OPTIMAL POWER ALLOCATION TO COGNITIVE USER UNDER JOINT POWER CONSTRAINTS WITH IMPERFECT CHANNEL STATE INFORMATION

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CERTIFICATE

This is to certify that the work entitled, “**Optimal Power Allocation to Cognitive User under Joint Power Constraints with Imperfect Channel State Information**” submitted by **Bindu Bharti** in partial fulfillment for the award of degree of **Master of Technology in Electronics and Communication Engineering, Jaypee University of Information Technology, Solan**, has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree or diploma.

Date

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ABSTRACT

In this dissertation, the optimal power allocation technique for a novel cognitive radio network under the joint power constraints has been explored. The performance metrics of cognitive radio network such as ergodic capacity and outage capacity over the fading channel with imperfect channel state information has been presented. In addition to this, the power consumption of cognitive transmitter has also been analyzed under the peak interference power constraint and joint peak transmit and peak/average interference power constraint has been illustrated. It has been discussed that the power consumption under the joint power constraints is less at the cost of reduction of capacity of the cognitive link. Furthermore, the dynamic spectrum accessing techniques — overlay, underlay and hybrid spectrum sharing approaches are exploited for the military communication and also the importance of the energy efficiency of the military cognitive radio network system is also explored. Moreover, we have also emphasized over the security threads and their mitigation. However, it is explored that the cross layer design of protocols is preferred for more energy efficiency and security.

LIST OF PUBLICATIONS

1. Bindu Bharti and G. Singh, “Analysis of Outage Capacity of Cognitive Radio Network with Imperfect Channel State Information”, IEEE Int. Conf. on Signal Processing and Communication, Noida, India, March 16-18, 2015.
2. Bindu Bharti and G. Singh, “Analysis of capacity limits over fading environment with partial channel state information for cognitive radio network”, Annals of Telecommunications, (Under review), April 2015.
3. Bindu Bharti and G. Singh, “Framework for Spectrum Sharing in Cognitive Radio Network for Military Applications”, IEEE Communication Magazine, (Under Review), April 2015.

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CHAPTER 1

INTRODUCTION

Wireless communication technologies are emerging at a rapid rate. Today, researchers/scientists mainly focus on the fifth generation technologies and new accessing techniques. There are some challenges of 5G networks such as high data rates, low latency, ubiquitous environment and multi radio accessing technologies. Therefore, to achieve high data rates and low latency, there is requirement of large bandwidth. But, there is a problem of spectrum scarcity. However, wireless communication is established on the spectrum from 3Hz -300 GHz but due to fixed spectrum allocation strategy there is problem of spectrum scarcity. The survey of Federal Communication Commission (FCC) has reported that the most of the licensed spectrum are underutilized [1]. Therefore, FCC/ spectrum allocation authority has opened the licensed bands to unlicensed users so that spectrum can be utilized in efficient way. Moreover, 5G demand for intelligent device which support ubiquitous environment, high data rates and overcome spectrum scarcity problem. In 2000, Mitolla has proposed a reconfigurable device which supports multiple technologies named as software defined radio (SDR) [2]. The limitation of this device is that it is not an intelligent device. Therefore, a new communication system is proposed named as *Cognitive Radio* is an "radio or system that sense its electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets" [2]. The cognitive radio (CR) system not only improves the spectral efficiency but also provide highly reliable and efficient wireless communication. Cognitive radio architecture depends on the three layers of the open system interconnection model (OSI) such as physical layer, MAC layer and Network layer.

1.1 Functions of the Cognitive Radio System

The main function of the cognitive radio system is *spectrum sensing, spectrum analysis, spectrum access and spectrum mobility.* In spectrum sensing, CR has to sense the spectrum status and the activities of primary users periodically. Moreover, spectrum sensing may be centralized or distributed. In centralized spectrum sensing, there is fusion center in the network, all the nodes in the CR network sense the status of spectrum individually and then transmit their sensed information to the fusion center. On the other hand, in distributed spectrum sensing all nodes sense the information and exchange the sensed information within their self and then take the decision. There are different spectrum sensing techniques which are broadly categorized as non-cooperative spectrum sensing, cooperative spectrum sensing and interference based detection as shown in Fig.1 [3]. The next step after spectrum sensing is spectrum analysis, the sensed information is analyzed to get the information about the spectrum holes then the decision is taken by optimizing the system performance metrics. The third step of CR system is spectrum access, after taking the decision on the spectrum holes now unlicensed user accesses the spectrum holes. In order to avoid the collision between the licensed and unlicensed user, the accessing of spectrum should be based on the MAC protocols. Final function of the CR system is spectrum mobility, it emphasize on the handoff of the operating frequency of CR system. The detail description of spectrum sensing, spectrum mobility and spectrum analysis technique is far from our discussion. In this dissertation, our main focus is on the spectrum sharing/ accessing techniques. The spectrum sharing techniques are broadly categorized as spectrum underlay, spectrum overlay and spectrum interweave approach as shown in Fig. 1.1.

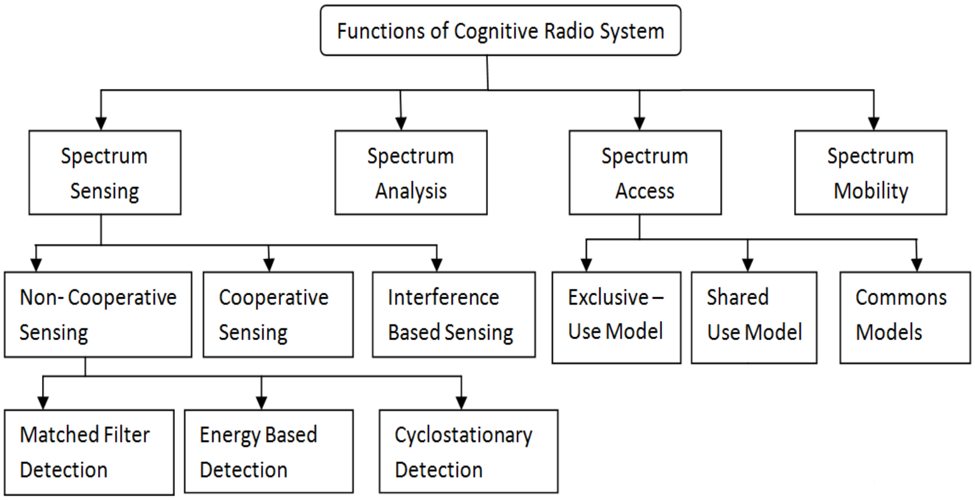


Fig 1.1 Functions of the cognitive radio system

1.1.1 Spectrum accessing techniques

It is the third step of cognitive radio system, after spectrum sensing and spectrum analysis. It is categorized as [4]:

(I) Exclusive use model: In this licensed user allocate the spectrum to the unlicensed/ cognitive user. The spectrum owner imposes some constraints and according to these constraints rules cognitive user optimizes its parameters such as power, frequency to achieve the best performance. There are two types of exclusive use model named as *long term exclusive use model and dynamic exclusive model.* In long term exclusive model, licensed user allocates the spectrum to cognitive user for certain period of time (few weeks) on the other hand in dynamic exclusive model small chunks of spectrums are allocated to cognitive user for short duration of time.

(II) Spectrum commons model: In this all cognitive users have same right to access the radio spectrum. It has three models, namely, uncontrolled, managed and private – commons sub models. In uncontrolled model there is no owner of spectrum that radio spectrum is ISM (2.4 GHz) and U-NII (5 GHz) which is being used by all cognitive user. There is no control on the transmitted power of cognitive user. In managed commons sub- model, radio spectrum is controlled jointly by a group of cognitive radios. On the other hand, in private commons sub-model, spectrum owner specify technology and protocols to the cognitive radio user. Spectrum owner give a command to cognitive user that command may contain the transmission parameters (e.g. time, frequency band and transmit power).

(III) Shared use model: In the shared use model, the licensed/primary user and unlicensed/cognitive/secondary user share the spectrum opportunistically or simultaneously. The spectrum sharing models are classified on the basis of architecture, spectrum allocation behavior, spectrum access techniques and scope as shown in Fig. 2 [4]. Moreover, the spectrum sharing techniques on the basis of the architecture of the network are classified as

(I) Centralized spectrum sharing: The spectrum allocation and access is controlled by the central entity/fusion center. The spectrum is allocated to all cognitive radios in the network via the central node which has the complete information about all the nodes in the network [5].

(II) Distributed spectrum sharing: In this spectrum allocation decision is taken by the individual node in the network. But the information about the spectrum is exchanged between the nodes in order to avoid the collision between the different cognitive nodes [6].

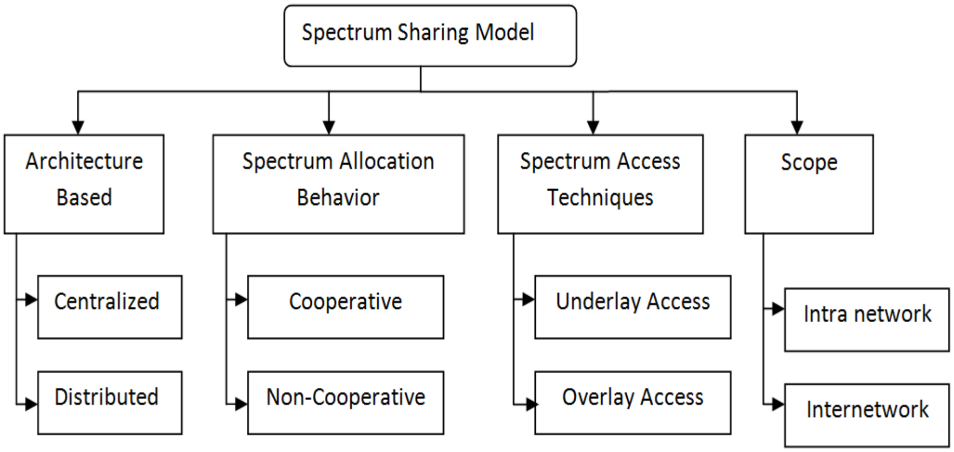


Fig 1.2 The spectrum sharing model of cognitive radio system

The spectrum sharing technique is also categorized on the basis of spectrum allocation behavior which is discussed as follows [7]:

(I) Cooperative spectrum sharing: In this the interference at the different nodes is noticed and the information of interference is exchanged between all the nodes and then decision of spectrum allocation is taken.

(II) Non-Cooperative spectrum sharing: In this interference on one node is measured and message is send to all nodes. With this spectrum sharing technique spectrum is not utilized properly.

The spectrum sharing technique is also categorized on the basis of scope which is discussed as follows:

(I) Intra network spectrum sharing: In this secondary user try to access the spectrum without causing interference to the primary user.

(II) Internetwork spectrum sharing: It is broader category of spectrum sharing which is based on certain spectrum policies.

The spectrum sharing techniques are also categorized on the basis of accessing of spectrum which is described as follows [8]:

(I) Overlay spectrum access: It is opportunistic spectrum accessing (OSA) technique, in this cognitive user is not allowed to share the spectrum until and unless it is not used by the primary user. This accessing technique can be applied in temporal or spatial domain [9]. In temporal domain, the cognitive user has to exploit the temporal opportunities to access the spectrum from the burst traffic of primary user. Spectral accessing technique in temporal domain requires joint design of spectrum sensing and spectrum accessing [10-11]. On the other hand in the spatial domain, cognitive user has to exploit the frequency band which is not used by the primary user in a particular geographical region. In overlay accessing the main focus is on the spatial domain overlay spectrum accessing because in this there is less variation in spectrum opportunity with time. The data rates achieved with spectrum overlay accessing techniques are significantly high but this spectrum accessing technique has limitations such as 1.) Cognitive user has to wait to get the hold on spectrum holes. 2.) Cognitive user has to stop the communication if the spectrum is needed by the primary user.

(II) Underlay spectrum access: According to this technique both primary and secondary user can access the spectrum at the same time at same frequency and at same location under some interference constraints. In this, the main focus is on the power control of cognitive user so that it will not interfere with the primary users. The main advantage of the spectrum underlay accessing over the spectrum overlay accessing technique is that cognitive user has not to wait for spectrum hole. The limitation of the spectrum underlay accessing is low data rates due to the limited power allocation. Therefore, optimal power allocation to cognitive user should be in such a way, which maximize the capacity and throughput of cognitive link, avoid interference to the primary user. The optimal power allocation to cognitive user is a crucial issue. There are different ways of optimal power allocation which are discussed in later section.

1.2 Optimal Power Allocation to Cognitive User

The power to cognitive user under some constraints can be allocated in such a way so that the capacity and throughput of cognitive link is maximized. The optimal power allocation in cognitive radio network is formulated by different ways as given below:

1.) Game theoretic approach
2.) Price auction
3.) Iterative water filling algorithm
4.) Convex optimization approach

(i) Game theoretic approach

Game theory has a long lasting history since 1838. Today, game theory approaches have been employed for the optimization system performance. In wireless communication network, game theory has been utilized for the resource allocation. User's interest in the game theory model is named as utility function. A game is defined as method of interaction between the players (users), where each player used their strategy to achieve the utility function while competing with others. In game theory model, strategy is a contingent plan and utility function provides every possible outcome of the game to the player [12]. As the wireless networks are emerging at a rapid rate, the optimal power allocation problem for decentralized network is came in to existence. For decentralized network game theory is a good approach to allocate power. The game theoretic models are broadly categorized as cooperative and non-cooperative game, strategic and extensive game and games with complete or incomplete information theoretic model [12]. Cooperative game theoretic models are utilized when cognitive user has perfect channel state information. As we know that practically it is difficult to gain perfect channel state information therefore, there is need of non-cooperative game theoretic models which support when cognitive user has imperfect channel state information. Some game theoretic models are *matching game model, Cournot game model, Bertrand game model, repeated game model, supermodular game model and potential game model* [13-14]. All game approaches have some pros and cons [15] therefore, according to the applications, game theoretic approach have to be chosen e.g when limited information is available to user for that scenario non-cooperative game approach is suitable. If users demands for long term QoS then repeated game approach has to be preferred. Game is a method of interaction between users where each user adjusts its strategy to optimize its utility. Many researchers have reported the optimal power allocation algorithm with game theoretic approaches [16-18]. Sharma and Teneketzis [19] have been illustrated the optimal power allocation for single CDMA based cell with interference and presence of selfish users. They have proposed the power allocation scheme which provides budget balance at nash equilibriums. In [20], optimal power allocation algorithm for distributed network with the consideration of practical limitations has been proposed. This algorithm has been provided the nearly optimum results as is provided by heuristic method. For cooperative game model constant power is allocated to the cognitive user to achieve the Pareto efficient vector of rates [21]. In [21], it has been also reported that punishment strategies significantly increase the rates in non-cooperative game model. The non-cooperative game theory model has been proposed for the joint power and rate control for the proposed model in [22]. They have analyzed, the uniqueness and Pareto efficiency of Nash equilibrium. Cooperative game theory model for optimal power allocation in cognitive radio network has been illustrated in [23]. They have been developed an alternative efficient and fair resource allocation by using Nash bargaining solutions over the cognitive radio game model.

(ii) Price auction approach

The optimal power allocation to cognitive user is also based on the price paid by the cognitive user to primary user for spectrum. The auction theory has been used in various areas of the wireless communication [24] such as auction theory for optimal power allocation [25] and for cognitive radio networking [26]. Huang [27], has been firstly introduced the approach of resource allocation on the basis of auction theory. However, cooperative transmission improves the communication system performance due to cooperation among users. In [27], the power auction algorithm has been proposed to allocate optimal power in relay cooperative network. They have reported that with proper chosen prices the power auction has achieved efficient resource allocation. In [28], power auction approach is implemented with game theory buyer /seller game theoretic model over cooperative communication network. The authors in [28], have reported that the position of relay in the network play an important role o increase source node utility. They have also discussed that to attract the source’s buyer proper prices have to be chosen by the relay user. Zou et.al [29] have been reported the power auction algorithm for the hybrid spectrum accessing technique. They have illustrated that in spectrum overlay technique the relay allocate the power to secondary user proportional to its payment without any constraints. On the other hand in the spectrum underlay approach cognitive user's own transmit power and power offered by relay is upper bounded to maintain the quality of service of the primary user. In [30], on the basis of the Nash equilibrium suboptimal, fair and efficient pricing scheme have been proposed. They have reported that the proposed pricing scheme is suboptimal in terms of the revenue maximization of the primary user and proved fair and efficient results for power allocation.

(iii) Convex optimization approach

The power allocation in cognitive radio network can be formulated as convex optimization problem under some constraints. The formulation of the optimization problem can be written as

$$\min_{\mathrm{x} \in \Omega} f(x) \tag{1.1}$$

$$s.t \begin{cases} g_i(x) \leq 0, for\ i = 1 \dots m \\ h_j(x) = 0, for\ j = 1..l \end{cases}$$

where, $f(x)$ is the objective function e.g. capacity of the cognitive link, throughput etc. and $g_i(x)$ and $h_j(x)$ are the constraints. In cognitive radio network, for optimal power allocation these constraints are mostly power constraints or interference temperature constraints. x is a parameter for the optimization and Ω is the range of the optimized parameter. There are many optimization approaches. These are broadly categorized as linear optimization and non-linear optimization problem. When the objective function and the constraints are linear then those problems are under the linear optimization approach. It is easier to optimize the linear problems via the linear programming approach. But, in wireless communication most of the problems are non- linear programming problem. It is complicated to solve the non-linear hard problem. Therefore, new approach has been proposed namely convex optimization approach. The condition for the function to be convex is given below:

$$f(\theta\, x_1 + (1-\theta)x_2) \leq \theta\, f(x_1) + (1-\theta)f(x_2) \tag{1.2}$$

where, θ is any arbitrary number and x_1 and x_2 are variables. The function is concave if $-f$ is convex. It is simplest to optimize the convex problem. If the problem is not convex, then firstly transform the problem to convex by different methods. There are various methods for the convex optimization such as Lagrangian method, Quadratic, Geometric, Semi-definite programming, Gradient and Newton method. According to the objective function and optimization complexity, various researchers have been utilized different optimization method for optimal power allocation. Shiung et.al [31], have proposed an optimal power allocation algorithm in order to maximize the sum spectral efficiency by using the Lagrangian method under the signal-to-interference power constraints. Various researchers have been reported the power allocation algorithm by using the Lagrangian dual method for different objective functions as discussed later. In [32], new strategy has been proposed to improve the energy efficiency under quality-of-service (QoS) constraints. They have illustrated that with the Lagrangian dual method rate is maximized with less complexity. Moreover, they have validated their proposed algorithm (based on Lagrangian dual method) with Monte Carlo method. As we move towards the orthogonal frequency divison multiplexing (OFDM) approach, there is problem of sub channel power allocation. Moreover, with the increase of number of sub-channels, complexity of algorithms increases at exponential rate. Therefore, Guo. etal. [33], have been proposed two sub-optimal algorithm by using Lagrangian method. Furthermore, in [34], the authors have illustrated the algorithm based on Lagrangian method to maximize the capacity of the cognitive link over Rayleigh fading channel. They have reported that with their proposed approach power is allocated effectively to multiple input multiple output (MIMO) cognitive radio system. Gradient based optimization approach is useful when there is problem to allocate power to multiple sub-channels. In [35], they have reported that greedy power loading method and gradient based method both have same complexity of order O (N). But, the gradient based method with adaptive step size has a fast rate to achieve optimal solution for power. In [36], resource allocation algorithm has been proposed for the hybrid (overlay/ underlay) spectrum accessing technique. They have analyzed that resource allocation with mixed programming algorithm is more complex, therefore, they have decompose the complex algorithm to sub-algorithms, by using

Lagrangian dual method and sub-gradient method. In [37], optimal power allocation to cognitive user in order to maximize the capacity under imperfect channel state information has been discussed by Lagrangian dual method. Since, Lagrangian method approach is best for non- linear convex problem but it does not work for non-linear non-convex problems. For those problems, happen that the problems are not convex. Therefore, to optimize such problem, firstly we have to transform the problem to parametric optimization problem then the implementation of $\in$-optimal algorithm will provide the optimal power allocation for energy efficient network [38].

(iv) Iterative water filling algorithm

The water filling algorithm is also efficient power allocation approach to maximize the capacity of the network. In general water filling algorithm is defined as the power allocation scheme in which more power is allocated to the sub channel having large SNR level in order to maximize the capacity. This water filling algorithm is exploited for orthogonal frequency division multiplexing (OFDM) based networks, where different power levels are allocated to all sub channels. Today, this algorithm can be utilized in the OFDM based cognitive radio network. But the conventional water filling algorithm cannot be used directly to the cognitive radio network because in the cognitive radio network power is allocated under some constraints. Therefore, the modification in the water filling algorithm is demanded. Qi et.al [39], have been proposed a power increment and power decrement water filling algorithm with less complexity in comparison to the traditional water filling algorithm. In [40], a water filling algorithm has been proposed when there is imperfect information between the SU-Tx and PU-Rx. The main objective in this algorithm is to allocate optimal power to all sub channels in efficient way in order to maximize the overall throughput of the cognitive user. They have reported that for the evaluation of optimal power the previous proposed water filling algorithms are based on the binary searching process. In their proposed algorithm they have eliminate this binary searching process. The water filling algorithm in the proposed algorithm executes only one time and gives the solution. Therefore, the convergence and execution rate of algorithm is increased. In [41], the robust iterative water filling algorithm is proposed for the optimal power allocation to cognitive user. They have designed the algorithm on the basis of the non- cooperative game theory model. In this power is allocated in order to increase the throughput under power constraint and interference power limits in OFDM based cognitive radio network. Forouzan and Ghorashi [42], have been proposed the efficient resource allocation algorithm for the downlink of OFDM based multi cell underlay cognitive radio network. The authors in [42] have considered the challenge that the power is allocated in such a way so that inter cell and intra cell interference must be avoided. They have reported that with the water filling algorithm higher throughput is achieved, because it loads more power to the cognitive user's band. The water filling algorithm for optimal power allocation is better to enhance the capacity of the cognitive link and this algorithm is the enhanced version of the minimum weighted leakage interference algorithm with fast convergence rate [43]. Some researchers have considered the traffic statistical parameter to formulate the power allocation problem [44] and they have reported that the modified version of the water filling algorithm under traffic statistical parameter is more efficient than the traditional water filling algorithm. The convergence rate of the water filling algorithm is fast [45]. It has been improved the performance of coexistence of multiple cognitive tactical radio network. The complete discussion over the water filling algorithm has been proved best power allocation technique for the OFDM based cognitive radio network.

1.3 Cognitive Radio in India

In European countries the provision for cognitive radio deployment has been provided. But it has not yet been introduced in India. Tripathi in [46] has given the overview that what steps should be taken by regulatory authorities in India to introduce the cognitive radio in India. In [47] it has been reported that in India average spectrum utilization is around 6.62% in frequency band 700 to 2700 MHz and 37% utilization of band is reported in GSM bands 900 MHz and 1800 MHz band. Therefore, to utilize the spectrum properly, it is good to deploy the cognitive radio technology in India. There are some frequency bands which can be opened for cognitive radio applications such as 450-470 MHz, 470-960 MHz, 1700-2200 MHz and 2.3 -2.4 GHz. In [48], it has been reported that some licensed bands are opened for low power wireless technology. The main advantage of cognitive radio is to enhance the rural connectivity, creating Wi-Fi hot spots in cities and public disaster management. Cognitive radio technology can be utilized in India to make Indian cities smarter by providing super Wi-Fi hot spot for public use at the center location of a city like market place, railway stations, airport etc. Cognitive radio has not been deployed in India but National Telecom Policy 2012 [49] has opened the way for cognitive radio network such as to make liberal use of spectrum to provide any service in any technology, to permit spectrum sharing between different bands.

1.4 Issues and Consideration in Spectrum Sharing

The main challenges in the spectrum sharing are [50]:

1. Common Control Channel: In cognitive radio networks a channel common to all user is basically depends on the topology of network and it varies overtime. Therefore, to mitigate common control channel problem either new techniques have to be implemented or local common control channels have to be used.
2. Dynamic Radio Range: In cognitive radio network there is dependency of radio range and operating frequency. Therefore, for this frequency aware spectrum sharing techniques have to be implemented.
3. Location information: It is very important to get the information about the primary user whom with secondary user is going to share the spectrum.

1.5 Related Work

The research on spectrum sharing in cognitive radio network has been started since decades. Some researchers are working on spectrum overlay accessing techniques and some are working on spectrum underlay accessing techniques. In spectrum overlay technique secondary user has to wait for the spectrum to vacant but in spectrum underlay both secondary and primary and secondary user communicate at same frequency at same time[51]. Therefore, the spectrum underlay accessing technique is preferable because in this secondary user has not to wait for spectrum accessing. Many researchers have reported the analysis of performance metrics of channel with spectrum underlay accessing technique under different power constraints [52-53]. In underlay accessing technique the main focus is that the performance of primary user should not be affected. Therefore, the optimal power allocation to cognitive user is crucial issue.

1.5.1 Performance metrics analysis with a pair of primary and secondary user in the network

1.5.1.1 *With perfect Channel state information between SU-Tx and PU-Rx*

The capacities of cognitive link decreases with the fading environment under transmit power constraints [54]. Therefore, there is need to consider the received power constraints at primary receiver during power allocation. The information about the channel condition and interference power constraint is provided by the primary user to the cognitive user. Gastpar [55] has first time analyzed the average capacity of additive white Gaussian noise channel (AWGN) under the received power constraints at the primary receiver with perfect channel state information between the cognitive transmitter and primary receiver. If the power allocation to cognitive user is under the received power constraints then it has been analyzed that the capacity of cognitive user link increases with the severe fading between the secondary transmitter and primary receiver link [56]. The optimal power allocation over fading channel under joint transmit power and received power constraints with perfect channel state information between the primary and secondary user has been illustrated in several literatures. In [57], it has been described that interference and transmit power constraints can be limited either by peak or average constraint. The consideration of peak or average constraint depends on the service running at the primary user. For delay sensitive services peak power constraints are preferred and for delay insensitive services average power constraints are preferred. It has been shown in their results that fading between the secondary user transmitter and primary user receiver is beneficial to enhance the capacity of the secondary user link. In [58], it has been discussed that the primary user allows the secondary user to share the spectrum only if primary user meet its minimum rate requirements. It has been reported that for the small average interference power capacity of primary link increases with transmit power limits but for the higher transmit power limits the capacity is limited by interference power constraints. To protect the primary user from interference of secondary user new constraint has been proposed in [59] i.e outage constraint. To study the capacity limits under the outage constraint require the channel state information whereas under interference temperature constraint there is no need of channel state information between the secondary transmitter and primary receiver. As we know that the wireless channel is time varying therefore it is also important to analyze the performance metrics in the dynamic fading channel is also important issue. Farraj and Ekin [60] have been analyzed the channel capacity and bit error rate over dynamic fading channel under primary outage constraint. If the power allocation to secondary user is under the outage probability constraint then the usage of the channel by the cognitive user should not increase the primary user's outage probability above a certain limit. It has been reported that the cognitive transmit power has linear relationship with the transmit power of primary user. In addition, to this it has been illustrated that the channel capacity and bit error rate depends on the environmental parameters and independent of the primary and the cognitive user's transmit power. Vassaki [61], has been allocated a power to cognitive user in order to increase the QoS of the primary user. They have considered two types of constraints for optimal power allocation to cognitive user in order to increase the effective capacity such as the traditional interference power constraint and inverse signal-to-interference plus noise ratio (SINR) constraint. They have reported that with secondary user perspective average interference power constraint provide better results of effective capacity than the peak constraints. On the other hand, with primary user perspective the peak constraints yield better effective capacity results. It has been illustrated that under the SINR constraint the outage probability of primary user decreases in comparison to the traditional interference power constraints. At same power threshold level, the peak interference power constraint protects better the primary transmission as comparison to the average interference power constraints [62]. From above discussion, it has been concluded that to improve the QoS of primary user and reduce the outage probability, SINR and outage constraints yield better results in comparison to traditional interference power constraint. In addition, to this to improve the channel capacity of secondary link it is good to allocate the power to secondary user under joint interference power constraint and transmit power constraints.

1.5.1.2 *With imperfect Channel state information between SU-Tx and PU-Rx*

So far we have discussed the performance metrics when the perfect channel state information is provided to secondary user by the primary user. But, practically it is not happened. Practically imperfect channel state information is provided by the primary user receiver to the secondary transmitter. Therefore, it is important to analyze the performance metrics when the channel state information between the primary and secondary user is imperfect. Many researchers have reported the performance analysis of channel under various power constraints with imperfect channel state information between the primary user receiver and secondary transmitter [63-65]. In [66], asymptotic analysis has been proposed to analyze the ergodic capacity limits under the average/peak transmit power and the outage interference power constraints. They have also reported the expenditure of power required to achieve the lower bounds of ergodic and outage capacity limits. Kundu et.al [67], have analyzed the performance metrics of channel's variation with imperfect channel state information. They have also discussed that how can be selected the cognitive relay in underlay accessing technique. In [68], they have analyzed the resource allocation problem under the consideration of scenario to maximize the throughput when there are sensing errors. They have proposed an algorithm for resource allocation by using basic of game theoretical approach.

1.6 Problem Statement

As we have discussed in literature survey, that many researchers have reported the different performance metric for the cognitive radio network with perfect and imperfect channel state information. They have reported the different power allocation approaches for the maximization of the capacity limits over the fading environment. Up to our knowledge no one has reported the capacity limit analysis of the cognitive radio link with the consideration of primary user interference when imperfect channel state information is provided to the cognitive user. Moreover, the approach used for the power allocation in [66], is asymptotic analysis is quite complex. Therefore, we have used the simple Lagrangian dual method for the power allocation under joint peak transmit power and peak/average interference power constraints. The analysis of the capacity limits (ergodic and outage capacity) with and without primary user interference has been done.

1.7 Organization of the Dissertation

Spectrum sharing is a very crucial issue in cognitive radio networks. Resource allocation in cognitive radio network can be done on the basis of frequency, time and optimal power allocation to cognitive user. Therefore in this dissertation, resource allocation to cognitive user is done on the basis of power.

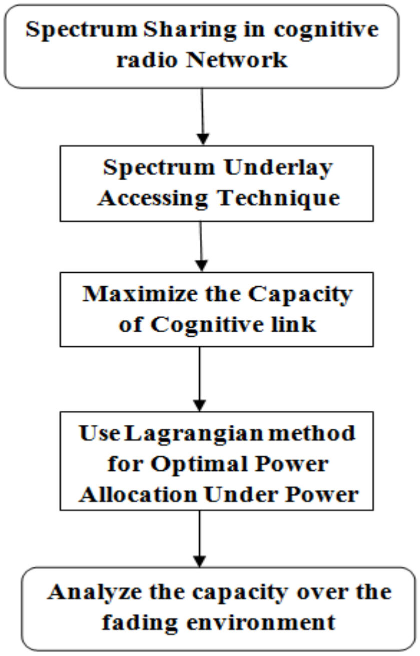


Fig 1.3 Overview of the Dissertation

The main focus is on the spectrum underlay accessing technique. Both primary and secondary user communicate at same frequency at same time but the power allocation to cognitive user is in such a way so that it does not affect the quality-of- service (QoS) of primary user. There are different performance metrics to study the channel performance such as capacity, throughput, bit error rate etc. In this dissertation, the performance of cognitive link is analyzed in terms of capacity over fading channel. There are different capacity notions for the different fading channel condition such as ergodic capacity for fast fading channel and outage capacity for slow fading channel. The overview of this dissertation is shown in Fig. 1.3. This dissertation is organized as follows in Chapter 2, the outage capacity of the proposed cognitive radio network is analyzed with and without the primary user interference. It has been considered that the primary user is provided with imperfect channel state information. In Chapter 3, the ergodic capacity of the cognitive radio network has been analyzed with and without primary user interference. The cognitive radio network for military communication has been discussed in Chapter 4. In Chapter 5, the conclusion of the dissertation and future scope of the work has been discussed.

CHAPTER 2

Analysis of the Outage Capacity of Cognitive Radio Network

2.1 Introduction

Information theory is the paradigm to study the performance limits in communication. The basic performance measurement parameter is capacity; Firstly, Shannon has given the upper bounded limit of capacity for the additive white Gaussian noise (AWGN) channel. However, in wireless environment due to multipath propagation signal experiences a fading. There are different capacity notions for fading channel. When the impulse response of the channel changes at a rate much slower than the transmitted baseband signal then that is named as slow fading channel. Therefore, the capacity notion used for the slow fading channel is outage capacity.

Therefore, the outage capacity is maximum transmission rate that can be maintained over the fading blocks with a given outage probability. In this chapter the outage probability/capacity of the cognitive link has been analyzed when power to cognitive user is allocated under joint peak transmit power and peak/average interference power constraints. However, mathematically the outage probability is expressed as [70]:

$$\Pr\{\log_2(1 + |\mathrm{h}|^2\ \mathrm{SNR}) < \mathrm{r}_0\} \tag{2.1}$$

where, h is random channel gain and r_0 is the transmitter's encoding rate. If the realization rate is less than the transmitter's encode rate then signal cannot be decoded by any method. For the proposed cognitive radio network, the outage capacity analysis for the cognitive link has been done. The problem is formulated as the minimization of the outage probability of the cognitive link and to gain this objective optimal power is allocated to cognitive user under some power constraints.

2.2 System Model

In this system model, we have considered multiple PUs and single CU which transmit data/information at same time. The CU shares the spectrum with one of the PU without affecting its QoS. For the interference-free spectrum sharing, the optimal power is allocated to the CU under the joint transmit power and received interference power constraints. In the proposed system model, we have considered discrete time flat fading channel where the received signal of CU depends on the transmitted signal, which is mathematically expressed as [70]:

$$y_{ss}(n) = x_{ss}(n)h_{ss}(n) + \sum_{i=1}^{n} x_p(n)\, h_{ps_i}(n) + w_{ss}(n) \tag{2.2}$$

where, n, $h_{ss}(n)$, $h_{sp}(n)$ and $h_{ps_i}(n)$ are the time index, channel gain of the CU link, channel gain between CU-Tx and PU-Rx and i^{th} PU-Tx and CU-Rx, respectively. $h_{ss}(n)$, $h_{sp}(n)$ and $h_{ps_i}(n)$ are the independent and identically distributed (iid) channel gain with exponential distribution. $w_{ss}(n)$ is the zero-mean complex symmetric additive white Gaussian noise (AWGN).

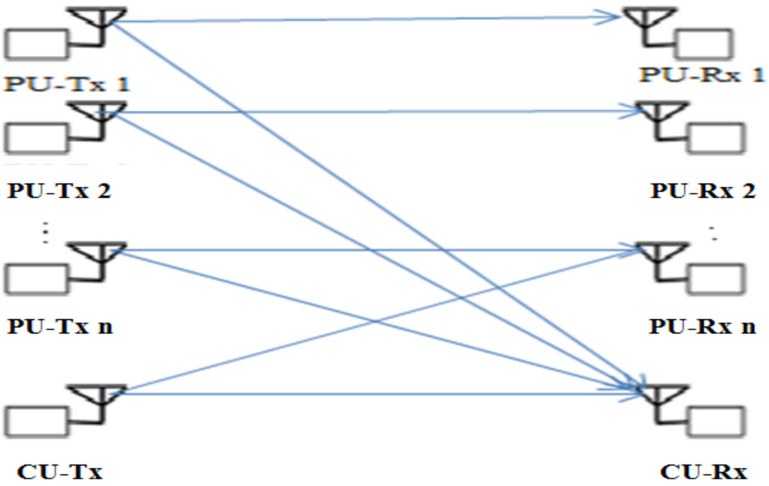


Fig 2.1 The spectrum sharing model of the cognitive radio network.

The partial channel state information is provided to CU-Tx by i^{th} PU, which is represented as $\check{h}_{sp_i}$(n). However, the CU estimates the channel gain by the minimum mean square error (MMSE) channel estimation technique. The channel estimation error is represented as:

$$\tilde{h}_{spi}(n) = h_{spi}(n) - \hat{h}_{spi}(n) \tag{2.3}$$

where, $\tilde{h}_{spi}(n)$ and $\hat{h}_{spi}(n)$ are the zero-mean circularly symmetric complex Gaussian distributed random variable with variance $(\sigma^2/2)$ and $(1-\sigma^2)/2$, respectively and for simplicity, we have ignore the time index. Due to the MMSE estimation characteristics, $\tilde{\mathrm{h}}_{spi}$ and $\hat{\mathrm{h}}_{spi}$ are the uncorrelated channel gain. The channel power gain is given by

$\left|h_{sp}\right|^2$, however the channel power gain of the CU link, between CU-Tx and PU-Rx link and i^{th} PU-Tx and CU-Rx link are represented by g_{ss} , g_{spi} and g_{ps}, respectively. Therefore, the optimization problem for outage capacity of cognitive link is expressed as

$$\min_{\mathrm{P}(\hat{g}_{sp\,1},\hat{g}_{sp\,2},\ldots\,\hat{g}_{spn}\,,g_{ss})\in \mathrm{R}} \Pr\left\{\log_2\left(1+\frac{\mathrm{g}_{\mathrm{ss}}\ \ \mathrm{P}(\hat{g}_{sp\,1},\hat{g}_{sp\,2},\ldots\,\hat{g}_{spn}\,,g_{ss})}{\sum_{i=1}^{n} g_{psi}*P_i+\mathrm{N}_0\ \mathrm{B}}\right)\right\} \le r_0 \tag{2.4}$$

where Pr{.} is the probability , r_0 is the transmitter's decoding rate and g_{ss}, g_{ps} and $\hat{g}_{sp}$ follows the Rayleigh distribution whose probability density function (pdf) is specified as: $e^{-g_{ss}}$, $e^{-g_{ps}}$ and $e^{-\hat{g}_{sp}/(1-\sigma^2)}/(1-\sigma^2)$, respectively [16]. When the multiple primary users are considered then pdf of the channel power gain between the cognitive transmitter and primary receivers is evaluated as follows:

Let $\widehat{g}_{spi}$ (i = 1...n) be iid random variables. It is assumed that the channel gain of cognitive link is independent from the channel gain between cognitive transmitter and primary receivers. Therefore, $\hat{g}_{sp}$ is expressed as:

$$\hat{g}_{sp} = \max\left(\widehat{g}_{spi}\right) \qquad i = 1..n \tag{2.5}$$

Then the cumulative distribution function of $\widehat{g}_{sp}$ is expressed as:

$$F_{\widehat{g}_{sp}}\left(\widehat{g}_{sp}\right) = \prod_{i=1}^{n} F_{\widehat{g}_{spi}}\left(\widehat{g}_{sp}\right) = \left(1-e^{-\frac{\widehat{g}_{sp}}{1-\sigma^2}}\right)^n \tag{2.6}$$

On differentiating Eq. (12) pdf of $\widehat{g}_{sp}$ is written as

$$f_{\widehat{g}_{sp}}\left(\widehat{g}_{sp}\right) = n\frac{e^{-\frac{\widehat{g}_{sp}}{1-\sigma^2}}}{1-\sigma^2}\left(1-\ e^{-\frac{\widehat{g}_{sp}}{1-\sigma^2}}\right)^{n-1} \tag{2.7}$$

On similar way, the pdf for multiple primary transmitter and cognitive receiver is expressed as:

$$f_{g_{ps}}\left(g_{ps}\right) = n\, e^{-g_{ps}}(1-\ e^{-g_{ps}})^{n-1} \tag{2.8}$$

However, both the channels are considered as Rayleigh fading channel and the probability density function of $\widehat{g_{sp}}$ and g_{ss} are represented as: $e^{-\hat{g}_{sp}/(1-\sigma^2)}/(1-\sigma^2)$ and $e^{-g_{ss}}$, respectively as discussed in [66]. N_0 and B are the noise power spectral density at primary receiver and total available bandwidth, respectively. Therefore, the capacity of cognitive link can be maximized by allocating the optimal power to SU-Tx.

2.3 Power Constraints

To minimize the outage probability optimal power is to be allocated to the cognitive user under some power constraints. We have considered P_{pk} and Q_{pk} as the peak transmit power of CU and peak interference power of PU-Rx, respectively. The instantaneous transmitted power of CU-Tx depends on the channel power gain g_{ss} and the estimated value g_{sp} which is denoted by $\hat{g}_{sp}$. However, the instantaneous power at the CU-Tx is expressed as [58]:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right) > 0, \forall\ (\hat{g}_{sp1} .. \hat{g}_{spn}, g_{ss}) \tag{2.9}$$

and the peak transmit power constraint is represented as [58]:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right) \leq P_{pk}, \forall\ (\hat{g}_{sp1} .. \hat{g}_{spn}, g_{ss}) \tag{2.10}$$

as well as the peak interference power constraint is provided as [58]:

$$g_{spi} P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right) \leq Q_{pki}, \forall\left(\hat{g}_{sp1} .. \hat{g}_{spn}, g_{ss}\right), \quad i = 1..n \tag{2.11}$$

However, the instantaneous peak interference power constraint is valid only for the short time. Due to this reason, the interference outage concept is introduced by Musavian and Aissa [63]. Therefore, the outage interference power constraint is represented as [63]:

$$P_r \left\{ g_{spi} \left(P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right)\right) \geq Q_{pki} \right\} \leq P_0 \tag{2.12}$$

where, $P_{\mathrm{r}}\{.\}$ and P_0 are the probability of function and outage interference level, respectively. Therefore, Equation (2.12) can be simplified as:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right) \leq \min\left(\frac{Q_{pki}}{\hat{g}_{spi} - \sigma^2 \ln P_0}\right), \ i = 1..n \tag{2.13}$$

In addition to this, the average interference power constraint is expressed as:

$$E\left[g_{spi}\ P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right)\right] \leq Q_{avgi}, i = 1..n \tag{2.14}$$

Due to the imperfect channel state information, the g_{spi} is not known. Therefore, the estimated value of g_{spi} is expressed as:

$$\hat{g}_{spi} = g_{spi} - \tilde{g}_{spi} \tag{2.15}$$

where, $\hat{g}_{spi}$, g_{spi} and $\tilde{g}_{spi}$ are the estimated, ideal (true) and estimated error values of the g_{sp}, respectively. Therefore, the average interference power constraint is expressed as [63]:

$$E\left[\hat{g}_{spi} P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right)\right] \leq Q_{avgi} - \sigma^2 E\left[\, P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right)\right] \tag{2.16}$$

For the optimal transmit power computation, the combination of instantaneous CU-Tx power, peak transmit power of CU and outage constraint is represented by R_1 and the combination of instantaneous CU-Tx power, peak transmit power of CU and average interference power constraint is represented by R_2.

2.4 Optimal Power Allocation to Minimize the Outage Probability

2.4.1 *Under peak transmit power and peak interference power constraints*

For the optimal power allocation $R \in R_1$ and two dimensional truncated channel inversions (2D-TCI) strategy is used over $\hat{g}_{sp}$ and g_{ss}. Therefore, the optimal transmit power of cognitive user is expressed as:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \hat{g}_{sp3} \cdots \hat{g}_{spn}, g_{ss}\right) = \begin{cases} \dfrac{(N_o B + \sum_{i=1}^{n} g_{ps} * P_i)(2^{r_o} - 1)}{g_{ss}}, \quad g_{ss} \geq \dfrac{(2^{r_0} - 1)(N_o B + \sum_{i=1}^{n} g_{ps} * P_i)}{P_{pk}} \text{ and} \\ \qquad \hat{g}_{spi} \leq \dfrac{g_{ss} Q_{pk}}{(N_o B + \sum_{i=1}^{n} g_{ps} * P_i)(2^{r_0} - 1)} + \sigma^2 \ln(P_0) \\ 0, \qquad \text{otherwise} \end{cases} \tag{2.17}$$

Let, $\frac{g_{ss} Q_{pk}}{(N_o B + \sum_{i=1}^{n} g_{ps} * P_i)(2^{r_0} - 1)} + \sigma^2 \ln(P_0)$ and $\frac{(2^{r_0} - 1)(N_o B + \sum_{i=1}^{n} g_{ps} * P_i)}{P_{pk}}$ is denoted by the auxiliary variables u and z, respectively. By substituting (2.17) in (2.8), we yield the outage probability as:

$$P_{out} = 1 - \iiint f_{\hat{g}_{sp}}\left(\hat{g}_{sp}\right) f_{g_{ss}}\left(g_{ss}\right) f_{g_{ps}}\left(g_{ps}\right) d\hat{g}_{sp}\, dg_{ss}\, dg_{ps} \tag{2.18}$$

where, $f_{\hat{g}_{sp}}(\hat{g}_{sp})$, $f_{g_{ps}}\left(g_{ps}\right)$ and $f_{g_{ss}}(g_{ss})$ are the probability density function of $\hat{g}_{sp}$, g_{ps} and g_{ss}, respectively. The outage capacity of the cognitive link under joint peak transmit power and peak interference power constraint is expressed as

$$C_{outage} = \log_2(1 + F^{-1}(1 - P_{out})\,\gamma) \tag{2.19}$$

where $F(x) = \Pr(g_{ss} > x)$ is the complementary cumulative distribution function of g_{ss} and γ is signal-to- noise ratio (SNR).

2.4.2 *Under peak transmit power and average interference power constraint*

To calculate the optimal power under joint peak transmit power and average interference power constraint, the objective function can be expressed as indicator function, which is given as:

$$Y = \begin{cases} 1\,, & \log_2\left(1 + \frac{g_{ss}\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}})}{(\mathrm{N_o\,B} + \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{g}_{\mathrm{ps}} * \mathrm{P}_{\mathrm{i}})}\right) < r_0 \\ 0, & otherwise \end{cases} \tag{2.20}$$

Let us consider λ is a dual variable associated with average interference power constraint, the Lagrangian function for this objective can be expressed as

$$L[\,\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}}), \lambda\,] =$$

$$E\{Y\} + \lambda\left(\mathrm{E}\left[g_{spi}\ \mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}})\right] - Q_{avg}\right) \tag{2.21}$$

Now, for 2nd constraint that is the peak transmit power as given by (2.8) become objective function. Therefore, the dual function can be expressed as:

$$\min_{\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}}) \in \mathrm{R}_2} E\{Y\} + \lambda\left(\mathrm{E}\left[g_{spi}\ \mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}})\right] - Q_{avg}\right) \tag{2.22}$$

For a particular fading state the dual function can be decomposed in to series of similar sub-dual function and each corresponds to one fading state. The decomposed dual function can be expressed as:

$$\min_{\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}})} \left\{Y + \lambda\left(\mathrm{g}_{\mathrm{spi}}\,\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}})\right)\right\}$$

$$\text{s.t}\quad \mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}}) \le P_{pk}\,,\ \mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}}) \ge 0 \tag{2.23}$$

At Y = 1, Eq. (2.23) can be minimized if $\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}}) = 0$ and minimum value will be 1. When Y = 0, it can be minimized if $\mathrm{P}(\hat{\mathrm{g}}_{\mathrm{sp}\,1}, \hat{\mathrm{g}}_{\mathrm{sp}\,2}, \hat{\mathrm{g}}_{\mathrm{sp}\,3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g}_{\mathrm{ss}}) =$

$\frac{(2^{r_0}-1)(\mathrm{N_o B}+\sum_{i=1}^{n} \mathrm{g_{ps}} * \mathrm{P_i})}{g_{ss}}$ and minimum value will be $\lambda\,(\hat{\mathrm{g}}_{\mathrm{spi}} + \sigma^2)\,\frac{(2^{r_0}-1)(\mathrm{N_o B}+\sum_{i=1}^{n} \mathrm{g_{ps}} * \mathrm{P_i})}{g_{ss}}$. The optimal power is expressed as $\mathrm{P}\left(\hat{\mathrm{g}}_{\mathrm{sp}1}, \hat{\mathrm{g}}_{\mathrm{sp}2}, \hat{\mathrm{g}}_{\mathrm{sp}3} \cdots \hat{\mathrm{g}}_{\mathrm{spn}}, \mathrm{g_{ss}}\right) =$

$$\begin{cases} \frac{(2^{r_0}-1)(\mathrm{N_o B}+\sum_{i=1}^{n} \mathrm{g_{ps}} * \mathrm{P_i})}{g_{ss}}, \hat{\mathrm{g}}_{\mathrm{sp}} < \frac{gss}{\lambda\,(\mathrm{N_o B}+\sum_{i=1}^{n} \mathrm{g_{ps}} * \mathrm{P_i})\,(2^{r_0}-1)} - \sigma^2, g_{ss} > \frac{(\mathrm{N_o B}+\sum_{i=1}^{n} \mathrm{g_{ps}} * \mathrm{P_i})(2^{r_0}-1)}{P_{pk}} \\ 0, \qquad otherwise \end{cases} \tag{2.24}$$

The value of λ can be computed by substituting the optimal power in (2.16). The outage probability and outage capacity can be evaluated in a similar way as in case of peak transmit and peak interference power constraint.

2.4.3 *Under average interference power constraint*

The optimal power allocation under the peak interference power constraint to minimize the outage probability is expressed as:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2} .. \hat{g}_{spn}, g_{ss}\right) = \min\left(\frac{Q_{pki}}{\hat{g}_{spi} - \sigma^2 \ln P_0}\right), i = 1..n \tag{2.25}$$

The outage probability is calculated as is discussed in previous section.

2.5 Power Consumption of the Cognitive Radio Transmitter

The average consumption of power of cognitive transmitter when optimal power is allocated under peak transmit power and peak interference power constraints without PU interference is expressed as:

$$E\left[P\left(\hat{g}_{spi}\ g_{ss}\right)\right] = Ei\left(1, \frac{1}{P_{pk}}\right) - Ei\left(1, \frac{Q_{pki}+1}{P_{pk}(1-\sigma^2)}\right)\exp\left(\frac{-\sigma^2 \log(P_0)}{1-\sigma^2}\right) \tag{2.26}$$

The average expenditure of power of cognitive user transmitter when the optimal power is allocated by considering only the peak interference power constraint.

$$E\left[P\left(\hat{g}_{spi}\ g_{ss}\right)\right] = Q_{pki}\exp\left(\frac{-\sigma^2 \log(P_0)}{1-\sigma^2}\right)\left(-\log\left(\frac{1-\sigma^2}{Q_{pk}}+1\right) - Ei\left(\frac{\sigma^2 \log(P_0)}{1-\sigma^2}\right)\right) \tag{2.27}$$

2.6 Simulation Results

2.6.1 *Simulation results and analysis of the outage capacity under different power constraints*

This section is mainly categorized in to two parts. In first part, we have discussed the simulation results when perfect channel state information is provided to the cognitive transmitter.

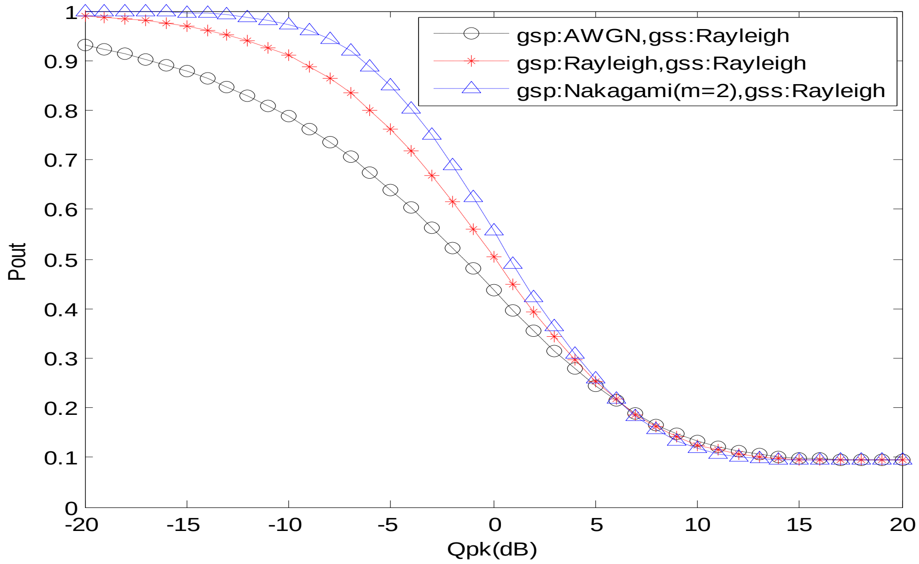


Fig 2.2 The analysis of the outage probability with the peak interference power with peak transmit power 10 dB

To analyze the outage capacity limits in perfect channel state scenario put $\sigma^2 = 0$, and analyze the results for different fading conditions Rayleigh fading, Nakagami fading and log-normal fading. The results for Rayleigh fading is validated with the literature reported in [58]. For the outage probability calculation for Nakagami and log normal for perfect channel state information refer Appendix I. It has been analyzed that if there is severe fading between the cognitive transmitter and primary receiver, it will be helpful to improve the capacity of cognitive link as shown in Fig. 2.2

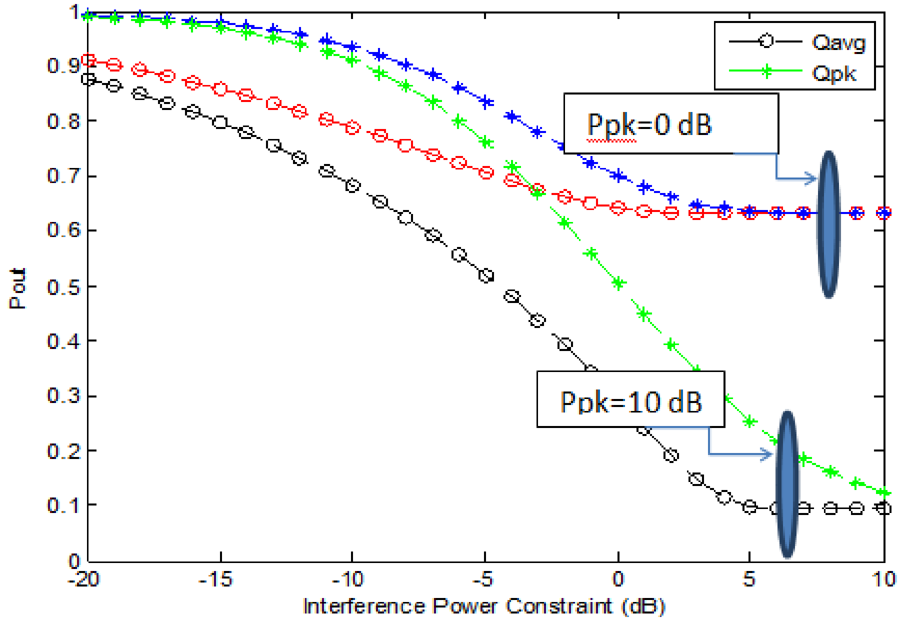


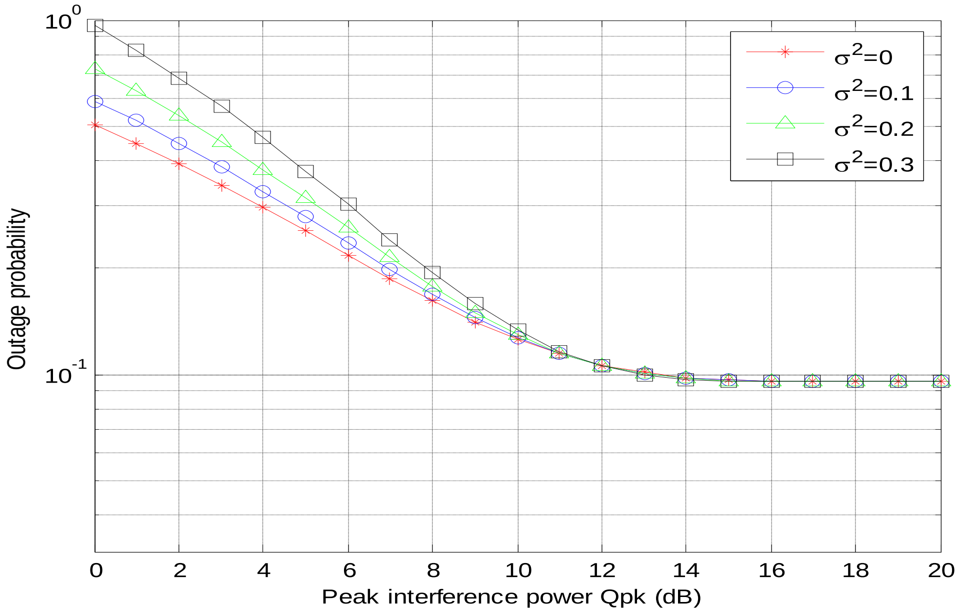
Fig 2.3 The outage probability analysis with the interference power constraints for different values of peak transmit power 0 dB and 10 dB.

interference constraint with peak transmit power 10 dB. It has been analyze that if there is Rayleigh fading between SU-Tx and PU-Rx then outage probability over Rayleigh fading channel is less as compared to nakagami fading channel up to approximately 9 dB average interference constraint. Moreover, when the peak interference power become sufficiently large in comparison to the peak transmits power the outage probability become same for Rayleigh and nakagami channel. It has been depicted that the fading between the SU-Tx and PU-Rx is good for low outage probability when peak interference power constraint is less as compared to peak transmit power constraint. In Fig. 2.3 the outage probability is analyzed with respect to peak and average interference power constraint at P_{the} peak transmit power 0 dB and 10 dB.

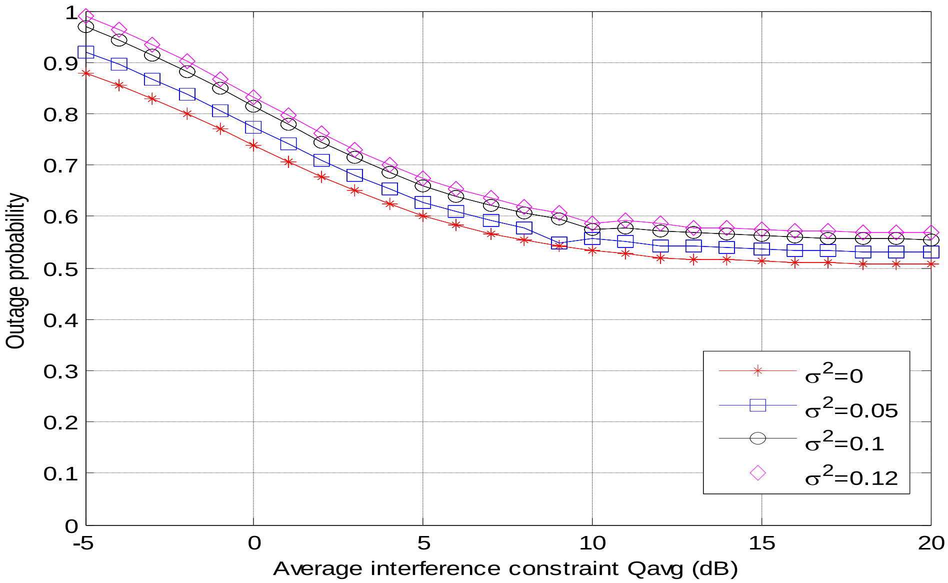
In this analysis, both g_{sp} (g_o) and g_{ss} (g_1) are rayeligh fading channel gain. The outage probability under peak interference power constraint is more as compared to average interference power constraint. Therefore, the average interference power constraints are better than the peak interference power. Now, in next part, we have discussed the numerically simulated results of the proposed system model of the cognitive radio network. Here, the outage probabilities are analyzed in two different cases.

Case 1 Outage Probability without primary user interference

The outage probability with respect to peak interference power for different values of the error variance with P_0 equals to 0.1 is shown in Fig. 2.4(a) and it has been illustrated that there is no significant effect of the error variance on the outage probability when the peak transmit power is less than or equal to the peak interference power constraint.



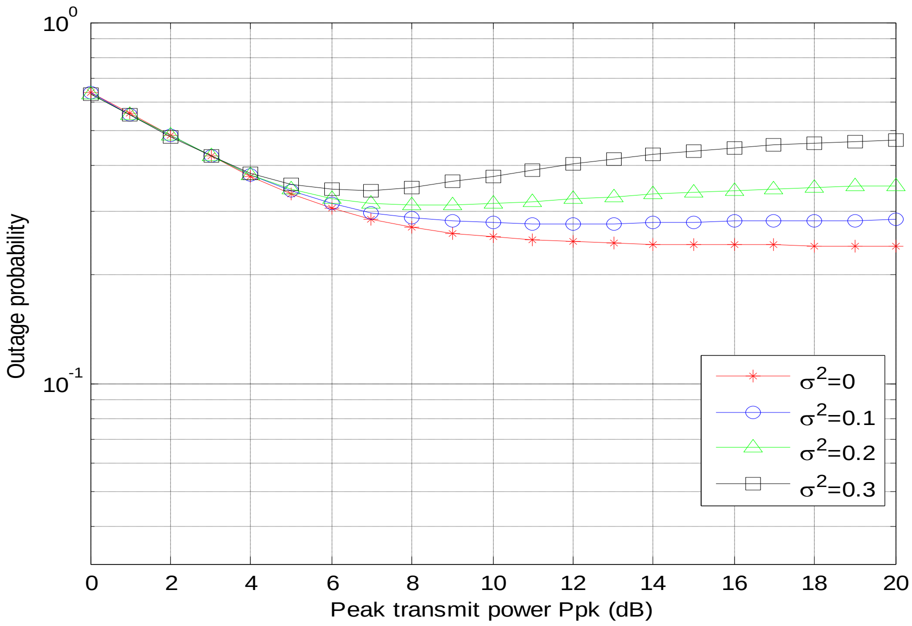
(a)



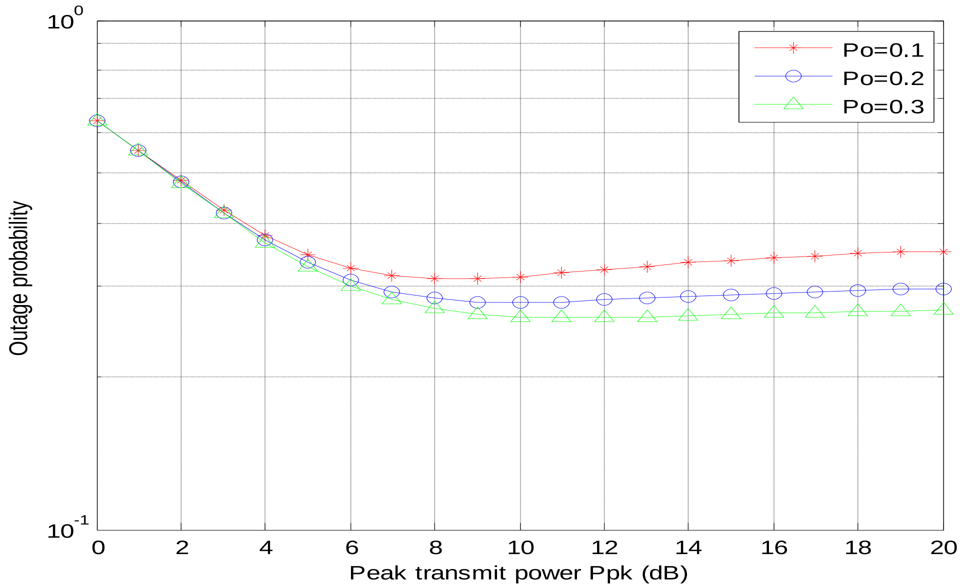
(b)

Fig 2.4 The effects of variance on the outage probability at arbitrary chosen value of the peak transmit power 10 dB and fixed data transmission rate ($r_0 = 1$ bits/sec/Hz) under (a) peak interference power and (b) average interference constraints.

There is a direct relationship between the error variance and outage probability as well as the inverse relationship between the outage probability and average interference power constraint as illustrated in Fig. 2.4(b). Fig. 2.5 depicts that when the peak transmit power is less than the peak interference power, the outage probability for different error variance as well as for the outage constraint remain same. We have considered 5 dB peak interference power constraint, the nature of the curves for error variance as well as for outage constraints are similar up to the 5 dB peak transmit power. With the increase in numerical values of the error variance for chosen value of the interference outage constraint (P_0 = 0.1), the outage probability increases significantly as shown in Fig. 2.5(a).Similarly, in Fig. 2.5(b), as the outage constraint increases for chosen value of the error variance (σ_p^2= 0.2), the outage probability reduces; however this reduction is significantly small for higher values of the P_0.



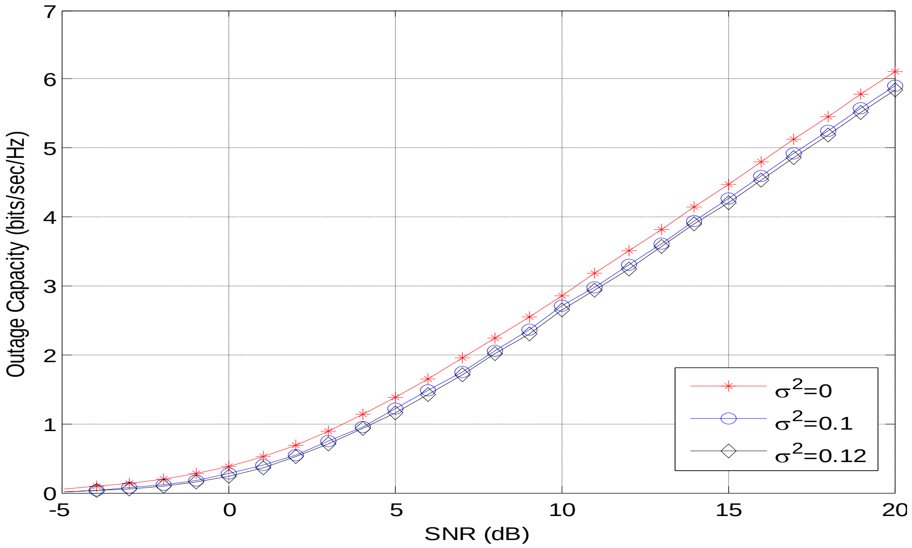
(a)



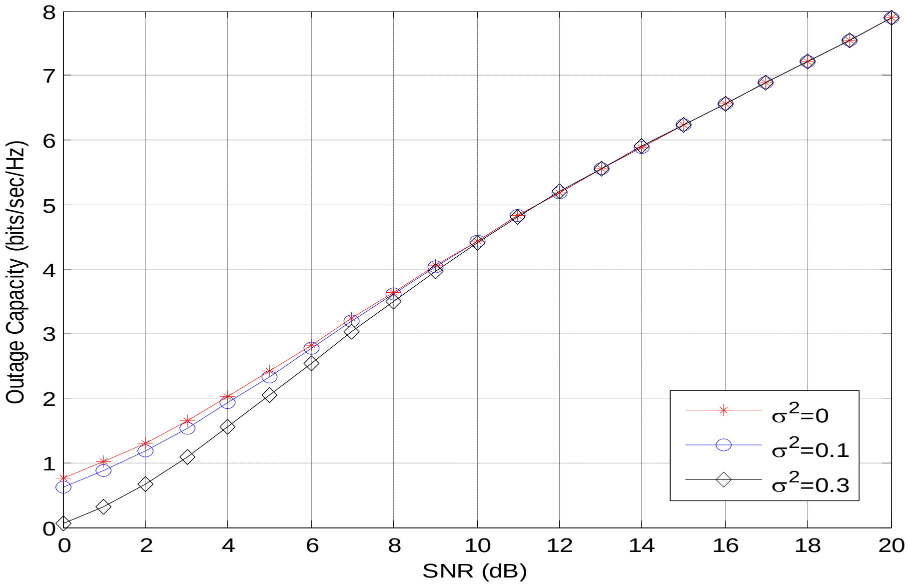
(b)

Fig 2.5 The effect of peak transmit power on the outage probability for arbitrary chosen value of the peak interference power 5 dB and fixed data transmission rate (r_0= 1 bits/sec/Hz) with (a) different values of the variance and (b) different values of outage constraint.

The effect of average SNR on the outage capacity for different values of the error variance is demonstrated in Fig. 2.6. From Fig. 2.6(a), it is illustrated that the outage capacity under joint peak transmit power and average interference power



(a)



(b)

Fig 2.6 the outage capacity versus signal to noise ratio for different values of the variance under peak transmit power constraint with (a) average interference constraint and (b) peak interference constraint

constraint decreases for significantly higher error variance. Furthermore, the outage capacity of the proposed communication system increases linearly with the

increase of the average SNR, particularly more than 5 dB. When the peak transmit power is greater/equal to the peak interference power, the outage capacity decreases with the increase of the error variance. However, there is no significant effect of error variance on the outage capacity after the 10 dB average SNR as shown in Fig. 2.6(b).

Case 2 The Outage probability analysis with primary user interference

In this section, the numerically simulated results of the outage probability of the cognitive link with primary user interference have been illustrated. The effect of single primary transmitter's interference on the outage probability of the secondary/cognitive link with varying the noise variance is demonstrated in Fig. 2.7. If we compare the Fig. 2.4(a) and Fig. 2.7 it is depicted that with the interference from single primary transmitter the outage probability of secondary link is significantly higher, however in both cases the behavior of curve with the noise variance remain same. The variations of outage probability with multiple

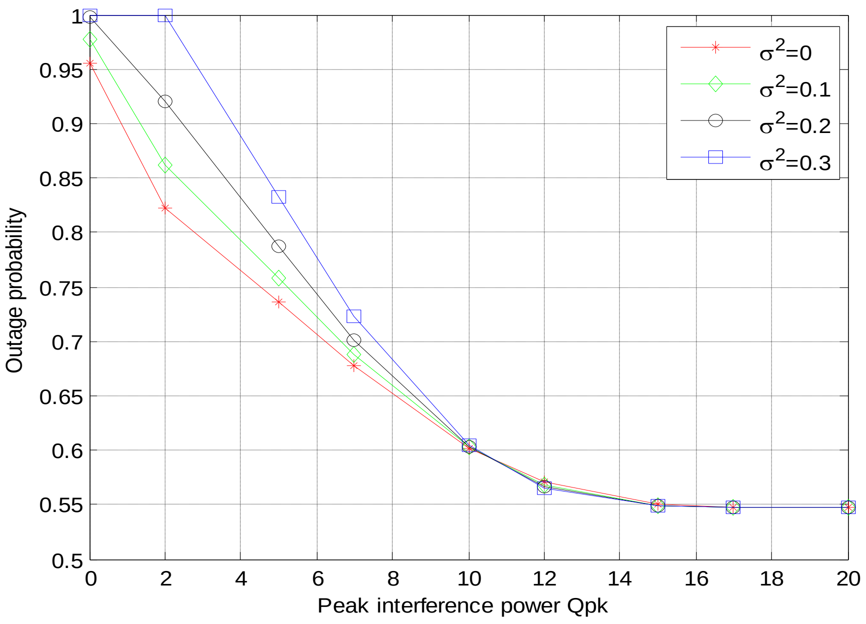
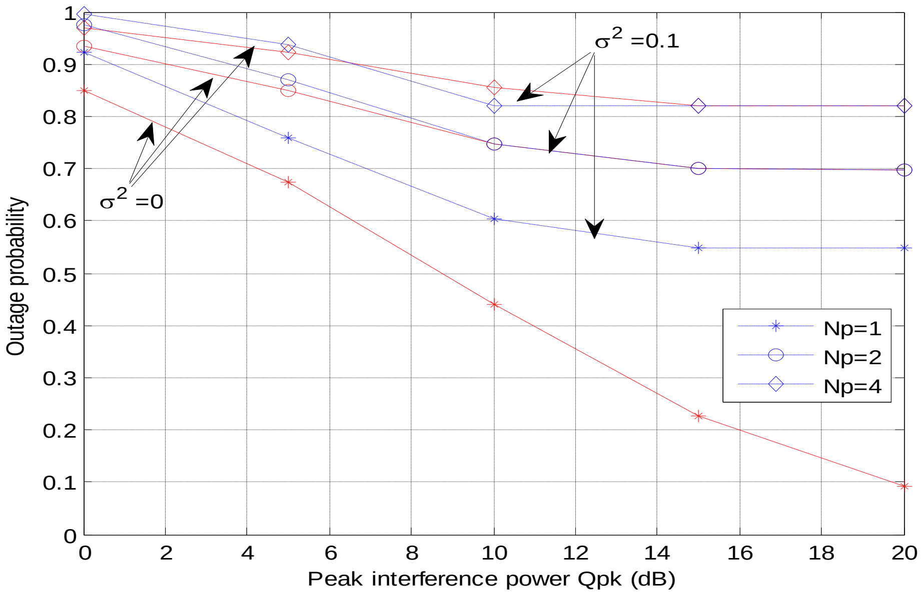
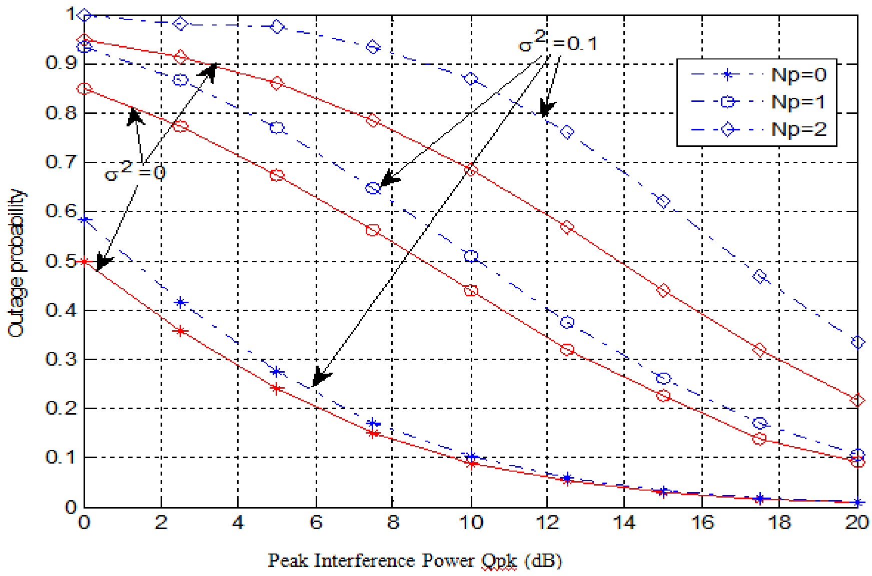


Fig 2.7 The outage probability versus peak interference power for different values of the variance when peak transmit power is fixed at 10 dB.

PU interference under the peak transmit power and peak interference power constraint is presented in Fig. 2.8 (a) for different values of the error variance.



(a)



(b)

Fig 2.8 The outage probability of cognitive user link with multiple primary users interference with variation in the peak interference power for chosen value of peak transmit power (10 dB) with fixed $\sigma^2 = 0$ and $\sigma^2 = 0.1$ under (a) peak transmit power and peak interference constraints and (b) peak interference only.

If the PUs interferes with the CU link, the outage probability levels rise. In case of without PU-Tx interference, it has been illustrated that as the peak transmit power is less than that of the peak interference power, the outage probability level remain same for different noise error variance but with the PU interference, the outage probability is constant with different outage probability levels. From Fig. 2.8 (a), it is depicted that the outage probability increases with the increase of PU's interference. Moreover, it is also analyzed that if the PUs increases above four then the data rate of CU link become very less therefore the communication cannot be established efficiently. Fig. 2.8 (b) demonstrated the effect of interference of the PU to the CU link when the transmit power to CU is allocated under the peak interference power constraint only. The comparison between Fig. 2.8 (a) and Fig. 2.8 (b) reveals that the outage probabilities under the joint peak transmit power and peak interference power is more in comparison to the individual peak interference power constraint. If the multiple numbers of PUs interfere to the CU link then the peak interference constraint provides better result.

2.6.2 *Simulation and result analysis for consumption of power of cognitive transmitter*

The consumption of power of CU-Tx under the joint peak transmit power and peak interference power as well as under the peak interference power only is portrayed in Fig.

2.9. It is exposed that the consumption of power under the joint constraints (the peak transmit power and peak interference power) is very less in comparison to that of the peak interference power constraint only. The power consumption of CU under the peak interference power constraint only is validated with the reported literature [58]. From Fig. 2.9, it is clarified that it is significantly much better to allocate power to CU under the joint constraints (the peak transmit power and peak interference power) as compared to the peak interference power constraint only.

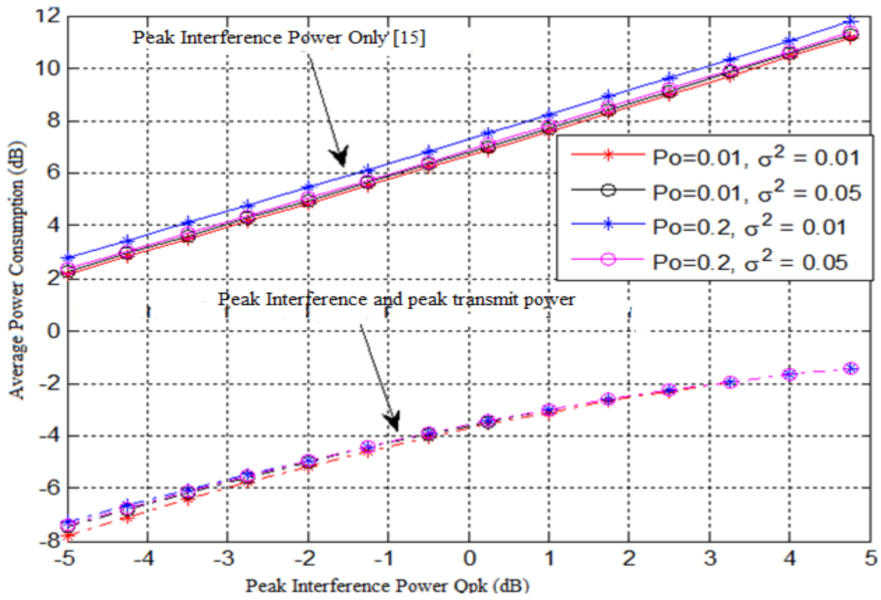


Fig 2.9 The average power consumption to achieve outage capacity limit of cognitive user transmitter with different combination of interference outage level and error variance under the peak transmit power and peak interference constraints as well as under the peak interference power constraint only.

Summary

In this chapter, we have discussed the outage probability when optimal power is allocated to cognitive user under the joint peak transmit power and peak interference power constraints for perfect channel state information as well as for imperfect channel state information. Moreover, the analysis with consideration of primary user interference and without primary user interference is also analyzed. It has been concluded that the outage probability of the cognitive link can be reduced if there is severe fading between the cognitive transmitter and primary receiver. Furthermore, it has been concluded that with the increasing number of primary user interference outage probability increases. Cognitive user can tolerate the interference only up to four users after this data rate will be very less.

Chapter 3

Analysis of the Ergodic Capacity of the Cognitive Radio Network

3.1 Introduction

As we have discussed in chapter 2, for slow fading channel the outage capacity is the performance metric to analyze the communication link. In slow fading case, we are interested to maximize the data rate over the coherence time period on the other hand in fast fading case we are interested to maximize the rate averaged over many coherence time period. Therefore, the ergodic capacity is the maximum achievable rate averaged over all the fading blocks. Within each block the impulse response is constant but it varies from one block to other. Mathematically, the ergodic capacity is expressed as

$$C_{ergodic} = E[log_2(1 + |h|^2\, SNR)] \ \ bits/s/Hz \qquad (3.1)$$

3.2 System Model

The system model for the analysis of the ergodic capacity of the cognitive radio network is considered similar as is taken to analyze the outage capacity in chapter 2. The ergodic capacity is analyzed over the Rayleigh fading channel with and without primary user interference has been analyzed. Therefore, the ergodic capacity for the cognitive radio link with primary user interference is computed by optimization problem as expressed below:

$$C_{ergodic} = \underset{P(\hat{g}_{sp\,1}, \hat{g}_{sp\,2}, \dots\, \hat{g}_{spn}, g_{ss}) \in R}{max} E\left[\ \log_2\left(1 + \frac{g_{ss}.P(\hat{g}_{\mathrm{sp}}, g_{ss})}{N_o.B + \sum_{i=1}^{n} g_{ps} * P_i)}\right)\right] \qquad (3.2)$$

where E{.} is the expected value and g_{ss}, g_{ps} and $\hat{g}_{sp}$ follows the Rayleigh distribution and their pdfs are expressed as in chapter 2.

3.3 Optimal Power Allocation to Maximize the Ergodic Capacity

3.3.1 *Under the joint peak transmit power and peak interference power constraints*

The joint peak transmit power and peak interference power constraints are combined as follows [8]:

$$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) \leq P(min\left(P_{pk}\ , \frac{Q_{pki}}{\widehat{g_{spi}} - \sigma^2 . \ln P_0}\right)) \tag{3.3}$$

Therefore, to maximize the ergodic capacity the optimal power allocation to cognitive user is expressed as follows:

$$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) = \begin{cases} P_{pk}\ , & \widehat{g_{sp_i}} \leq \frac{Q_{pki}}{P_{pk}} + \sigma^2 \ln P_0 \\ \frac{Q_{pki}}{\widehat{g_{spi}} - \sigma^2 \ln P_0}\ , & otherwise \end{cases} \tag{3.4}$$

From (3.4), it is observed that when the outage interference constraint is satisfied then the CU transmit with peak power otherwise power has to be reduced according to the channel power gain, error variance and outage constraint. It indicates that the severe fading between the cognitive user transmitter and primary user receiver is good to protect the primary user and maximizing the cognitive user throughput.

3.3.2 *Under the peak transmit power and average interference power constraint*

The optimal powers under the peak transmit power and the average interference power constraints are computed by the Lagrangian method as follows [70]:

$$L\big(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}), \lambda\big) = E\left(\log_2(1 + P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) \frac{g_{ss}}{N_0 B}\right) -$$
$$\lambda\,(E\big(\hat{\text{g}}_{\text{sp}}\ P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss})\big) - Q_{av} + \sigma^2 E(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}))) \tag{3.5}$$

For particular fading state the Eq. (3.5) can be represented as:

$$\underset{P(\hat{\text{g}}_{\text{sp}}, g_{ss})}{max} \log_2\left(1 + \frac{P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) g_{ss}}{\sum_{i=1}^{n} g_{psi} * P_i + \text{N}_0\ \text{B}}\right) - \lambda\,(\hat{\text{g}}_{\text{sp}}\ P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) - Q_{av} +$$
$$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss})) - \mu\left(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) - P_{pk}\right) +$$
$$v\, P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) \tag{3.6}$$

s.t $P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) \geq 0, P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) \leq P_{pk}$

The dual function of Eq. (3.6) is represented as:

$$L\big(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}), \lambda, \mu, v\big) =$$
$$log\left(1 + \frac{P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss})}{N_0 B}\right) - \lambda\left(\hat{\text{g}}_{\text{sp}} P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) - Q_{av} +\right.$$

$$\sigma^2 P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss})\Big) - \mu\left(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) - P_{pk}\right) + v\, P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) \tag{3.7}$$

By using Karush-Kuhn-Tucker (KKT) conditions, the optimal power is computed as

$$\frac{\partial L\left(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}), \lambda, \mu, v\right)}{\partial P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss})} = \frac{g_{ss}}{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B} + P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) g_{ss}} - \lambda\left(\hat{g}_{\mathrm{spi}} + \sigma^2\right) - \mu + v = 0 \tag{3.8}$$

$$\mu\left(P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) - P_{pk}\right) = 0 \tag{3.9}$$

$$v\, P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}\right) = 0 \tag{3.10}$$

From Eq. (3.8), we get:

$$P\left(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}\right) = \frac{K}{\lambda\left(\hat{g}_{\mathrm{spi}} + \sigma^2\right) + \mu - v} - \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}} \tag{3.11}$$

If we consider, $P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) < P_{pk}$, it is possible only if

$$\hat{g}_{\mathrm{sp}} \geq \frac{K}{\lambda\left(P_{pk} + \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}}\right)} - \sigma^2,$$

so it contradicts the assumption. Therefore,

$$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) = P_{pk}, \text{ if } \hat{g}_{\mathrm{sp}} \leq \frac{K}{\lambda\left(P_{pk} + \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}}\right)} - \sigma^2.$$

Suppose, if

$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) > 0$

when $\hat{g}_{\mathrm{sp}} \geq \frac{K}{\lambda\left(P_{pk} + \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}}\right)} - \sigma^2$ from Eq. (3.10) $v = 0$ then Eq. (3.11) become:

$$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) = \frac{K}{\lambda\left(\hat{g}_{\mathrm{spi}} + \sigma^2\right) + \mu} - \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}}$$

then $P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots \hat{g}_{spn}, g_{ss}) > 0$ which results

$$\frac{K}{\lambda\left(\hat{g}_{\mathrm{spi}} + \sigma^2\right) + \mu} - \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}} > 0 \quad \text{since } \mu \geq 0,$$

$$\frac{K}{\lambda\left(\hat{g}_{\mathrm{spi}} + \sigma^2\right)} - \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}} > \frac{K}{\lambda\left(\hat{g}_{\mathrm{spi}} + \sigma^2\right) + \mu} - \frac{\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N_0\ B}}{g_{ss}} > 0,$$

Therefore, if $\hat{\mathrm{g}}_{\mathrm{spi}} \geq \frac{K g_{ss}}{\lambda(\sum_{i=1}^{n} g_{psi} * P_i + \mathrm{N}_0\ \mathrm{B})} - \sigma^2$,then

$P\big(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots\ \hat{g}_{spn}, g_{ss}\big) = 0$

and if

$$\frac{K}{\lambda\left(P_{pk} + \frac{\sum_{i=1}^{n} g_{psi}\ * P_i + \mathrm{N}_0\ \mathrm{B}}{g_{ss}}\right)} - \sigma^2\ \leq \hat{\mathrm{g}}_{\mathrm{spi}}\ \leq \frac{K g_{ss}}{\lambda(\sum_{i=1}^{n} g_{psi}\ * P_i + \mathrm{N}_0\ \mathrm{B})} - \sigma^2$$

then $P\big(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots\ \hat{g}_{spn}, g_{ss}\big) = \frac{K}{\lambda(\hat{\mathrm{g}}_{\mathrm{spi}} + \sigma^2)} - \frac{N_0}{g_{ss}}$

Therefore, the optimal power allocations under the peak transmit power and average interference power constraints are expressed as:

$$P(\hat{g}_{sp1}, \hat{g}_{sp2}, \dots\ \hat{g}_{spn}, g_{ss}) = \begin{cases} P_{pk} & if\ \frac{K}{\lambda\left(P_{pk} + \frac{N_0 B}{g_{ss}}\right)} - \sigma^2 \geq \hat{\mathrm{g}}_{\mathrm{spi}} \\ \frac{K}{\lambda(\hat{\mathrm{g}}_{\mathrm{sp}} + \sigma^2)} - \frac{N_0}{g_{ss}} & if\ \frac{K}{\lambda\left(P_{pk} + \frac{N_0 B}{g_{ss}}\right)} - \sigma^2\ \leq \hat{\mathrm{g}}_{\mathrm{sp}} \leq \frac{K g_{ss}}{\lambda N_0} - \sigma^2 \\ 0, & otherwise \end{cases} \tag{3.12}$$

3.4 Power Consumption of Cognitive Transmitter without Primary User's Interference

The average power consumption of CU-Tx under the peak transmit power and peak interference power constraint is the expressed as:

$$E\big[P\big(\hat{g}_{spi}\ g_{ss}\big)\big] = P_{pk} - \frac{P_{pk}}{1-\sigma^2}\ \exp(\frac{Q_{pk\ i}}{P_{pk}} + \sigma^2 \log(P_0) - \frac{Q_{pki}}{1-\sigma^2}\ \exp(-\sigma^2 \log(P_0))\, Ei(-\frac{Q_{pki}}{P_{pk}\,(1-\sigma^2)}) \tag{3.13}$$

3.5 Simulation Results and Analysis

The discussion of proposed model is organized in two parts. First is linked with the ergodic capacity analysis when perfect channel state information is provided to cognitive user. Moreover, the ergodic capacity is analyzed under receiver power constraints as similar in [56]. We have validated the results with the literature reported in [56]. To analyze the ergodic capacity of the cognitive link we have considered the noise variance value $\sigma^2 = 0$. If there is fading between SU-Tx and PU-Rx then the capacity of secondary link will be more as compared to no fading channel. Fading between the SU-Tx and PU-Rx is beneficial. But from Fig. (3.1), we analyze that from 0 to 10 dB SNR, capacity is less in Nakagami channel as compared to AWGN channel. If signal strength increases then capacity of fading channel and AWGN channel will be same.

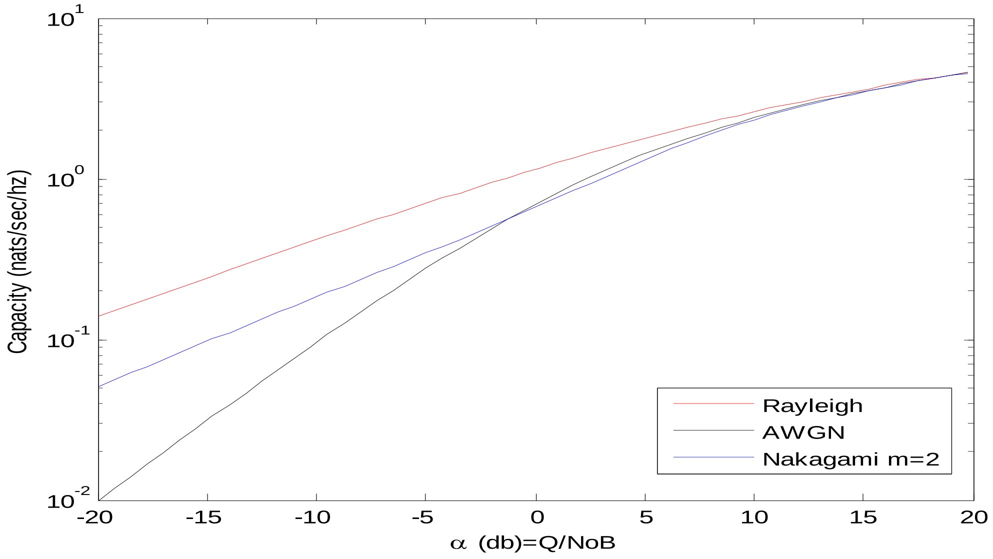


Fig 3.1 The analysis of the ergodic capacity of cognitive link with signal to noise ratio under average received power constraint

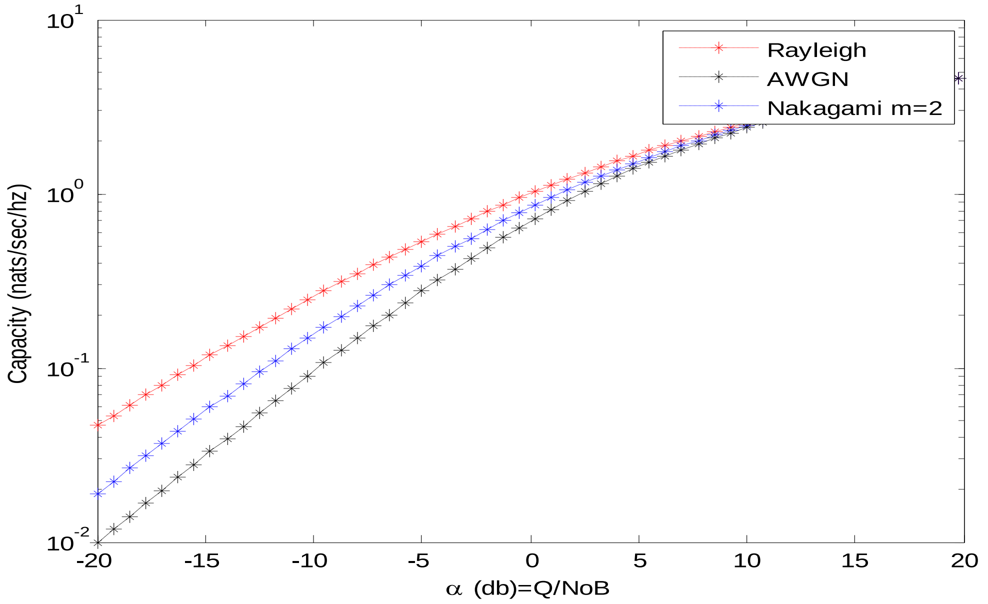


Fig 3.2 The analysis of the ergodic capacity with the signal to noise ratio under peak received power constraint

In fig. 3.2 , if there is fading between SU-Tx and PU-Rx then capacity of secondary link will increase. As the signal strength increases after 10 dB all channels capacity will tend to be same. On comparing both average and peak interference constraint it has been illustrated that the average interference constraints are better than the peak interference power constraints.

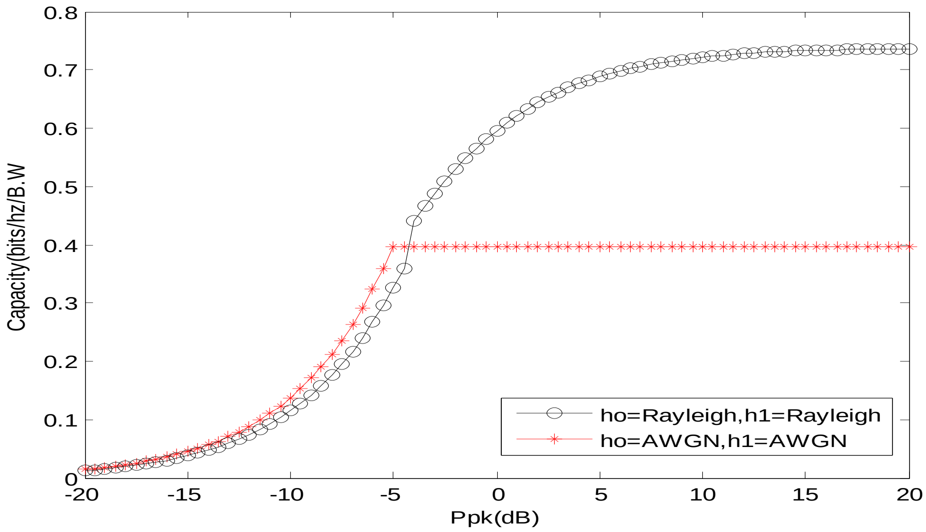


Fig 3.3 The analysis of the ergodic capacity with peak transmit power constraint for peak interference power is -5 dB over different fading channels

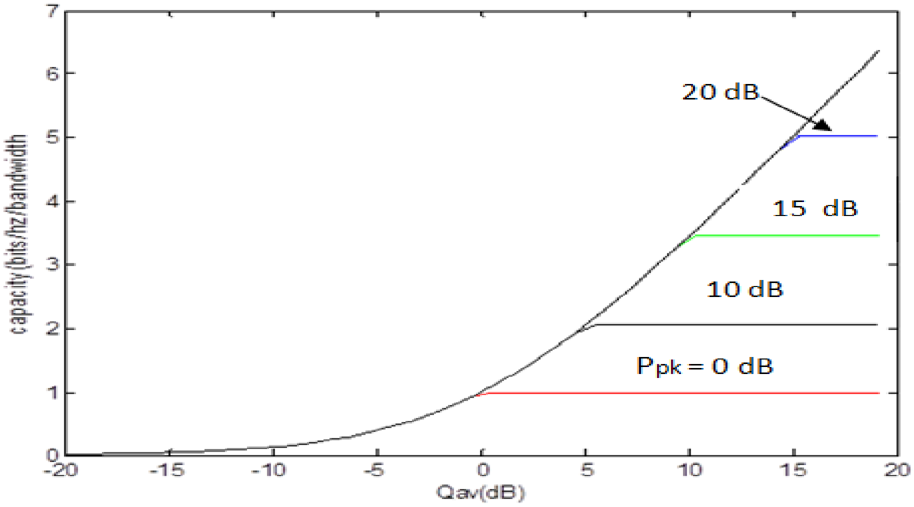


Fig 3.4 The analysis of the ergodic capacity under peak transmit power and average interference power constraints for different numerically chosen value of peak transmit power.

In Fig. 3.3, the peak interference power -5 dB is considered. It has been analyzed that at low transmit power, the capacity over AWGN channel is more as compared to fading channel upto peak interference power threshold i.e -5 dB. When both channels are AWGN, capacity of secondary link becomes constant after -5 dB and capacity of secondary link after -5 dB will increase if both channels are fading channel. If the peak interference power constraint is less, then over fading channel capacity of secondary link will start to increase at less peak transmit power. In Fig. 3.4,the ergodic capacity is analyzed with respect to average interference power constraint at different peak transmit power values over Rayleigh fading channels . It has been depicted that when peak transmit power is more as compared to average interference power, the ergodic capacity become constant. The capacity of the cognitive link can be increased with the increase of peak transmit power. Now, in next part the analysis of ergodic capacity with imperfect channel state information has been discussed. We have numerically simulated the ergodic capacity with or without the interference of PU-Tx to the CU link of the proposed cognitive radio network model. In Fig. 3.5, the ergodic capacity is computed without PU-Tx interference to the CU link with peak transmit power for different values of the error variance at arbitrary chosen peak interference power (-5 dB). The numerically simulated result for ergodic capacity of cognitive link with perfect channel state information between CU-Tx and PU-Rx is validated with reported literature [58]. However, if the peak transmits power is below the peak interference power then the ergodic capacity for different

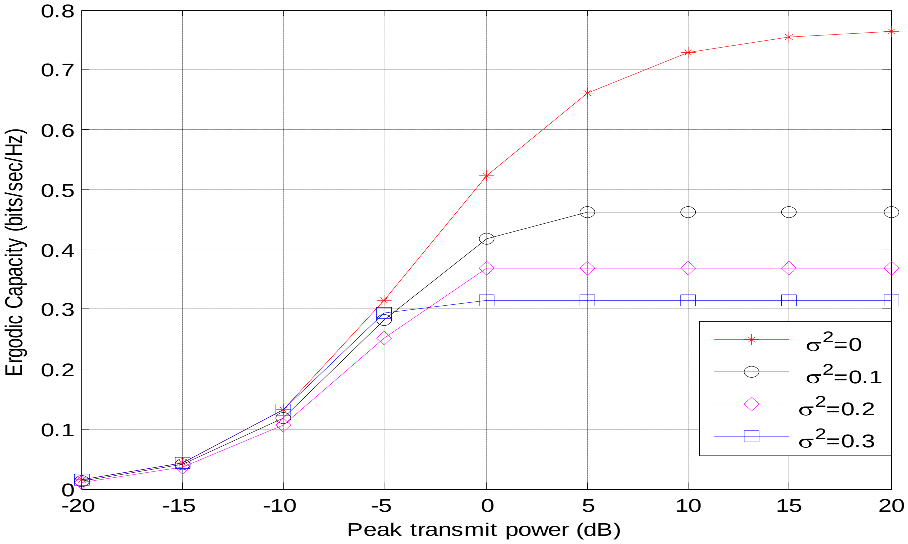


Fig 3.5 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak interference power (-5 dB).

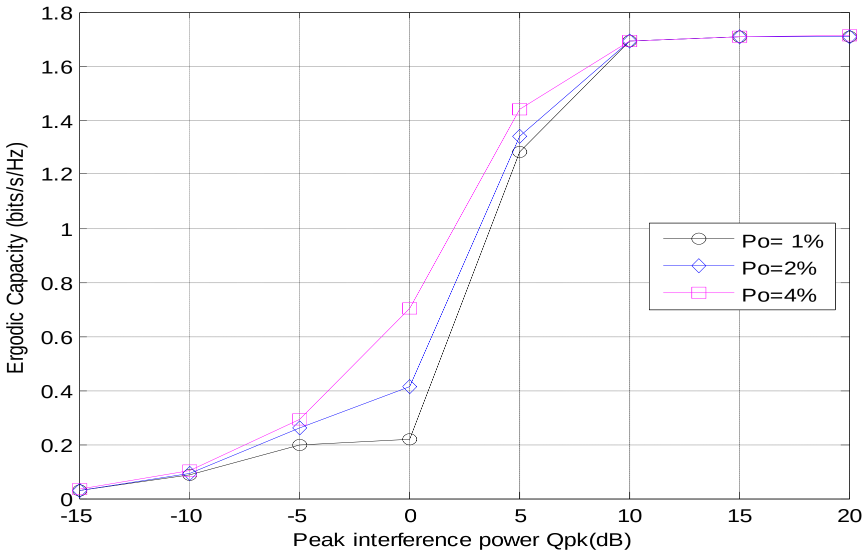


Fig 3.6 The response of peak interference power on the ergodic capacity (bits/s/Hz) for different values of the interference outage level at arbitrary chosen value of the peak transmit power (10 dB) and error variance 0.2.

channel conditions (various values of error variance) increases monotonically and above the peak interference power the ergodic capacity becomes constant gradually as shown in Fig. 3.5. In addition to this, it is also depicted that with the increase of noise variance, the ergodic capacity reduces in comparison to the perfect channel state information. In Fig. 3.6, the ergodic capacity is analyzed for different interference outage level with fixed noise variance 0.2. It is also presented that with the increase of interference outage level, the ergodic capacity level rises but when the peak transmit power is greater than that of peak interference power then there is no significant effect of increasing interference outage level. In addition to this, the average power expenditure of CU-Tx is investigated in Fig. 3.7 with the peak interference power for different combinations of interference outage level and noise error variance. It is also depicted that there is significantly more power consumption if the interference outage level rises for fixed error variance. On the other hand, if the interference level is fixed then with the increase of noise variance, the average power consumption of the CU decreases. Moreover, it reveals that with the increase of interference power constraint, the power consumption of CU-Tx is monotonically increased. The variation of ergodic capacity under the joint peak transmit power

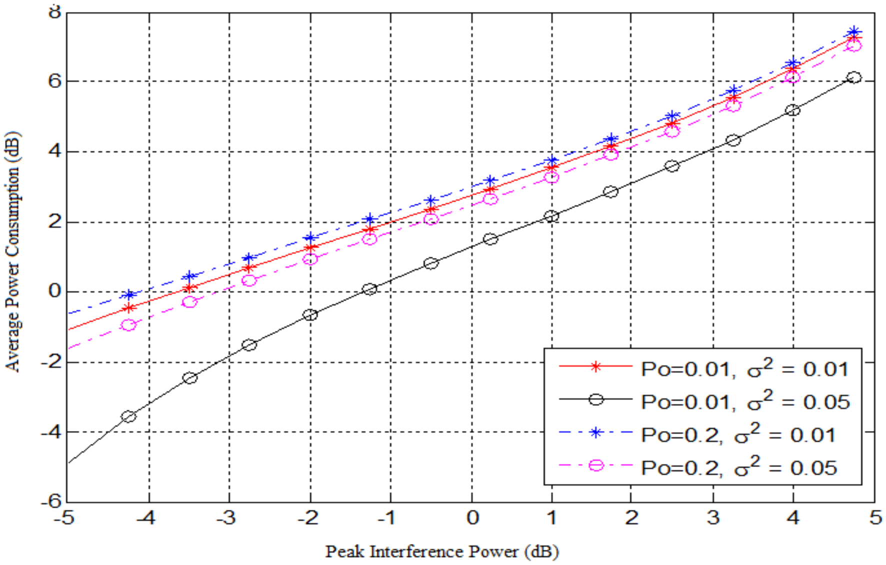


Fig 3.7 The average power consumption to achieve ergodic capacity limits of cognitive transmitter with different combination of interference outage level and error variance.

and average interference power constraints without consideration of interference of primary user is illustrated in Fig. 3.7. It has been illustrated that when the peak transmit power is more than the average interference power, there is variation in ergodic capacity with error variance. However, when the peak transmits power becomes less than that of the average interference power, the ergodic capacity for different error variance values remain same. In addition to this, the numerically simulated result of the ergodic capacity with perfect channel state information is validated with literature reported in [58].

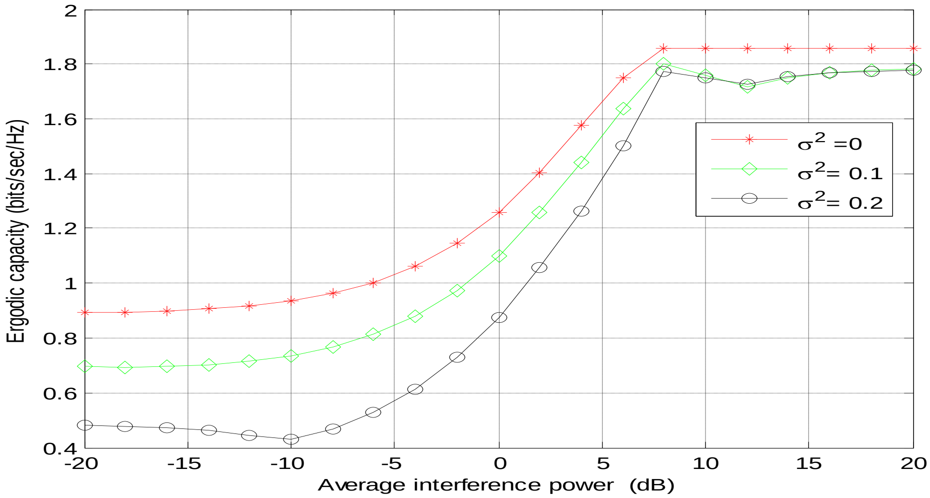


Fig 3.8 The response of average interference power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak transmit power (5 dB).

Moreover, the comparison of Fig. 3.5 and Fig 3.8 reveal that the average interference power constraint is better than that of the peak interference power constraint. The effects of interference of PUs on the ergodic capacity of CU link under the joint peak transmit power and peak interference power for different error variance is illustrated in Fig. 3.9. It is shown that as the interference of the PU to CU link increases, the ergodic capacity of the CU link decreases. With the comparison of Fig. 3.5 and Fig. 3.9 it is revealed that there is significant reduction in the ergodic capacity at the peak transmit power, the peak interference power and noise error variance 5 dB,-5 dB and 0.1, respectively. In addition to this it is analyzed that as the number of PUs increase above two then the reliable communication cannot achieve.

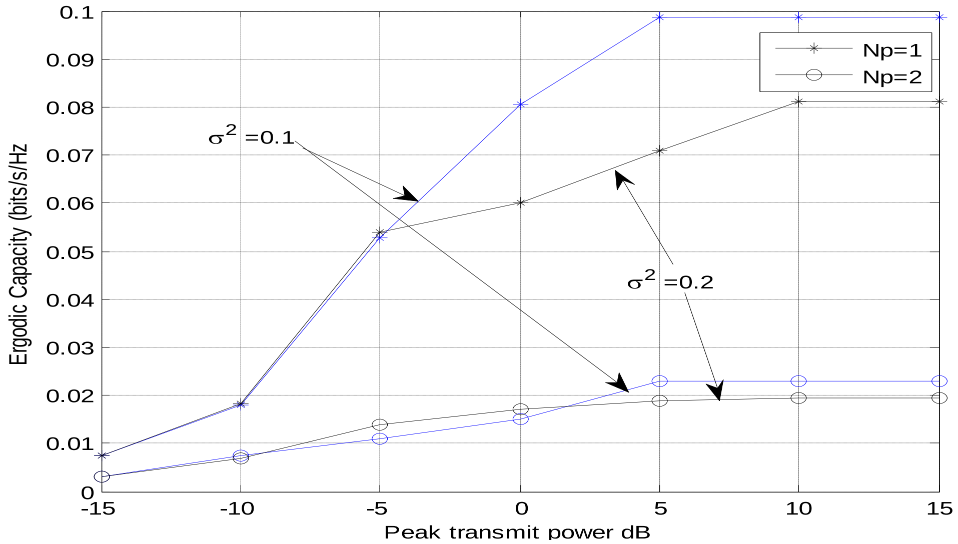


Fig 3.9 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) of cognitive user link with multiple primary users interference with arbitrary chosen values of the fixed peak interference power (-5 dB) with fixed noise variance $\sigma^2 = 0.1$ and $\sigma^2 = 0.2$

Summary

In this chapter, the ergodic capacity is analyzed with perfect channel state information and without perfect channel state information. It has been concluded that the severe fading between the cognitive transmitter and primary receiver is fruitful for the cognitive link. Moreover it has been illustrated that with the increase of noise variance capacity decreases and for reliable communication cognitive user cannot tolerate the interference more than four users.

CHAPTER 4

Framework for Spectrum Sharing in Cognitive Radio Network for Military Applications

4.1 Introduction

In this chapter, the dynamic spectrum accessing techniques — overlay, underlay and hybrid spectrum sharing approaches are exploited for the military communication. In addition to this, the importance of the energy efficiency of the military cognitive radio network system is also discussed. Moreover, we have also emphasized over the security threads and their mitigation. However, it is explored that the cross layer design of protocols is preferred for more energy efficiency and security. Recently, the innovation in wireless communication technologies for the commercial applications has been offer to the military. However, some potential requirements of the military communication are different from that of the commercial communication network such as lack of infrastructure, multi-hop networks, self-organizing networks, multiple heterogeneous networks in same geographical region and electromagnetic environment [71]. Due to the difference between the commercial and military communication requirements, more focus on the military communication establishment is required. The military communication technology mainly focuses on the efficient use of the bandwidth and the interoperability of equipment among the armed forces. The interoperability of communication system among armed forces is achieved by the software defined radio (SDR). The military communication is carried on the dedicated spectrum and this fixed spectrum allocation policy leads to the spectrum crunch. However, some spectrum bands of the commercial application are more desirable for the military applications such as ultra-high frequency (~500 to 700 MHz), which is used by the television (TV) broadcasters. The penetration power of this spectrum band is better and it provides better RF characteristics in comparison to that of the shorter wavelength. The Federal Communication Commission (FCC) survey has reported that most of the band of TV spectrum is underutilized and have opened the spectrum to cognitive user so that spectrum can be utilized properly [2].

For the spectrum sharing with opened channels and with all militants, the cognitive radio is an intelligent technology, which is the extension of SDR and defined as intelligent system that senses the environment and uses the methodology to learn about the sensed parameters. In addition to this, according to the environmental requirements, the cognitive radio system update its parameters such as modulation scheme, transmission power, frequency bands, network protocols etc. [57]. The multiple requirements of the military can be fulfilled by 5G commercial innovative technologies such as the device centric architectures, millimeter wave communication, massive MIMO, smarter devices, heterogeneous network deployment, flexible spectrum management and self-organizing networks. The research on all these technologies is under progress. Recently, European Union Commission has launched some projects, named as METIS-2020, 5GNOW, SOLDER etc, to implement such technologies [72].

The next generation innovative technologies for military communication should meet some challenges such as mitigation of interference, novel antenna technologies and energy efficient protocols. The fulfillment of these technologies truly benefit the current and next generation of war-fighters. The interference during spectrum sharing can be mitigated by using novel spectrum accessing technique. However, before discussion of spectrum sharing in military network, one important thing is to be discussed that is spectrum sensing, which is the first step of cognitive radio communication system. The spectrum sensing for military communication should be in secure way because it may be sensed the suspicious spectrum. The two main approaches of spectrum sensing are cooperative centralized and distributed spectrum sensing [12]. In the centralized spectrum sensing the complete sensed information is send to the fusion center and then the fusion center decides whether the sensed spectrum is secure or not. The centralized approach of spectrum sensing has some limitations such as if the fusion center is hacked by attackers then complete network will get down. On the other hand, in the distributed sensing approach all users exchange their sensed information with their self. However, the combination of centralized and distributed network will be fruitful for the military communication. The beacon signals for spectrum sensing should be encrypted so that the attackers or commercial user cannot come to know about the sensing action of military user. Recently, for secure spectrum sensing the dynamic trust management scheme is proposed which will detect and mitigate the spectrum sensing data falsification attacks in cooperative spectrum sensing [73]. The next step of cognitive radio after spectrum sensing is the spectrum accessing. Presently, in commercial wireless innovation, we are moving from static spectrum accessing to dynamic spectrum accessing for efficient spectrum utilization. Therefore, it is important to choose best spectrum accessing technique which not only supports the spectrum efficiency but also mitigate the interference. The dynamic spectrum accessing is broadly categorized into three parts as: 1) dynamic exclusive model, 2) open sharing model and 3) hierarchy access model [5].

In the dynamic exclusive model, the licensed spectrum is used for exclusive use only [12]. In the open sharing model, the unlicensed spectrum (ISM band) is shared between multiple unlicensed users and in hierarchy access model, the licensed and unlicensed user can share the spectrum. This accessing model is further categorized in to two categories such as: 1) spectrum underlay and 2) spectrum overlay accessing techniques [12]. Even for better results, the overlay and underlay approach can be combined. In the spectrum overlay approach, the cognitive user can access the band only if that is not used by the licensed user. However, in the spectrum underlay approach both licensed and unlicensed/cognitive user access the spectrum simultaneously but under the power constraints so that the unlicensed user cannot interfere with the licensed user. The spectrum accessing techniques with the different military communication scenarios is discussed in this article. During the emergency military has to carry the radio to disastrous places or borders, therefore, the minimization of power consumption of military radio during the spectrum sensing and spectrum sharing is also an important issue. The remainder of the chapter is organized as follows. In section 4.2 we have proposed the framework for the spectrum sharing in cognitive radio network for military applications. In section 4.3, the spectrum accessing techniques are discussed when the military user shares the ultra high frequency (UHF) band. Moreover, the spectrum accessing techniques has also described when the sharing is in between the military bands. In section 4.4, we have briefly described over the energy efficiency and security issues during spectrum sharing. In section 4.5, the conclusion with some energy issues in military communication has discussed.

4.2 Framework for the Military Cognitive Radio Network

However, the military has sufficient spectrum band for communication, recently in several countries military has opened their frequency band for commercial applications, but during the military troop deployment extra spectrum band is required to provide quality-of-service (QoS) and high data rates without latency. Therefore, for the spectrum sharing during the emergency, a framework has been proposed for military application. In normal days, the military does not prefer to share the unlicensed band even though UHF band is useful but during emergency if there is no free-spectrum band in the military communication spectrum then military communication network can share the unlicensed band or it can share the bands of different military networks. However, different spectrum sharing approaches and issues such energy efficiency and security are shown in

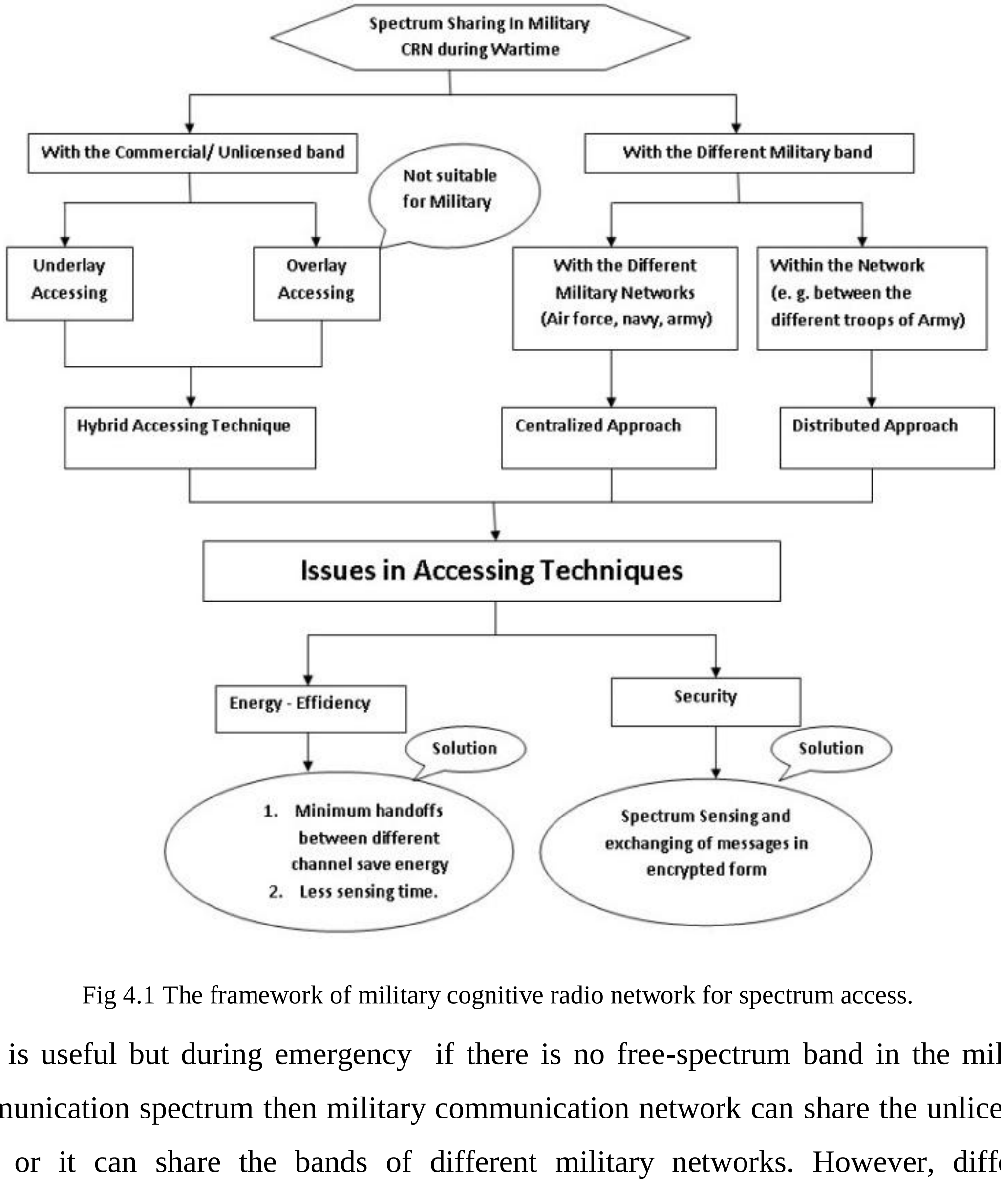


Fig 4.1 The framework of military cognitive radio network for spectrum access.

Fig. 4.1.The description of different spectrum sharing approaches and issues is described in section III , IV and V.

4.3 System Model

We have proposed two system models, 1) Spectrum sharing between the commercial and military users. 2) Spectrum sharing between the different military networks.

4.3.1 System Model- I

In this model, we have considered four cells as shown in Fig. 4.2, however the cell structure for military application is not specified but to study the spectrum management, we have considered two cells of commercial network (A and C) and two cells of the military network (B and D). In this model, the military user will appear as a cognitive user/unlicensed user with respect to the commercial user/primary user. The military user will share the spectrum with different spectrum accessing techniques over the Rayleigh fading channel condition. It has been considered that the partial channel state information is provided to cognitive user by the commercial user. In addition to this, it has been considered that all channels independent and identically distributed.

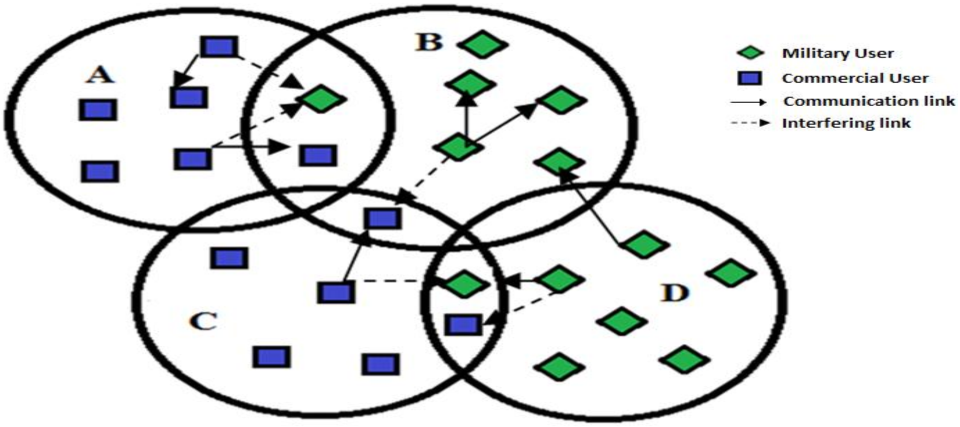


Fig 4.2 The proposed network model for spectrum sharing between the commercial and military band.

4.3.1.1 UNDERLAY ACCESSING TECHNIQUE

The commercial underlay accessing technique can be used for military spectrum sharing purpose with some modification. When this technique is used for commercial purpose, main consideration is the optimal power that should be allocated to the cognitive user so that it will not interfere with the licensed user. However, in case of military applications, the primary interest is not to avoid the interference to the licensed user spectrum but aim is to hide the military user's identity. The power allocated to cognitive user is under the noise floor of licensed user, which may benefit the military user because the military communication is carried out in attenuated environment with less power levels over wide-band spectrum [12]. Therefore, the communication of military users under the noise floor will hide their identity. For the proposed model, the power is allocated to military user under the peak/average interference power constraints at the licensed user, the peak transmit power constraints and signal-to-interference noise ratio constraint at the military user. The data rates achieved by military user over the faded channels when the spectrum sharing is under the peak transmit power and peak interference power constraints are shown in Fig. 4.3, which revealed that the average rate per unit bandwidth increase with the increase of transmit power even if the tolerance level of the licensed user is significantly less. It is depicted from the Fig. 4.3, at the numerically chosen value 0 dB transmit power 0.51 bits/s/Hz data rate is achieved. This result can prove better communication for the military because it performs over the wide-spectrum band. It is also depicted that sufficient data rate can be achieved even if there is more noise variance. Therefore, the spectrum underlay approach is more useful for the military communication.

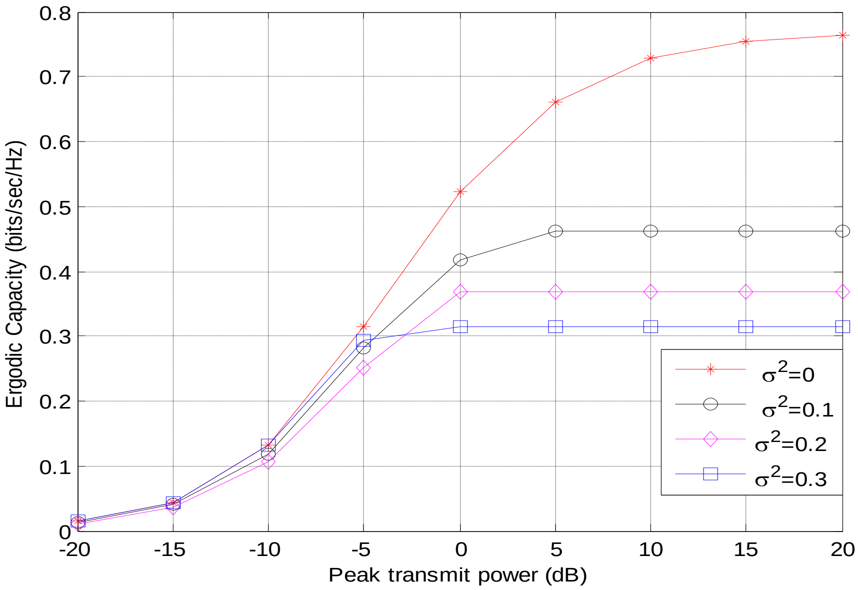


Fig 4.3 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak interference power (-5 dB).

4.3.1.2 OVERLAY ACCESSING TECHNIQUE

According to the overlay spectrum technique, the military user has to detect the free spectrum, if the spectrum is available then military user can access that spectrum otherwise it has to wait for spectrum. However, during emergency military user cannot wait for the spectrum to get free. Therefore, this spectrum sharing technique is not desirable for the proposed system model.

4.3.1.2 DYNAMIC HYBRID ACCESSING TECHNIQUE

In addition, to underlay and overlay accessing techniques, a new spectrum accessing technique has been reported in the literature [29] such as hybrid spectrum accessing technique, which provides higher spectral efficiency in comparison to the overlay/underlay spectrum accessing techniques. Moreover, Chen and Lei [74] has been proposed a "*dynamic allocation hybrid sharing transmission mode of overlay and underlay"* algorithm for dynamic spectrum allocation, which support heterogeneous services over the cognitive radio network. However, the implementation of this algorithm maximizes the total capacity of the military link while maintaining the total power budget. According to this algorithm, the cognitive user senses the orthogonal frequency division multiple access (OFDM) channels, where some channels may be idle and some may be busy. Therefore, the spectrum underlay accessing technique is preferred over the busy channel and spectrum overlay accessing technique is used over the idle channel, which increases the overall capacity of the cognitive link. Furthermore, this algorithm is suitable for the proposed system model. With this spectrum accessing technique, the military users have not to wait to access the spectrum, it can switch from underlay to overlay accessing technique as per the availability of the spectrum bands. It is demonstrated in Fig. 4.4 that if the large number of licensed sub channels are available then throughput of the military user link is significantly increased. In addition to this, it has been also illustrated that the dynamic allocation hybrid sharing transmission mode of overlay and underlay is best in best in comparison to the overlay sharing algorithm and hybrid underlay and overlay algorithm. Hence, this algorithm is more suitable for military applications.

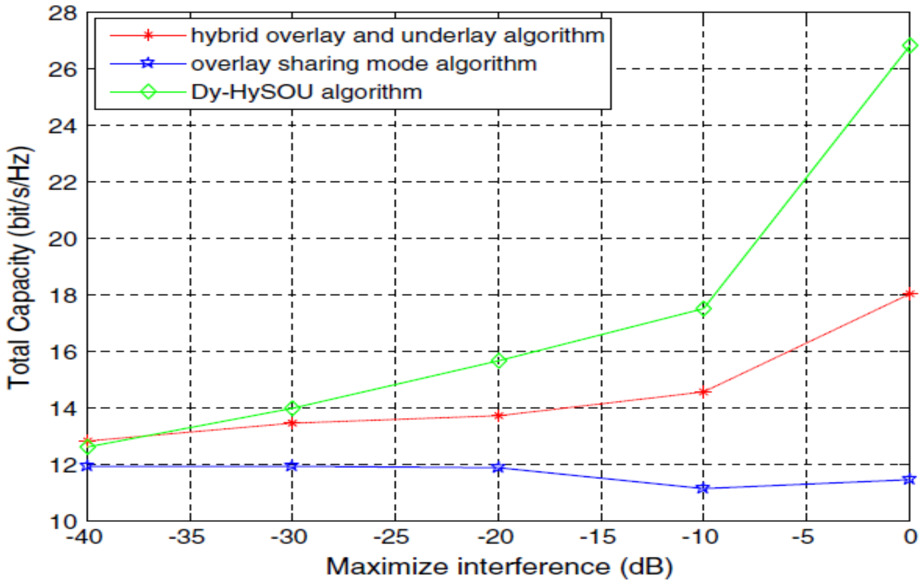


Fig 4.4 The analysis of the total capacity of the military link with the variation of interference level of licensed user [74].

4.3.2 System Model-II

In this model, we have considered three networks- air force, naval network and army network, which are connected to each other via the control center. In each network, intelligent radio systems are deployed. According to the demand of the spectrum, one network is act as an unlicensed network with respect to the other. However, the spectrum allocation to particular troop is decided from the control center. There is exchange of information between the different control centers. On the basis of coordination, the spectrum sharing techniques are broadly categorized as [12]: 1) Centralized Spectrum Sharing and 2) Distributed spectrum sharing.

4.3.2.1 CENTRALIZED SPECTRUM SHARING TECHNIQUES

In the centralized spectrum sharing, there is one centralized node which decides the spectrum allocation to all the users in cognitive radio network. All the cognitive radio systems in the network sense the environment and send their sensed channel information to the centralized node and then centralized node decide which spectrum band has to be allocated to the cognitive user. This same policy of spectrum allocation can be used in military, where all different networks send their request to the control center for the demand of spectrum. In the control center after proper analysis of sensed information, free spectrum band is allocated to the requesting network. For the model shown in Fig.

4.5 the opportunistic spectrum accessing technique can be utilized. If any military network is not using their complete military communication bands then it can offer this to requesting military network. The geo-location database approach is the example of centralized spectrum sharing approach [12].

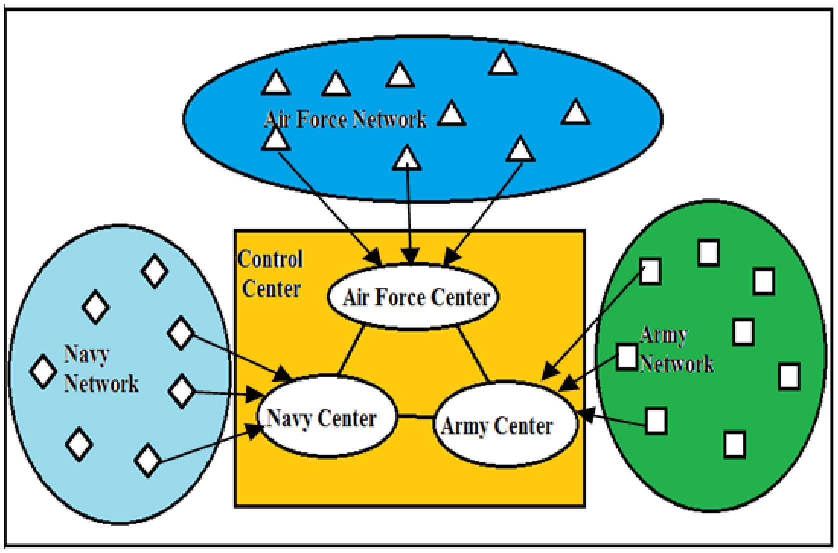


Fig 4.5 The proposed model of spectrum sharing between three different military networks

4.3.2.2 DISTRIBUTED SPECTRUM SHARING TECHNIQUES

Moreover, the distributed spectrum sharing approach is also useful for the coordination between the all cognitive users in the network. In this, all the cognitive users are active and have complete information (operating frequency, location of cognitive user) about the other nodes. According to this approach, all the cognitive users are independent to exchange the information between them. The p*eer-to-peer coexistence* protocol is one of the examples of distributed spectrum sharing [12]. According to this protocol, messages will be exchanged between the spectrum sharing systems via well defined interface. In the distributed spectrum sharing, the exchanging of information between the trusty nodes is important. Therefore, the message exchanging should be in encrypted form so that the assaulter cannot decrypt that message. It is a security issue which is discussed in section IV. In Fig. 4.6, we have considered a distributed army network where *A*, *B*, *C* and *D* military troops are in war zone, *E*, *F* are in alert zone and *G* is in the safe zone. In this, it is considered that every troop has the complete information about the other troop. Therefore, if there is attack on *A*, *B*, *C* troop then there is requirement of high data rates for the quicker exchange of information in order to help the soldiers and save the life of soldiers. Because of the limited spectrum availability of a particular troop high data rates is not achieved. Therefore, there is requirement of large bandwidth to reduce the latency in communication. Consequently, it is appropriate to utilize the spectrum of the troop which is in safe zone, so troop *A* will share the spectrum with troop *G* by using opportunistic spectrum accessing technique. On the other hand, if it is happened that the complete army network is in alert zone then army troop can share the spectrum with other military network as shown in Fig. 4.5. Hence the combination of centralized and decentralized approach is proved to be fruitful for military communication.

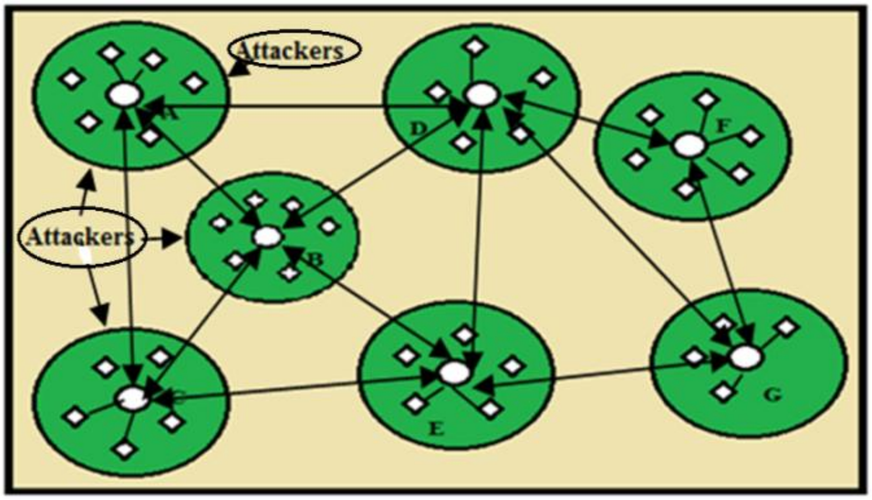


Fig 4.6 The decentralized spectrum sharing in the army network.

4.4 Energy Efficiency During Dynamic Spectrum Access

In addition to the spectrum sharing issue, the energy efficiency is also very crucial issues of the military cognitive radio communication network, which have been presented in this section. The energy efficiency of the cognitive radio communication network system is mainly depends on the operations on following three layers of OSI (open system interconnection) model: 1) Physical layer, 2) MAC layer and 3) Network layer. However, the energy consumption in these layers can be significantly improved by using coordinated energy management approach [75]. At the time of military troops, the communication systems have to be significantly high data-rate transmission/reception with long battery life. According to the cognitive cycle proposed by Mitola [12] such as the sense→ decision→ adapt, there is more power consumption at each stages. For the spectrum sensing, two energy efficient approaches have been proposed in reported literature [76]. One is the confidence voting and other is cluster-collect forward, however in the present article, we have emphasized on the power consumption during dynamic spectrum access/opportunistic spectrum access. During the spectrum sharing, there is power consumption when the cognitive radio communication system hand-off takes place. However, there is significantly more power consumption during hand-offs, therefore it is important to design an energy efficient algorithm by which less energy is consumed during the spectrum sharing. As we have discussed aforementioned, the main objective of spectrum sharing is to provide efficient bandwidth to the military user in order to achieve high data rates. With the increase of data rates, the power consumption of the communication system is increased. Therefore, it is important to maintain the trade-off between the data rates and power consumption of cognitive radio communication system. The military cognitive radio systems demand for spectrum sharing protocols, which supports the energy efficient as well as high data rates transmission/reception systems. For the commercial applications, the optimization power allocation technique to achieve high energy efficiency and high data rates is reported in literature [77] and the authors have reported the energy efficiency under hybrid spectrum sharing technique of the cognitive radio system, which is increased at the cost of throughput. However, this technique is not fruitful for the military communication but the approach proposed by Song in [78], for the maximization of energy efficiency and throughput of the cognitive radio system can be utilized for military communication system. Therefore, for energy efficient military cognitive radio system, the energy efficient protocols have to be designed which maximizes the signal-to-noise ratio (SNR), data rates and minimize the power consumption of cognitive radio system.

4.5 Security During Dynamic Spectrum Access

Apart from the energy efficiency issue during the spectrum sharing, secure communication is also a crucial issue. In the aforementioned discussion several spectrum sharing approaches have been discussed such as underlay, overlay, hybrid, centralized and decentralized. With different spectrum sharing approaches, several types of security attacks come into picture such as: 1) Denial of service attack 2) Primary user emulation attack and 3) Belief manipulation attack [79]. In the centralized cognitive radio network, the chances of masquerade attack are significantly high. The attack on central node can damage the complete cognitive radio network. However, this attack can be reduced by distributing the encryption key to the entire cognitive users, which results the jamming of attack to common control channel. With reference to such attack, Xu et al [80] have proposed two strategies for the defense services such as: 1) Link layer defense (switching to different channel by frequency hopping technique) and 2) Network layer defense (legal user's change their position form the interference imposed by attackers). The switching to adversary's channel can happen because of the lack of security; therefore the chances of primary user emulation attack are high. The remedy for this attack is provided by public key certificates. The cognitive users have to follow the public key certificate which is digitally signed by licensed user [81]. However, the coordination between all cognitive users can improve the accuracy of detection. With the updating of cognitive radio system parameters such as modulation scheme, frequency of operation and transmit power, the probability of belief manipulation attack increases. However, if the attacker come to know that the cognitive radio system is maximizing its throughput or any other performance metric, it will generate manipulated parameters therefore it cannot maximize the performance metric. As per the author's knowledge, for the belief manipulation attack so far no effective remedy is provided. Moreover, all these attacks took place at different OSI layers, therefore to overcome all these attacks, the cross-layer security protocols have to be proposed, which will overcome all the attacks. In [81], the binary trust based defensive protocol has been proposed for the cross-layer security. Therefore, for secure military cognitive radio network, protocol designer have to focus on the cross layer design of protocols.

Summary

Cognitive radio systems are emerged as a potential tool for the military communication networks. The efficient spectrum sharing approaches overcome the spectrum scarcity problem in the military networks during emergency. Moreover, the energy efficient protocols of cognitive radio system improve the power efficiency of the communication system. The intelligent behavior of the cognitive radio system is also helpful to diffuse the bombs which are controlled through electromagnetic waves. The interoperability and reconfigurability of the cognitive radio system replaces the multiple radios in military by a single radio system. For the military communication the more emphasize is on the cross layer protocols design for energy efficiency and security.

CHAPTER 5
Conclusion and Future Scope

5.1 Conclusion

In this chapter, the conclusion of the analysis of ergodic capacity and outage capacity with and without perfect channel state information for proposed system spectrum sharing model of cognitive radio network has been discussed. It has been illustrated that for slow fading channel, the performance metric outage capacity has to be preferred. Moreover, the analysis of the outage capacity/ outage probability with power constraints illustrated that if the power allocation is under the constraints then the chances of cognitive link to get in outage decreases. It has also been concluded that as the interference from the primary users increase it also responsible for the system to enter in outage. Therefore, the overall outage capacity of the cognitive link will decrease. In the same way, for the fast fading channels the ergodic capacity notion has been analyzed. It has been illustrated in chapter 3 that if more number of primary users interfere with the cognitive link then the cognitive link fails to provide reliable communication. Furthermore, it has been illustrated that with the increase of noise variance in channel estimation the ergodic capacity of cognitive link decreases but it has also been analyzed the ergodic capacity increases as the peak transmit power is less than the peak/average interference power. In last chapter 4, the scope of the cognitive radio network for military communication has been discussed. It has been concluded that for the military communication the designing of the algorithm should be cross layer design. It is preferable to use hybrid accessing technique in the military cognitive radio network. The security and energy based protocols are most demanding for the military communication.

5.2 Future Scope

The optimal power allocation in underlay accessing technique has been greatly explored but still the analysis of the cognitive radio network in the generalized fading channel and sharing among the multiple secondary users is a crucial issue. It is important to analyze that how many optimum number of secondary users can share the one channel at a time without deteriorating the QoS of the primary user over the generalized fading channel.

APPENDIX

In the wireless communication, due to the multipath propagation there is fluctuation in amplitudes, phases or multipath delays of a radio signal over a short/long period of time which is called as small/large scale fading [82]. Fading is caused due to the interference of two or more multipath signals coming at the receiver. Fading is good if there is constructive interference otherwise it deteriorates the signal. In this dissertation the main consideration is of small scale fading. Small scale fading is categorized in to two parts due to multipath time delay spread such as flat fading and frequency selective fading and on the basis of Doppler spread such as fast fading and slow fading. Therefore, if there is fading in the environment the Shanon capacity notion cannot be used to analyze the performance metric. Shanon capacity theorem is valid only for AWGN channel. Therefore, to analyze the performance of fading environment in terms of capacity, different capacity notions are used such as ergodic capacity and outage capacity.

Ergodic Capacity is the average of the maximum achievable rate over the fading blocks. It is preferable in the fast fading environment. In the similar way, for the slow fading channel outage capacity notion is used which is defined as maximum rate achieved over the channel when the channel realization rate is less than the transmitter's decode rate. When the communication link has AWGN channel condition then ergodic capacity can be described by Shanon Capacity theorem [69] as represented below:

$$C_{awgn} = B\log_2(1+SNR) \tag{A.1}$$

Moreover, when we deal with the fading channel conditions, the knowledge of the fading distribution is important. Therefore, the channel power gain having gamma distribution is expressed as follows [82]:

$$\mathrm{f(x)} = \frac{\mathrm{m^m x^{m-1}}}{\Gamma \mathrm{m}} \mathrm{e^{-mx}}, \mathrm{x} \geq 0 \tag{A.2}$$

For *Nakagami-m fading channel*, *m* = 2. where '*m*' is defined as the ratio of line of sight signal power to that of the multipath component and '*x*' is an random variable. Moreover, for *Rayleigh fading channel*, *m* = 1. Therefore, the distribution of the channel power gain over Rayleigh fading channel is expressed as follows:

$$f(x) = e^{-x}, x \geq 0 \tag{A.3}$$

Furthermore, for the log normal fading environment, the channel power gain g_o and g_1 is modeled by a log normal random variable $\boldsymbol{e^{X_o}}$ and $\boldsymbol{e^{X_1}}$. X_o and X_1 are independently distributed with zero mean and variance σ^2. $\frac{g_o}{g_1} = e^Y, Y = X_o - X_1$ being a zero-mean Gaussian random variable with a variance of $2\sigma^{2.}$ Channel capacity of secondary link depends on the joint channel statistics through g_1/g_o with pdf $\mathbf{f_{g1/go}(.)}$. The table for the conditional pdf and independent pdf of different fading channel is shown below

g_0	f_{g_0}	g_1	f_{g_1}	$f_{g_1/g_0}(x)$
Rayleigh	$e^{-g_o}, g_o \geq 0$	*Rayleigh*	$e^{-g_1}, g_1 \geq 0$	$\frac{1}{(1+x)^2}, x \geq 0$
Nakagami	$4\, g_o e^{-2g_o}, g_o \geq 0,$	Nakagami m=2	$4\, g_o e^{-2g_o}, g_o \geq 0,$	$\frac{x}{\beta(2,2)(x-1)^4}, x \geq 0$
Log − normal shadowing	$e^{-g_o}, g_o \geq 0$	*Log − normal shadowing*	$e^{-g_1}, g_1 \geq 0$	$\frac{(e^{-\frac{x^2}{4\sigma^2}})}{2\sqrt{\pi}}, x \geq 0$

Project Implementation Code

Simulation Tool: Matlab, Maple

Code1:

Fig 2.2 The analysis of the outage probability with the peak interference power with the peak transmit power 10 dB

```
%% Outage probability with peak interference power constraint and peak transmit power constraint

clc
```

```
clear all
close all
Qpk=-20:20;
Q=10.^(Qpk./10);
Ppk=10;
P=10.^(Ppk./10);
for jj=1:length(Q)
 syms g1
aa= erf(0.707*sqrt(g1*Q(jj)));
Pw=int((aa*exp(-g1)),1/P,inf);
Pwr(jj)=1-(Pw);
Praly(jj)=1-exp(-1/P)+(exp(-(Q(jj)+1)./P))/(Q(jj)+1);
y=(2*Q(jj)+1)/P;
Png_rl(jj)=1+(exp(-y)/(2*Q(jj)+1))*((2*Q(jj))/P + (2*Q(jj)/(2*Q(jj)+1))+ 1)-exp(-1/P);
end
Pwr=double(Pwr);
Y=plot(Qpk,Pwr,'--ko');
hold on;
Y1=plot(Qpk,Praly,'--r*');
hold on;
Y2=plot(Qpk,Png_rl,'--b^');
%title('Outage Probability under Peak or Average interference power constraint');
xlabel('Qpk(dB)');
ylabel('Pout');
legend([Y Y1 Y2], 'gsp:AWGN,gss:Rayleigh'
,'gsp:Rayleigh,gss:Rayleigh','gsp:Nakagami(m=2),gss:Rayleigh');
```

Code 2:

Fig 2.3 The outage probability analysis with the interference power constraints for different values of peak transmit power 0 dB and 10 dB.

```
%%Outage probability under peak or average interference power constraint
clc
clear all
close all
Qavg=-20:15;
Q=10.^(Qavg./10);
Ppk=[0 10];
P=10.^(Ppk./10);
plotstyle={'--ro','--ko'};
for ii=1:length(P)
for jj=1:length(Q)
    syms go g1
    Ld=sqrt(1/(exp(2*Q(jj))-1))
    aa=int((exp(-go)*exp(-g1)),go,0,g1/Ld);
    bb=int(aa,g1,1/P(ii),inf);
```

```
   Pr(jj)=1-double(bb);
end
Y=plot(Qavg,Pr,plotstyle{ii});
hold on;
end
% %%Outage probability under average interference power constraint
Ppk=-20:10;
P=10.^(Ppk./10);
Qpk=[0 10];
Q=10.^(Qpk./10);
plotstyle={'--b*','--g*'};
 for ii=1:length(Q)
for jj=1:length(P)
   syms  g1
  zz=int(exp(-g1),1/P(jj),inf);
  ww=int(exp(-g1*(Q(ii)+1)),1/P(jj),inf);
  yy=double(zz)-double(ww);

   Pr1(jj)=1-yy;
end
Y1 =plot(Ppk,Pr1,plotstyle{ii});
%hold on;
 end
xlabel('Interference Power Constraint (dB)');
ylabel('Pout');
%title('Outage Probability under Peak or Average Interefernce Power Constraint');
legend([Y Y1],'Qavg','Qpk');
```

Code 3:

Fig 2.4 (a) The effects of variance on the outage probability at arbitrary chosen value of the peak transmit power 10 dB and fixed data transmission rate (r0 = 1 bits/sec/Hz) under (a) peak interference power and

```
clc
clear all
close all
Po=0.1;sig=[0 0.1 0.2 0.3] ;
Ppk=10; % in db
P=10^(Ppk/10);
Qpk=0:1:20;
Q=10.^(Qpk./10);
NoB=1; % assumption NoB=1;
%gss=1; % perfect information of secondary channel
ro=1;
plotst={'-r*','-bo','-g^','-ks'};
```

```
for k=1:length(sig)
for jj=1:length(Q)
    syms gsp gss;
    t1=(2^(ro)-1)/P;
    t2=gss*Q(jj)+(sig(k)*log(Po));
    I1=int(exp(-gsp/(1-sig(k))),0,t2);
    I2=int(I1*exp(-(gss)),t1,inf);
    ww=abs(double(I2)/(1-sig(k)));
    C(jj)=1-ww;
end

Y(k,:)=semilogy(Qpk,C,plotst{k});
hold on;
xlabel('Peak interference power Qpk (dB) ');
ylabel('Outage probability');
grid on;
axis([0,20,10^-1.5,10^0]);
C1=gaminv((1-C),1,1);
W(k,:)=log2(1+C1.*Q);
grid on;
end
legend([Y(1,:), Y(2,:), Y(3,:)
,Y(4,:)],'\sigma^2=0','\sigma^2=0.1','\sigma^2=0.2','\sigma^2=0.3');
```

Code 4

Fig 2.4 (b) The effects of variance on the outage probability at arbitrary chosen value of the peak transmit power 10 dB and fixed data transmission rate (r0 = 1 bits/sec/Hz) under (b) average interference constraints.

```
clc
clear all
syms gsp gss Ld
Qavg=-5:5:20;
Q=10.^(Qavg./10);
Ppk=10;
P=10.^(Ppk./10);
s=[0 0.05 0.1 0.12];
plotst={'-r*','-bs','-ko','-md'}
for k=1:length(s)
for jj=1:length(Q)
    sig=s(k);
    A=1-sig;
    syms L
    gss=1/P;
    bb=expint(-(L+1)*gss/(A*L));
    pavg=+exp(sig/A)*bb-expint(-gss);
```

```
    qq=(A*L+1)*(A-sig)*expint(-(A*L*gss+gss)/(A*L));
    qq1=-A*exp(-gss*((1/(A*L))+1));
    W=(exp(sig/A)*(qq+qq1))/(A*L+1)-(A*expint(-gss));
   L1=solve(W+sig*pavg-Q(jj))
   Y=abs(double(L1));
   tt=(A*Y)*exp((sig/A)-(gss*(A*Y+1)/(A*Y)));

   tt3(jj)=exp(-gss)-tt/(A*Y+1)
    Pr(jj)=1-tt3(jj)

end
Y(k,:)=plot(Qavg,Pr,plotst{k});
hold on;
axis([-5,20,0,1]);
grid on;
xlabel('Average interference constraint Qavg (dB)');
ylabel('Outage probability');
Pr1=gaminv((1-Pr),1,1)
W1(k,:)=log2(1+Pr1.*Q);
end
legend([Y(1,:), Y(2,:), Y(3,:),Y(4,:)
],'\sigma^2=0','\sigma^2=0.05','\sigma^2=0.1','\sigma^2=0.12');
```

Code 5:

Fig 2.5 (a) The effect of peak transmit power on the outage probability for arbitrary chosen value of the peak interference power 5 dB and fixed data transmission rate (r0= 1 bits/sec/Hz) with (a) different values of the variance

```
clc
clear all
close all
Po=0.2;sig=[0 0.1 0.2 0.3] ;
Qpk=5; % in db
Q=10^(Qpk/10);
Ppk=0:1:20;
P=10.^(Ppk./10);
NoB=1; % assumption NoB=1;
%gss=1; % perfect information of secondary channel
ro=1;
plotst={'-r*','-bo','-g^','-ks'};
for k=1:length(sig)
for jj=1:length(P)
    syms gsp gss;

    t1=(2^(ro)-1)/P(jj);
    t2=gss*Q+(sig(k)*log(Po));
```

```
    I1=int(exp(-gsp/(1-sig(k))),0,t2);
    I2=int(I1*exp(-(gss)),t1,inf);
    ww=abs(double(I2)/(1-sig(k)));
    C(jj)=1-ww;
end
Y(k,:)=semilogy(Ppk,C,plotst{k});
hold on;
xlabel('Peak transmit power Ppk');
ylabel('Outage probability');
end
legend([Y(1,:), Y(2,:), Y(3,:)
,Y(4,:)],'\sigma^2=0','\sigma^2=0.1','\sigma^2=0.2','\sigma^2=0.3');
```

Code 6

Fig 2.5 (b) The effect of peak transmit power on the outage probability for arbitrary chosen value of the peak interference power 5 dB and fixed data transmission rate (r0= 1 bits/sec/Hz) with (b) different values of outage constraint

```
clc
clear all
close all
Po=[0.1 0.2 0.3];sig=0.2 ;
Qpk=5; % in db
Q=10^(Qpk/10);
Ppk=0:1:20;
P=10.^(Ppk./10);
NoB=1; % assumption NoB=1;
%gss=1; % perfect information of secondary channel
ro=1;
plotst={'-r*','-bo','-g^'};
for k=1:length(Po)
for jj=1:length(P)
    syms gsp gss;

    t1=(2^(ro)-1)/P(jj);
    t2=gss*Q+(sig*log(Po(k)));
    I1=int(exp(-gsp/(1-sig)),0,t2);
    I2=int(I1*exp(-(gss)),t1,inf);
    ww=abs(double(I2)/(1-sig));
    C(jj)=1-ww;
end
Y(k,:)=semilogy(Ppk,C,plotst{k});
hold on;
xlabel('Peak transmit power Ppk (dB)');
ylabel('Outage probability');
grid on;
```

```
axis([0,20,10^-1,10^0]);
end
legend([Y(1,:), Y(2,:), Y(3,:)],'Po=0.1','Po=0.2','Po=0.3');
```

Code 7:

Fig 2.7 The outage probability versus peak interference power for different values of the variance when peak transmit power is fixed at 10 dB

```
%% outage capacity interefernce from primary user is considered
% Program is evaluated in maple
clc
clear all
close all
Q=[0 2 5 7 10 12 15 17 20];
Pp=10;Ppk=10;
OC1=[0.9556 0.82292 0.7368 0.677371 0.6023 0.57029 0.550398 0.5478 0.547582] % sig=0
OC2=[0.977319 0.862168 0.7574 0.68726 0.6025 0.5687 0.5497 0.5477 0.54758]; % sig=0.1
OC3=[0.99823 0.9197 0.78702 0.7013 0.6031 0.5671 0.54917 0.54768 0.54758]; % sig=0.2
OC4=[1 1 0.83244 0.7224 0.60434 0.56539 0.54866 0.547633 0.54758]; %sig=0.3
Y1=semilogy(Q,OC1,'-*r');hold on;
Y2=semilogy(Q,OC2,'-gd');hold on;
Y3=semilogy(Q,OC3,'-ok');hold on;
Y4=semilogy(Q,OC4,'-bs');hold on;
axis([0,20,0.4,1]);
grid on;
xlabel('Peak interference power Qpk ');
ylabel('Outage probability');
legend([Y1,Y2,Y3,Y4],'\sigma^2=0','\sigma^2=0.1','\sigma^2=0.2','\sigma^2=0.3');
```

Code 8:

Fig 2.8(a) The outage probability of cognitive user link with multiple primary users interference with variation in the peak interference power for chosen value of peak transmit power (10 dB) with fixed σ2 = 0 and σ2 = 0.1 under (a) peak transmit power and peak interference constraints and

```
% Calculation is done in maple
clc
clear all
close all
%Po=0.2, Ppk=10,Pp=10,NoB=1,ro=1,sig=0
Q=0:5:20;
N1=[0.850665 0.675 0.44125 0.22629 0.0927];
N2=[0.93529 0.8507 0.7472 0.7011 0.69838];
N4=[0.9692 0.92246 0.8555 0.8212  0.819033];
```

```
plotst={'-r*','-bo','-g^'};
 figure(1)
Y1= plot(Q,N1,'-r*');
hold on;
Y2= plot(Q,N2,'-ro');
hold on;Y3= plot(Q,N4,'-rd');
hold on;
xlabel('Peak interference power Qpk with \sigma^2 =0');
ylabel('Outage probability');
%%
%Po=0.2, Ppk=10,Pp=10,NoB=1,ro=1,sig=0.1
N1=[0.92232 0.7574 0.6025 0.5497 0.5475];
N2=[0.97472 0.86877 0.74786 0.7005 0.69838];
N4=[0.995056 0.93577 0.82077 0.8190 0.81903];
% figure(2)
Y1= plot(Q,N1,'--b*');
hold on;
Y2= plot(Q,N2,'--bo');
hold on;Y3= plot(Q,N4,'--bd');
hold on;
xlabel('Peak interference power Qpk');
ylabel('Outage probability');
legend([Y1,Y2,Y3],'Np=1','Np=2','Np=4');
grid on;
```

Code 9:

Fig.2.8 (b) The outage probability of cognitive user link with multiple primary users interference with variation in the peak interference power for chosen value of peak transmit power (10 dB) with fixed σ2 = 0 and σ2 = 0.1 under (b) peak interference only.

```
%% Outage probability under peak interference constraints only
clc
clear all
close all
Pp=10; m=[ 1 2 3]; ro=1;Q=-20:5:15;sig=0;po=log(0.1);B=1/(1-sig);
Qpk=10.^(0.1*Q);
plotst={'-r*','-ko','-gd','-c^'}
for kk=1:length(m)
    n=m(kk);
for jj=1:length(Qpk)

    syms gsp gss gps
     A=(2^(ro)-1)*(1+n*gps*Pp)*(gsp-sig*log(po))/(Qpk(jj));
    Pr1= int(exp(-B*gsp)*B*exp(-gss)*(n*exp(-gps)*(1-exp(-gps))^(n-1)),gss,0,A);
    Pr2=int(Pr1,gsp,0.001,inf);
    Pr2=int(Pr2,gps,0.01,inf);
```

```
    Pr(jj)=double(Pr2)
end
semilogy(Q,Pr,plotst{kk});
end
xlabel('Peak received interference Qpk (dB)');
ylabel('OutageProbability');
figure
sig=0.1
for kk=1:length(n)
    n=m(kk);
for jj=1:length(Qpk)

    syms gsp gss gps
     A=(2^(ro)-1)*(1+n*gps*Pp)*(gsp-sig*log(po))/(Qpk(jj));
    Pr1= int(exp(-B*gsp)*B*exp(-gss)*(n*exp(-gps)*(1-exp(-gps))^(n-1)),gss,0,A);
    Pr2=int(Pr1,gsp,0.001,inf);
    Pr2=int(Pr2,gps,0.001,inf);
    Pr(jj)=double(Pr2)
end
semilogy(Q,Pr,plotst{kk});
end
xlabel('Peak received interference Qpk (dB)');
ylabel('OutageProbability');
sig=0.2
for kk=1:length(n)
    n=m(kk);
for jj=1:length(Qpk)

    syms gsp gss gps
     A=(2^(ro)-1)*(1+n*gps*Pp)*(gsp-sig*log(po))/(Qpk(jj));
    Pr1= int(exp(-B*gsp)*B*exp(-gss)*(n*exp(-gps)*(1-exp(-gps))^(n-1)),gss,0,A);
    Pr2=int(Pr1,gsp,0.001,inf);
    Pr2=int(Pr2,gps,0.001,inf);
    Pr(jj)=double(Pr2)
end
semilogy(Q,Pr,plotst{kk});
end
xlabel('Peak received interference Qpk (dB)');
ylabel('OutageProbability');
```

Code 11:

Fig 2.9 The average power consumption to achieve outage capacity limit of cognitive user transmitter with different combination of interference outage level and error variance under the peak transmit power and peak interference constraints as well as under the peak interference power constraint only.

```
%expenditure of power outage capacity when peak interefrence is considered
%only
clc
clear all
close all
Q=-5:0.75:5; Qpk=10.^((0.1).*Q);Ppk=10.^(0.1*5); S=[ 0.01 0.02];P1=[0.01  0.2 ];B1=1./(1-S);
plotst={'-r*','-ko',; '-b*','-mo'};
plotst1={'-.r*','-.ko',; '-.b*','-.mo'};
lgnd={'Po=0.01, \sigma^2 = 0.01','Po=0.2, \sigma^2 = 0.01';'Po=0.01, \sigma^2 = 0.02','Po=0.02, \sigma^2 = 0.02';'Po=0.01, \sigma^2 = 0.05','Po=0.01, \sigma^2 = 0.05'};
Z=zeros(length(S)*length(P1));
 for kk=1:length(P1)
for jj=1:length(S)
   sig=S(jj);
   B=B1(jj);
Po=P1(kk)
% Ppk=0.001
P1=(expint(1/Ppk)-expint(B.*(Qpk+1)./Ppk)*exp(-B*sig*log(Po))); %both peak transmit and peak interefernce
P=(Qpk.*exp(-sig.*log(Po).*B)).*(-log((1./(B.*Qpk))+1)-1*expint(sig*log(Po)*B));% peak interefernce only
Pwr=10.*log10(P);
Pwr1=10.*log10(P1);
YY(kk,jj)=plot(Q,Pwr,plotst{kk,jj});
hold on;
YY1(kk,jj)=plot(Q,Pwr1,plotst1{kk,jj});
hold on;
grid on;
   end
end
xlabel('Peak interference power Qpk(dB)');
ylabel('Average power (dB)');
legend([YY(1,1),YY(1,2),YY(2,1),YY(2,2)],'Po=0.01, \sigma^2 = 0.01','Po=0.01, \sigma^2 = 0.05','Po=0.2, \sigma^2 = 0.01','Po=0.2, \sigma^2 = 0.05');
```

Code 12:

Fig 3.1 The analysis of the ergodic capacity of cognitive link with signal to noise ratio under average received power constraint and Fig 3.2 The analysis of the ergodic capacity with the signal to noise ratio under peak received power constraint

```
clc
clear all
close all
alpha=-20:0.75:20; % alpha =Q/No*B
gama=zeros(1,2);
```

```
for jj=1:length(alpha)
    %% average received power constraints
    syms x t
    y=10^(alpha(jj)/10);
    gama=solve(x-log(1+x)-y);
    for k=1:length(gama)
        w=gama(k);
        if (w-log(1+w)==y)
            break
        end
    end
    C(jj)=(log(1+(double(w))));
    cawgn(jj)=(log(1+y));
     gama1=solve((t^3/(1+t^2))-y);
     gama1=double(gama1);

     uu=gama1(1);
   Cng(jj)=log(1+uu)-uu/(1+uu)^2;
%% peak received power constraint
vv=log(y);
Craly(jj)=(y*vv)/(y-1);
%nakagami
aa= (y^2)*log(y);
bb=3*y*log(y);
cc=y^3-3*y^2+3*y-1;
Cng1(jj)=(y*(aa-bb-2+2*y))/(cc);
end
figure (1)
a1=semilogy(alpha,C,'r');
xlabel('\alpha (db)=Q/NoB');
ylabel('Capacity (nats/sec/hz)');
hold on;
b1=semilogy(alpha,cawgn,'k');
hold on;
c1=semilogy(alpha,Cng);
hold on;
legend([a1 b1 c1],'Rayleigh','AWGN','Nakagami m=2');
figure (2)
d1=semilogy(alpha,Craly,'--r*');
xlabel('\alpha (db)=Q/NoB');
ylabel('Capacity (nats/sec/hz)');
hold on;
q1=semilogy(alpha,Cng1,'--b*');
hold on;
p1=semilogy(alpha,cawgn,'--k*');
legend([d1 p1 q1],'Rayleigh','AWGN','Nakagami m=2');
```

Code 13:

Fig 3.3 The analysis of the ergodic capacity with peak transmit power constraint for peak interference power is -5 dB over different fading channels

```
clc
clear all
close all
alpha=-20:0.75:20; % alpha =Q/No*B
gama=zeros(1,2);

for jj=1:length(alpha)
    %% average received power constraints
    syms x t
    y=10^(alpha(jj)/10);
    gama=solve(x-log(1+x)-y);
    for k=1:length(gama)
        w=gama(k);
        if (w-log(1+w)==y)
            break
        end
    end
    C(jj)=(log(1+(double(w))));
    cawgn(jj)=(log(1+y));
     gama1=solve((t^3/(1+t^2))-y);
     gama1=double(gama1);

     uu=gama1(1);
   Cng(jj)=log(1+uu)-uu/(1+uu)^2;
%% peak received power constraint
vv=log(y);
Craly(jj)=(y*vv)/(y-1);
%nakagami
aa= (y^2)*log(y);
bb=3*y*log(y);
cc=y^3-3*y^2+3*y-1;
Cng1(jj)=(y*(aa-bb-2+2*y))/(cc);
end
figure (1)
a1=semilogy(alpha,C,'r');
xlabel('\alpha (db)=Q/NoB');
ylabel('Capacity (nats/sec/hz)');
hold on;
b1=semilogy(alpha,cawgn,'k');
hold on;
c1=semilogy(alpha,Cng);
hold on;
```

```
legend([a1 b1 c1],'Rayleigh','AWGN','Nakagami m=2');
figure (2)
d1=semilogy(alpha,Craly,'--r*');
xlabel('\alpha (db)=Q/NoB');
ylabel('Capacity (nats/sec/hz)');
hold on;
q1=semilogy(alpha,Cng1,'--b*');
hold on;
p1=semilogy(alpha,cawgn,'--k*');
legend([d1 p1 q1],'Rayleigh','AWGN','Nakagami m=2');
```

Code 13:

Fig. 3.4 The analysis of the ergodic capacity under peak transmit power and average interference power constraints for different numerically chosen value of peak transmit power.

```
%%Ergodic capacity under peak transmit and average interference constraint
clc
clear all
close all
Qavg1=-20:0.9785221:20;
Qavg=10.^(Qavg1./10);
P=[0:5:20];
P=10.^(P./10);
no=1;plotStyle = {'r','k','g','b','k'};
for k=1:length(P)
for jj=1:length(Qavg)
   Ld=1/(no*(Qavg(jj)+no));
   if (1/(Ld*no))>1>(1/(Ld*(P(k)+no)))
      C(jj)=log2(1/Ld);
   elseif 1<= 1/Ld*(P(k)+no)
      C(jj)=log2(1+ P(k)/no);
   else
      C(jj)=0;
   end
end
plot(Qavg1,C,plotStyle{k});
hold on;
end
xlabel('Qav(dB)');
ylabel('capacity(bits/hz/bandwidth');
```

Code 14:

Fig 3.5 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak interference power (-5 dB).

Calculation is in maple

```
%%Ergodic Capacity peak transmit power and peak interference power only
%%noise is considered
clc
clear all
close all
Ppk=-20:5:20;
Co= [0.01428 0.04426 0.1326 0.3136 0.52167 0.6614 0.72839 0.75455 0.7637];
C1=[0.01286 0.0399 0.1189 0.28294 0.4184 0.46205 0.46205 0.46205 0.46205];
C2=[0.01145 0.0356 0.1067 0.25036 0.3685 0.3685 0.3685 0.3685 0.3685 ];
C3=[0.01428 0.04426 0.13151 0.2924 0.3140 0.3140 0.3140 0.3140 0.3140 ];

 Y1=   plot(Ppk,Co,'-r*');hold on;
 Y2 =  plot(Ppk,C1,'-ko');hold on;
 Y3=   plot(Ppk,C2,'-md');hold on;
 Y4=  plot(Ppk,C3,'-bs');hold on;
legend([Y1,Y2,Y3,Y4],' \sigma^2=0',' \sigma^2=0.1', '\sigma^2=0.2','\sigma^2=0.3');
xlabel('Peak transmit power (dB)');
ylabel('Ergodic Capacity (bits/sec/Hz)');
grid on;
```

Code 15:

Fig 3.6 The response of peak interference power on the ergodic capacity (bits/s/Hz) for different values of the interference outage level at arbitrary chosen value of the peak transmit power (10 dB) and error variance 0.2.

```
% ergodic capcity variation with intereference outage level
%Ppk=5 dB,sig=0.2
Qpk=-15:5:20;
S_0=[0.1518 0.334 0.661 1.21 1.54 1.71 1.71 1.7105];%sig=0;

S_1=[0.028 0.085 0.2 0.22 1.28  1.69 1.71 1.71];%Po=0.01 sig=0.2
S_2=[0.031 0.0938 0.263 0.4154 1.34 1.69 1.71 1.71];
S_3=[0.035 0.105 0.2907 0.705 1.44 1.69 1.71 1.715];
%Y1=plot(Qpk,S_0,'-r*');
%hold on;
Y2=plot(Qpk,S_1,'-ko');
hold on;Y3=plot(Qpk,S_2,'-bd');
hold on;Y4=plot(Qpk,S_3,'-ms');
hold on;
grid on;
legend([ Y2 Y3 Y4],'Po= 1%','Po=2%','Po=4%');
xlabel('Peak interference power Qpk(dB)');
ylabel('Ergodic Capacity (bits/s/Hz)');
grid on;
```

Code 16:

Fig. 3.7 The average power consumption to achieve ergodic capacity limits of cognitive transmitter with different combination of interference outage level and error variance.

```
%expenditure of power

Qpk=-5:0.75:5; Q=10.^((0.1).*Qpk);Ppk=10.^(0.1*5); S=[ 0.01 0.05];P1=[0.01
0.2];B1=1./(1-S);
plotst={'-r*','-ko',; '-.b*','-.mo'};
lgnd={'Po=0.01, \sigma^2 = 0.01','Po=0.2, \sigma^2 = 0.01';'Po=0.01, \sigma^2 =
0.02','Po=0.02, \sigma^2 = 0.02';'Po=0.01, \sigma^2 = 0.05','Po=0.01, \sigma^2 = 0.05'};
Z=zeros(length(S)*length(P1));
 for kk=1:length(P1)
for jj=1:length(S)
   sig=S(jj);
   B=B1(jj);
Po=P1(kk)
P=abs(Ppk-Ppk.*exp((Q./Ppk+sig*log(Po)*B))- Q.*B.*exp(-
sig*log(Po)).*expint((Q.*B)./Ppk));% when pk transmit and peak receive constraints is
considered
Pwr=10.*log10(P);
YY(kk,jj)=plot(Qpk,Pwr,plotst{kk,jj});
hold on;grid on;
 end
 end
xlabel('Peak interference power Qpk(dB)');
ylabel('Average power (dB)');
legend([YY(1,1),YY(1,2),YY(2,1),YY(2,2)],'Po=0.01, \sigma^2 = 0.01','Po=0.01,
\sigma^2 = 0.05','Po=0.2, \sigma^2 = 0.01','Po=0.2, \sigma^2 = 0.05');
```

Code 17:

Fig. 3.8 The response of average interference power (dB) on the ergodic capacity (bits/s/Hz) for different values of variance at arbitrary chosen value of the peak transmit power (5 dB).

```
S=[ 0 0.1 0.2];P= [5]
A=1./(1-S);Ppk=10.^(0.1.*P); L=0:0.01:1;
Q =-20:2:20
Qavg=10.^(0.1*Q);
plost={'-r*','-gd','-ko','m^'}
for kk=1:length(S)
    sig=S(kk);
    B=A(kk);
for jj=1:length(Q)
syms lambda
```

```
X1= (-(-Ppk+exp(1/Ppk)*expint(1/Ppk)+sig*lambda*Ppk^2)*exp((-
B+sig*B*lambda*Ppk)/(Ppk*lambda))/(Ppk^2*lambda))
X2=exp(-B/(lambda*Ppk)+B*sig)/B
X3=1/B
I2=Ppk*(-X1 -X2+X3) % integral of PPk
% when other than ppk power is allocated
Z1=exp((-B/(Ppk*lambda))+B*sig)
Z2= exp(sig*B)*lambda/(lambda+B)
Y1= (1/(lambda*B))*(Z1-Z2)
%%
Q1=-log((lambda+B)/B)
Q2=-expint(B/(lambda*Ppk))
Y2=(-sig*exp(sig*B)/lambda)*(Q1-Q2)
%%
R1=(-(-
exp(B*sig)*lambda*expint(1/1000*(B+lambda)/lambda)+exp(B*sig)*B*sig*lambda*ex
pint(1/1000*(B+lambda)/lambda)-exp(1/1000*(1000*B*sig*lambda-B-
lambda)/lambda)*B+exp(B*sig)*B^2*sig*expint( 1/1000*(B+lambda)/lambda)-
exp(B*sig)*B*expint( 1/1000*(B+lambda)/lambda))/((B+lambda)*B^2))
R2=((-6.331539364*Ppk*lambda-1.*exp(1/Ppk)*expint( 0.1000000000e-
2*(Ppk+1000.)/Ppk)*B+6.331539364*B*sig*lambda*Ppk)*exp(B*(-
1.+sig*lambda*Ppk)/(Ppk*lambda))/(B^2*Ppk*lambda))
Y3=R1+R2
I1=B*(Y1+Y2+Y3)
I(jj)=I1+I2
Sol(jj)=solve(I(jj)-Qavg(jj));
L1(jj)=abs(real((double(Sol(jj)))));
lambda=L1(jj);gamma=0.577215;
syms gss gsp

L=L1(jj)
T(kk,jj)=L
a=(1/(L*(Ppk+(1/gss))))-sig;b =(gss/L)-sig
C=B*log((gss*(1/(L*(gsp+sig)))))*exp(-gss)*exp(-gsp*B)
C1=int(C,gsp,a,b)
C2=int(C1,gss,0.01,inf)
G=abs(double(C2))
X1=B*log((1+gss*Ppk))*exp(-gss)*exp(-B*gsp);
X2=int(X1,gsp,0,a)
X3=int(X2,gss,0.01,inf)
G1=abs(double(X3))
YY(kk,jj)=G+G1

 Cap= ((-lambda*exp(-B*sig)*(log(lambda)+gamma+log((lambda-B)/lambda))/(lambda-
B)+lambda*log(lambda)*exp(-B*sig)/(lambda-B)+lambda*exp(-
B*sig)*(gamma+log((lambda-B)/lambda))/(lambda-B)+exp(B*sig)*(-
```

```
log(B/lambda)+log(B/lambda+1))+exp(B*(-
1+sig*lambda*Ppk)/(Ppk*lambda))*log(lambda)+exp(B*(-
1+sig*lambda*Ppk)/(Ppk*lambda)+1/Ppk)*expint( 1/Ppk)-log(lambda)*exp(-
B/(Ppk*lambda)+B*sig)-expint(B/(Ppk*lambda))*exp(B*sig))/B);
 Cap1=(exp(1/Ppk)*expint(1/Ppk)-(exp((sig*B*lambda*Ppk-
1+lambda)/(lambda*Ppk))*expint(1/Ppk)));
 YY(kk,jj)=((Cap+Cap1)/log(2));
end
Z(kk,:)=plot(Q,YY(kk,:),plost{kk});
hold on;
end
xlabel('Average interference power  (dB)');
ylabel('Ergodic capacity (bits/sec/Hz)');
legend([Z(1,:),Z(2,:),Z(3,:)],'\sigma^2 =0','\sigma^2= 0.1','\sigma^2= 0.2');
```

Code 18:

Fig. 3.9 The response of peak transmit power (dB) on the ergodic capacity (bits/s/Hz) of cognitive user link with multiple primary users interference with arbitrary chosen values of the fixed peak interference power (-5 dB) with fixed noise variance σ2 = 0.1 and σ2 = 0.2

```
%% when multiple primary users interfere with secondary link ergodic capacity
%qpk=-5 dB
 Ppk=-15:5:15;
S1_1=[0.0076 0.018 0.0528 0.0806 0.0986 0.0986 0.0986 ];
S1_2=[0.003 0.0075 0.014 0.017 0.023 0.023 0.023];
Y3=plot(Ppk,S1_1,'-b*');
hold on;
Y4=plot(Ppk,S1_2,'-bo');
hold on;
S2_1=[0.0076 0.0184 0.054 0.060037 0.071 0.081 0.081];
S2_2=[0.003 0.007 0.013 0.015 0.019 0.01958 0.01958];
Y3=plot(Ppk,S2_1,'-k*');
hold on;
Y4=plot(Ppk,S2_2,'-ko');
hold on;
grid on;
xlabel('Peak transmit power (dBm)');
ylabel('Ergodic Capacity (bits/s/Hz');
legend([Y3 Y4],'Np=1','Np=2');
```

REFERENCES

[1] Federal Communications Commission, “Notice of proposed rule making and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies,” ET Docket No. 03-108, Feb. 2005.

[2] J. Mitola, and G. Q. J. Maguire,., “Cognitive radio: making software radios more personal,” IEEE Personal Commun. Mag., vol. 6, no. 4, pp. 13–18, Aug. 1999.

[3] T. Yucek and H. Arslan, “ A survey of spectrum sensing algorithms for cognitive radio applications,” IEEE Commun. Surveys and Tutorials, vol. 11, no.1, 2009.

[4] I.F Akyildiz et.al, “A survey on spectrum management in cognitive radio networks,” IEEE Communication Magazine, pp. 40-48, April 2008

[5] O. Ileri, D. Samardzija, and N. B. Mandayam, “Demand responsive pricing and competitive spectrum allocation via spectrum server,” Proc. IEEE DySPAN 2005, pp. 194–202, Nov. 2005.

[6] Q. Zhao, L. Tong, A. Swami, and Y. Chen, “Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework,” IEEE Journal on Selected Areas in Communications: Special Issue on Adaptive, Spectrum Agile and Cognitive Wireless Networks, vol. 25, no. 3, pp. 589–599, April 2007.

[7] H. Zheng and L. Cao, “Device-centric spectrum management,” Proc. IEEE DySPAN 2005, pp. 56–65, Nov. 2005.

[8] R. Menon, R. M. Buehrer, and J. H. Reed, “Outage Probability based comparison of underlay and overlay spectrum sharing techniques,” Proc. IEEE DySPAN, pp. 101–109, Nov. 2005.

[9] T. Fujii and Y. Suzuki, “Ad-Hoc Cognitive Radio,” in Proceedings of the first IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2005.

[10] Q. Zhao, L. Tong, and A. Swami, “Decentralized cognitive MAC for dynamic spectrum access,” in Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), Nov. 2005.

[11] A.M. Wyglinski, M. Nekovee and T. Hou, “Cognitive Radio Communications and Networks,” Academic Press, Boston, 2010.

[12] E. Hossain, D. Niyato and Zhu Han, “Dynamic Spectrum Access and Mangement in Cognitive Radio Networks,” Cambridge University Press, New York, 2009.

[13] A. Chengquan, Liu Yang, “ A Matching Game Algorithm for Spectrum Allocation Based on POMDP Model,” in Proc. Of IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM), pp. 1-3,2011.

[14] Dusit Niyato, Ekram Hossain, “A game-theoretic approach to competitive spectrum sharing in cognitive radio Networks,” in Proc. Wireless Communications and Networking Conference (WCNC), pp. 16-20,2007.

[15] Qiufen Ni et.al, “Spectrum allocation based on game theory in cognitive radio networks,” Journal of Networks, vol. 8, no. 3, pp. 712-722.

[16] D. Li et.al, “Coalitional game theoretic approach for secondary spectrum access in cooperative cognitive radio networks,” IEEE Trans, on Wireless Commun., vol. 10, no. 3, March 2011.

[17] H. wang et.al, “Cooperative spectrum sharing in cognitive radio networks: A game-theoretic approach,” Proc. International Conference on Communications (ICC), Cape- Town, pp. 1-5, May 2010.

[18] N. Omidvar et.al, “A game theoretic approach for power allocation in the downlink of cognitive radio networks,” IEEE workshop on Computer aided modeling and design of communication links and networks (CAMAD), Kyoto, pp. 158-162, June 2012.

[19] S. Sharma and D. Teneketzis, “A game theoretic approach to decentralized optimal power allocation for cellular networks,” vol. ,no. ,pp. , 2010.

[20] H. Li et.al, “Distributed resource allocation for cognitive radio network with imperfect spectrum sensing,” Proc. 78th Vehicular Technology (VTC fall), Las Vegas (NV), pp. 1-6, 2013.

[21] R.Ektin et.al, “Spectrum sharing for unlicensed bands,” IEEE Journal on selected areas in communication, vol. 25,no. 3, pp.517-528, 2007.

[22] P. Zhou, W. Yuan, W. Liu, and W. Cheng, “Joint power and rate control in cognitive radio networks: A game-theoretical approach,” in Proc. IEEE Int. Conf. Commun., Beijing, pp. 3926–3301, 2008.

[23] A. Attar, N. Mohammad Reza, and A. A. Hamid, “Cognitive radio game for secondary spectrum access problem,” IEEE Trans. Wireless Commun., vol. 8, no. 4, pp. 2121–2131, Apr. 2009.

[24] V. Krishna, “Auction Theory,” Academic Press, London, UK, 2002.

[25] M. Dramitinos, G. Stamoulis, and C. Courcoubetis, “Auction-based resource reservation in 2.5/3G networks,” Mobile Networks and Applications, vol. 9, no. 6, pp. 557–566, December 2004.

[26] J. Huang, R. Berry, and M. L. Honig, “Auction-based spectrum sharing,” Mobile Networks and Applications, vol. 11, no. 3, pp. 405–418, June 2006.

[27] J. Huang, Z. Han, M. Chiang, and H. V. Poor, “Auction-based resource allocation for cooperative communications,” IEEE J. Sel. Areas Commun., vol. 26, no. 7, pp. 1226–1237, Sep. 2008.

[28] B. Wang, Z. Han, and K. J. Liu, “Distributed relay selection and power control for multiuser cooperative communication networks using buyer/seller game,” in Proc. IEEE INFOCOM, Bercelona , pp. 544–552, May 2007.

[29] J. Zou et.al, “Optimal power allocation for hybrid overlay/underlay spectrum sharing in multiband cognitive radio network,” IEEE Trans. on Vehicular Technology, vol. 62, no. 4, pp. 1827-1837, May 2013.

[30] Hui Yu et.al, “Pricing for uplink power control in cognitive radio networks,” IEEE Transactions on Vehicular Technology, vol. 59 ,no. 4 , pp. 1769-1778 , Jan. 2010.

[31] D. Shiung and K-C Chen, “On the optimal power allocation of a cogniitve radio network,” Proc. 20th International Symposium on Personal, Indoor and Mobile Radio Commun., Tokyo, pp. 1241-1245, 2009

[32] Z. Zhang et.al, “ Energy efficient power allocation strategy in cognitive relay networks,” Radio Engineering, vol. 21, no.3, pp. 809-814,2012.

[33] Jia Guo et.al, “Subchannel and Power allocation in OFDMA- Based Cognitive radio networks,” Proc. IEEE Int. Conf. on Communication (ICC), Cape Town, pp. 1-5,2010.

[34] J. Mao, et.al, “Power allocation over fading cognitive MIMO channels : An ergodic capacity perspective,” IEEE Trans. Vehicular Technology, vol. 61,no.3, pp. 1162-1173, March 2012.

[35] W-C Pao and Y-F Chen, “Adaptive gradient based methods for adaptive power allocation in OFDM- Based Cogntive radio networks,” IEEE Trans. on Vehicular Technology, vol.63, no. 2, pp. 836-848, Feb.2014.

[36] J. Zou, H. Xiong, D. Wang., and C.W. Chen, “Optimal power allocation for hybrid overlay/underlay spectrum sharing in multiband cognitive radio networks,” IEEE Transactions on Vehicular Technology, vol. 62, no. 4, pp. 1827–1837, 2013.

[37] Xin kang et.al, “Optimal power allocation strategies for fading cognitive radio channel with primary user outage constraint,” IEEE Journal on Selected Areas in Communication , vol. 29, no. 2, Feb. 2011.

[38] M. Naeem et.al, “Optimal power allocation for green radio: Fractional programming approach,” vol. 7, no.12, pp. 1279-1286, Aug. 2013.

[39] Q. Qi et.al, “An efficient water filling algorithm for power allocation in OFDM based cognitive radio systems,” Proc. IEEE International Conference on Systems and Informatics, Yantai, pp. 2069-2073, 2012.

[40] Xun Zhou et.al, “ An efficient power allocation algorithm for OFDM based underlay cognitive radio network,” Proc. IEEE Global Telecommunications conference 2011, Houston, Tx, USA, pp.1-5.

[41] P.Jum et.al, “ A worst case robust distributed power allocation in OFDM based cognitive radio network,” Proc. 32nd Chinese Control Conference (CCC) 2013, Xian, pp. 6422-6427.

[42] N. Forouzan and S. A Ghorashi, “New algorithm for joint sub-channel and power allocation in multicell OFDMA – based cognitive radio networks,” Institution of Engineering and Technology, vol.8, no. 4, pp. 508-515, march 2014.

[43] F. Rezai and A. Tadaion, “Interference alignment in cognitive radio networks,” Institute of Engineering and Technology Commun., vol. 8, no. 10, pp.1769-1777, March 2014.

[44] E. Hosseini and A. Falahati, “Improving water-filling algorithm to power control cognitive radio systembased upon traffic parameter and QoS,” Wireless Pers. Commun., vol. 70, no. 4, pp. 1747-1759, 2012

[45] V. LeNir and B. Scheers, “Implementation of an adaptive OFDMA PHY/MAC on USRP platforms for cognitive tactical radio network,” Proc. IEEE Military Commun. and Information Systems Conference, 2012, Gdansk, pp.1-7.

[46] P. S. M Tripathi, A Chandra and R Prasad, “Deployment of cognitive radio in India,” Wireless Pers. Communication, vol. 76, pp. 523-533, 2014.

[47] K.P Patil, “Spectrum utilization and management in cognitive radio network (Ph.D. Dissertation) CTiF, Aalborg University, Denmark, 2014.

[48] WPC Wing. www.wpc.dot.gov.in.

[49] NTP2012. www.dot.gov.in.

[50] B.Wang, Liu and K.JR, “Advances in cognitive radio networks : A survey ,” IEEE Journal of Selected Topics in Signal Processing, vol. 5, no.1, pp. 5-23, Jan 2011.

[51] D. Datla et.al, “A apectrum surveying framework for dynamic spectrum access network,” IEEE Trans. on Vehicular Tech., vol. 58, no. 8, pp. 4158-4168, 2009

[52] M. Elalem and L Zhao, “Effective capacity optimization for cognitive radio network based on underlay scheme in gamma fading channel,” Proc. Int. Conf. on Computing Networking and Communication, San Diego, CA, pp. 714-718, 2013.

[53] M. Elalem and L. Zhao, “Effective capacity optimization for cognitive radio network based on underlay scheme in game fading channel,” Int. Conf. on Computing Networking and Communication, San Diego, CA, pp. 714-718, 2013.

[54] A. J. Goldsmith and P.P Varaiya, “Capacity of fading channels with channel side information,” in IEEE Transactions on Information Theory, vol. 43, no. 6, pp. 1986-1992, Nov. 1997.

[55] M. Gastpar, “On capacity under received-signal constraints,” Proc. Allerton Conf. Communications, Control, Computing, Monticello, IL,Oct. 2004, pp. 1322–1331.

[56] A. Ghasemi and E.S. Sousa, “Capacity of fading channels under spectrum sharing constraints,” Proc. IEEE International Conference on Commun. (ICC ‘06) June 2006, Istanbul, pp. 4373-4378.

[57] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” IEEE Journal Selected Areas Communication, vol. 23, no. 2, pp. 201-220, Feb. 2005.

[58] X. Kang, Y.-C, Liang, A. Nallanathan, H.K Garg and R. Zhang, “Optimal power allocation for fading channels in cognitive radionetworks : Ergodic capacity and outage capacity,”IEEE Trans, Wireless Commun., vol. 8, no. 2, pp. 940-950, February 2009.

[59] L. Musavian and S. Aissa, "Capacity of spectrum-sharing channels with minimum rate requirements," IEEE Proc. ICC 2008, pp.4639-4643.

[60] A.K Farraj and S Ekin , "Performance of cognitive radios in dynamic fading channels under primary outage constraint", Wireless Pers. Commun., vol. 73, no. 8, pp. 637-649, May 2013.

[61] S Vassaki , M.I Poulakis, A.D Panagopoulous and P. Constantinou , "QoS driven power allocation under peak and average interefrence power constraints in cognitive radio networks",Wireless Pers. Commun., vol. 78, pp. 449-474, April 2014.

[62] Xin Kang et.al , " Optimal power allocation strategies for fading cognitive radio channels with primary user outage constraint," IEEE Journal on Selected Areas in Communications, vol. 29, no. 2, pp. 374-382, Feb. 2011.

[63] L. Musavian and S. Aissa, "Fundamental capacity limits of cognitive radio in fading environments with imperfect channel state information," IEEE Trans. On Commun., vol. 57, no. 11, pp. 3472-3480, Nov. 2009.

[64] H. A Suraweera, P. J Smith and M Shafi, "Capacity limits and performance analysis of cognitive radio with imperfect channel knowledge," IEEE Trans. Vehicular Tech., vol. 59, no. 4, pp. 1811-1822, May. 2010.

[65] Son K et.al, "Power allocation policies with full and partial inter- system channel state information for cognitive radio networks", Wireless Netw., vol. 19, pp. 99-113, June 2012.

[66] Z Rezki and M-S Alouini, "Ergodic capacity of cognitive radio under imperfect channel-state information," IEEE Trans. Vehicular Tech., vol. 61, no. 5, pp. 2108-2119, June 2012.

[67] S. Kundu, B. Prasad and S. D Roy, " Spectrum sharing networks with imperfect channel state information," Proc. Third International Conference on Computer, Communication, Control and Information Technology, Hooghly, pp. 1-6, Feb. 2015.

[68] H. Li, Q. Guo, T. Tang and Q.Z Li, "Distributed resource allocation problem for cognitive radio network with imperfect spectrum sensing," Proc. IEEE 78th Vehicular Technology Conference , Las Vegas, NV, pp. 1-6, 2013.

[69] Tse D and Viswanath P, "Fundamentals of Wireless Communication", Cambridge University Press, U.K, 2005.

[70] Boyd S and Vandenberghe L, "Convex Optimization",Cambridge: Cambridge University Press, U.K, 2004.

[71] M.S Vassiliou, S Shah and T MacDonald, "Crucial differences between commercial and military communications technology needs: Why the military still needs its own research," Proc. IEEE Military Communication Conference (MILCOM), 2013, San Diego, CA , pp. 342-347.

[72] R.C- Santiago, Michał Szydełko, Adrian Kliks, Fotis Foukalas, Yoram Haddad, Keith E. Nolan, Mark Y. Kelly, Moshe T. Masonta, and Ilangko Balasingham, "5G: The Convergence of

wirelesscommunications", Wireless Pers. Commun., (Online) March 2015, DOI 10.1007/s11277-015-2467-2.

[73] Y. E Sagduyu, "Securing cognitive radio networks with dynamic trust against spectrum sensing data falsification," Proc. IEEE Military Communication Conference (MILCOM) 2014, Baltimore, MD, pp. 235-241.

[74] Y Chen, Q Lel and X- Yuan, "Resource allocation based on dynamic hybrid overlay/underlay for heterogeneous services of cognitive radio networks," Wireless Pers. Commun., vol. 79, pp. 1647-1664, July 2014.

[75] M. Masonta, Y. Haddad, L. De Nardis, A. Kliks and O. Holland, "Energy efficiency in future wireless networks: Cognitive radio standardization requirements", Proc. IEEE, Interenational workshop on computer aided modeling and design of communication links and networks, Barcelona, pp. 31-35, Sep. 2012.

[76] S. Wang, "Energy efficient spectrum sensing and access for cognitive radio networks," IEEE Transactions on Vehicular Technology, vol. 61, pp. 906-912, Dec. 2011.

[77] Tau Qiu, T. Song, Z. He and B. Tian, "Energy-efficient transmission for hybrid spectrum sharing in cognitive radio networks," Proc. Vehicular Tech. Conf., Budapest, pp. 1-5, May 2011.

[78] F. Yuanfang, L. , Xu Wenjun and Li Shengyu, " Energy – efficient power allocation algorithms for OFDM-based cognitive relay neworks with imperfect spectrum sensing," Proc. IEEE, International Conference on Communication Workshops, June 2014, Sydney, NSW, pp. 337-342.

[79] M. Elkashlan et.al "On the security of cognitive radio networks," IEEE Trans. on Vehicular Tech. ,online Sep. (2014), DOI 10.1109/TVT.2014.2358624.

[80] W. Xu, T. Wood, W. Trappe and Y. Zhang, "Channel surfing and spatial retreats: Defenses against wireless denial of service," Proc. of the 3rd ACM Workshop on Wireless Security, pp. 80-89, Philadelphia, PA, USA, January 2004.

[81] C. Zou and C. Chigan, "Licensed receiver detection and authentication in simplex licensed networks," Proceedings of the IEEE International Workshop on Recent Advances in Cognitive Communications and Networking, pp. 924-929, Houston, TX December 2011.

[82] A. Papoulis and S.U Pillai, " Probability, Random Variables and Stochastic Processes, 4th edition," Mc Graw Hill Europe, Jan. 2002.