best branches to be combined raises from $N_c = 3$ to $N_c = 4$. On the contrary, average post processed SNR for S-STBC/GSC CR increases from 2.64 to 2.77 Bits/Sec/Hz for $K = 1$ and 3.05 to 3.16 Bits/Sec/Hz for $K = 4$ when N_c increases from 3 to 4 at $\epsilon_{PU} = 0.4$. It can be seen that MUD gain of ~10% and 15% is obtained for S-TAS/GSC and S-STBC/GSC CR systems for $N_c = 3$ as well as 4, respectively.

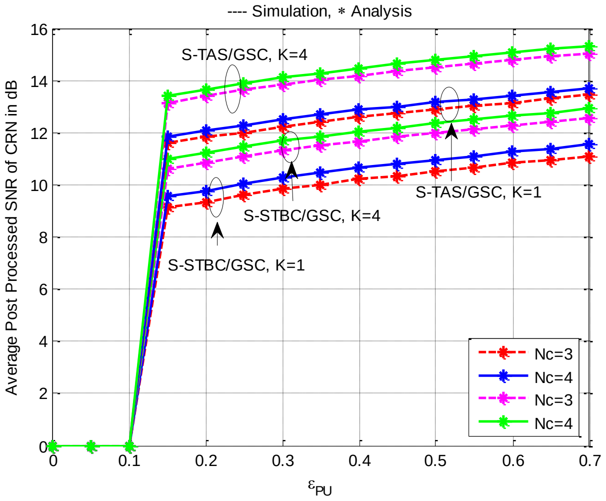


Fig. 4.11: Average Post Processed SNR of S-TAS/GSC and S-STBC/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

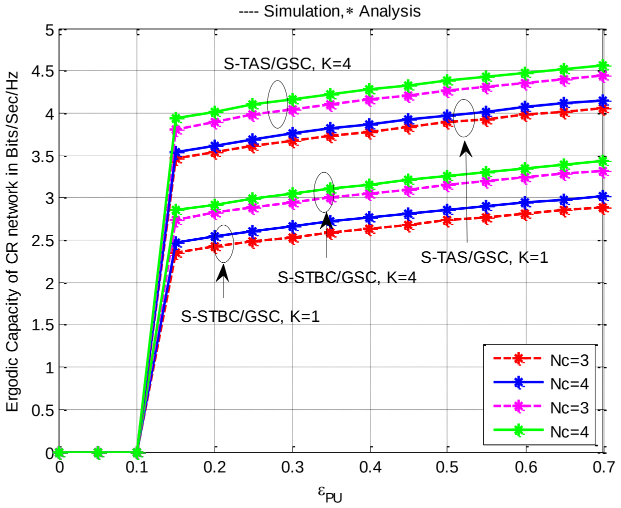


Fig. 4.12 Ergodic Capacity of S-TAS/GSC and S-STBC/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

Figure 4.13 presents the Average bit error rate for S-TAS/GSC CR system which improves from 0.000011 to 8.09×10^{-9} at $K = 1$ and 3.47×10^{-9} to 1.47×10^{-9} at $K = 4$ when number of best branches to be combined increments from $N_c = 3$ to $N_c = 4$.

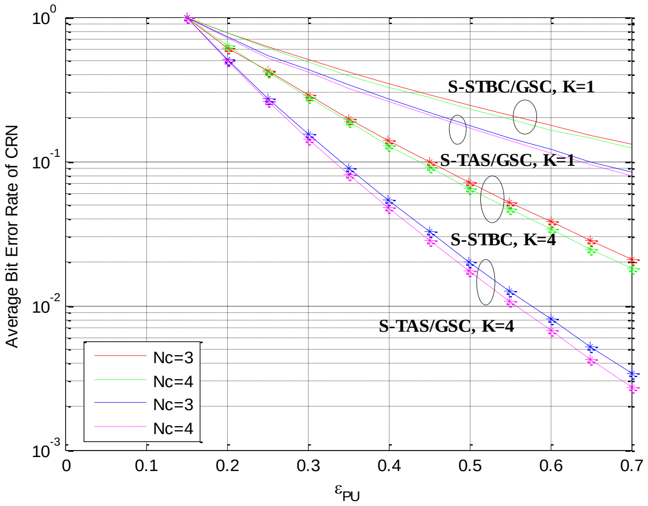


Fig. 4.13: Average Bit Error Rate of S-TAS/GSC and S-STBC/GSC with K=1 and 4 under primary outage ϵ_{PU} at $\xi = 0.1$

And Average bit error rate for S-STBC/GSC CR increase from 0.00028 to 0.00020 at $K = 1$ and further drops from 4.56×10^{-6} to 1.81×10^{-6} for $K = 4$ when $N_c$raises from 3 to 4 at $\epsilon_{PU} = 0.4$. It can be seen that significant MUD gain is achieved for both S-TAS/GSC and S-STBC/GSC CR systems.

Table-4.4 Throughput Performance Comparison between S-TAS/GSC and S-STBC/GSC CR systems at $\xi = 0.1$

Metrics (N_c, K)	**Average post processed SNR [dB] for S-TAS/GSC**	**Average post processed SNR [dB] for S-STBC/GSC**	**Ergodic Capacity [bits/Sec/Hz] for S-TAS/GSC**	**Ergodic Capacity [bits/Sec/Hz] for S-STBC/GSC**	**Average Bit Error Rate for S-TAS/GSC**	**Average Bit Error Rate for S-STBC/GSC**	$\frac{\gamma_{S-TAS/GSC}}{\gamma_{S-STBC/GSC}}$ **at K=4**	$\frac{C_{S-TAS/GSC}}{C_{S-STBC/GSC}}$ **at K=4**
$N_c = 3, (\boldsymbol{K} = \boldsymbol{4})$	14.36	11.67	4.16	3.05	3.47×10^{-9}	4.56×10^{-6}	2.6 dB	36%
$N_c = 4, (\boldsymbol{K} = \boldsymbol{4})$	14.64	12.03	4.28	3.16	1.47×10^{-9}	1.81×10^{-6}		

Table-4.4 outline the comparison of performance analysis between scheduled TAS/GSC and scheduled STBC/GSC CR systems at $K = 4$. From the table, we deduce that average post processed SNR of S-TAS/GSC provides SNR gain of 2.6 dB over S-STBC/GSC CR system. Also the ergodic capacity of S-TAS/GSC renders gain of 36% over S-STBC/GSC CR system when the number of best branches to be combined increases from $N_c = 3$ to $N_c = 4$, respectively. It is because in TAS the whole power to be transmitted is allocated to the best transmit antenna, whereas in STBC power to be transmitted is distributed among all the transmit antennas.

4.5 Conclusions

In this chapter, we have examined the performance of STBC/GSC CR system under the impact of PU outage constraint, when PU and CR user transmit concurrently on the same spectrum. A new transmit power strategy for CR-Tx is deployed so as to avoid harmful interference to primary network. Numerical and simulation results indicate that STBC/GSC CR system is capable of achieving all the advantages over STBC/MRC system in terms of reduced overall system complexity, low power consumption and signal processing with almost similar performance.

Also, we have examined the performance of S-TAS/GSC and S-STBC/GSC with varying number of CR users from $K = 1$ to 4, respectively under the impact of PU outage constraint. We have obtained approximate analytical formulations for average post processed SNR, ergodic capacity and ABER for the proposed systems. Numerical results indicate that S-TAS/GSC has the capability to improve overall system output than S-STBC/GSC system. It has been also shown that performance improvements in terms of SNR and capacity gains obtained through scheduled MIMO systems is higher than the non-scheduled system by MUD.

Chapter 5 discusses the impact of interference from multiple co-located PU transmitters on the proposed CR network. The effect of co-channel interference is studied by employing the optimal diversity combining scheme i.e. optimum combining at the CR-Rx. The proposed CR-OC system is analyzed under Average Interference Power constraint (AIP).

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Chapter 5

Performance Analysis of Optimum Combiner in Cognitive Radios with multiple Primary Interferers under Peak Interference Power constraint

This chapter investigates the performance of power limited Cognitive Radio system with Optimum Combiner at the CR-Rx under the influence of interference from multiple primary user transmitters in a flat Rayleigh fading channel. An approximate analytical result for the PDF of maximum signal-to-interference ratio at the output of CR-OC receiver is derived. Using derived PDF, the closed form expressions for the performance metrics, viz. Average post processed SIR, ergodic capacity, Average bit error rate and outage probability of CR-OC system are obtained by taking into account peak interference power constraint denoted by 'Q' defined by the primary network. Based on the achieved results, it is concluded that the performance of the proposed system degrades when number of primary interferers exceeds from $L_t = 3$. *Analytical results for CR-OC system are validated through Monte Carlo simulations also.*

5.1 Introduction

For significant increase in spectral efficiency of a wireless network and better utilization of limited available radio spectrum, frequency reuse becomes a necessary phenomenon. In such a scenario, the transmitted data may get corrupted by nearby communicating users which results into co-channel interference (CCI) [53]. Thus co-channel interference is the major hindrance in bandwidth limited communication systems. In underlay cognitive radios, SU shares the spectrum with PU simultaneously hence we adopted different spectrum access techniques which are capable of reducing the CCI effect.

Diversity reception with array processing is a powerful technique which suppresses the detrimental effects of interference and fading [45-47]. Antenna arrays can provide diversity paths to combat multipath fading of the desired signal as well as the interference at the intended receiver [41]. Spatial diversity is an efficient solution, using multiple antennas at one or both sides of the transmission link, to alleviate the effects of multipath fading and enhance system throughput. Hence, to improve system capacity of CR networks different combining techniques such as selection combining (SC), maximal ratio combining (MRC) [49-50], optimum combining (OC) [99-100] etc. are studied in the literature [88-90]. MRC, a combining technique applied in presence of noise and independent fading, is thoroughly studied in MIMO as well in cognitive radios [93-97].The weight vector at each antenna element compensates the effect of phase shift which is proportional to the received signal strength and maximizes the SNR. In [96], the authors analyzed MRC in the presence of co-channel interference. The result shows that it maximizes the SNR at the output and is the most effective choice in noise limited scenario. However, it becomes sub-optimal option in the presence of interference. Whereas in OC [102-104], the received signal at different antenna elements are properly weighted and combined to maximize the SINR at the receiver output. In [97], the authors studied and analyzed the performance comparison of MRC, EGC and OC in the presence of interference. The study considered MRC with arbitrary number of interferers, whereas in OC [102], the number of interferer sources was larger than the number of antenna elements, such that the array degrees of freedom are not sufficient enough to completely null the interference. However, even a moderate increase in SNR at the Rx output may result in significant improvement in system capacity. MRC is also analyzed in the presence of multiple equal power interferers in a Nakagami fading scenario [94]. The authors showed that the MRC is beneficial even in interference limited environment and increasing the order of diversity further improves the system performance. In [98], the authors have examined the analytical performance evaluation of generalized selection combining (GSC) in interference environment in terms of SINR and SNR. This paper considers the two extreme cases i.e. when number of best branches to be combined is $L_c = 1$ (SC) and $L_c = N_r$ (MRC). They also provided the new outage analysis, which gives insight to the GSC reception in the interference limited environment.

To enhance the performance of Cognitive radio network, various diversity combining techniques have been employed. In [62], the authors have analyzed the ergodic capacity of spectrum sharing system employing MRC at the secondary user receiver (SU-Rx). In [52], the authors have studied the GSC in terms of ergodic capacity in a cognitive radio environment under the imperfect CSI. In [87], the author has analyzed the spectrum sharing system with MRC diversity in terms of ergodic capacity and symbol error rate (SER), when the proposed system is constrained of transmit power constraint. The impact of multiple PU trans-receivers on the single relay spectrum sharing system has been analyzed in [97]. Also the outage performance of spectrum sharing CR system by employing MRC at SU under the influence of interference from multiple PU's has been examined in [108]. The OC is also studied with transmit antenna selection (TAS) for aggregate interference from multiple secondary users in underlay CR [109]. All this prior work on diversity combining improved our insight into the usefulness of diversity combining schemes in cognitive radios. Motivated by these observations, we observed that MRC mitigate the effects of fading, however it fails to combat interference. OC addresses both the problems of multipath fading and the effect of interference. Thus by considering the advantages of OC over MRC, we have studied and analyzed the underlay spectrum sharing CR system by employing Optimum Combining at CR Rx under the impact of multiple PU interferers.

The main contributions of this chapter are summarized as following:

(i) An approximate analytical expression for the probability density function (PDF) of signal to interference ratio (SIR) at the CR-Rx output is derived, considering the interference effect from L_t primary transmitters having equal power.

(ii) Using the derived PDF, a closed form expression average post processed SIR, ergodic capacity, average bit error rate (ABER) and outage probability are obtained.

The system model for the proposed CR-OC scheme is discussed in the following section.

5.2 System Model

Consider an underlay CR interference limited scenario which consists of a CR base station, a CR Rx, a PU Rx and L_t PU interferers. CR base station and CR Rx are equipped with $N_t(i = 1 \dots N_t)$ and $N_r = (j = 1 \dots N_r)$ antennas, respectively as shown in figure 5.1.

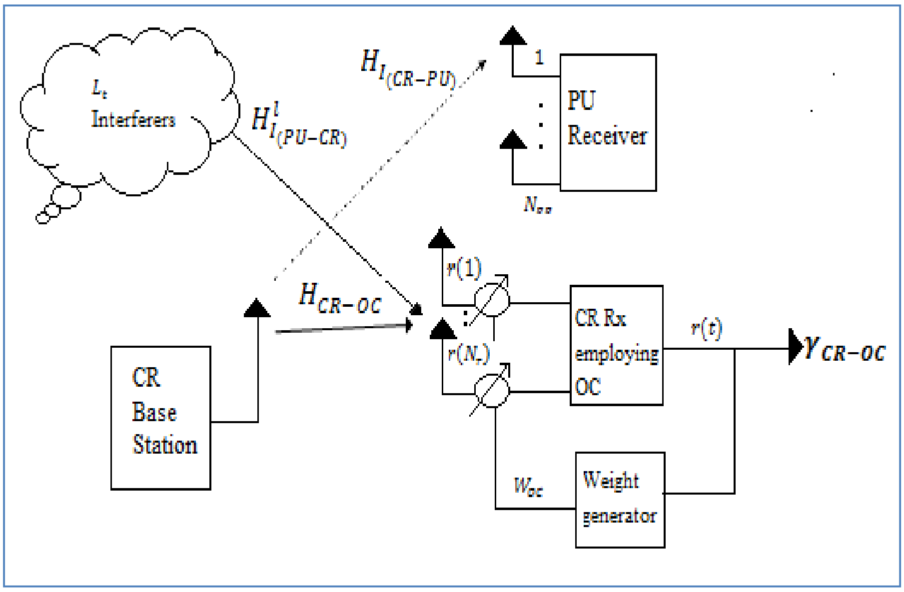

Fig. 5.1 : Block diagram of CR-OC system with PU interferers.

The L_t Interferers are equipped with single transmit antenna and PU Rx has $N_{pr}(k = 1 \dots N_{pr})$ receive antennas. The interference temperature limit is denoted by 'Q' which is the maximum allowable interference received power at the PU-Rx. We also assume that the number of interferers at the CR-Rx are larger than the size of the receive antenna array i.e. $(L_t \geq N_r)$. This chapter assumes slowly varying Rayleigh flat fading channel. We further assume that the level of interference is sufficiently high for the effect of thermal noise on the system performance is negligible. Let $\boldsymbol{H}_{CR-OC}$ be an $(N_t \times N_r)$ dimensional channel matrix between CR-Tx and the CR-

Rx. Let $\boldsymbol{H}_{I(PU-CR)}^{l}$ denotes the $(1 \times N_r)$ dimensional channel matrix between the l^{th} PU interferer and the CR-Rx. In addition, let $\boldsymbol{H}_{I(CR-PU)}$ denotes $(N_t \times N_{pr})$ dimensional channel matrix between the CR-Tx and the PU-Rx. The entries g_{Nt-Nr}, $\boldsymbol{h}_{PU-CR}^{l}$ and $\boldsymbol{h}_{CR-PU}$ of $\boldsymbol{H}_{CR-OC}$, $\boldsymbol{H}_{I(PU-CR)}^{l}$ and $\boldsymbol{H}_{I(CR-PU)}$ are independent and identically distributed (i.i.d) exponential random variables. We denote signal bandwidth as 'B' and the variance of additive white Gaussian noise as 'N_0'. The system employs Binary Phase Shit Keying (BPSK) and all channels path gains are assumed to be an i.i.d random variables. The transmit power of all L_t interferers is assumed to be equal and is denoted by P. Considering the interference from all the interferers, the combined received signal $\boldsymbol{r(t)}$ [104] at the output of receive antenna array is given as

$$\boldsymbol{r(t)} = \sqrt{P_t}\boldsymbol{H}_{CR-OC}\, x_{CR-OC} + \sum_{l=1}^{L_t} \sqrt{P}\boldsymbol{h}_{PU-CR}^{l}\, x_l, \tag{5.1}$$

where x_{CR-OC} and x_l are the desired and the l^{th} interfering signal. Let P_t and P denotes the transmit power of CR-Tx and l^{th} PU interferer, respectively. . The vectors $\boldsymbol{h}_{PU-CR}^{l}$ $(l = 1 \ldots L_t)$ are i.i.d with $E[\boldsymbol{h}_{PU-CR}^{l}] = 0$ and covariance matrix $\varepsilon = E\left[\boldsymbol{h}_{PU-CR}^{l}\left(\boldsymbol{h}_{PU-CR}^{l}\right)^{H}\right]$. All the channel coefficients have zero mean and σ^2 variance. Assuming that the CR-Tx has perfect channel state information (CSI) of interference link i.e. from CR-Tx to PU-Rx, the maximum permissible transmit power of CR-Tx (P_t) at each instant is given by [89]

$$P_t = \frac{Q}{\boldsymbol{h}_{CR-PU}}\ , \tag{5.2}$$

where, $\boldsymbol{h}_{CR-PU} = \sum_{k=1}^{N_{pr}} \boldsymbol{h}_{CR-PU(k)}$ is a Chi-Square distributed random variable with $2N_{pr}$ degrees of freedom and the probability density function (PDF) of $\boldsymbol{h}_{CR-PU}$ is given by

$$f_{h_{CR-PU}}(\boldsymbol{h}_{CR-PU}) = \frac{1}{\Gamma(N_{pr})}\boldsymbol{h}_{CR-PU}{}^{N_{pr}-1} e^{-\boldsymbol{h}_{CR-PU}}\ , \tag{5.3}$$

where, Γ is the standard Gamma function [104] and is given as $\Gamma(N_{pr}) = (N_{pr} - 1)!$.

5.3 Performance Analysis of CR-OC system

The OC weight vector [104] that maximizes the SIR at the output of CR-Tx is written as

$$\boldsymbol{W}_{OC} = \boldsymbol{R}^{-1}\boldsymbol{H}_{CR-OC}\ , \tag{5.4}$$

where $\boldsymbol{R}$ denotes the interference covariance matrix [104] conditioned on channel vector of L_t interferers and given by

$$\boldsymbol{R} = \sum_{l=1}^{L_t} \boldsymbol{h}_{PU-CR}^{l} \left(\boldsymbol{h}_{PU-CR}^{l}\right)^{H}; \tag{5.5}$$

where $(.)^{H}$ represent the complex conjugate transpose. Next, we derive PDF for the SIR of CR-OC system in the presence of L_t equal power interferers.

PDF of Maximum SIR at the CR-Rx

From (5.2) the SIR ($\boldsymbol{\gamma}_{CR-OC}$) at the output of CR-Rx is given by

$$\boldsymbol{\gamma}_{CR-OC} = P_t(\boldsymbol{H}_{CR-OC})^{H}\boldsymbol{R}^{-\mathbf{1}}\boldsymbol{H}_{CR-OC} \tag{5.6}$$

$$= \frac{Q}{h_{CR-PU}}(\boldsymbol{H}_{CR-OC})^{H}\boldsymbol{R}^{-\mathbf{1}}\boldsymbol{H}_{CR-OC} \tag{5.7}$$

Let $\boldsymbol{R} = P\boldsymbol{R}_{\mathbf{1}}$,

where $R_1 = \sum_{l=1}^{L_t} \boldsymbol{h}_{PU-CR}^{l} \left(\boldsymbol{h}_{PU-CR}^{l}\right)^{H}$.

Therefore, $\boldsymbol{\gamma}_{CR-OC}$ in (5.6) becomes

$$\boldsymbol{\gamma}_{CR-OC} = \frac{Q}{\boldsymbol{h}_{CR-PU}P}(\boldsymbol{H}_{CR-OC})^{H}\boldsymbol{R}^{-\mathbf{1}}\boldsymbol{H}_{CR-OC} \tag{5.8}$$

$$= \frac{Q}{P\,\boldsymbol{h}_{CR-PU}}\boldsymbol{z} \ , \tag{5.9}$$

where, $\boldsymbol{z}$ =$(\boldsymbol{H}_{CR-OC})^{H}\boldsymbol{R}^{-\mathbf{1}}\boldsymbol{H}_{CR-OC}$.

The PDF of random variable $\boldsymbol{z}$ is given by [104]

$$f_z(z) = \frac{\Gamma(L_t+1)}{\Gamma(N_r)\Gamma(L_t+1-N_r)}\frac{z^{N_r-1}}{(1+z)^{L_t+1}} \ , \quad z \geq 0, 1 \leq N_r \leq L_t \tag{5.10}$$

The PDF in (5.10) is a modified form of central F-Distribution [99]. The density of the '$\boldsymbol{z}$' does not depend upon the form of the covariance matrix $\boldsymbol{R}$. Thus the performance of the OC is the same regardless whether the fading at each receive antenna is independent or not. However, this is true only for the case $L_t \geq N_r$. Since F Distribution can be converted into Chi-Square distribution [89], therefore (5.10) can be rewritten as

$$f_z(z) = \frac{(L_t+1-N_r)^{K_r}}{\Gamma(N_r)} z^{N_r-1} e^{-(L_t+1-N_r)z} \tag{5.11}$$

From (5.9), the marginal PDF for the ratio of two random variables $\boldsymbol{z}$ and $\boldsymbol{h}_{CR-PU}$ is obtained by substituting

$$\mu = \frac{\boldsymbol{z}}{\boldsymbol{h}_{CR-PU}} \tag{5.12}$$

$$\beta = \boldsymbol{h}_{CR-PU} \tag{5.13}$$

By applying division of two random variables [110], the approximate PDF $f_\mu(\mu)$ of random variable $\boldsymbol{\mu}$ can be written as

$$f_\mu(\mu) = \frac{(L_t+1-N_r)^{N_r}\Gamma(N_r+N_{pr})}{\Gamma(N_{pr})\Gamma(N_r)} \frac{\mu^{N_r-1}}{[(L_t+1-N_r)\mu+1]^{N_r+N_{pr}}} \tag{5.14}$$

The complete solution of above equation is solved in **Appendix-A**. Now we will derive the PDF of maximum SIR at the output of CR-Rx

$$\boldsymbol{\gamma}_{CR-OC} = \frac{Q}{P\,\boldsymbol{h}_{CR-PU}} \boldsymbol{z} \tag{5.15}$$

$$= \frac{Q}{P} \mu$$

(5.16)

By using the transformation as defined in (5.16), the density of the maximum SIR $\boldsymbol{\gamma}_{CR-OC}(\gamma)$ is found as

$$f_{\gamma_{CR-OC}}(\gamma) = \frac{\Gamma(N_r+N_{pr}-1)}{\Gamma(N_r-1)\,\Gamma(N_{pr}-1)}\left(\frac{Q}{P(L_t+1-N_r)}\right)^{N_{pr}}\frac{\gamma^{N_r-1}}{\left(\gamma+\frac{Q}{P(L_t+1-N_r)}\right)^{N_r+N_{pr}}} \qquad (5.17)$$

The PDF in (5.17) represents the final density function of SIR at the output of CR-Rx of CR-OC system. After deriving the PDF of the CR-OC system, the performance metrics are examined as follows:

(a) Average Post Processed SIR

The average post processed SIR or the first moment of $\boldsymbol{\gamma}_{CR-OC}$ at the output of CR-Rx under the influence of multiple PU interferers is given as

$$\mathrm{E}[\,\boldsymbol{\gamma}_{CR-OC}] = \frac{\Gamma(N_r+N_{pr}-1)}{\Gamma(N_r-1)\,\Gamma(N_{pr}-1)}\left(\frac{Q}{P(L_t+1-N_r)}\right)^{N_{pr}} \times$$

$$\int_0^\infty \frac{\gamma^{N_r}}{\left(\gamma+\frac{Q}{P(L_t+1-N_r)}\right)^{N_r+N_{pr}}}\,d\gamma \qquad (5.18)$$

Solving (5.18) the average post processed SIR of the CR-OC system is expressed as

$$\mathrm{E}[\,\boldsymbol{\gamma}_{CR-OC}] = \frac{\Gamma(N_{pr}-1)\,\Gamma(N_r+1)}{\Gamma(N_r)\,\Gamma(N_{pr})}\,\frac{Q}{P(L_t+1-N_r)} \qquad (5.19)$$

(b) Ergodic Capacity

The ***ergodic Capacity*** **(**C_{CR-OC}**)** of CR-OC network is defined as the maximum long term achievable rate and determined by averaging over all the channel states of a fading channel. It is given by [111]

$$C_{CR-OC} \quad = \int_0^\infty log_2\left(1+\mu\frac{Q}{P}\right) f_\mu(\mu)\,d\mu$$

$$= \frac{(L_t+1-N_r)^{N_r}}{\Gamma(N_r)\Gamma(N_{pr})}\left(N_r+N_{pr}- \quad 1\right)! \quad \int_0^\infty \frac{log_2\left(1+\mu\frac{Q}{P}\right)\mu^{N_r-1}}{[(L_t+1-N_r)\mu+1]^{N_r+N_{pr}}}\,d\mu$$

$$(5.20)$$

By further solving (5.20), we get

$$C_{CR-OC} = \frac{\left(N_r+N_{pr}-1\right)!}{\Gamma(N_r)\Gamma\left(N_{pr}\right)}\sum_{p=0}^{N_r-1}\binom{N_r-1}{p}(-1)^{N_r-1-p}$$

$$\frac{1}{\log(2)}\frac{1}{\left(N_r + N_{pr} - p - 1\right)^2} \times$$

$$_2F_1\left(1, N_r + N_{pr} - p - 1; N_r + N_{pr} - p, ; \frac{N_r - L_t + \frac{Q}{P} - 1}{\frac{Q}{P}}\right), \tag{5.21}$$

where, $_2F_1$ is the hypergeometric function and it is defined as in [105]. Equation (5.21) represents the final expression for the ergodic capacity of the CR-OC system. The complete solution of (5.21) is given in **Appendix B**.

(c) **Outage Probability**

The outage probability is an important statistical measure in the design of spectrum sharing system in fading environment in presence of interference. It is the probability of unsatisfactory reception over the intended coverage area. The outage probability is the probability that the received SIR is below a given threshold required to achieve radio reception in fading environment [103]. It is expressed as

$$P_{Outage}^{CR-OC} = \Pr\left(\boldsymbol{\gamma}_{CR-OC} < \gamma_t\right) \tag{5.22}$$

$$= \int_0^{\gamma_t} f_{\gamma_{CR-OC}}(\gamma) d\gamma\ , \tag{5.23}$$

where, γ_t is the SIR threshold. Its value depends on the modulation technique used and also on the desired performance criterion [103]. It is also known as cumulative distribution function. Solving (5.23) the outage probability of CR-OC system is found as

$$P_{Outage}^{CR-OC} = \frac{\left(N_r + N_{pr} - 1\right)!}{N_r \Gamma(N_r) \Gamma\left(N_{pr}\right)} \left(\frac{Q}{P(L_t + 1 - N_r)}\right)^{-N_r} {\gamma_t}^{N_r}$$

$$_2F_1\left(N_r, N_r + N_{pr}, N_r + 1, \frac{(N_r - L_t - 1)P\gamma_t}{Q}\right) \tag{5.24}$$

(d) Average Bit Error Rate

An average Bit Error Rate [113-115] is an important parameter for the analysis of performance of CR-OC system and is derived under peak interference power constraint Q at PU-Rx. In case of BPSK modulation, the probability of error computed at a given value of $\gamma_{CR-OC}(\gamma)$ in terms of Gaussian - Q function is given by [112]

$$P_{e_{CR-OC}} = Q\left(\sqrt{2\,\gamma_{CR-OC}(\gamma)}\right) \tag{5.25}$$

Therefore, the ABER of CR-OC system is obtained by integrating (5.16) over $f_{\gamma_{CR-OC}}(\gamma)$ and is given by

$$P_{e_{CR-OC}} = \int_0^\infty Q\left(\sqrt{2\mu\frac{Q}{P}}\right) f_{\gamma_{CR-OC}}(\gamma)d\gamma \tag{5.26}$$

The Q-function and complementary error function are related as

$$Q\left(\sqrt{2\gamma}\right) = \frac{1}{2}erfc(\sqrt{\gamma}) \tag{5.27}$$

The above expression in (5.27) can be evaluated and the ABER of CR-OC system is obtained as

$$= \frac{1}{2}\frac{\Gamma\left(N_r + N_{pr} - 1\right)}{\Gamma(N_r - 1)\,\Gamma\left(N_{pr} - 1\right)}\left(\frac{Q}{P(L_t + 1 - N_r)}\right)^{N_{pr}}$$

$$\int_0^\infty erfc\left(\sqrt{\mu\frac{Q}{P}}\right) \times \frac{\gamma^{N_r - 1}}{\left(\gamma + \frac{Q}{P(L_t + 1 - N_r)}\right)^{N_r + N_{pr}}}\ d\gamma \tag{5.28}$$

$$P_{e_{CR-OC}} = \frac{1}{2}\frac{\Gamma\left(N_r + N_{pr} - 1\right)}{\Gamma(N_r - 1)\,\Gamma\left(N_{pr} - 1\right)}\left(\frac{Q}{P(L_t + 1 - N_r)}\right)^{N_{pr}}$$

$$\frac{1}{N_{pr}\sqrt{\pi}\,\Gamma\left(N_r + N_{pr}\right)}\left(\frac{P(L_t + 1 - N_r)}{Q}\right)^{0.5 - N_r - N_{pr}}$$

$$\left(\frac{Q}{P(L_t + 1 - N_r)}\right)^{1 - N_r - N_{pr}}\left(-2N_{pr}\left(\frac{P(L_t + 1 - N_r)}{Q}\right)\right)^{N_{pr}}$$

$\sqrt{\frac{Q}{P}}\ \Gamma\left(-0.5 + N_{pr}\right)\Gamma(-0.5 + N_r)\ {}_pF_q\left[\frac{1}{2}, \frac{1}{2} + N_r\,; \frac{3}{2}, \frac{3}{2} - N_{pr}\,; \frac{Q^2}{P^2(L_t+1-N_r)}\right] + \sqrt{\frac{P(L_t+1-N_r)}{Q}}\left(N_{pr}\sqrt{\pi}\ \left(\frac{P(L_t+1-N_r)}{Q}\right)\right)^{N_{pr}}\ \Gamma(N_r)\Gamma\left(N_{pr}\right)$ -

$$\left(\frac{Q}{P}\right)^{N_{pr}} \Gamma\left(0.5 - N_{pr}\right)\Gamma\left(N_r + N_{pr}\right) {}_pF_q\left(N_{pr}, N_{pr} + N_r; \frac{1}{2} + N_{pr}, N_{pr} + 1\,; \frac{Q^2}{P^2(L_t + 1 - N_r)}\right) \tag{5.29}$$

By using the derived PDF of SIR of the CR-OC system, we have derived closed form expressions for average post processed SIR, ergodic capacity, outage probability and ABER. Following section discusses analytical as well as simulated results of the proposed system.

5.4 Results and Discussion

In this section, we present numerical results in terms of average post processed SIR from Eq. (5.19), ergodic capacity from Eq. (5.21), Probability of Outage from Eq. (5.24) and ABER from Eq. (5.29) for CR-OC system to verify simulation counterpart in flat Rayleigh faded environment. The obtained results are discussed in two parts:

(i) First part demonstrates the proposed system with varying number of PU interferers.

(ii) Second part shows the achieved results with varying number of CR-Rx antennas.

(a) Performance Analysis of the proposed system with varying number of PU interferers (L_t).

The proposed CR-OC network consist of one transmit antennas i.e. $N_t = 1$ at CR-Tx and CR-Rx is assumed to be equipped with three receive antennas i.e. $N_r = 3$. The primary network comprises of L_t PU-Txs having single transmitting antenna and a PU-Rx is equipped with two receive antennas i.e. $N_{pr} = 2$. All the PU interferers are assumed to be transmitted with equal power i.e. 10 dB. The channel is modelled as flat Rayleigh faded with complex Gaussian distribution with mean = 0, variance = 1 and is denoted as $CN(0,1)$. The noise is considered white. For finding system parameters such as average post processing SNR and ergodic capacity, a block consisting of 200 random bits is sent from transmitter with all the bits having values 0 or 1. The bits are transmitted using BPSK modulation as ± 1. The signal is transmitted using BPSK modulation.

At the receiver side, the received signal at the input of optimum combiner is multiplied with OC weight vector and then combined output is obtained at the output of CR-Rx. The OC weight vector is conditioned on the covariance matrix and channel gain matrix from CR-Tx to CR-Rx. Based on the received SIR at the CR-Rx, the system is examined in terms of average post processed SIR and ergodic capacity.

To find bit error rate and outage probability of the proposed system, the received signal after being weighted gets decoded. This decoded signal is compared with the original reference signal and number of bits in error is found. Now to find ABER, the received erroneous bits get divided by the total number of bits sent. This procedure is average over 1000 channel realizations for each value of ‘Q’ which varies from 1dB to 10 dB. We assume that the number of PU interferers affecting CR network are i.e. $L_t = 3,4,5,6$ and PU-Rx is equipped with $N_{pr} = 2$ receive antennas. The CR base station and CR-Rx is equipped with $N_t = 1$ and $N_r = 3$ antennas, respectively.

The figure 5.2 and figure 5.3 give the average post processed SIR and ergodic Capacity of CR-OC system. It can be observed from figures 5.2 and 5.3 that at Q = 5db when number of interferers are increased from $L_t = 3$ to $L_t = 6$, the average post processed SIR and Ergodic Capacity falls from 0.94 to 0.23 dB and 1.03 to 0.38 bits/sec/Hz.

Furthermore, the average post processed SIR and ergodic capacity of the CR-OC system improve when ‘Q’ is increased i.e. the received interference power constraint at PU-Rx is increased which further allows CR-Tx to transmit with increased power.

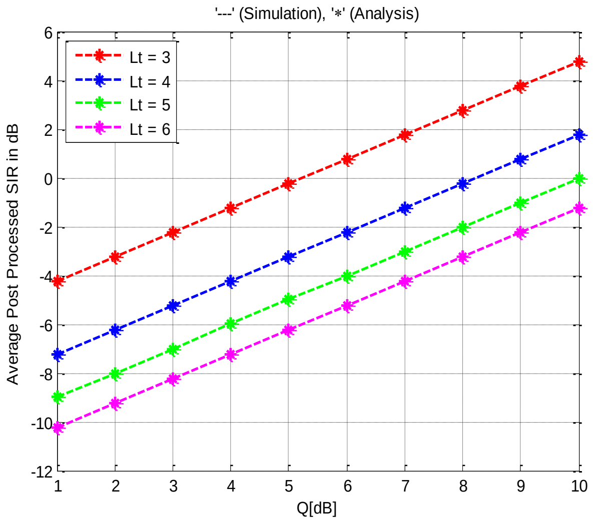

Fig. 5.2 Average Post Processed SIR of CR-OC system.

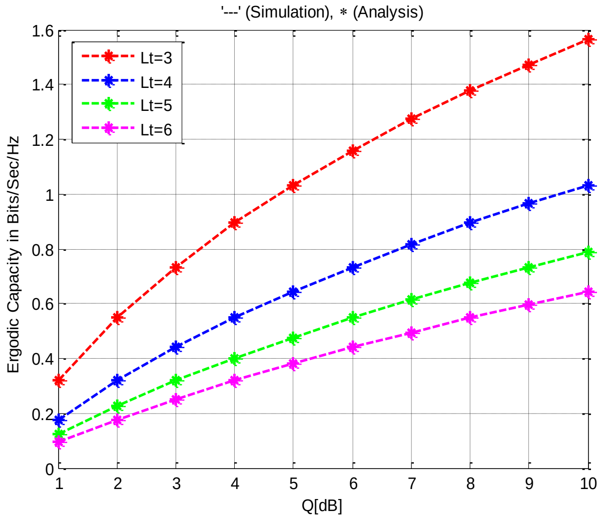

Fig. 5.3 Ergodic Capacity of CR-OC system.

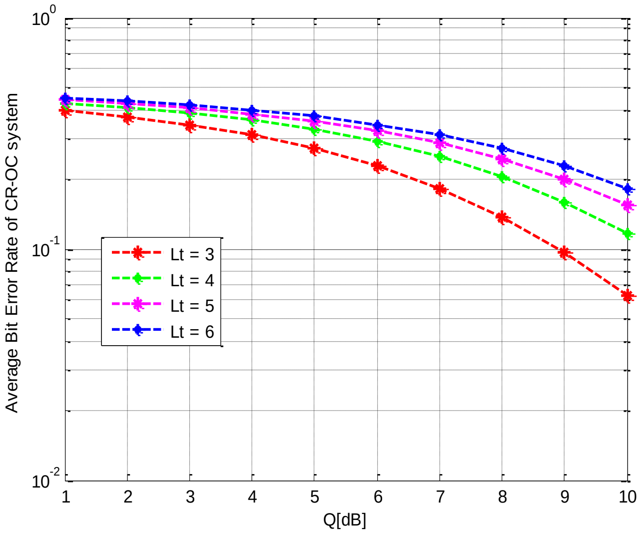

Fig. 5.4 Average Bit Error Rate of CR-OC system.

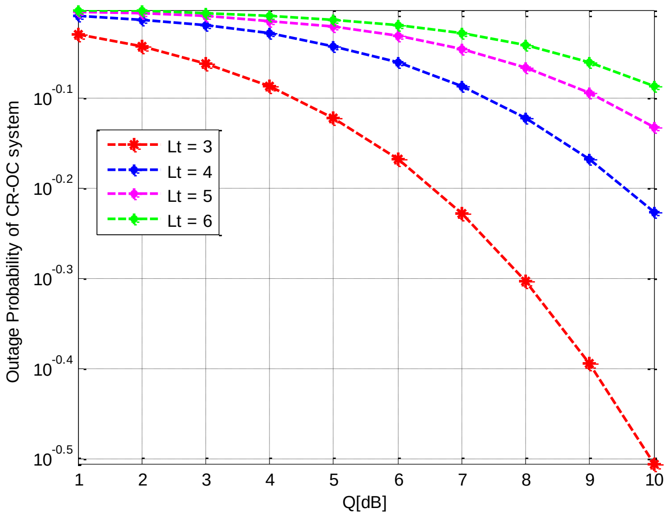

Fig. 5.5 Outage probability for CR-OC system.

We can observe from figures 5.4 and 5.5 that the average bit error rate degrades from 0.270 to 0.374 and outage probability increases from 0.75 to 0.97 when the number of PU interferers are increased from $L_t = 3$ to $L_t = 6$ at Q = 5dB. Thus the average bit error rate and outage probability of the CR-OC system becomes better when ‘Q’ is increased and the performance of the proposed system degrades as number of interfering sources are increased.

Table-5.1 shows the performance of CR-OC system in terms of average post processed SIR, ergodic capacity, ABER and probability of outage. It is shown in the Table-5.1 that average post processed SIR falls when number of PU interferer increases from $L_t = 3$ to 6.

Table-5.1 Performance Evaluation of the CR-OC system with varying number of PU interferers.

Simulation Details $N_t = 1$, $N_{pr} = 2$, $N_r = 3$, $L_t = 3{,}4{,}5{,}6$ and $Q = 5$ dB $P = 10\ dB$				
Metrics **Interferers**	**Average Post Processed SIR [dB]**	**Ergodic Capacity [Bits/Sec/z]**	**Average Bit Error Rate** $\boldsymbol{P_{e_{CR-OC}}}$	**Outage Probability** $\boldsymbol{P_{Outage}^{CR-OC}}$
$L_t = 3$	0.948	1.033	0.270	0.754
$L_t = 4$	0.474	0.644	0.328	0.907
$L_t = 5$	0.316	0.477	0.356	0.952
$L_t = 6$	0.237	0.381	0.374	0.970

Thus it results in the SNR loss of 0.474 dB when L_t goes from 3 to 4, 0.158 dB when L_t goes from 4 to 5 and 0.079 dB when L_t goes from 5 to 6. It is also shown that ergodic capacity gains of the proposed system is achieved as 60 % when L_t goes from 3 to 4, 35 % when L_t increases from 4 to 5 and ~25 % as L_t increases from 5 to 6, respectively.

The ABER of OC-CR system increases from 0.270 to 0.374 as number of PU interferers increases from 3 to 6. As seen from the fig. 5.4, we can observe that when $L_t = 3$ at $Q = 5$ dB the ABER is 0.270, the same error rate is achieved at $Q = 6, 6.5$ & ~ 7 dB at $L_t = 4{,}5\ and\ 6$, respectively. We can conclude that there is a power loss of 1, 1.5 and 2 dB when number of PU interferer increases from 3 to 6. The following part of results analyze the proposed CR-OC system with varying number of CR-Rx receive antennas, N_r.

(b) Performance Analysis in terms of Diversity Gain with varying number of receiver antennas (N_r).

The simulation details for this section are same as defined in section 5.4 (b). This section assume that the number of PU interferers affecting CR network are i.e. $L_t = 3$ and PU-Rx is equipped with $N_{pr} = 2$ receive antennas. The CR base station and CR-Rx is equipped with $N_t = 1$ and varying receive antennas at the CR-Rx i.e. $N_r = 3,4,5,6$, respectively.

In this section, we demonstrate the diversity gain in terms of average post processed SIR at CR-OC output and probability of outage of the proposed system. In figure 5.6, the performance analysis of average post processed SIR at the optimum combiner output is examined with varying number of N_r receive antennas for the proposed system. It can be seen from the figure that the diversity gain is substantially increased, when number of CR-Rx receiver antennas i.e. N_r increases from 3 to 6 as effect of channel fading weakens when number of receive antennas increases . The average post processed SIR of CR-OC system rise from 0.237 dB to 1.897 dB.

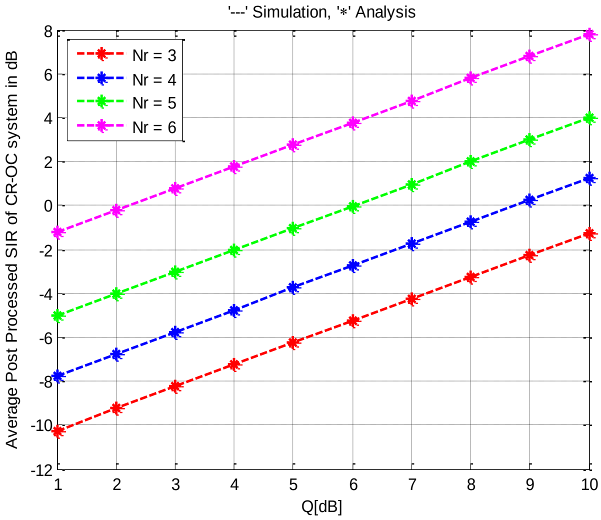

Fig. 5.6 Average Post processed SIR with varying number of N_r receive antennas for CR-OC system.

In Figure 5.7, the diversity gain of the proposed system is shown in terms of probability of outage for the proposed system with varying number of N_r receiver antennas. It can be seen that from the achieved result that outage probability of the CR-OC system drops from 0.970 to 0.469 when the number of N_r antennas increase from 3 to 6, respectively.

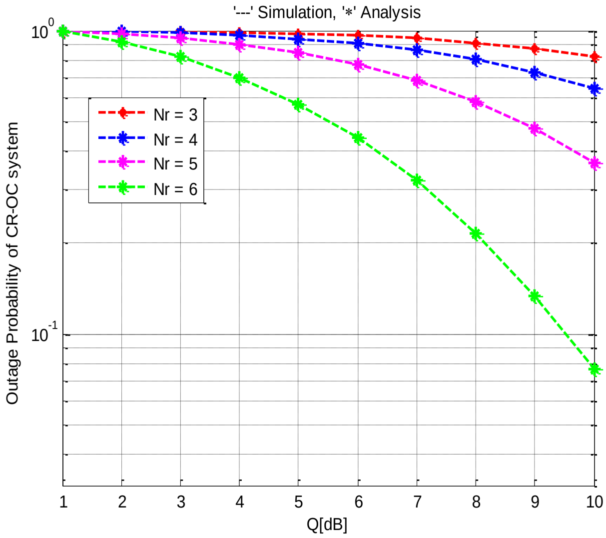

Fig. 5.7 Probability of outage with varying number of N_r receiver antennas for CR-OC system.

Table-5.2 Performance evaluation of Diversity gain of CR-OC system with fixed number of PU interferer i.e. L_t and with the varying number of CR N_r receiver antennas.

Assumptions $N_t = 1, N_{pr} = 2, L_t = 6, N_r = 3, 4, 5, 6, Q = 5dB\ P = 10\ dB$				
Performance Metrics	(L_t, N_r) **(3, 3)**	(L_t, N_r) **(3, 4)**	(L_t, N_r) **(3, 5)**	(L_t, N_r) **(3, 6)**
Average Post Processed SIR of CR-OC system	0.237	0.421	0.790	1.897
Probability of Outage of CR-OC system	0.970	0.925	0.807	0.469

In Table-5.2, the performance evaluation of CR-OC system is analyzed with fixed number of PU interferer i.e. L_t and with varying number of CR-Rx antennas i.e. N_r. We can see from the

Table-5.2 that as the number of $N_r$increase from 3 to 4, 4 to 5 and 5 to 6, the average post processed SIR heightens from 0.237 dB, 0.421 dB, 0.790 dB and 1.897 dB. Thus the SIR gain of the proposed system is achieved at N_r goes from 3 to 4, 4 to 5 and 5 to 6 is 0.184 dB, 0.369 dB and 1.107 dB respectively. Also the diversity of the proposed system is studied in terms of outage probability. It is shown that when number of $N_r$increases from 3 to 4, 4 to 5 and 5 to 6, the outage probability of the CR-OC system falls from 0.970, 0.925, 0.807 and 0.469 at Q = 5 dB, respectively. Hence it is thus concluded that the diversity gain of the system improves considerably when number of PU interferer becomes greater or equal to the number of CR receive antennas i.e. $L_t \geq N_r$.

5.5 Conclusions

In this chapter, we have examined the performance of OC-CR system under the impact of PU interferers when PU and CR user transmit concurrently on the same spectrum. The conventional transmit power strategy for CR-Tx is taken into consideration i.e. by taking interference temperature (Q) limit at the PU-Rx so as to avoid harmful interference to primary network. We have derived analytical expressions for average post processed SIR, ergodic capacity, ABER and outage probability for the proposed system. Here, we demonstrate the diversity gain of the OC-CR system in terms of number of PU interferers. We observe that when the number of PU interferers (L_t) are close to the receive antenna diversity (N_r), the OC-CR system performs considerably better. However, when the number of PU interferers becomes very large i.e.$L_t \gg N_r$, the diversity gain begins to vanish.

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Chapter 6

Conclusions and Future scope

6.1 Conclusions

A reliable wireless communication system is capable of providing improved spectral parameters e.g. overall throughput, substantial capacity gains and reduced average error rate etc. In this thesis, we have proposed and analysed CR system which deals with efficient utilization of spectrum resources, reduced system complexity, power consumption and overall implementation cost. The proposed system fulfils all the aims of this research work defined at Section 1.2, as follows:

- The first aim i.e. to manage interference of the CR network is achieved by incorporating various interference power constraints. These constraints plays very vital role in underlay spectrum access, as received power at the PU-Rx should be below some predefined value.
- The second aim i.e. improved throughput is achieved by employing different spatial diversity schemes at the CR-Tx and various diversity combining schemes at the CR-Rx, respectively. The overall system is further enhanced by realising the proposed system in multiuser scenario.
- The third aim of the research work i.e. efficient spectrum utilization is attained by employing underlay spectrum sharing method in which PU and SU communicates simultaneously. In this, the SU utilizes the same frequency spectrum which is already allocated to the PU. The secondary user doesn’t require extra spectrum resources for its communication.

Our considered system also aims at reducing the deleterious effect of fading which is performed by employing antenna selection at both the transmitter and receiver. Apart from the formulated objectives, we also designed an underlay CR system which is capable of combating the malicious impact of interferers by deploying optimum combining scheme at the intended receiver.

First of all, the hybrid combining scheme i.e. GSC is employed in power limited CR under the impact of Rayleigh fading scenario. Also the proposed scheme is simulated under Rician fading environment. The performance comparison of GSC CR system between Rayleigh as well as Rician fading has been tabulated. With this, **objective 1 and 2** have been accomplished.

A new TAS/GSC scheme is examined in underlay CR in which the transmit power of CR-Tx is kept very less than the interference temperature limit as defined by the primary network. Expressions for an approximate PDF, average post processing SNR and ergodic capacity are derived for the proposed system in multiuser environment. The achieved results show the significant capacity as well as SNR gains are obtained when the spatial diversity is achieved through TAS and GSC in scheduled scenario. This work concludes the defined **objective 3**.

Objective 4 is achieved by analyzing an underlay CR system with MIMO thus employing space time block coding at the Tx and GSC combining at the CR-Rx, respectively. This objective is investigated by formulating an approximate PDF of the proposed system and also deriving closed form expressions for the average post processed SNR and ergodic capacity. An approximate expression is derived for the MGF and ABER of the STBC/GSC CR system. The considered system is constrained of the outage probability margin of the primary network, thus the transmit power strategy for the CR-Tx monitors the probability of outage threshold as defined by PU. This chapter also includes the performance comparison between scheduled TAS/GSC and scheduled STBC/GSC CR system in terms of average post processing SNR, ergodic capacity and the ABER.

We have also investigated the performance of optimum combining in spectrum sharing CR under the influence of equal power PU interferers by considering the interference temperature constraint as defined by the primary network. The proposed model is analyzed in terms of average post processed SIR, ergodic capacity, ABER and outage probability by deriving PDF of the CR-OC system. The results obtained shows that the system under consideration is capable of reducing the effect of co-channel interference but diversity gain vanishes as the number of interferers becomes larger than the antenna elements at the Rx.

Table 6.1 Summary of achieved results at a glance

Proposed systems	**Transmit power control strategy based upon PU constraint**	**Results obtained**	**Conclusions**
S-TAS/GSC CR system ***(Objective-1,2 & 3)***	Interference temperature limit (Q)	S-TAS/GSC CR achieves SNR gain and capacity gain as **~ 1.5 dB** and **12%** for GSC as well as MRC over conventional TAS/GSC CR system. Also the conventional TAS/GSC system is studied for Rician fading scenario.	GSC (4,3) performs almost very similar to optimal MRC scheme. Results in reduced system complexity, power consumption and signal processing.
S-TAS/GSC CR system	Outage probability of primary network and Peak transmit power (PTP) of CR-Tx	For the proposed system GSC(4,3) and MRC {(4,4)} achieves same outcomes over TAS/GSC CR system: SNR gain as **1.7dB** and capacity gain of **~ 10%**.	Overall reduced system complexity by incorporating joint transmit and receive diversity. Scheduling among CR users achieves significant capacity gains.
STBC/GSC CR system ***(Objective-4)***	Outage probability of primary network and Peak transmit power (PTP) of CR-Tx	For the proposed system GSC(4,3) and MRC {(4,4)} achieves same outcomes: SNR gain as **~ 0.49dB** and capacity gain of **~ 4%.**	Obtained results are the function of best combined receiver branches. Very negligible throughput loss is occurred between the performance of MRC and GSC.
Comparison between S-TAS/GSC and S-STBC/GSC	Outage probability defined at PU Peak transmit power (PTP) of CR-Tx	S-TAS/GSC CR provides SNR and capacity gain as **2.6 dB** and **36%** Over S-STBC/GSC CR system.	S-TAS/GSC CR system performs better than the S-STBC/GSC CR system in terms of all the performance metrics.
CR-OC CR system	Average interference power (AIP) received at PU-Rx	SIR gain falls from **0.474 dB** to **0.079 dB** and Capacity gain reduced to **25 %** as number of interferer increases from 3 to 6.	Achieved performance parameters are a function of PU interferers and the number of receiver antennas. Diversity gain begins to reduce when number of interferers become larger than the receive antennas.

6.2 Future Scope

As our research work deals with the underlay spectrum sharing access technique with TAS/GSC and STBC/GSC in multiuser scenario, this work can be extended and analyzed with the following possibilities:

- As we have discussed the various spectrum access policies i.e. underlay, overlay and interweave, which also aims at utilizing the available spectrum resources efficiently. We have analyzed our formulated objectives for research work by employing underlay spectrum sharing access. The proposed work can be extended to the other spectrum access schemes such as interweave spectrum access which senses the unused licensed part of spectrum by using various spectrum sensing methods. Whereas, in overlay spectrum access the CR users splits it's transmit power into two halves. The half of its power is utilized for relaying the messages of PU and the remaining half power is used for its own communication.
- This system can be extended to cooperative scenario, where the data is transmitted to the intended Rx via relays. By employing various spectrum access methods, the proposed system becomes cooperative CR system. This cooperative CR system can be analyzed by applying antenna selection at the Tx, Rx and the relay nodes, respectively.
- The last contribution of this thesis is focused on interference limited scenario. This is analyzed by deploying optimum combining under the impact of multiple PU interferers. Apart from the work done, the proposed CR-OC system can be studied by employing various spatial diversity schemes such as TAS and STBC.
- The research work presented in this thesis can be tested in interference limited environment by considering multiple PU interferers.
- In this thesis, the CR users are assumed to be immobile, results can be achieved by taking mobile or moving CR nodes.
- Lastly, the optimum combining in CR can be extended to TAS as well as MIMO systems in scheduled multiuser environment.
- To explore an emerging 5G technology, the behavior of channel fluctuations at millimeter wave (mmWave) frequency bands needs to be analyzed with different fading scenarios. Hence this research work can be realized with various fading models such as: Nakagami fading model, TWDP (Two-wave with diffused power) model, $\kappa - \mu$ fading model etc.

The work done includes TAS by choosing single best antenna out of all available transmit antennas, it can be extended further by selecting more than one best antenna. Similarly, one best user is selected on the basis of highest post processing SNR or it can be called as greedy scheduling algorithm. This can also be analyzed by deploying other scheduling algorithms.

Appendix A

PDF of maximum SIR

Let us define N_r i.e. the number of receive antennas at the CR-Rx and N_{pr} as the number of receive antennas at the PU-Rx are integers valued.

The joint PDF [109] of random variables μ and β is given as

$$f_{\mu,\beta}(\mu,\beta) = |\beta| \times f_z(z) f_{\boldsymbol{h}_{CR-PU}}(\boldsymbol{h}_{CR-PU})\Big|_{z=\mu\beta,\, \boldsymbol{h}_{CR-PU}=\beta} \tag{A1.1}$$

Using (5.3) and (5.10), the marginal PDF for the ratio of two random variables z and $\boldsymbol{h}_{CR-PU}$ is obtained as

$$f_\mu(\mu) = \frac{(L_t+1-N_r)^{N_r}}{\Gamma(N_{pr})\Gamma(N_r)} \int_0^\infty \beta\, (\mu\beta)^{N_r-1} e^{-(L_t+1-N_r)\mu\beta} \beta^{N_{pr}-1} e^{-\beta}\, d\beta \tag{A1.2}$$

By re-arranging (A1.2), we obtain

$$f_\mu(\mu) = \frac{(L_t+1-K_r)^{K_r}}{\Gamma(N_{pr})\Gamma(K_r)} \mu^{N_r-1} \int_0^\infty \beta^{N_r+N_{pr}-1}\, e^{-\beta[(L_t+1-N_r)\mu+1]} d\beta \tag{A1.3}$$

Using identity [116], we get

$$I_1 = \int P_n(v)\, e^{bv}\, dv = \frac{e^{bv}}{b} \sum_{j=0}^{n} \frac{(-1)^j}{b^j} P_n^{(j)}(v) \tag{A1.4}$$

where $P_n^{(j)}(v)$ denotes the j^{th} derivative of $P_n(v)$.

By comparing the identity defined in (A1.4) with (A1.3), we get

$P_n(\beta) = \beta^{N_r+N_{pr}-1}$,
$n = N_r + N_{pr} - 1$ and
$b = -[(L_t + 1 - N_r)\mu + 1]$

The j^{th} derivative of $P_n(\beta)$ is obtained as

$$P_n^{(j)}(\beta) = \frac{(N_r+N_{pr}-1)!}{(N_r+N_{pr}-1-j)!}\beta^{N_r+N_{pr}-1-j} \tag{A1.5}$$

From (A1.3), the integration involved can be written in the form of (A1.4) as

$$=\int_0^\infty \beta^{N_r+N_{pr}-1}\, e^{-\beta[(L_t+1-N_r)\mu+1]}\, d\beta \tag{A1.6}$$

Also by putting above values in (A1.6), the above equation can be modified as

$$= \int_0^\infty \frac{e^{-[(L_t+1-N_r)\mu+1]\beta}}{-[(L_t+1-N_r)\mu+1]}\sum_{j=0}^{N_r+N_{pr}-1} \frac{1}{[(L_t+1-N_r)\mu+1]^j} \times \frac{(N_r+N_{pr}-1)!}{(N_r+N_{pr}-1-j)!}\beta^{N_r+N_{pr}-1-j}\, d\beta \tag{A1.7}$$

By solving (A1.7), we get

$$= \frac{(L_t+1-K_r)^{K_r}}{\Gamma(N_{pr})\Gamma(K_r)}\mu^{N_r-1}\frac{e^{-[(L_t+1-N_r)\mu+1]\beta}}{-[(L_t+1-N_r)\mu+1]}\sum_{j=0}^{N_r+N_{pr}-1}\frac{1}{[(L_t+1-N_r)\mu+1]^j} \times \frac{(N_r+N_{pr}-1)!}{(N_r+N_{pr}-1-j)!}\beta^{N_r+N_{pr}-1-j}\Bigg|_{\beta=0}^{+\infty}$$

$$f_\mu(\mu) = \frac{(L_t+1-K_r)^{K_r}}{\Gamma(N_{pr})\Gamma(K_r)}\mu^{N_r-1}\frac{(N_r+N_{pr}-1)!}{[(L_t+1-N_r)\mu+1]^{N_r+N_{pr}}} \tag{A1.8}$$

Hence, the PDF of maximum SIR for the CR-OC system is given in (5.14).

Appendix B

Derivation of Ergodic Capacity

By Substituting $y = (L_t + 1 - N_r)\mu + 1$ in (5.20) and applying binomial expansion, we get

$$C_{CR-OC} = \frac{(N_r+N_{pr}-1)!}{\Gamma(N_r)\Gamma(N_{pr})} \sum_{p=0}^{N_r-1} \binom{N_r-1}{p} (-1)^{N_r-1-p} \int_1^{\infty} log_2\left(1 + \frac{yQ}{P(L_t+1-N_r)} - \frac{Q}{P(L_t+1-N_r)}\right) y^{p-N_r-N_{pr}} dy \qquad \text{(A2.1)}$$

The integral in above equation, denoted as I_2 can be solved by partial integration method and is given by

$$I_2 = \frac{Q}{\log(2) P(N_r+N_{pr}-p-1)} \int_1^{\infty} \frac{1}{y^{N_r+N_{pr}-p-1}} \frac{1}{(L_t+1-N_r)+y\frac{Q}{P}-\frac{Q}{P}} dy \qquad \text{(A2.2)}$$

By solving (A2.2), the above equation is denoted by I_3 and is written as

$$I_3 = \frac{1}{\frac{Q}{P}(N_r+N_{pr}-p-1)} \; {}_2F_1\left(1, N_r + N_{pr} - p - 1; N_r + N_{pr} - p; \frac{N_r-L_t+\frac{Q}{P}-1}{\frac{Q}{P}}\right) \qquad \text{(A2.3)}$$

By putting (A2.3) in (A2.1), we obtain the final expression for the ergodic capacity of CR-OC system, which is given in (5.21

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