ENHANCING CAPACITY IN UNDERLAY COGNITIVE RADIO NETWORK THROUGH INTERFERENCE ALIGNMENT

BY

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ZARIA

JANUARY, 2017

DECLARATION

I declare that the work in this Dissertation entitled “Enhancing Capacity in Underlay Cognitive Radio Network through Interference Alignment” was carried out by me in the Department of Electrical and Computer Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

Isiyaku YAU ____________________ ____________________

Signature Date

CERTIFICATION

This Dissertation entitled "ENHANCING CAPACITY IN UNDERLAY COGNITIVE RADIO NETWORK THROUGH INTERFERENCE ALIGNMENT" by Isiyaku YAU meets the regulations governing the award of the degree of Master of Science in Telecommunications Engineering by Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literature.

Chairman, Supervisory Committee	________________	_____________
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Dean, School of Postgraduate Studies	________________	_____________
(Prof. K. Bala)	Signature	Date

DEDICATION

This dissertation is dedicated to Almighty God.

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All praise is due to Almighty God Who taught with the pen. And taught man what he knew not.

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ABSTRACT

As the number of wireless systems and services grow exponentially, the radio spectrum is becoming increasingly a scarce resource. Again the current fixed spectrum-licensing policy has made the radio spectrum underutilized. Cognitive Radio (CR) aims at providing solution to address the imbalance between spectrum scarcity and spectrum underutilisation by allowing cognitive users, called Secondary Users (SUs), to share the spectrum with the licensed users called Primary Users (PUs) in a manner that the PUs do not suffer harmful interference. This work considered an underlay cognitive radio network with a single PU and three SUs. The work is aimed at mitigating the cognitive intra-network interference with a view to enhancing the effective sum capacity of the SUs. The PU is protected through interference temperature (IT) model. Ergodic Interference Alignment (IA) scheme under the IT constraints is developed for mitigating the mutual interference among the SUs. To provide a benchmark to gauge the performance of the developed model, the sum capacity through time-division scheme is first obtained. A closed form expression for the sum capacity of three-user underlay cognitive channel is derived. Applying the ergodic IA with IT constraints enhances the sum capacity of the SUs thereby achieving 23.54% and 24.77% gain in the channel sum capacity under maximum and average IT limits respectively. This gain is with respect to time-division scheme at signal-to-noise-ratio of 19dB. By utilizing the long delay time associated with ergodic IA to send more bits in time-division scheme, 3.0094 bps/Hz and 3.1741 bps/Hz gains in spectral efficiency was achieved under maximum and average IT limits over a full time-division scheme at SNR of 19dB.

TABLE OF CONTENTS

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: LITERATURE REVIEW

CHAPTER THREE: METHODOLOGY

CHAPTER FOUR: RESULTS AND DISCUSSION

CHAPTER FIVE: SUMMARY, CONCLUSION AND RECOMMENDATION

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
CR	Cognitive Radio
CSI	Channel State Information
DoF	Degree of Freedom
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FSPTF	FCC Spectrum Policy Task Force
IA	Interference Alignment
IT	Interference Temperature
ITM	Interference Temperature Model
MATLAB	MATrix LABoratory
PEP	packet error probability
PSD	Power Spectral Density
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
RR	Reconfigurable Radio
SDR	Software Defined Radio
SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise-Ratio
SU	Secondary User
TDMA	Time Division Multiple Access
UWB	Ultra-Wide Band

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Due to rapidly expanding market of wireless broadband and multimedia applications, the number of wireless systems and services grow exponentially: As a consequence, the radio spectrum has become a very scarce and precious resource. With the current static spectrum licensing policy, it has reached the extent that nearly the entire prime spectrum has been allocated for different applications leaving little or no spectrum for emerging wireless systems and services (NTIA, 2011). Studies have shown that a major part of the spectrum is underutilised (FCC, 2002). 85% of the spectrum is wasted temporally in some bands below 3 GHz (Zhao & Sadler, 2007). Meaning that, there exist temporary space-time-frequency voids, referred to as spectrum holes or white spaces that are not always in use in both the licensed and unlicensed bands, as shown in Fig. 1.1 (Ezio *et al.*, 2013).

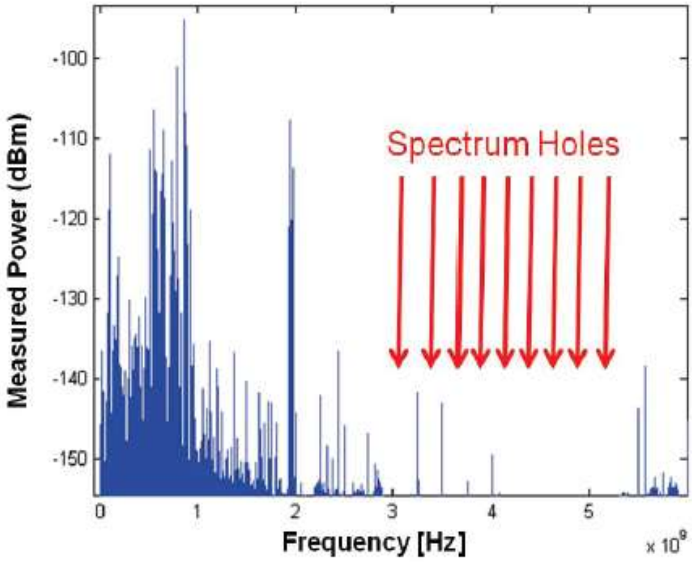

Fig. 1.1: A Typical Spectral Occupancy Measurements in an Urban Area at Mid-Day (Ezio *et al.*, 2013)

Again, spectral utilization is not optimised. A statistical report placed the spectral opportunity utilisation in New York City at 13% during the high demand period of political convention that took place in 2004 (Ezio *et al*., 2013).

Out of the imbalance between scarcity of preferred spectrum and underutilisation was born the idea of Cognitive Radio (CR) to improve spectrum utilization. CR uses advanced radio and signal processing technology along with novel spectrum allocation policies to share the spectrum as a Secondary User (SU) in a manner that the Primary (licensed) Users (PUs) are as unaffected as possible (Goldsmith *et al*., 2009).

“Cognitive Radio System (CRS) is a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, establish policies, and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objective and to learn from the results obtained” (Sector, 2009).

CR, therefore, differs from conventional radio devices in its cognitive capability and reconfigurability. Cognitive capability means the ability to sense and gather information from the surrounding environment, such as information about operating frequency, bandwidth, transmit power, modulation scheme, etc. This capability enables a secondary user to identify the best available spectrum. Reconfigurability allows for rapid ability to adapt the operational parameters and protocols according to the sensed information in order to achieve the desired performance. These cognitive functionalities require a software-defined radio platform for implementation (Kandeepan & Andrea, 2012).

1.1.1 Software-Defined Radio

The Software-Defined Radio (SDR) provides a key enabling technology for the realization of CRs. To support the cognitive functionalities within the radio, it needs a reconfigurable feature which is enabled by software. The SDR is also referred to as Reconfigurable Radio (RR) (Kandeepan & Andrea, 2012). SDR is defined as “radio transmitter and/or receiver employing a technology that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software. These exclude changes to operating parameters, which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard” (Sector, 2009). The software package that makes the SDR cognitive is referred to as Cognitive Engine (CE).

1.1.2 Cognitive Cycle

The CE is the “brain” or intelligent agent of the CR (Zhao & Morales-Tirado, 2012). The CR interacts with its environment through a learning process known as cognitive cycle. It comprises three basic functions of spectrum sensing, spectrum predicting, and spectrum management as shown in Fig. 1.2.

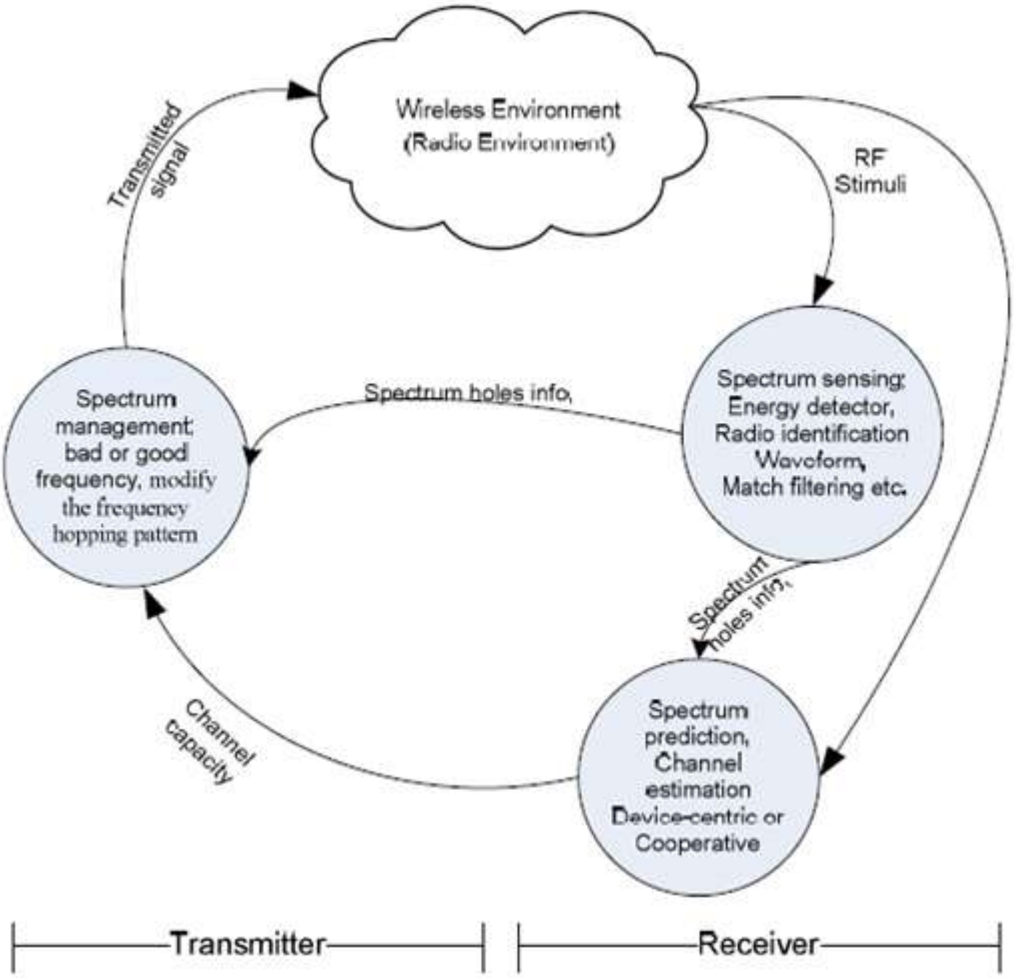

Fig. 1.2: Basic Cognitive Cycle Model (Tabassam *et al*., 2011)

1.1.3 Cognitive Radio Paradigms

Three main cognitive radio paradigms exist: interweave, underlay, and overlay cognitive radio (Maamari *et al*., 2014).

The interweave approach is based on the idea of opportunistic communication which was the original motivation for cognitive radio (Mitola, 2009). A report by the Federal Communication Commission (FCC) has shown that a major part of the spectrum is not always utilized (FCC, 2002). Only 38% of the licensed spectrum remains occupied and the remaining part (referred to as frequency voids or white spaces or spectrum holes) is underutilized in the most crowded area near downtown Washington, DC, where there exists an intense government and commercial spectrum use (Idoudi *et al*., 2014). The spectrum holes change with time and geographic location and can be used for communication by the SUs. This allows for opportunistic frequency re-use which improves the spectrum utilization as shown in Fig. 1.3 (Wang & Liu 2011). An opportunistic cognitive radio is therefore an intelligent wireless communication system that intelligently detects occupancy in the different parts of the spectrum and then opportunistically communicates over spectrum holes with minimal interference to the active users (Ezio *et al*., 2013)

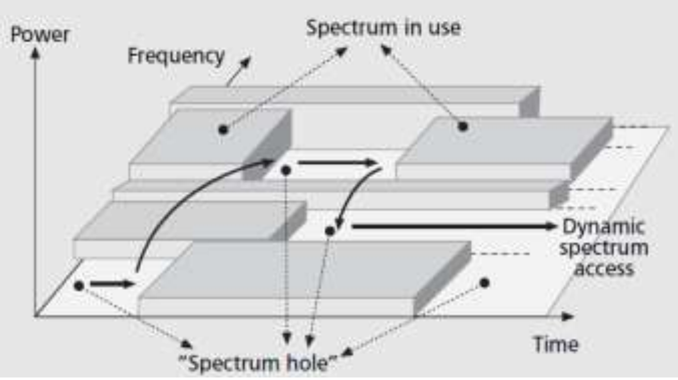

Fig. 1.3: Illustration of Spectrum White Space (Wang & Liu, 2011)

In the underlay paradigm, the SUs operate provided they cannot significantly interfere with the existing communication of the PUs. This concurrent transmission of SUs and PUs is allowed for when the interference generated by the SUs is below an acceptable noise floor for the PUs. The interference power constraint on the SUs can be compensated by access to a wide bandwidth over which the secondary signal can be spread and de-spread to provide useful Signal-to-Noise Ratio (SNR) for their communication as shown in Fig. 1.4 (Ezio *et al*., 2013).

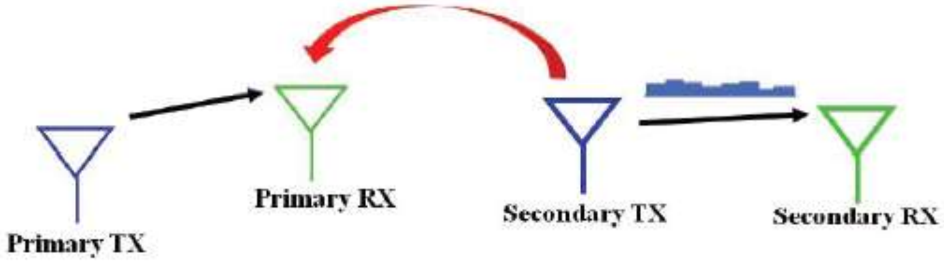

Fig. 1.4: Underlay Paradigm: Wideband Signalling (Ezio *et al*., 2013)

In the overlay cognitive radio also, PU and SU's transmission occur simultaneously. Here, the SUs use part of their transmit power to assist (relay) the primary transmission. The relaying of the PU is to compensate for the decrease in its SNR due to the interference by the secondary transmission through a suitable choice of power spit by the secondary transmitter which may facilitate the non-cognitive transmission. To realize this, the secondary nodes require knowledge about channel gains, encoding techniques, and possibly the transmitted data sequences of the primary users as illustrated in Fig. 1.5 (Ezio *et al*., 2013).

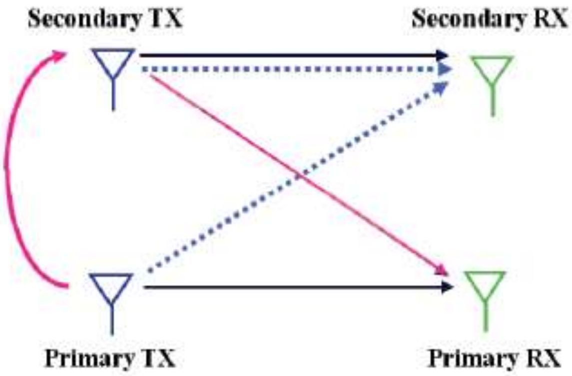

Fig. 1.5: Overlay Paradigm (Ezio *et al*., 2013)

Cognitive radio networks are based on the notion of minimal interference. So, understanding the interference channel provides a fundamental building block to both the capacity as well as encoding and decoding strategies for these networks.

1.2 PROBLEM STATEMENT

Interference is an inevitable phenomenon that has made the capacity of the wireless network interference-limited by using the conventional interference management schemes. Interference alignment is a novel transmission approach with which the sum-capacity of the time-varying interference networks using limited resources of time and frequency can be increased linearly with the number of users. In an underlay CR, an SU is allowed to share common spectrum with a PU provided the received interference level at the PU is below the interference temperature (IT) limit. This constraint translates to limiting the transmit power of the SU which in turn reduces its achievable capacity. In the case of multiple SUs, the situation becomes worse. This is because the transmit power of each SU may be lower and the SUs will have to deal with mutual interference among them. There is need to mitigate this cognitive intranetwork interference in order to improve the sum capacity of the SUs. This work proposed to develop an interference alignment scheme with IT constraints model with a view to enhancing the sum capacity of the SUs.

1.3 AIM AND OBJECTIVES

The aim of this research work is to enhance the sum capacity achieved by secondary users in underlay cognitive radio network using interference alignment technique.

The objectives of this research are as follows:

i. To evaluate the achievable sum capacity of an underlay cognitive channel under interference temperature model

ii. To mitigate mutual interference among multiple users of CR in underlay approach through interference alignment with interference temperature constraints model

iii. To validate the developed model by comparing its performance in terms of sum capacity achieved with generic TDMA scheme.

1.4 METHODOLOGY

The step by step approach of the proposed methodology is itemized as:

i. Adopting a spectrum sharing system model to the underlay CR network using the interference temperature model

ii. Development of time-sharing mathematical model for three-user underlay CR network under interference temperature constraints

iii. Simulation and analysis of the SUs' sum capacity achieved in (ii) above

iv. Development of ergodic interference alignment with interference temperature constraints model for three-user underlay CR network

v. Simulation and analysis of sum capacity achieved by the developed model in (iv) above

vi. Validation of the developed model by comparing its performance with generic TDMA scheme

1.5 SIGNIFICANCE OF RESEARCH

When designing a wireless communication system, understanding achievable capacity limits of data transmission is a preliminary and important step. For over thirty years, the capacity region of the interference channel has remained an open problem (Ghasemi-Goojani, & Behroozi, 2014). This is because one of the fundamental problems in wireless networks is coping with and exploiting interference, which is not yet entirely understood (Cadambe & Jafar, 2008). The concept of Degrees of Freedom (DoF) was introduced to approximate the capacity of interference channel. Interference Alignment (IA) is a recent transmission strategy for mitigating interference, thereby achieving higher capacity in terms of DoF. The CR system seeks to address the current problem of spectrum scarcity and underutilization.

1.6 DISSERTATION ORGANISATION

The general introduction has been presented in Chapter One. The rest of the chapters are structured as follows: Detailed review of fundamental concepts covering CR paradigms, relevant principle model equations and techniques as well as review of similar works are carried out in Chapter Two. Chapter three is devoted for the step-by-step procedure taken to describe the system model mathematically in order to develop the ergodic IA with IT constraints model. Performance analysis and discussion of the results obtained are presented in Chapter Four. Finally, conclusion and recommendation for further work make up Chapter Five. The list of cited references and MATLAB codes are provided at the end of this dissertation.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents the review of fundamental concepts and the review of similar research works relevant to this research. Under concepts, discussions will cover support paradigms, principle model equations and techniques available to use in order to justify the suitable one for this work. On the other hand, the review of similar researches will establish the extent of research in the subject area so that a different approach can be used to achieve the desired significant contributions.

2.2 REVIEW OF FUNDAMENTAL CONCEPTS

The review of fundamental concepts pertinent to the proposed research work is presented. These concepts are discussed in length in order to justify the choice of model and technique used in this research. The suitability of these concepts contributed to achieving the contributions made.

2.2.1 Comparative Review of Cognitive Radio Paradigms

The different approaches Secondary Users (SUs) take to cooperate with the Primary Users (PUs) give rise to three main cognitive radio network paradigms, namely:

i. Interweave

ii. Underlay

iii. Overlay

i. Interweave Paradigm

This approach is also referred to as Opportunistic Spectrum Access (OSA) for it represents the opportunistic transmission of the SUs based on knowledge of the available spectrum holes. The whole idea is based upon the original motivation of CR that the spectrum resource is under-utilized (Ezio *et al*., 2013). Hence, allowing SUs to opportunistically use the spectrum holes without yielding severe performance degradation to the PUs will result in an improved spectral efficiency. The manner in which the SU interweaves it signal makes this paradigm to be considered as interference avoiding behaviour as depicted in Fig. 2.1. The interweave technique, therefore, requires detection of the PUs (licensed or unlicensed) in one or more of the space-time-frequency dimensions. This detection (through spectrum sensing) is quite challenging because PU activity is dynamic in nature with respect to time as well as geographical location (Kandeepan & Andrea, 2012).

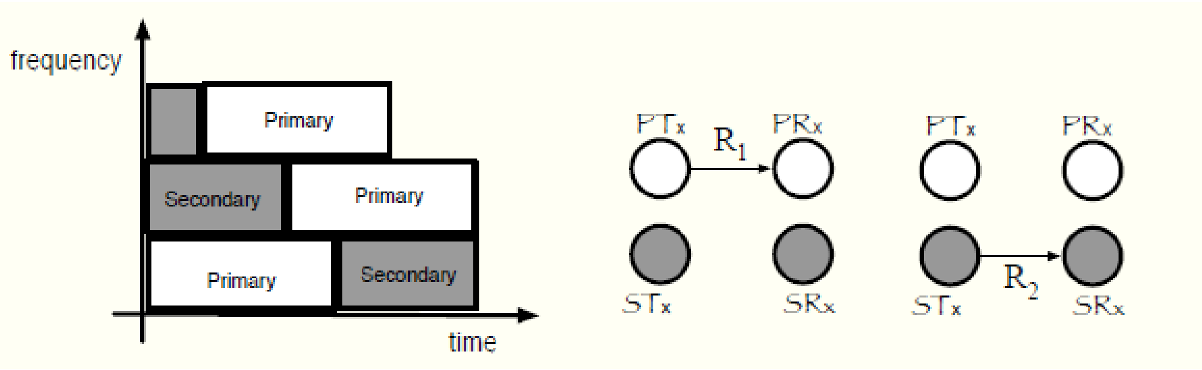

Fig. 2.1: Spectrum Interweave for Interference Avoidance (Kandeepan & Andrea, 2012)

ii. Underlay Paradigm

The underlay paradigm, allows for the simultaneous transmission of primary and cognitive users as long as the interference caused by the SU at the PUs is limited to some acceptable threshold. The interference threshold may be defined in terms of spectral mask of the Power Spectral Density (PSD) of the interference over all frequencies within the underlay frequency band. The SU then needs not determine the exact interference it causes to the PU. Rather it can spread its signal over a very wide bandwidth such that the interference PSD is below the noise floor at any PU location. The spread signals are then despread at each of their intended secondary receivers. This spreading scheme is the concept of both spread spectrum and Ultra Wideband (UWB) communications. Another way to meet the imposed interference threshold, is for the SUs to be conservative in their transmit power. For this reason, the underlay approach is also called interference controlling behaviour as illustrated in Fig. 2.2. The collective interference limit is sometimes called the interference temperature limit. Alternatively, the interference is controlled by exploiting the available Channel State Information (CSI) or multiple antennas at the SUs through adaptive power allocation or transceiver optimization. The concurrent transmission mode of the underlay paradigm makes it yield a better spectral utilisation (Kandeepan & Andrea, 2012).

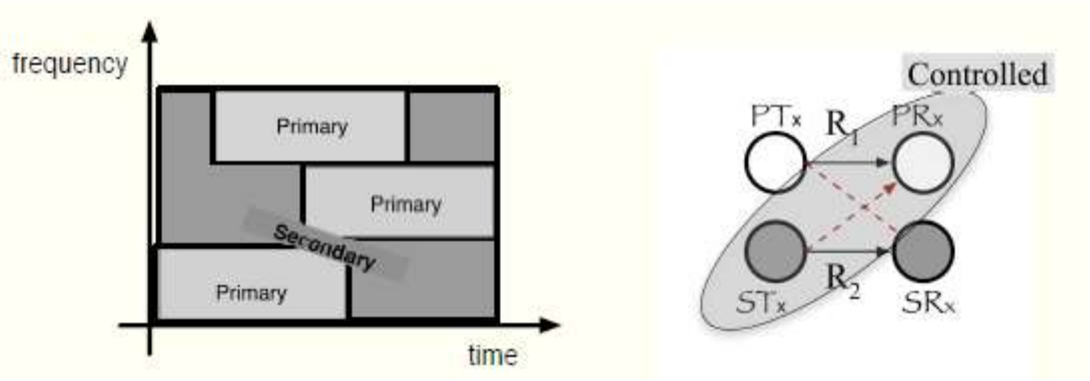

Fig. 2.2: Spectrum Underlay for Interference Control (Kandeepan & Andrea, 2012)

iii. Overlay Paradigm

The overlay paradigm also permits concurrent transmission of primary and cognitive users. In this approach, the SUs require a noncausal knowledge about the PU’s transmitted data sequence (message) and the way the sequence is coded (codebook). Using this information, the SUs are able to cancel or mitigate the interference by using part of their transmit power to assist (relay) the primary transmission. The relaying serves as a compensation for the interference offset. In this regard, the overlay paradigm is referred to as interference mitigating behaviour as shown in Fig. 2.3. Primary transmission may be enhanced in this way and a better spectral efficiency of the network achieved. However, the practical realization is very challenging for the need of the noncausal side information at the SUs (Kandeepan & Andrea, 2012).

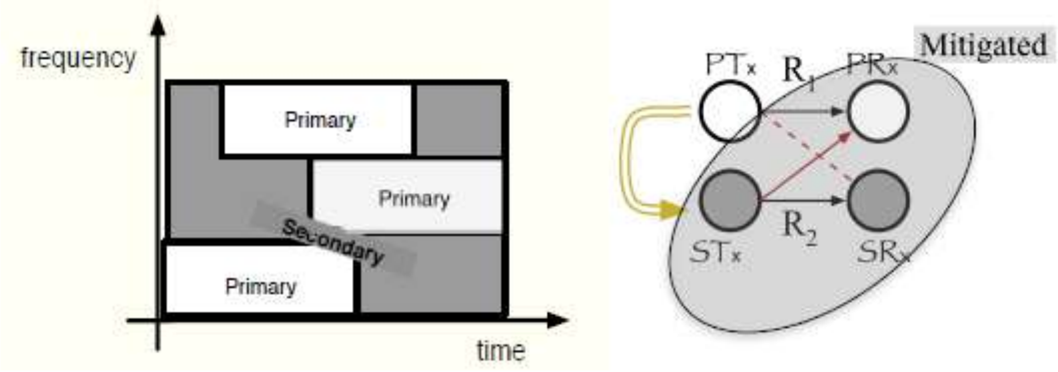

Fig. 2.3: Spectrum Overlay for Interference Mitigation (Kandeepan & Andrea, 2012)

Considering three main distinguishing factors Table 2.1 summarises the comparison between interweave, underlay, and overlay CR paradigms.

Table 2.1: Comparison of Underlay, Overlay and Interweave Cognitive Radio Paradigms

Distinguishing parameter	**Interweave**	**Underlay**	**Overlay**
Side Information	CR user knows the spectral holes in space, time, or frequency devoid of the primary users.	CR Tx knows the channel strengths to primary receiver(s).	SUs know channel gains, codebooks and possibly the messages of the non cognitive users.
Simultaneous Transmission	Cognitive user transmits simultaneously with a non cognitive user only in the event of a false spectral hole detection.	Simultaneous transmission is possible given that interference caused is below an acceptable limit.	Also allows concurrent transmission; the interference to non cognitive user is offset by using part of the cognitive user's power to relay the non cognitive user's message.
Transmit power	Cognitive user's transmit power is limited by the range of its spectral hole sensing.	Cognitive user's transmit power is limited by the interference constraint.	Cognitive user transmits at any power and relays the primary for the offset caused.

2.2.2 Noise in Wireless Environment

Unwanted electrical signals are always present in electrical systems. These unwanted signals which arise from various sources are referred to as noise. Man-made sources of noise include carriers from transmitters other than those desired to receive. This noise is referred to as interference. Natural sources of noise include the atmosphere, the sun, and the ground around a receiving antenna. Noise limits the performance of a communications system because it tends to mask the desired signal (Sadeque, 2015).

In wireless channel specifically, a noise source may either have additive or multiplicative effect. The additive noise comes from noise generated within the receiver itself, such as thermal and shot noise in active and passive components. It also includes noise from external sources such as atmospheric effects, cosmic radiations and interference from other transmitters and electrical appliances. The multiplicative type of noise arises from the various processes the transmitted waves encounter on their way from the transmitter antenna to the receiver antenna. The multiplicative processes are but not limited to reflection, absorption, scattering, diffraction and refraction (Simon & Alejandro, 2007).

2.2.2.1 Additive White Gaussian Noise (AWGN)

A classical result in Information Theory states the fact that the Gaussian noise is considered as the worst-case additive noise in point-to- point channels. This means that, for a fixed noise variance, the Gaussian noise minimizes the capacity of an additive noise channel (Sadeque, 2015). The thermal noise is a natural source that cannot be eliminated. The model for thermal noise in communication channels is referred to the AWGN and is shown in Fig. 2.4. It is described as follows:

i. The noise is additive: The noise adds positive and negative random values to the amplitude of the signal.

ii. The noise is white, that is, its power spectral density is flat. Theoretically, white noise has unlimited bandwidth and all frequencies are represented equally. In practice, white noise has a uniform spectral density within a given bandwidth of interest.

iii. The noise has a Gaussian, or normal probability density because it is obtained from the agitation of a very large number of independent atomic particles. This distribution arises when a large number of independent sources contribute additively to the end result, as long as the contribution of each is small compared to the sum.

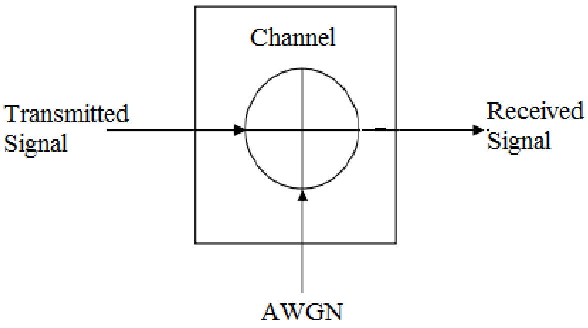

Fig. 2.4: AWGN Channel Model (Awon *et al*., 2012)

The output $\mathrm{Y(t)}$ of the AWGN channel is thus modelled as

$$\mathrm{Y(t) = X(t) + N(t)} \tag{2.1}$$

where, $\mathrm{X(t)}$ is the input waveform, regarded as a real random process and $\mathrm{N(t)}$ is a real white Gaussian noise process with noise power density $\mathrm{N_o}$ which is independent of $\mathrm{X(t)}$.

2.2.3 Fading in Wireless Environment

The AWGN channel model is not a suitable model for wireless mobile propagation environment. This is because it assumed a non-time varying characteristic of point to point channel where the received signal is deterministically a scaled version of the transmitted signal. However, this is not the case when channels vary to fading. Fading is the rapid fluctuation of received signal strength which occurs when the signal is received from many reflections or paths (such as reflection from buildings). One of the most adopted models for multipath fading is the Rayleigh fading statistical model.

2.2.3.1 Rayleigh Distribution

The Rayleigh distribution is used to model the amplitude and phase of the multipath fading signal with non-LOS between the transmitter and receiver antennas. The Probability Density Function (PDF) of the Rayleigh distribution is expressed as (Kabiri *et al.*, 2015)

$$f_R(r) = \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right), \ \ r \geq 0 \tag{2.2}$$

where, r is the envelope of the received signal, and σ^2denotes the time-average power of the received signal before the envelope detection.

2.2.3.2 Channel State Information (CSI)

The Channel State Information or Channel Side Information CSI refers to available knowledge about the channel and propagation environment (pathloss, shadowing, fading, etc.). It is also called channel coefficient which is usually denoted by h. CSI is related to the channel gain, g, by (Sboui, *et al.*, 2013)

$$g = |h|^2 \tag{2.3}$$

2.2.4 Interference in Cognitive Radio Network

As an inevitable phenomenon in wireless networks, interference has been a fundamental factor of concern in the design and operation of communication systems. In wireless systems, interference emanate from various sources such as Radio Frequency (RF) emissions from transmitters having an emission band partly or wholly overlapping the desired transmission band. This results in unwanted signal from other sources injecting energy into the desired channel. With the advent of cognitive radios, interference analysis, characterization, control, and mitigation have been a key factor and become a crucial point in the realization of such systems (Kandeepan, & Andrea 2012).

In the context of CR networks, interference may be classified into two types: intra and internetwork interference. Intranetwork interference refers to the interference caused within one network (either a primary or CR network), while internetwork interference refers to the mutual interference between the primary and CR networks (Xu *et al*., 2013). Internetwork interference management is very important for CR networks for the fact that performance degradation of primary users must be avoided at all cost (Hong *et al*., 2009).

2.2.4.1 Metrics to Quantify Interference and its Effects

Generally interference causes performance degradation. To manage the degradation, there is need to quantify how much interference is generated, and what is the effect of the interference.

The following parameters are commonly used to quantify interference (Kandeepan, & Andrea 2012):

i. Interference level or interference power, I, (this translates to Interference Temperature (IT) in CR)
ii. Signal-to-Interference Ratio (SIR)
iii. Signal-to-Interference plus Noise Ratio (SINR)

To quantify the effect of interference, the most commonly used parameters are (Kandeepan, & Andrea 2012):

i. Symbol Error Probability (SEP)
ii. Bit Error Probability (BEP)
iii. Codeword Error Probability (CEP)

iv. packet error probability (PEP)

v. Quality of Service (QoS)

2.2.4.2 Interference Temperature (IT)

In a spectrum sharing cognitive radio, the approach to prevent harmful interference at the legacy/primary users would be to limit the transmit power of secondary user to below the noise floor of interference at a given primary receiver. This approach becomes more challenging due to increased mobility and variability of the radio spectrum. To address this problem, FCC Spectrum Policy Task Force (FSPTF) has proposed a metric for interference assessment called interference temperature (Wang & Liu 2011).

The IT is a measure of the RF power available at a receiving antenna to be delivered to a receiver, reflecting the power generated by other emitters and noise sources. Assuming an interferer operates at a frequency, $\mathrm{f_c}$ Hz, with bandwidth, W Hz, producing an average power, $\mathrm{I(f_c, W)}$ watts, at a receiving antenna, the IT in Kelvin is given by (Wang & Liu 2011) as

$$\mathrm{T_I(f_c, W) = \frac{I(f_c, W)}{k\,W}} \tag{2.4}$$

where, $\mathrm{k = 1.38 \times 10^{-23} J/K}$ is the Boltzmann's constant.

The FCC adopted the IT metric to establish an IT limit, $\mathrm{T_L}$, as the maximum tolerable interference level that PU can tolerate within its frequency band in a given place. Any SU must guarantee that its transmission added to existing interference should not go beyond $\mathrm{T_L}$ at the PU receiver. This is modelled as (Kandeepan, & Andrea 2012)

$$\mathrm{T_I(f_c, W) + \frac{L.I}{k_B W} \leq T_L(f_c)} \tag{2.5}$$

where:

$\mathrm{T_I(f_c, W)}$ is the existing IT,

$\frac{\mathrm{L.I}}{\mathrm{k\ W}}$ is the IT from SU,

I is the SU transmit power and L is the attenuation which is due to fading and pathloss.

$\mathrm{L.I}$ gives the interfering power at the PU from the SU.

2.2.5 Channel Capacity

The capacity of a single user channel as defined by Shannon equals the maximum data rate at which information bits can be transmitted with arbitrarily small error probability. (Ezio *et al*., 2013). To compute the upper bound to the bit rate of a given AWGN transmission channel, the Shannon's capacity, C, formula is used and it is given by (Qiao *et al*., 2013):

$$\mathrm{C = w\log_2(1 + SNR)} \tag{2.6}$$

where, w is the channel bandwidth of the user, and SNR is its Signal to Noise Ratio.

For a fading channels, however, SNR is a random variable and its variation is very fast in fast-fading channel. Therefore, the concept of ergodic capacity is introduced. The ergodic capacity is given by (Sboui, *et al.*, 2013) as

$$C = \mathrm{E}[\log(1 + gP^*)] \tag{2.7}$$

where, E[.] denotes expectation, and P^* is the optimal power.

2.2.5.1 Degrees of Freedom

The capacity expressions for most of the wireless networks have remained an open problem for decades. Fundamental performance limits are only available in a few special cases. With the addition of cognitive users the capacity becomes even more difficult to obtain (Ezio *et al*., 2013). The difficulty inherent in obtaining the capacity region of the wireless channel has led to an important capacity approximation called Degrees of Freedom (DoF). The DoF, d, of a network can be interpreted as the number of resolvable (interference-free) signal dimensions. It is defined as (Goldsmith *et al*., 2009):

$$\mathrm{d} = \lim_{\mathrm{SNR}\to\infty} \frac{\mathrm{C(SNR)}}{\log(\mathrm{SNR})} \tag{2.8}$$

Thus,

$$\mathrm{C(SNR)} = \mathrm{d}\log(\mathrm{SNR}) + \mathrm{o}(\log \mathrm{SNR}) \tag{2.9}$$

where, $\mathrm{o}(\log \mathrm{SNR})$ is an approximation error which tends to zero as SNR increases.

All the logarithms are in base two.

2.2.6 Interference Channel Model

The interference channel model depicts a scenario where the transmission medium is shared by multiple transmitter-receiver pairs. Each transmitter sends message signal to its intended receiver and subsequently generates interference to other receivers.

Consider a K-user interference channel shown in Fig. 2.5 where there are K principal links and $\mathrm{K(K-1)}$ interfering links. (Cadambe & Jafar, 2008)

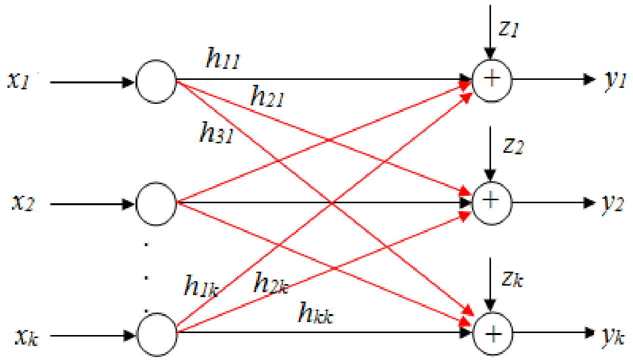

Fig. 2.5. K-User Interference Channel (Cadambe & Jafar, 2008)

Each receiver observes noisy linear combinations of the transmitted signals given by (Cadambe & Jafar, 2008)

$$y_i = \sum_{j=1}^{k} h_{ij} x_j + z_i \tag{2.10}$$

where:

y_i is the received signal by the ith receiver,

x_j is the transmitted signal by the jth transmitter,

h_{ij} is the channel coefficient of the link between jth transmitter and ith receiver

z_i is the additive white Gaussian noise (AWGN) at the jth receiver.

The array of the channel coefficients h_{ij} forms the channel matrix, H, which gives the channel response written as (Cadambe & Jafar, 2008)

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1k} \\ h_{21} & h_{22} & \cdots & h_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ h_{k1} & h_{k2} & \cdots & h_{kk} \end{bmatrix} \tag{2.11}$$

2.2.7 Interference Mitigation

Interference is one of the fundamental characteristics of wireless communication systems, in which multiple transmissions occur simultaneously over a common communication channel. Since interference is one of the limiting features of a wireless network, how to deal with it optimally is one of the most important aspects of communication in a multiuser scenario. Three conventional interference management approaches have been already useful. They are discussed as follows:

i. **Decoding the interference:** If the interference is strong, the interfering signal is first decoded and subtracted from the desired signal. This approach is less common in practice due to complexity of multi-user detection and is supported by capacity results in ‘strong interference’. The difficulty attached to this scheme is in generalization to more than two-user scenario (Cadambe & Jafar, 2008).

ii. **Treating as noise:** Where the interference is weak it can be treated as additional noise. Thus, an increase in transmit power together with single user encoding/decoding suffice (Cadambe & Jafar, 2008).

iii. **Orthogonalizing:** For a strong interference network, the channel access can be orthogonalize in time or frequency. This forms the basis of time (frequency) division multiple access. Interference is avoided among multiple users by sharing the channel access time or spectrum in a “cake-cutting” fashion. Suppose a channel is occupied by one user with a single antenna, the achievable capacity may be obtained using equation (9). This means that the channel has one degree of freedom. The capacity per user for the k-user interference channel would be $\frac{1}{k}$ of the capacity of a single user channel. That is each user gets $\frac{1}{k}$ DoF (Cadambe & Jafar, 2008).

2.2.7.1 Interference Alignment

Interference Alignment (IA) is a recent transmission strategy that combines transmitter precoding and receiver interference suppression to achieve optimal network degrees of freedom (Gomadam *et al*., 2011).

The idea of IA has challenged most of conventional wisdom about the sum capacity limit of wireless channels. In the traditional orthogonalizing scheme (TDMA and FDMA) on a k-user interference channel, the outerbound per user is $\frac{1}{k}$ of the channel sum capacity. But by applying IA technique a user gets up to $\frac{1}{2}$ of the channel sum capacity. In other words, each user is able to achieve a DoF of $\frac{1}{2}$ giving a total of $\frac{k}{2}$ DoF of the channel. From equation (2.9), the sum capacity is therefore written as

$$\mathrm{C(SNR)} = \frac{\mathrm{k}}{2}\log(\mathrm{SNR}) + \mathrm{o}(\log \mathrm{SNR}) \tag{2.12}$$

It is easily seen that the network sum capacity increases linearly with the number of users. Successful implementation of IA would render the capacity of wireless channels interference unlimited. In a ‘cake-cutting’ notion, it implies that every user gets half the cake. IA restricts all interference at every receiver to approximately half of the received signal dimension leaving the other half interference-free for the desired signal (Gomadam *et al*., 2011).

IA can be constructed in the following dimensions.

i. **Time:** (either through propagation delay or through coding),

ii. **Space:** (beamforming across multiple antennas),

iii. **Frequency:** (either through Doppler shift or by coding across multiple carriers with frequency selective coefficients), and

iv. **Codes:** (through lattice or multilevel codes that align interference within signal levels)

2.2.7.2 Example of Interference Alignment via Delay Offset

To conceptualize time delay IA, consider the k-user interference network shown in Fig. 2.6. Each channel is associated with a propagation delay. Assume the propagation delay to be equal to one symbol duration for all desired signal paths and two symbol durations for all paths that carry interference signals.

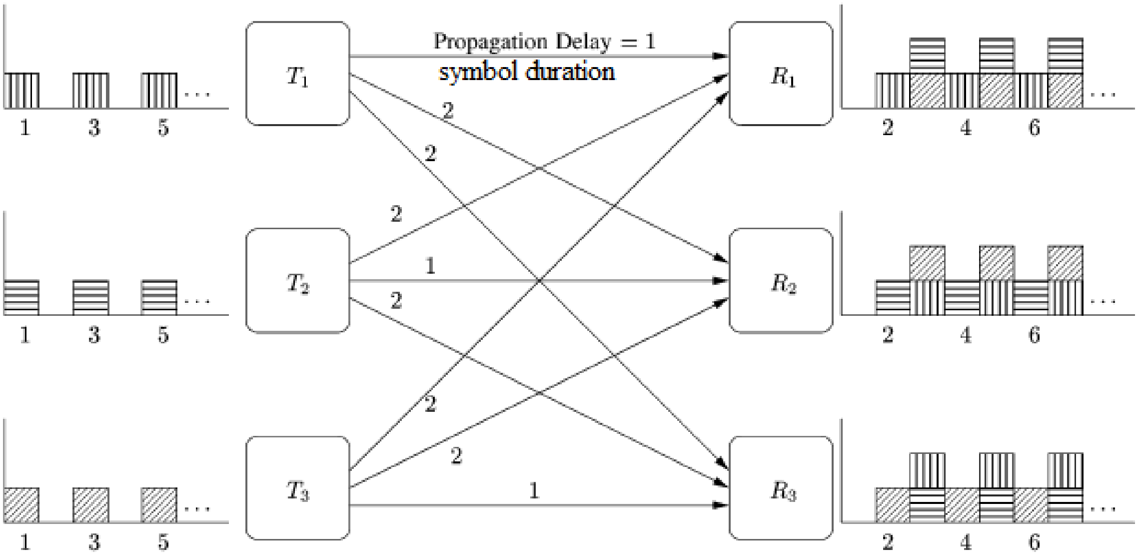

Fig. 2.6: Interference Alignment (Cadambe & Jafar, 2008).

The channel output at receiver $i \in \{1,2,\ldots k\}$ is defined as (Cadambe & Jafar, 2008)

$$y_i(n) = \sum_{j \neq i} x_j(n-2) + x_j(n-1) + z_i(n) \tag{2.13}$$

where during the nth time slot (symbol duration) transmitter j sends symbol $x_j(n)$ and $z_j(n)$ is AWGN. All inputs and outputs are complex.

In the absence of interference, a user would achieve a capacity, C, given by (Cadambe & Jafar, 2008) as

$$C = \log(1 + P) \tag{2.14}$$

With all the interferers present, suppose each transmitter transmits only during odd time slots (with power 2P) and is silent during the even time slots. At receiver 1, the symbols sent from its desired transmitter (transmitter 1) are received free from interference during the even time slots and all the undesired (interference) transmissions are received simultaneously during the odd time slots. Thus, each user is able to access the channel one-half of the time with no interference from other users. Each user achieves a rate, R, given by (Cadambe & Jafar, 2008) as

$$\mathrm{R} = \frac{1}{2}\log(1 + 2\mathrm{P}) \qquad (2.15)$$

The interference alignment technique described above is only possible when the nodes are deployed at specific locations (Mathar & Zivkovic, 2009). Fig. 2.7 illustrates the node placement orientation in order to perform the alignment task in the time domain.

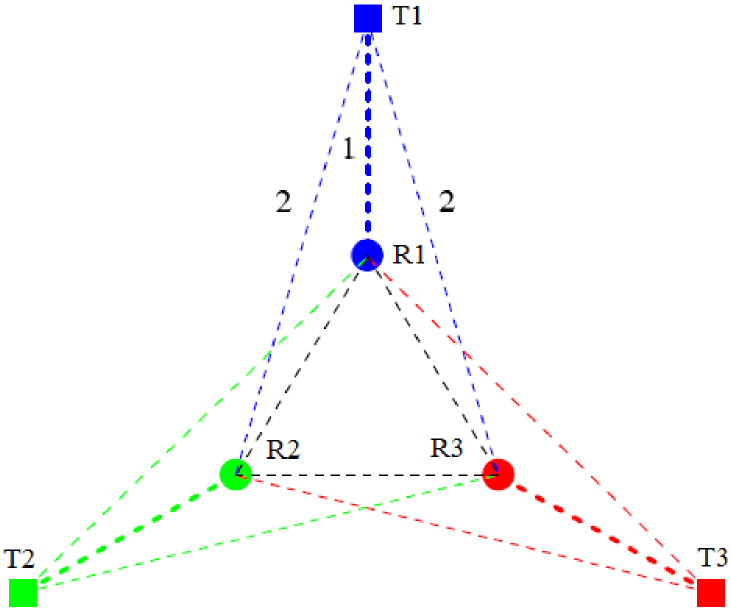

Fig. 2.7. Node Placement for 3-User IA (Mathar & Zivkovic, 2009)

2.2.7.3 Ergodic Interference Alignment

This scheme relies on the availability of time-varying, independent channel coefficients that are drawn from distributions with uniform phase (Nazer *et al.*, 2012). Suppose K transmitters send out signals $X_1, X_2, \dots, X_K$ at time t under channel matrix $H = \{h_{kl}\}$. Each receiver observes:

$$Y_k[t] = \sum_{l=1}^{K} h_{kl} X_l + Z_k[t] \tag{2.16}$$

where, $Z_k[t]$ is independent and identically distributed (i.i.d) additive noise.

The transmitters wait until the complementary channel matrix, H_C, is realized at time, t_C and then resend $X_1, X_2, \ldots, X_K$. H_C is expressed as

$$H_C = \begin{bmatrix} h_{11} & -h_{12} & \cdots & -h_{1k} \\ -h_{21} & h_{22} & \cdots & -h_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ -h_{k1} & -h_{k2} & \cdots & h_{kk} \end{bmatrix} \tag{2.17}$$

The received signal at each receiver is now

$$Y_k[t_C] = h_{kk} X_k - \sum_{l \neq k}^{K} h_{kl} X_l + Z_k[t_C] \tag{2.18}$$

Thus, the total received signal is obtained by adding $Y_k[t]$ and $Y_k[t_C]$ as

$$Y_k[t]+Y_k[t_C] = 2h_{kk} X_k + Z_k[t] + Z_k[t_C] \tag{2.19}$$

It can be observed that an interference free channel is obtained after two channel uses. Hence, for a time-varying Gaussian interference channel, the achievable rate per user is obtained using equation (2.7) as

$$R_k = \frac{1}{2} \mathrm{E}[\log(1 + 2|h_{kk}|^2 P)] \tag{2.20}$$

2.3 REVIEW OF SIMILAR WORKS

The following presents a critical review of similar research works:

Cadambe *et al*., (2010) introduced the novel idea of asymmetric complex signalling to perform interference alignment for complex Gaussian 3 user interference channel with constant channel coefficients. The alignment scheme was concerned only with the phase and not with the magnitudes of the channel coefficients. The maximum achievable DoF was found to be 1.2. However, the main limitation of this alignment scheme for the 3-user case, was the fact that each signal vector could only align with interference at no more than one undesired receiver, which translated into the maximum of 1.2 degrees-of-freedom for the 3 user interference channel.

Gomadam *et al*., (2011) developed a distributed numerical approach to interference alignment in interference channels to complement previously developed analytical approaches. To address the overwhelming overhead incurred in practice for the requirement of obtaining global channel knowledge necessary for interference alignment, iterative algorithms that utilize the reciprocity of wireless networks to achieve interference alignment with only local channel knowledge at each node were proposed. The approach also improved the performance of interference alignment algorithms at low/moderate SNR. Again the approach adopted minimized interference to unintended receiver nodes. It was thus considered a cognitive approach. Numerical comparisons to orthogonal schemes, simultaneous transmission schemes and selfish interference avoidance schemes showed that the benefits of distributed interference alignment algorithm were significant and close to the theoretical predictions. Considering a 4-user channel with 5 antennas at each node, the numerical algorithm achieved a total DoF of 8 as against 5 obtainable with the orthogonal scheme. However, the iterative algorithms were not effective in obtaining interference alignment solutions for channels demanding symbol extensions even though long symbol extensions would in general be a requirement to achieve the optimal degrees of freedom for time-varying channels with single-antenna nodes.

Torbatian *et al*., (2012) proposed an interference alignment algorithm which achieved the total K/2 DoF over a quasi static K-user asynchronous interference channel. To provide the required channel variation for the interference alignment the links were converted to ISI links and accordingly to time-varying channels. In the proposed scheme, there was no need to have the channel state information of the links at the transmitter side. Instead, the full state information of the asynchronous delays was required at all nodes to facilitate in performing the alignment task. However the effectiveness of the scheme was only shown mathematically among homogenous users. There is need, therefore, to demonstrate the achievable DoF in heterogeneous scenario such as cognitive radio network.

Maso *et al*., (2012) introduced an interference alignment scheme called cognitive interference alignment (CIA) that allowed the coexistence of an orthogonal frequency division multiplexing (OFDM) macro-cell and a cognitive small-cell deployed in a two-tiered structure and transmitting over the same bandwidth in an underlay setting. Thus, the micro-cell base station, the licensee would be unaware of the cognitive small cell. Optimal linear strategy for the single antenna secondary base station was derived to maximize the spectral efficiency, accounting for both signal sub-space structure and power loading strategy. Considering spectral efficiency of the secondary link, 84% spectral efficiency was achieved. The proposed scheme only focused on the maximum achievable spectral efficiency of the secondary link neglecting the impact of the primary system interference on the secondary mobile equipment.

Rezki & Aloini, (2012) investigated a communication system where a PU and an SU share the same spectrum under interference constraint. The SU is aware of the CSI of the secondary link but knows only the statistics and an estimated version of the cross link. Optimum power profile and the ergodic capacity of the secondary link were derived for general fading channels with a continuous probability density function under the average and peak transmit power constraints. Numerical results showed that for a Rayleigh fading channels, the capacity does not increase with the power, implying that the interference constraint was harmful at high power regime, whereas at low power regime, it has a marginal impact, corresponding to the ergodic capacity under average or peak transmit power constraint. However, a feedback is required in the secondary transmitter-primary receiver link to improve the channel estimation quality.

Nazer *et al.*, (2012) developed a simple communication strategy called ergodic interference alignment, for the K-user interference channel with time-varying fading. At any time instant, each receiver observed a superposition of the transmitted signals plus noise. The standard approach to such a scenario usually resulted in each transmitter-receiver pair achieving a rate proportional to 1/K its interference-free ergodic capacity. The ergodic IA scheme relied on the availability of time-varying, independent channel coefficients drawn from distributions with uniform phase. Given two well chosen time indices, the channel coefficients from interfering users were made to exactly cancel. By adding up the two observations during the given time indices, each receiver obtained its desired signal without any interference. The technique allowed each user to achieve ½ its interference-free ergodic capacity at any signal-to-noise ratio. However the scheme was applied to users in homogenous settings (where all users are primary). Again, there existed a very long delay between the given time indices necessary to achieve the ergodic IA which resulted in low spectral efficiency.

Xu *et al.*, (2013) developed practical interference alignment and cancellation scheme for MIMO underlay cognitive radio to optimize SUs' performance while trying to avoid interfering the PU. The spatial dimensions provided by MIMO antennas permitted finding the null space of interference at the PU's receiver using a Blind Null Space Learning (BNSL) algorithm. SUs then sent their signals to this null space. Interference cancellation at the SUs' receivers was done by applying interference suppression matrix to the received signal with a view to eliminating the PU's interference. However, these interference mitigation approaches imposed a limitation in the number of antennas at the secondary transmitter and receiver by the number of antennas at the primary receiver and transmitter respectively. Consequently, the sum capacity was constrained in terms of multiplexing gain. Again the requirement of having global channel states at the SUs' transmitters for aligning the interference among the SUs would incur extra communications overhead. The BNSL algorithm performed well only when channels are static which is on the contrary in time-varying channels.

Xu & Mao, (2013) implimented a cooperative spectrum leasing scheme that combined two advanced physical layer techniques; that is, Multiple-Input Multiple-Output (MIMO) and distributed interference alignment, in Cognitive Radio (CR) networks. In the deployed scheme the primary user acted as a leader and decided on the division of the channel access time, selecting a set of secondary users that served as followers for spectrum leasing. The primary user would collect revenue from the selected secondary users proportional to their transmit powers (or, data rates). It was established that leasing spectrum to secondary users assisted in enhancing the primary and secondary users' utility, but the secondary users were constrained in their transmit power which limited their sum capacity.

Chou et at., (2013) devised an iterative interference alignment algorithm to maximize the sum capacity, thereby obtaining maximal achievable DoF in K-user MIMO interference system. The algorithm aimed to design a set of linear precoding matrices at every sender for aligning the interfering signals and the corresponding decoding at each receiver matrices for cancelling the interference. The scheme provided solution towards improving both Signal to Interference plus Noise Ratio (SINR) and Signal to Jamming and Noise Ratio (SJNR) with a view to having a greater sum capacity performance. However, the work considered a quasi-static flat fading channel which would not work well in a fast fading wireless environment.

Loch *et al*., (2014) employed practical interference alignment scheme in the frequency domain for OFDM-based wireless access networks. They investigated the gains achievable by frequency IA in practice for a scenario with multiple access points and clients. The assumption made by prior work of all nodes having the same SNR was addressed by designing mechanisms that adaptively chose which nodes shall perform IA on which subcarriers depending on current channel conditions. The scheme implemented was validated on software-defined radios achieved up to 30% gain compared to plain OFDM. However, the IA required a very high SNR, which was the limitation of this work.

Morales-Cespedes *et al*., (2015) proposed a blind interference alignment scheme for partially connected cellular networks. The scheme relied on receivers with one reconfigurable antenna and allowed users at the cell edge to be served by all the Base Stations (BS) in their proximity in order to cancel intra-cell and intercell interference. Users near the BS treated intercell interference as noise and were termed “private” users while those at the cell edge who were connected to all BS in their proximity were the “shared” users. The proposed scheme allowed mitigation of intracell and intercell interference without the need for knowledge of the channel state information at the transmitter. However, the scheme achieved the information theoretic Degrees-of-Freedom bound for symmetric settings only, where the number of private users per cell was the same. Thus the scheme would not stand the stochastic behaviour of users in the wireless mobile environment.

Rosas *et al.*, (2016) proposed an optimal power allocation technique using Genetic Algorithm (GA) for maximization of ergodic capacity under different fading channel approaches in cognitive radio network. The technique studied the maximization of an SU’s ergodic capacity considering the constraints of maximum transmit power of SU, interference threshold at PU and interference on the SU. The optimal power allocation strategy enhanced the performance by maximizing ergodic capacity of Underlay CR under the different fading channels. However, the work only applied to a single user in the underlay CR approach.

From the literature reviewed, it is evident that much work has been done to mitigate interference in CR network using different interference management schemes. For underlay CR under interference constraint, a single SU is only considered. There need for the investigation of the impact of multiple SUs on the sum capacity of the underlay cognitive channel. Applying IA would potentially mitigate the mutual interference that would occur as the number of SUs increases and also improve the channel sum capacity. This would lead to a problem of maximizing the sum capacity under the interference constraint.

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

This chapter describes the detailed procedure carried out in developing an interference mitigation technique among secondary users of underlay cognitive radio with a view to enhancing their sum capacity.

3.2 SYSTEM MODEL

A spectrum sharing model is considered as illustrated in Fig. 3.1 where three Secondary Users (SUs) underlay their transmissions in the same narrow-band frequency as the Primary User (PU). A user is defined as transmitter- receiver pair.

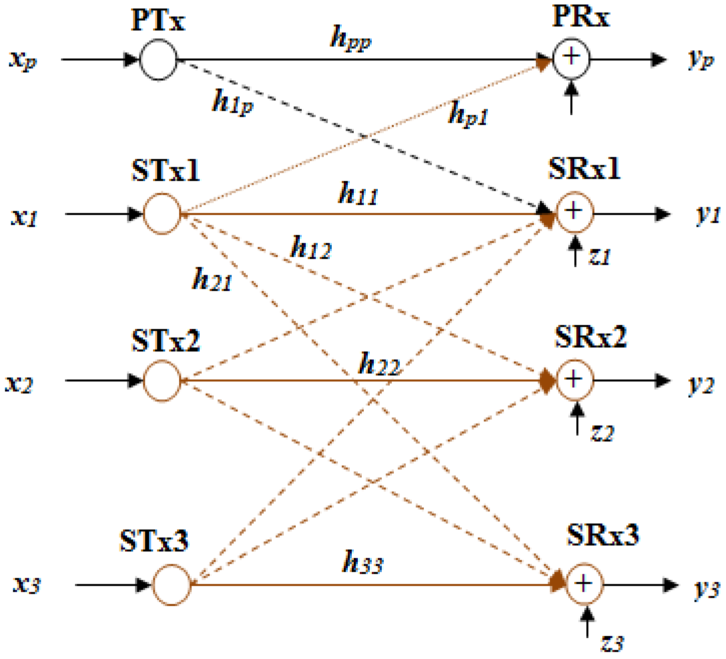

Fig. 3.1: System Model: 3 SUs Coexisting with a Single PU

The PU is licensed to freely exploit the spectrum; whereas the SU, is allowed to share the spectrum with the PU without harming the latter's communication. This condition is met by ensuring that the maximum received interference power, $P_{I_{max}}$ at PU is below a given threshold. The interference temperature metric, IT, would be used as measure of the interference power as proposed by the FCC, 2002.

The channel coefficient between transmitter j to receiver i is denoted as h_{ij}. All the channel coefficients are assumed to be independent and identically distributed (i.i.d) random variable following Rayleigh distribution.

The following forms of interference exist;

i. Inter-network interference of two kinds: SU-PU interference and PU-SU interference

ii. SU-SU intra-network interference

The received signal at the primary receiver, y_p, is a noisy linear combination of the signals from the intended primary transmitter and unintended secondary transmitters which can be modelled as (Xu *et al.,* 2013):

$$y_p = h_{pp} x_p + \sum_{k=1}^{3} h_{pk} x_k + z_p \tag{3.1}$$

where:

h_{pp} and h_{pk} are the channel coefficient between the PU transmitter and PU receiver and the channel coefficient between the k^{th} SU transmitter and the PU receiver respectively;

x_p and x_k are the signals transmitted by the PU transmitter and the k^{th} SU transmitter respectively;

z_p is an additive white Gaussian noise with zero mean and unit variance at the primary receiver.

Similarly the channel model for the jth SU receiver is as follows

$$y_j = h_{jp} x_p + \sum_{k=1}^{3} h_{jk} x_k + z_p \tag{3.2}$$

where, $j = 1, 2, 3$

The SU-PU inter-network interference is modelled using the concept of interference temperature as proposed by the FCC, 2002.

3.2.1 Interference Temperature Model (ITM)

The interference temperature, T_I, is a measure of power and bandwidth occupied by interference. It is defined as (Benedetto *et al.*, 2013)

$$T_I = \frac{P_R}{k.B} \tag{3.3}$$

where, P_R is the received interference power,

B is the signal bandwidth, and $k = 1.38 \times 10^{-23}$ (Joules per Kelvin degree) is the Boltzmann's constant.

In the underlay approach, SU must guarantee that its transmission added to the existing interference temperature must not exceed an interference temperature limit, T_L, which would be set by a regulatory body for a given geographic location. This is expressed as

$$T_I + \frac{L.P}{k.B} \leq T_L \tag{3.4}$$

where, P is the transmit power of the SU.

$\frac{L.P}{k.B}$ is therefore the temperature equivalent of the SU's transmission.

L is the attenuation which is due to fading and pathloss.

$L.P$ gives the interfering power at the PU from the SU.

For a given bandwidth, B, the SU determines its transmit power, P, subject to interference constraint of equation (3.4) which is given by.

$$P \leq \frac{k.B(T_L - T_I)}{L} \tag{3.5}$$

Thus,

$$E[|x_k|^2] = P \leq \frac{k.B(T_L - T_I)}{L} \tag{3.6}$$

Equation (3.6) ensures that the total power in the terms $\sum_{k=1}^{3} h_{pk} x_k$ of equation (3.1) do not cause harmful interference at the PU receiver.

3.2.2 Establishing Interference Temperature Limits (T_L)

At the moment, the interference temperature limits have not been established by the regulatory authorities. The FCC radiation limits for Ultra-Wide Band (UWB) devices could be used to calculate the equivalent interference temperature limits. This is because the UWB technology is a form of spectrum sharing technique that works in a similar manner as the underlay CR system. For instance, the radiation limits ranges from -75.3 dbm/MHz to -41.3 dbm/MHz (Padilla, 2014). The corresponding T_L therefore are 2.1386 × 10^6 K and 5.3718 × 10^9 K obtained using equation (3.3).

It assumed that exiting interference temperature is considered as the background noise temperature of 290 K. Since $T_L \gg T_I$, $T_L - T_I \approx T_L$, thus equation (3.6) becomes

$$E[|x_k|^2] = P \leq \frac{kBT_L}{L} \tag{3.7}$$

Next, the achievable capacity of the SUs is investigated assuming a normalized capacity measured in bits per channel use (bpcu).

3.3 ACHIEVABLE USABLE CAPACITY OF SUs

The interference from the PU is assumed to be very strong so that each SU could first decode it and subtract from the received signal without incurring any decrease in its achievable rate (Rini *et al.,* 2011). Thus, for a 3-user fully connected CR the received signal vector at j-th SU receiver is obtained from equation (3.2) as

$$y_k = h_{kk} x_k + \sum_{i \neq k}^{3} h_{ki}\, x_i + z_p, i = 1, 2,3 \tag{3.8}$$

Each SU would clearly be better off if it had exclusive access to secondary transmission and faced no interference from other SUs. Precisely, if $h_{ki} = 0\ \forall i \neq k$, each secondary receiver sees a point-to-point link from its transmitter and can achieve the interference-free capacity, C. The interference-free capacity would be determined under two constraints, namely; maximum interference temperature limits and average interference temperature limits.

3.3.1 Maximum Interference Temperature Limits

In this setting, a maximum interference temperature limit is fixed. The SU is not allowed to exceed this threshold regardless of the channel condition. This is applicable to delay-sensitive PU. Therefore, instantaneous channel gain of the cross link is assumed to be available at the SU transmitter. The capacity, C, is solution to the following optimization problem.

$$C = \max_{P \geq 0} \mathrm{E}[\log(1 + g_{ss}P)] \tag{3.9}$$

Subject to

$$g_{ps}P \ \leq \ kBT_L \tag{3.10}$$

where, $\mathrm{E}[.]$ is the expectation operator,

g_{ss} and g_{ps} are the channel gains of the secondary link and the cross link.

The solution of this problem is simple to derive and the optimal power, P^*, is given by

$$P^* = \frac{kBT_L}{g_{ps}} \tag{3.11}$$

Putting equation (3.11) in equation (3.9) gives

$$C = \max_{P \geq 0} \mathrm{E}\left[\log\left(1 + \frac{g_{ss}}{g_{ps}}\psi\right)\right] \tag{3.12}$$

where, $\psi = kBT_L$is the signal to noise ratio of AWGN channel with zero mean and unit variance.

The ratio of the random variables $\frac{g_{ss}}{g_{ps}}$ is another random variable, X, with pdf given by (See Appendix 1)

$$f_X(x) = \frac{1}{(1+x)^2} \tag{3.13}$$

Putting equation (3.13) into equation (3.12) using analytical method gives

$$C = 1.44 \int_0^\infty \log(1 + \psi x) \frac{1}{(1+x)^2} dx \tag{3.14}$$

$$C = 1.44 \frac{\psi \log \psi}{\psi - 1} \qquad \text{Bits per channel use (Bpcu)} \tag{3.15}$$

3.3.2 Average Interference Temperature Limits

From the spectrum-sharing point of view, an average interference temperature constraint is reasonable when the PU's QoS is determined by the average SNR. This is applicable for delay-insensitive service. This constraint is less stringent than the maximum IT limit. Subsequently, the ergodic capacity is obtained by solving the following optimization problem.

$$C = \max_{P \geq 0} \mathrm{E}[\log(1 + g_{ss}P)] \tag{3.16}$$

Subject to

$$\mathrm{E}\left[g_{ps}P\right] \ \leq \ kBT_L \tag{3.17}$$

The optimal power, P^*, is obtained using the Lagrangian method, given by

$$P^* = \left(\frac{1}{\lambda g_{ps}} - \frac{1}{g_{ss}}\right)^+ \tag{3.18}$$

where, $(.)^+ = \max(0,.)$ and λ is the Lagrange multiplier, found by solving the constraint with equality as

$$\mathrm{E}\left[\left(\frac{1}{\lambda} - \frac{g_{ps}}{g_{ss}}\right)^+\right] = kBT_L \tag{3.19}$$

Since g_{ss} and g_{ps} are independent and identically distributed, then $\frac{g_{ss}}{g_{ps}}$ and $\frac{g_{ps}}{g_{ss}}$ have the same pdf. Let $\frac{1}{\lambda} = \ \gamma$ so that equation (3.19) is now written as

$$\int_0^{\gamma} (\gamma - x)\frac{1}{(1 + x)^2}dx = \gamma - \log(1 + \gamma) = kBT_L \tag{3.20}$$

Thus,

$$\gamma - \log(1+\gamma) = \psi \tag{3.21}$$

Putting equation (3.18) into equation (3.16) using analytical method gives

$$C = 1.44 \int_{\frac{1}{\gamma}}^{\infty} (\gamma x) \frac{1}{(1+x)^2} dx \tag{3.22}$$

Thus,

$$C = 1.44 \log(1+\gamma(\psi)) \qquad \text{Bpcu} \tag{3.23}$$

where, $\gamma(\psi)$ is the solution to equations (3.21) for a given ψ.

Equations (3.15) and (3.23) give the interference-free capacity under maximum and average interference temperature limits which would be used to gauge the performance of the proposed interference mitigation technique.

For the three SUs to underlay there transmission, a simple technique for mitigating the interference is to have transmitters take turns using the channel usually termed as time-division. If the channel access time is partitioned equally between transmitters, the capacity per user, C_{su} would be given by

$$C_{su} = \frac{1}{3} \mathrm{E}[\log(1 + g_{ss}P^{*})] \tag{3.24}$$

Thus, putting equations (3.15) and (3.23) in equation (3.24) gives the corresponding capacity per user under maximum and average interference temperature limits as

$$C_{su\_max} = \frac{1.44}{3} \frac{\psi \log \psi}{\psi - 1} \qquad \text{Bpcu} \tag{3.25}$$

$$C_{su\_av} = \frac{1.44}{3}\log(1+\gamma(\psi)) \qquad \text{Bpcu} \tag{3.26}$$

3.4 ERGODIC INTERFERENCE ALIGNMENT UNDER IT CONSTRAINTS

For a time varying interference channel, the achievable capacity per user, C_{su_EIA}, using ergodic interference alignment is given by (Nazer *et al.*, 2012)

$$C_{su\_EIA} = \frac{1}{2}E[\log(1+2|h_{kk}|^2 P)] \tag{3.27}$$

where, P is the transmit power of the user.

The sum capacity achieved for fully connected 3 underlay CR users under the IT constraints is formulated as follows.

3.4.1 Ergodic IA under Maximum IT Limits

The sum capacity, C_{Σ}^{EIA}, achieved for a fully connected 3-users is solution to the following optimization problem.

$$C_{\Sigma}^{EIA} = \max_{P\geq 0}\frac{3}{2}\mathrm{E}[\log(1+2g_{ss}P)] \tag{3.28}$$

Subject to

$$\sum_{k=1}^{3} g_{pk}\,P \;\leq\; kBT_L \tag{3.29}$$

The optimal power, P^*, is just given by

$$P^* = \frac{kBT_L}{\sum_{k=1}^{3} g_{pk}} \tag{3.30}$$

Putting equation (3.30) into equation (3.28) gives

$$C_{\Sigma}^{EIA} = \max_{P \geq 0} \frac{3}{2} \mathrm{E}\left[\log\left(1 + 2\frac{g_{ss}}{\sum_{k=1}^{3} g_{pk}}\psi\right)\right] \tag{3.31}$$

Let the ratio of the random variables $\frac{g_{ss}}{\sum_{k=1}^{3} g_{pk}}$ be another random variable, Y, with pdf given by (See Appendix 2)

$$f_Y(y) = \frac{3}{(1+y)^4} \tag{3.32}$$

Putting equation (3.32) into equation (3.31) gives

$$C_{\Sigma}^{EIA} = 1.44 \times \frac{9}{2}\int_{0}^{\infty} \frac{\log(1+2\psi y)}{(1+y)^4} dy \tag{3.33}$$

Thus,

$$C_{\Sigma}^{EIA} = 1.44 \times \frac{24\psi^3 \log 2\psi - 36\psi^3 + 24\psi^2 - 3\psi}{2(2\psi - 1)^3} \qquad \text{Bpcu} \tag{3.34}$$

3.4.2 Ergodic IA under Average IT Constraint

The sum capacity, C_{Σ}^{EIA}, achieved is solution to the following optimization problem.

$$C_{\Sigma}^{EIA} = \max_{P_{su} \geq 0} \frac{3}{2} \mathrm{E}[\log(1 + 2g_{ss}P)] \tag{3.35}$$

Subject to

$$\mathrm{E}\left[\sum_{k=1}^{3} g_{pk}\, P\right] \leq kBT_L \tag{3.36}$$

The optimal power, P^*, is obtain using Lagrange method as

$$P^* = \left(\frac{1}{\lambda \sum_{k=1}^{3} g_{pk}} - \frac{1}{2g_{ss}}\right)^+ \tag{3.37}$$

The Lagrange multiplier, λ, is found by solving the constraint with equality as

$$\mathrm{E}\left[\left(\frac{1}{\lambda} - \frac{\sum_{k=1}^{3} g_{pk}}{2g_{ss}}\right)^+\right] = kBT_L \tag{3.38}$$

Let the ratio of the random variables, $\frac{\sum_{k=1}^{3} g_{pk}}{g_{ss}}$, be another random variable, Z, with pdf given by (See Appendix 3)

$$f_Z(z) = \frac{3z^2}{(1+z)^4} \tag{3.39}$$

Let $\frac{1}{\lambda} = \gamma$ so that equaion (3.36) will be written as

$$\int_0^{\gamma} (\gamma - z)\frac{3z^2}{(1+z)^4}dz = \frac{4\gamma^4 - 18\gamma^2 - 27\gamma - 11}{4(1+\gamma)^3} - \frac{3}{2}\log(1+\gamma) = kBT_L \tag{3.40}$$

Thus,

$$\frac{4\gamma^4 - 18\gamma^2 - 27\gamma - 11}{4(1+\gamma)^3} - \frac{3}{2}\log(1+\gamma) = \psi \tag{3.41}$$

Now, putting equation (3.32) into equation (3.35) gives

$$C_{\Sigma}^{EIA} = 1.44 \times \frac{9}{2}\int_{\frac{1}{\gamma}}^{\infty} \frac{\log(2\gamma)}{(1+y)^4}dy \tag{3.42}$$

Hence, the sum capacity, C_{Σ}^{EIA}, in bpcu is obtained as

$$C_{\Sigma}^{EIA} = 1.44\left[\frac{3}{2}\log(1+\gamma(\psi)) - \frac{3\gamma(\psi)(2+3\gamma(\psi))}{4(1+\gamma(\psi))^2} + \frac{3\gamma(\psi)^3\log 2}{2(1+\gamma(\psi))^3}\right] \tag{3.43}$$

where, $\gamma(\psi)$ is the solution to (3.41) for a given ψ.

3.5 UTILIZING THE EXPECTED DELAY OF ERGODIC ALIGNMENT

A major drawback of ergodic alignment scheme is a very long delay incurred to attain half the interference-free rate. This limits the scheme to applications where high rates are far more valuable than low delays. Thus, the spectral efficiency of the ergodic alignment becomes very low due to the long delay time during which the users have to stay quite waiting for the realization of the complimentary channel matrix. To better the spectral efficiency of the proposed ergodic IA under IT constraints, the waiting time (expected delay) can be exploited by the SUs for sending delay-sensitive messages. The spectral efficiency gain is obtained as follows.

Let τ be the expected delay time slots between the two transmissions to achieve ergodic alignment. If the SUs utilize the expected delay time slots in a time-division scheme, the spectral efficiency is given by

$$\eta_{EIA} = 2 \times \frac{3}{2}\mathrm{E}[\log(1 + 2g_{ss}P^{*})] + \tau \times \mathrm{E}[\log(1 + g_{ss}P^{*})] \quad \text{bps/Hz} \tag{3.44}$$

For a full time-division SUs, the spectral efficiency, η is

$$\eta = (2 + \tau)\mathrm{E}[\log(1 + g_{ss}P^{*})] \quad \text{bps/Hz} \tag{3.45}$$

Subtracting equation (3.45) from equation (3.44), the gain in spectral efficiency, $\eta^{'}$, is obtained as

$$\eta^{'} = 3\mathrm{E}[\log(1 + 2g_{ss}P^{*})] - 2\mathrm{E}[\log(1 + g_{ss}P^{*})] \quad \text{bps/Hz} \tag{3.46}$$

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

In this section, the achievable capacity of the Secondary Users (SUs) under the interference temperature (IT) model is presented. The goal is to investigate the total sum capacity achieved by the underlay network in order to establish a benchmark for gauging the performance of the proposed Interference Alignment (IA) technique under the IT model.

4.2 CAPACITY UNDER INTERFERENCE TEMPERATURE LIMIT

In Fig. 4.1, the capacity per user under maximum IT limit is plotted in bits per channel use as a function of the SNR using equation (3.25) as in Appendix 4. Similarly, Fig. 4.2, shows the capacity per user under average IT limit plotted in bits per channel use as a function of the SNR using equation (3.26) as in Appendix 5. An equal time sharing scheme is adopted among the SUs in order to avoid mutual interference. A Rayleigh fading channel is considered in the simulation. For all values of SNR, a non-varying AWGN channel capacity is also plotted on the graph for the purpose of comparison. Due to the fading nature of the channel coefficients, the capacity of a Rayleigh fading channel is greater than that of the pure AWGN channel for all values of the average SNR under the same IT limit (Sboui *et al.*,2013). This statement holds only at low SNR levels as indicated in Fig. 4.1 and 4.2.

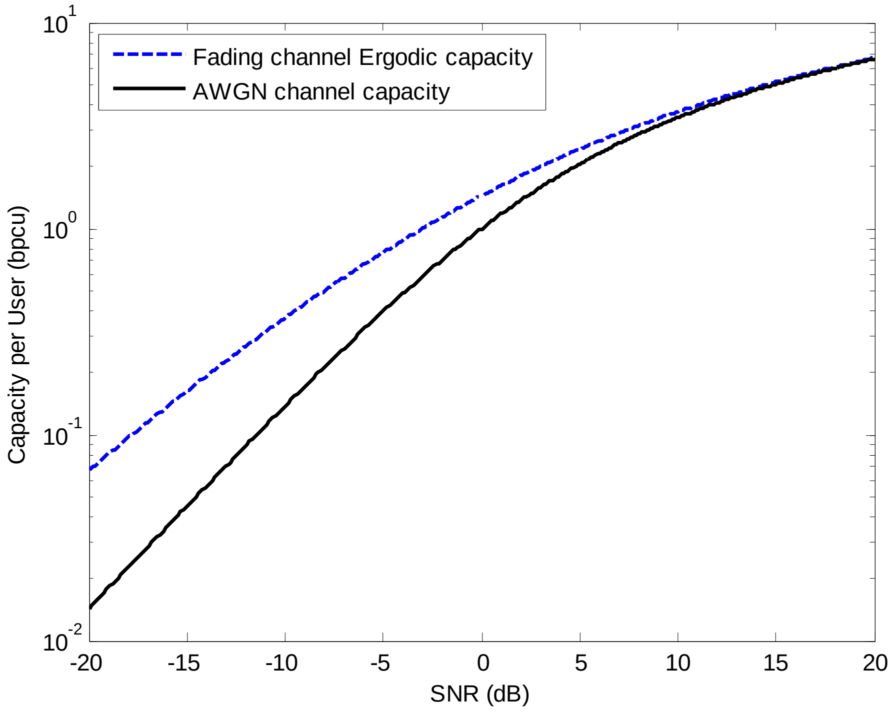

Fig. 4.1: Capacity per User through Time Division User under Maximum IT Limit

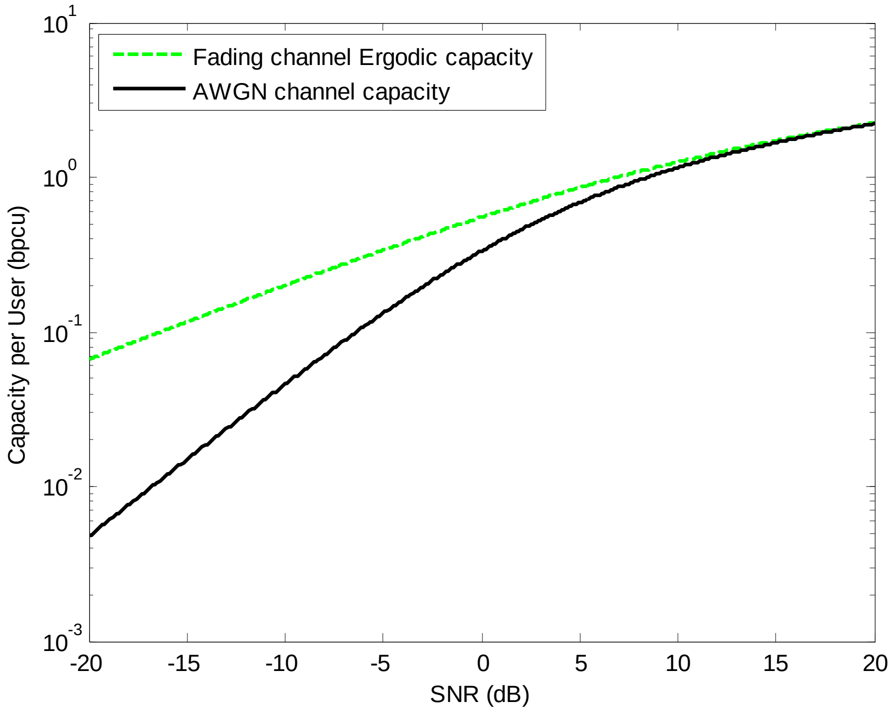

Fig. 4.2: Capacity per User through Time Division under Average IT Limit

Comparison of the sum capacities of the SUs under maximum IT limit and average IT limit for the same SNR in done in Fig. 4.3. The plots were obtained using equations (3.15) and (3.23) as in Appendix 6. The capacities in the former case are generally lower than those of the latter which results due to the more restrictive nature of the maximum (as opposed to the average) IT constraint.

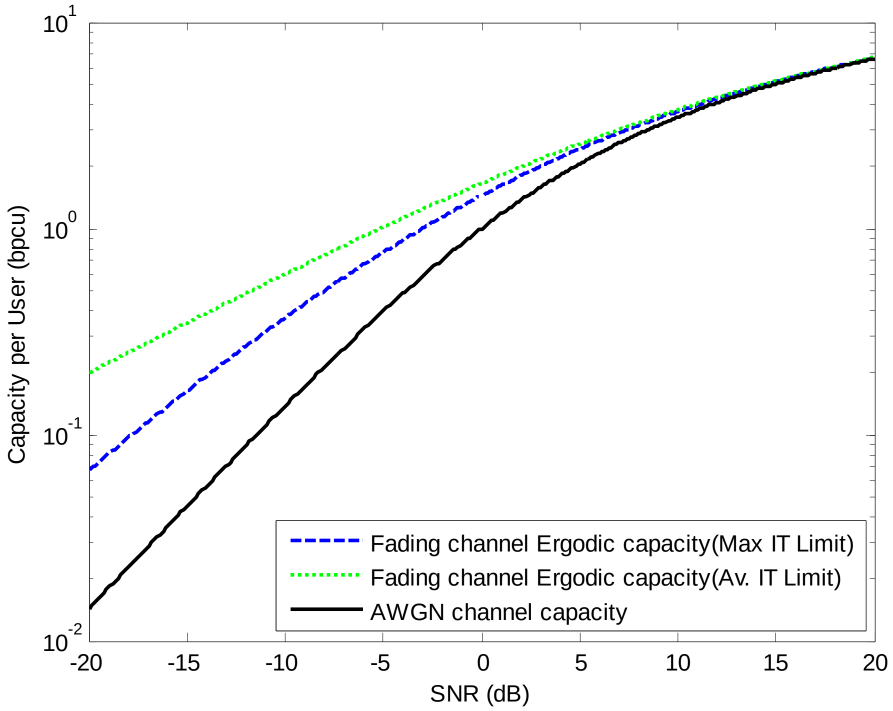

Fig. 4.3: Sum Capacity through Time Division

4.3 ACHIEVABLE SUM CAPACITY THROUGH ERGODIC IA UNDER IT LIMITS

Fig. 4.4 and Fig. 4.5 show the sum capacity achieved through ergodic IA under maximum and average interference temperature limits using equations (3.34) and (3.43) as in Appendix 7 and 8. For all values of SNR under average IT limit, the achievable sum capacity through ergodic IA is higher than that obtained through time-division. But in the case of Max. IT limit below 6.2dB, the capacity achieved through ergodic IA is below that of time-vision. This due to the more restrictive nature of the maximum (as opposed to the average) IT constraint.

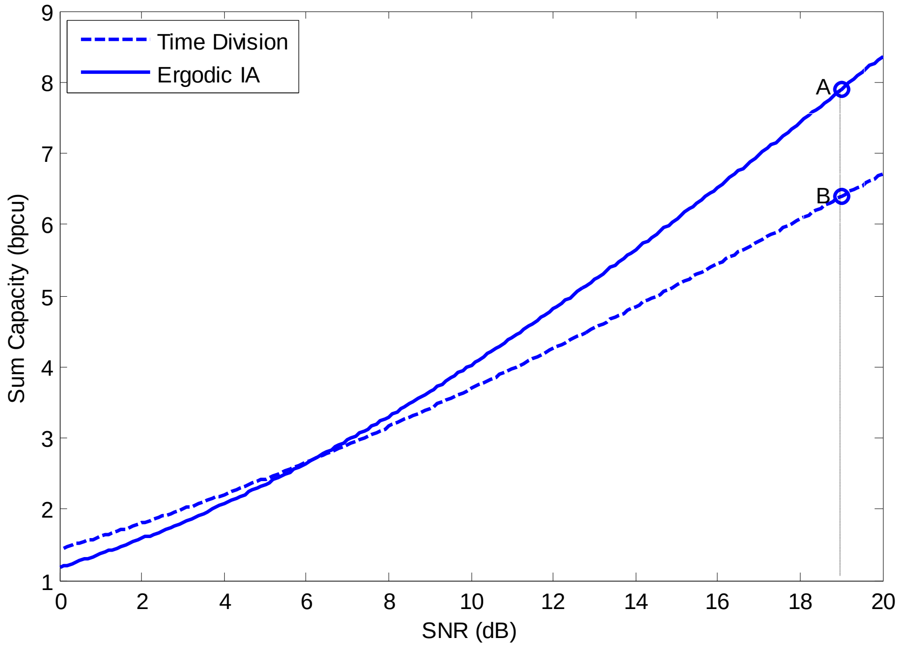

Fig. 4.4: Sum Capacity under Maximum IT Limits

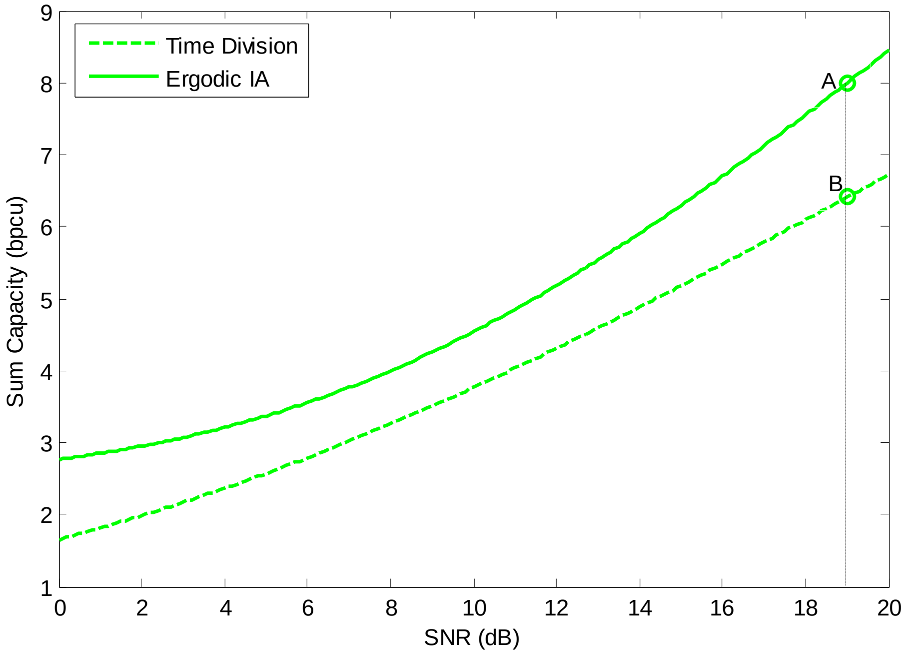

Fig. 4.5: Sum Capacity under Average IT Limits

The typical values of SNR of UWB (an underlay communication) applications are around 19 dB. Thus, the performance of the developed model is evaluated at 19 dB under maximum and average IT limits as follows:

Maximum IT Limit

The sum capacities achieved through the developed ergodic IA under IT limits and the time division scheme are given by the coordinates A(19 dB, 7.8968 bpcu) and B(19 dB, 6.3921 bpcu) respectively in Fig. 4.4.

The capacity gain $= 7.8968 - 6.3921 = 1.5047$ bpcu

The capacity gain $= \frac{1.5047}{6.3921} \times 100\ \% = 23.54\ \%$

Average IT Limit

The sum capacities achieved through the developed ergodic IA under IT limits and the time division scheme are given by the coordinates A(19 dB, 7.9943 bpcu) and B(19 dB, 6.4073 bpcu) respectively in Fig. 4.5.

The capacity gain $= 7.9943 - 6.4073 = 1.5870$ bpcu

The capacity gain $= \frac{1.5870}{6.4073} \times 100\ \% = 24.77\ \%$

Comparison of the achievable capacity under IT constraints with that of the time-division scheme is done in Fig. 4.6. It also gives an upper bound to the capacity which corresponds to capacity achievable by non-interfering cognitive users.

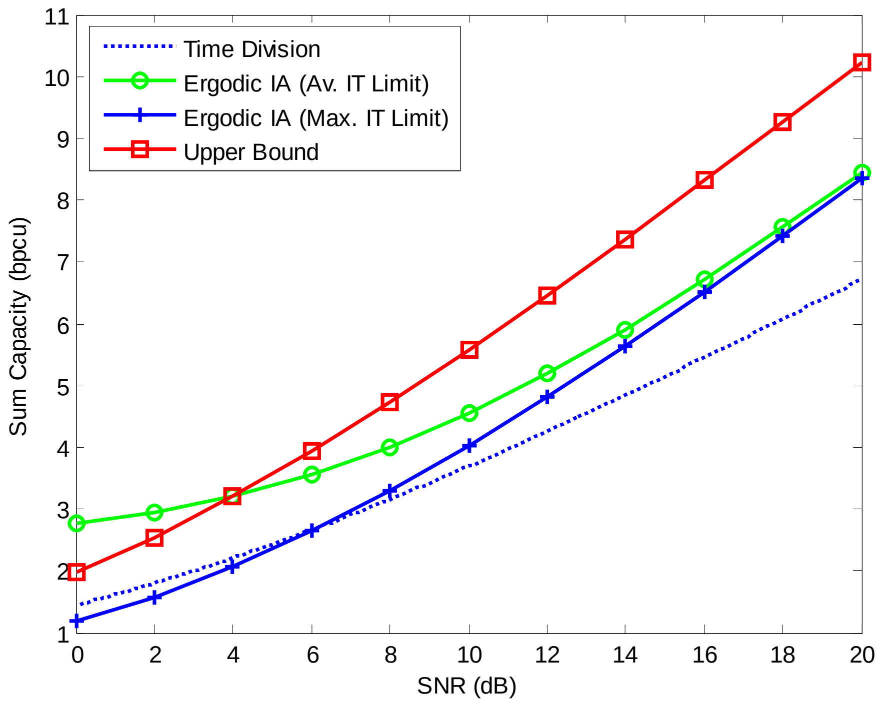

Fig. 4.6: Sum Capacity Comparison

4.4 SPECTRAL EFICIENCY GAIN

Spectral efficiency gain was achieved through exploiting the long delay necessary for the ergodic alignment. By utilizing the waiting time slot to send delay sensitive bits in time-division scheme, 3.0094 bps/Hz and 3.1741 bps/Hz gains in spectral efficiency was achieved under maximum and average IT limits over a full time-division scheme at SNR of 19dB. These gains were evaluated using equation (3.46).

4.5 VALIDATION

Validation is carried out in order to compare the performance of the developed model with time division scheme. The parameters considered are the achievable sum capacity and spectral efficiency. Table 4.1 shows the comparison.

Table 4.1: Performance Evaluation of the Developed Ergodic IA under IT Limits

Parameter	**Maximum IT limit**		**Average IT limit**	
	Generic TDMA	**Ergodic IA**	**Generic TDMA**	**Ergodic IA**
Sum Capacity (bpcu)	6.3921	7.8968	6.4073	7.9943
Spectral Efficiency (bps/Hz)	η	$\eta + 3.0094$	η	η +3.1741

Where η is the spectral efficiency for a full time-division SUs which is a function of the expected delay time, τ, before the realization of the complementary channel coefficient.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 SUMMARY

This research work has proposed to mitigate the mutual interference among multiple Secondary Users (SUs) in underlay cognitive radio network aimed at enhancing the sum capacity the SU. Ergodic Interference Alignment (IA) was applied under Interference Temperature (IT) constraints and the achievable sum capacity derived. This chapter summarises the whole dissertation. Conclusion, significant contributions, and limitations encountered during the course of this research are presented. Recommendations for further research are also suggested.

5.2 CONCLUSIONS

Cognitive Radio (CR) communication is considered a promising solution in order to address the spectrum shortage problem. Out of three main CR paradigms considered in the literature, this work has focussed on underlay approach. In the underlay CR, an US is allowed to share common spectrum with a PU provided the received interference level at the PU is below the interference temperature (IT) limit. This constraint on the transmit power of the SUs would continue to lower the sum capacity the cognitive channel as the number of SUs increases. Interference alignment is a novel transmission approach with which the sum-capacity of the time-varying interference networks increases linearly with the number of users. Ergodic interference alignment scheme under the IT constraints is developed for mitigating the mutual interference among the SUs. To provide a benchmark to gauge the performance of the developed model, the sum capacity through time-division scheme is first obtained. A closed form expression for the sum capacity of three-user underlay cognitive channel is derived. The ergodic IA has a major drawback of a very long delay in order to achieve half the interference-free rate. Thus, the spectral efficiency of the ergodic alignment would be low. The waiting time (expected delay) is exploited thereby improving the spectral efficiency.

5.3 LIMITATIONS

The limitations of this research work are as follows:

i. The work only considered equal transmit power allocation among the SUs.
ii. A Rayleigh fading environment is assumed to demonstrate the performance of the developed model. The effects of other fading distributions were not considered.
iii. Perfect knowledge of Channel State Information (CSI) was assumed to be available at both the transmitters and receivers.
iv. The developed model applies only to cognitive underlay network with three SUs.

5.4 RECOMMENDATIONS

The following are possible areas recommended for further work:

i. The effect of dynamic power allocation among the SUs can be investigated to further improve the achievable sum capacity.
ii. More generalized fading distributions such as Nakagami-m and α- μ distributions can be considered so that the model can be adapted to suit different environment.
iii. There is need to investigate the impact of noisy or imperfect CSI on the developed model.
iv. The work could be extended to show the effect of increasing number of SUs on the achievable capacity.

5.5 SIGNIFICANT CONTRIBUTIONS

A lot of research works has been done on interference mitigation in cognitive radio network. Many works have also been conducted on capacity analysis of underlay cognitive radio paradigm. Again, there have being significant progressive works on demonstrating the applicability of interference alignment on wireless communications. The significant contributions of this research work are as follows:

i. Deriving a closed form expression for sum capacity of three underlay cognitive users through ergodic IA under IT constraints.
ii. Applying the ergodic IA with IT constraints enhances the sum capacity of the SUs thereby achieving 23.54% and 24.77% gain in sum capacity under maximum and average IT limits respectively. This gain is with respect to time-division scheme at signal-to-noise-ratio of 19dB.
iii. By utilizing the long delay time associated with ergodic IA to send more bits in time-division scheme, 3.0094 bps/Hz and 3.1741 bps/Hz gains in spectral efficiency was achieved under maximum and average IT limits over a full time-division scheme at SNR of 19dB.

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APPENDIX 1

Pdf of the Ratio of the Random Variables $\frac{g_{ss}}{g_{ps}}$

Since the channel fading follows the Rayleigh pdf, both g_{ss} and g_{ps} would be exponentially distributed with unit mean. Thus,

$$f_{g_{ss}}(x) = f_{g_{ps}}(x) = e^{-x}$$

Let g_{ss} = X , g_{ps} = Y and $\frac{g_{ss}}{g_{ps}}$ =Z. Thus,

$$f_X(x) = e^{-x}$$

$$f_Y(y) = e^{-y}$$

The CDF, $F_Z(z)$, is first obtained as

$$F_Z(z) = P\left(\frac{X}{Y} \leq Z\right) = P(X \leq YZ)$$

$$= \int\int f_X(x)\, f_Y(y)dxdy$$

$$F_Z(z) = \int_0^{\infty}\int_0^{yz} e^{-x}\, e^{-y}dxdy = \frac{z}{1+z}$$

Now the pdf $f_Z(z)$is found as

$$f_Z(z) = \frac{dF_Z}{dz} = \frac{1}{(1+z)^2}$$

Thus,

$$f_{\frac{g_{ss}}{g_{ps}}}(x) = \frac{1}{(1+x)^2}$$

APPENDIX 2

Pdf of the Ratio of the Random Variables $\frac{g_{ss}}{\sum_{k=1}^{3} g_{pk}}$

Let $g_{ss} =$ X so that $f_X(x) = e^{-x}$, $g_{p1} + g_{p1} + g_{p3} = Y$ and $\frac{g_{ss}}{\sum_{k=1}^{3} g_{pk}} = Z$

$f_Y(y)$ is found using the following theorem.

Suppose Y_1, Y_2, ..., Y_n be independent exponential random variables all having the same parameter λ. Then, the density of their sum $S_n = Y_1 + Y_2 + \ldots + Y_n$ is given by

$$f_{S_n}(x) = \begin{cases} \dfrac{(\lambda x)^{n-1} \lambda e^{-\lambda x}}{(n-1)!} & if\ x \geq 0 \\ 0 & otherwise \end{cases}$$

Putting n = 3 and λ = 1 gives

$$f_Y(y) = \frac{y^2}{2} e^{-y}$$

Now,

$$F_Z(z) = \int_0^{\infty} \int_0^{yz} e^{-x} \frac{y^2}{2} e^{-y} dx dy = 1 - \frac{1}{(1+z)^3}$$

The pdf $f_Z(z)$is found as

$$f_Z(z) = \frac{dF_Z}{dz} = \frac{3}{(1+z)^4}$$

Thus,

$$f_Y(y) = \frac{3}{(1+y)^4}$$

APPENDIX 3

Pdf of the Ratio of the Random Variables $\frac{\sum_{k=1}^{3} g_{pk}}{g_{ss}}$

Let $\sum_{k=1}^{3} g_{pk} = \mathrm{X}$, $g_{ss} = Y$ and $\frac{\sum_{k=1}^{3} g_{pk}}{g_{ss}} = Z$, so that $Z = \frac{X}{Y}$

Now,

$$f_X(x) = \frac{x^2}{2} e^{-x}$$

and

$$f_Y(y) = e^{-y}$$

The CDF of Z is given by

$$F_Z(z) = \int_0^{\infty} \int_0^{yz} \frac{x^2}{2} e^{-x}\, e^{-y} dx dy = 1 - \frac{3z^2 + 3z + 1}{(1+z)^3}$$

The pdf $f_Z(z)$is found as

$$f_Z(z) = \frac{dF_Z}{dz} = \frac{3z^2}{(1+z)^4}$$

APPENDIX 4

M-file for Plotting the Graph of Capacity per User through Time Division User under Max. IT Limit

```
clc
clear all
close all
snr_dB = -20:0.1:20;
snr_su = 10.^(snr_dB/10);

%Calculation of Capacities
C = (snr_su.*log2(snr_su))./(snr_su - 1);
C_awgn = log2(1 + snr_su );

semilogy(snr_dB, C, 'b--', 'LineWidth', 2); hold on
semilogy(snr_dB,C_awgn, 'k', 'LineWidth', 2); hold on %grid on;
legend('Fading channel Ergodic capacity','AWGN channel capacity');
%title('Capacity under Max IT Limit');
xlabel('SNR (dB)'); ylabel('Capacity per User (bpcu)');
```

APPENDIX 5

M-file for Plotting the Graph of Capacity per User through Time Division under Av. IT Limit

```
clc
clear all
close all

snr_dB = -20:0.1:20;
snr_su = 10.^(snr_dB/10);

% Calculation of capacities
for i = 1:length(snr_su)
  alpha = snr_su(i);
  f = @(gam)(gam - log(1 + gam) - alpha);
  gam=fzero(f,sqrt(100*alpha));
  C(i)=(1/3)*(log2(1 + gam));
end
C_awgn = (1/3)*log2(1 + snr_su );

semilogy(snr_dB, C, 'g--', 'LineWidth', 2); hold on
semilogy(snr_dB, C_awgn, 'k', 'LineWidth', 2); %grid on;
legend('Fading channel Ergodic capacity','AWGN channel capacity');
%title('Capacity under Max IT Limit');
xlabel('SNR (dB)'); ylabel('Capacity per User (bpcu)');
```

APPENDIX 6

M-file for Plotting the Graph of Sum Capacity through Time Division

```
clc
clear all
close all

snr_dB = -20:0.1:20;
snr_su = 10.^(snr_dB/10);

% Calculation of capacities

% 1. Fading channel Ergodic capacity(Max IT Limit
C1 = (snr_su.*log2(snr_su))./(snr_su - 1);

% 2. Fading channel Ergodic capacity(Av. IT Limit
for i = 1:length(snr_su)
  alpha = snr_su(i);
  f = @(gam)(gam - log(1 + gam) - alpha);
  gam = fzero(f,sqrt(100*alpha));
  C2(i)= (log2(1 + gam));
end

% 3. AWGN channel capacity
C_awgn = log2(1 + snr_su );

semilogy(snr_dB, C1, 'b--', 'LineWidth', 2); hold on
semilogy(snr_dB, C2, 'g:', 'LineWidth', 2); hold on
semilogy(snr_dB, C_awgn, 'k', 'LineWidth', 2); %grid on;
legend('Fading channel Ergodic capacity(Max IT Limit)', ...
    'Fading channel Ergodic capacity(Av. IT Limit)', ...
    'AWGN channel capacity');
%title('Capacity under Max IT Limit');
xlabel('SNR (dB)'); ylabel('Capacity per User (bpcu)');
```

APPENDIX 7

M-file for Plotting the Graph of Sum Capacity under Max. IT Limits

```
clc
clc
clear all
close all

snr_dB = 0:0.1:20;
snr_su = 10.^(snr_dB/10);

%Calculation of Capacities

% 1. Time sharing under Max IT
C1 = (snr_su.*log2(snr_su))./(snr_su - 1);

% 2. EIA under Max IT
C2 = (1/log(2))*(24*snr_su.^3.*log(2*snr_su) - 36*snr_su.^3 ...
    + 24*snr_su.^2 - 3*snr_su)./(2*(2*snr_su - 1).^3);

plot(snr_dB, C1, 'b--', 'LineWidth', 2); hold on
plot(snr_dB,C2, 'b', 'LineWidth', 2); %grid on;
legend('Time Division', 'Ergodic IA');
%title('Capacity under Max IT Limit');
xlabel('SNR (dB)'); ylabel('Sum Capacity (bpcu)');
```

APPENDIX 8

M-file for Plotting the Graph of Sum Capacity under Av. IT Limits

```
clc
clear all
close all
snr_dB = 0:0.1:20;
snr_su = 10.^(snr_dB/10);

% Calculation of capacities

% 1. Time sharing
for i = 1:length(snr_su)
  alpha1 = snr_su(i);
  f1 = @(gam1)(gam1 - log(1 + gam1) - alpha1);
  gam1 = fzero(f1,sqrt(100*alpha1));
  C1(i) = (log2(1 + gam1));
end

% 2. Ergodic IA
for i = 1:length(snr_su)
  alpha2 = snr_su(i);
  f2 = @(gam2)((4*gam2^4 - 18*gam2^2 - 27*gam2 -11)/(4*(gam2 + 1)^3)...
      - 1.5*log(gam2 + 1) - alpha2);
  gam2 = fzero(f2, (alpha2 + 5));
  C2(i) = (1/log(2))*(1.5*log(1 + gam2)...
      - 0.75*gam2*(3*gam2 + 2)/(1 + gam2)^2 ...
  + 1.5*gam2^3*log(2)/(1 + gam2)^3);
end

plot(snr_dB, C1, 'g--', 'LineWidth', 2); hold on
plot(snr_dB, C2, 'g', 'LineWidth', 2); hold on %grid on;
legend('Time Division','Ergodic IA');
%title('Capacity under Max IT Limit');
xlabel('SNR (dB)'); ylabel('Sum Capacity (bpcu)');
```

APPENDIX 9

M-file for Plotting the Graph of Sum Capacity

```
clc
clear all
close all

snr_dB = 0:0.1:20;
snr_su = 10.^(snr_dB/10);

% Calculation of capacities

% 1. Time sharing
C1 = (snr_su.*log2(snr_su))./(snr_su - 1);

% for i = 1:length(snr_su)
%   alpha1 = snr_su(i);
%   f1 = @(gam1)(gam1 - log(1 + gam1) - alpha1);
%   gam1 = fzero(f1,sqrt(100*alpha1));
%   C1(i) = (log2(1 + gam1));
% end

% 2. Ergodic IA (Av. IT limits)
for i = 1:length(snr_su)
  alpha2 = snr_su(i);
  f2 = @(gam2)((4*gam2^4 - 18*gam2^2 ...
      - 27*gam2 -11)/(4*(gam2 + 1)^3) - 1.5*log(gam2 + 1) - alpha2);
  gam2 = fzero(f2, (alpha2 + 5));
  C2(i) = (1/log(2))*(1.5*log(1 + gam2) ...
      - 0.75*gam2*(3*gam2 + 2)/(1 + gam2)^2 ...
      + 1.5*gam2^3*log(2)/(1 + gam2)^3);
end

% 3. Ergodic IA (Max. IT limits)
C3 = (1/log(2))*(24*snr_su.^3.*log(2*snr_su) - 36*snr_su.^3 ...
    + 24*snr_su.^2 - 3*snr_su)./(2*(2*snr_su - 1).^3);

% 4. Upper bound
h = (randn(1,100)+1i*randn(1,100))/sqrt(2);
sigma_z = 1;
p = (sigma_z^2)*snr_su./(mean(abs(h).^2));
% C_erg_awgn = (log2(1+mean(abs(h).^2).*p/(sigma_z^2)));
C4 = (3/2)*mean((log2(1+2*((abs(h).^2).')*p/(sigma_z^2))));

plot(snr_dB, C1, 'b:', 'LineWidth', 2); hold on
plot(snr_dB, C2, 'g', 'LineWidth', 2); hold on
plot(snr_dB, C3, 'b', 'LineWidth', 2); hold on
plot(snr_dB, C4, 'r', 'LineWidth', 2);
legend('Time Division','Ergodic IA (Av. IT Limit)', ...
    'Ergodic IA (Max. IT Limit)', 'Upper Bound');
xlabel('SNR (dB)');
ylabel('Sum Capacity (bpcu)');
```