“TRANSMIT POWER OPTIMIZATION IN COGNITIVE RADIO NETWORKS USING GAME THEORETIC APPROACH”

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MASTER OF TECHNOLOGY
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By

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CERTIFICATE

This is to certify that the work titled "**TRANSMIT POWER OPTIMIZATION IN COGNITIVE RADIO NETWORKS USING GAME THEORETIC APPROACH**" submitted by "**Anjana Sharma**" in partial fulfillment for the award of degree of M. Tech at Jaypee University of Information Technology, Waknaghat 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.

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ABSTRACT

One of the major challenges in design of any wireless networks is the maximum utilization of the frequency spectrum. Numerous studies on spectrum utilization show that most of the allocated spectrum is not utilized. So spectrum underutilization motivates for opportunistic spectrum access. Cognitive Radio, with its ability of opportunistic and dynamic spectrum access is a promising technology to effectively address the spectrum underutilization problem. The basic idea in cognitive radio is to permit some unlicensed (secondary) users to operate in a licensed frequency band, without causing interference to the licensed (primary) user. The cognitive radio link intelligently sense the frequency segment in the radio spectrum, and jumps into any temporarily unused spectrum rapidly without interfering the primary users. A critical design challenge for cognitive radio networks is to establish a balance between two conflicting terms, i.e. transmit power and interference. Use of power control is an efficient way to increase the total capacity of the network by allowing secondary users to intelligently transmit by controlling their power in order to make sure that qualities of service of primary users remain unaffected.

Several approaches have been proposed in the recent years for regulating the transmit power of secondary users in cognitive radio networks. There are two categories of cognitive radio operations: opportunistic spectrum access which allow secondary user (SU) to access frequency band that was allocated to primary user (PU) when primary user is inactive and spectrum sharing which allow secondary user to transmit simultaneously with primary user even when primary user is active as long as quality of service (QoS) of PU transmission is not degraded to an acceptable level. This dissertation explores the challenges and requirements of the power control in spectrum sharing scenario. Game theory is an appropriate tool for solving a problem where decision is to be taken in distributed manner. So, the problem of transmit power control in spectrum sharing cognitive radio network is investigated based on a game theoretic framework with interference constraint imposed to protect the licensed user. The

optimal power control for the secondary user over different fading environment is considered using repeated game model with perfect information. Matlab simulations performed for the repeated game to validate the approach.

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LIST OF ABBREVIATIONS

CR	Cognitive radio
PU	Primary user
SU	Secondary user
BS	Base station
QoS	Quality of service
SNR	Signal to noise ratio
SINR	Signal to interference ratio
SDR	Software defined radio
DSA	Dynamic Spectrum Access
CSI	Channel state information
ITU	International Telecommunication Union
RF	Radio frequency
FCC	Federal Communication Commission
BER	Bit error rate
CRAHN	Cognitive radio ad-hoc network
RTT	Round trip time
RTS	Request to send
CTS	Clear to send

CHAPTER 1

INTRODUCTION

The electromagnetic radio spectrum is a natural resource, the use of which by transmitters and receivers is licensed by governments. The increasing demand for access to content and services, and the exponential growth in wireless applications and technologies, results in a crowded spectrum, although recent spectrum utilization measurements have shown that the spectrum occupancy is low when examined as a function of frequency, time and space. Thus, the concept of Dynamic Spectrum Access (DSA) is considered a solution to the problem of inefficient use of the spectrum. The key enabling technology of DSA is known as Cognitive Radio.

Cognitive Radio is an intelligent wireless communication system that learns from the environment and can regulate its operation parameters to suite efficient utilization of unused radio frequencies [1,2].Cognitive radio basically consists of ad-hoc networks, formed by several nodes randomly distributed in space. These nodes coexist with primary spectrum users, and are able to sense and exploit unused bands or “holes” for opportunistic access without being harmful to the primary spectrum users. Holes in cognitive radio terms are electromagnetic spectrum sub-bands assigned to primary users, which are partially or fully underutilized at various times and locations

One of the great challenges to face while designing Cognitive Radio Networks is to find a proper MAC level solution such that both licensed and unlicensed systems can cooperate. By having proper knowledge of different metrics of the system, the MAC layer solution can be designed by keeping in mind some goals related to these metrics such as QoS, outage probability, capacity etc. The logical operational functions of the cognitive radio were first described by J. Mitola [3]. S. Haykin [1] modified the cognitive radio functions to emphasis its three fundamental physical layer processes, namely radio scene analysis, channel-state estimation and predictive modeling, and transmit-power control. Our focus is on the determination of transmit power so that there is a fair sharing of radio frequencies. CR users are expected to be uncoordinated opportunistic users, whereas there are conflicting interests among the CR users [4], [5]. This motivates the use of game theory to do research on CR networks. Compared to traditional centralized solutions, the game-theoretical approach has the advantage of distributed implementation for CR networks: each CR user only takes care of their own utility maximization, and it does not need to know other users' payoff (or utility function). Transmit power control scheme in cognitive networks can be categorized as either cooperative or non - cooperative. Under cooperation, secondary users can negotiate with each other and agree on how to utilize and distribute the spectrum resources. Under non-cooperation, the users can selfishly aim to maximize their transmit power.

1.1.Motivation:

In Cognitive Radio networks, power control deals with the selection of transmit power for CR users that achieves high spectrum efficiency by enabling CR users to reuse the PUs' spectrum bands under the interference constraints imposed by PUs. Cognitive technology is considered as a promising technology for spectrum exploitation dynamically. By integrating the capability of the cognitive technology in the traditional wireless networks, the spectrum scarcity problem can be solved. So this work is motivated by the need to advancement of research in cognitive radio technology Also there is need to seek an efficient solution to the problems posed by the control of transmit power in cognitive radio networks.

1.2.Objective

Transmit power of secondary users in cognitive radio networks will inevitably introduce interference to primary users. At the core of the cognitive radio architecture is the cognitive engine, which is the functional unit responsible for the control of transmit power. Power control has been studied for ad-hoc networks [6,7,8,9].From this study it is clear that there exist three connected but conflicting concepts namely transmitting power, bandwidth, and interference in wireless communication system. Increasing one of them in a network causes conflicts in the others. Consequently, for the efficient use of resources in any wireless network it is mandatory to maintain a balance between them. In all these papers interference management through power control has been proposed. The amount of transmission power is such that it is sufficient to be received at the receiver and do not create interference to other user.

But, in cognitive radio the task of interference management is more complicated because of the presence of two types of users, primary and secondary. In [10] a two-phase power control in center controlled cognitive radio network is given which have results in more overheads. For ad-hoc network with no central controller distributed power control is essential. Game theory can be used in distributed power control. In [11] power allocation with interference is proposed but without the consideration on the protection of primary (licensed) users. In [12] Instead of applying interference power constraint at the primary user (PU) receiver for the secondary user (SU) to protect the primary transmission, constraint on the maximum tolerable outage probability for the PU due to the SU transmission is proposed, but with the assumption that perfect instantaneous channel state information (CSI) is available on the SU channel.

The key objective of this dissertation is to find power control scheme in cognitive radio using game theory with consideration on the protection of primary user. Each secondary user has a certain power budget available for transmission. More power is used; higher will be end to end throughput of cognitive radio network. But at the same time, interference toward the primary network will also increase. So the main objective of the proposed work is optimal power allocation at the secondary user nodes leading end to end throughput maximization, while satisfying the interference constraint.

1.3.Outline of Dissertation

Chapter 1 includes the brief introduction of the subject of transmit-power control in cognitive radio networks using game theory, motivation behind this dissertation, and the objectives of this research.

Chapter 2 describes detailed information about cognitive radio. A literature review of the research that has been done in the related areas of spectrum sensing and spectrum management is described

In **Chapter 3** Game theory, different models of Game theory are described. It also includes the application of Game theory in Cognitive Radio.

Chapter 4 contains the Power control methods in ad-hoc networks as well as Cognitive Radio. The advantage and disadvantage of all the existing methods are discussed in detail. Both the centralized and distributed transmit power control of Secondary Users (unlicensed users) has been implemented respecting the QoS of the Primary users. For distributed power control Repeated Game model has been used. Firstly Simplified Path Loss Model is used to allocate transmit power to the Secondary Users. Then combined effect of Path Loss and Shadowing on transmit power of Secondary users is considered. Rayleigh fading impact on threshold is discussed.

In **Chapter 5** proposed algorithm, flowcharts, simulation parameters, corroborating simulations with results are provided

Chapter 6 presents the recommendations, future work and conclusion.

CHAPTER 2

COGNITIVE RADIO

The electromagnetic spectrum is generally considered scarce due to the limited availability of usable frequency bands. Hence, the use of spectrum is regulated a fixed spectrum assignment policy, i.e. the spectrum is regulated by governmental agencies and is assigned to license holders or services on a long term basis for large geographical regions .Standard bodies like the International Telecommunication Union (ITU), European Conference of Postal and Telecommunications Administration (CEPT), European Telecommunications Standard Institute (ETSI) and International Special Committee on Radio Interference (CISPR) are responsible for the standardization of radio frequency (RF) bands. The allocation of frequencies, as specified by standards, is assigned in three ways:

- **Restricted Frequency Bands:** These bands are restricted from use by anyone they are exclusively reserved for radio astronomy.
- **Open Frequency Bands:** These bands are allocated by government and are free for use by anyone as long as they operate within certain transmit power limits. Some of the commonly identified ranges of open frequencies in most countries are 2.4 GHz, 5.2/5.3/5.8 GHz and those above 60 GHz
- **Licensed Frequency Bands:** These are spectrum set aside for commercial purposes and only licensed users may transmit within the range of procured frequency bands. Examples of services operated in this band of frequencies are TV channels, radio, cellular services, and so forth. [13]

Within the range of licensed spectrum, not all users are active all the time and at all locations. A large portion of the assigned spectrum is used sporadically as illustrated in Fig. 2.1, where the signal strength distribution over a large portion of the wireless spectrum is shown. The spectrum usage is concentrated on certain portions of the spectrum while a significant amount of the spectrum remains unutilized

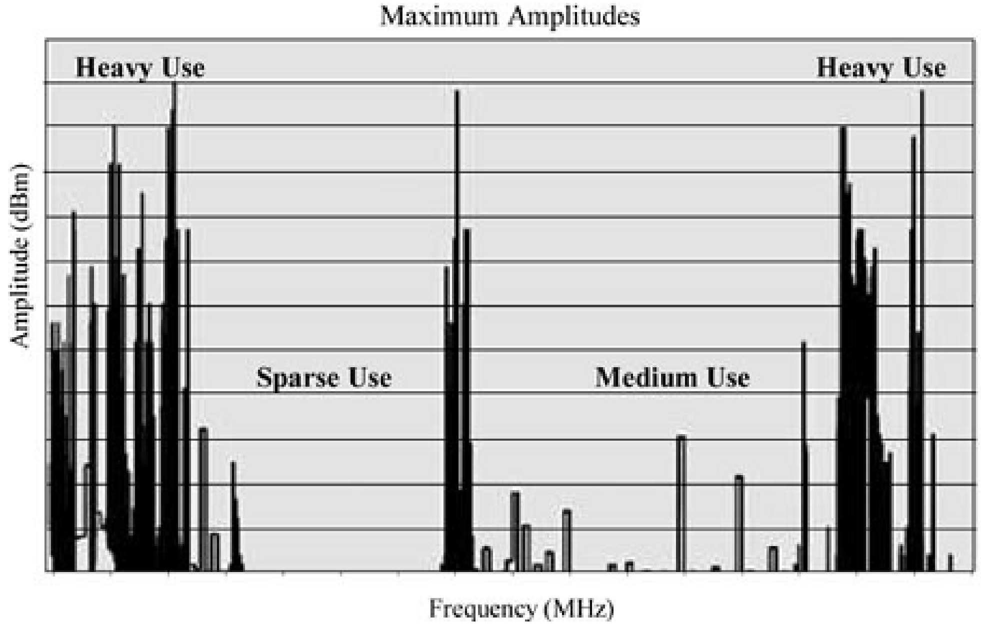

Fig.2.1 Spectrum utilization.

A spectrum utilization survey in New York was done by the Federal Communication Commission (FCC) .This survey indicates that between the frequencies range of 30 MHz to 3 GHz, there is only 13.1% spectrum occupied [14].

There was a fixed assignment policy in the past and it served well. But in the recent years there is a sudden increase in the access to the limited spectrum for mobile services. This increase is challenging the effectiveness of the traditional fixed spectrum policies. So limited available spectrum and the spectrum underutilization necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically [15]. Dynamic spectrum access is proposed to solve these current spectrum inefficiency problems. Dynamic spectrum access enables users to adjust communication parameters (such as operating frequency, transmission power, and modulation scheme) in response to the changes in the wireless environment [15-16].

2.1 Introduction to Cognitive Radio

DSA enables implementation of Cognitive Radio (CR) that brings a promise to increase spectrum utilization at a minimum cost by using licensed spectrum whenever spectrum owners do not use it. Cognitive radio brings a revolution in the field of wireless networks because of its characteristics which grant the unlicensed users the opportunity to utilize the spectrum bands of licensed users when they are not in use.

The idea of cognitive radio was first presented by J. Mitola [3], primarily as a means of exploring effective utilization of the radio spectrum. The term is derived from the English word, “cognition,” which is defined by the Encarta dictionary as, “the mental faculty or process of acquiring knowledge by the use of reasoning, intuition, or perception.” The Global Standards Collaboration (GSC) a group from the ITU, proposed the following definition for Cognitive Radio (CR)

> *“A radio system employing technology that allows the system: to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.”*

The two main objectives of Cognitive Radio are:

- Highly reliable communications whenever and wherever needed
- Efficient utilization of the radio spectrum

The operation of cognitive radio is assisted by its core, the Software Defined Radio (SDR). Cognitive Radio is not expected to be fully implemented until the complete Software Defined Radio (SDR) hardware become available in a suitable size. The term SDR was introduced in the late 1990s by some manufacturers who created radio terminals capable of using more than one communication technique (e.g., GSM and CDMA); that is the terminals can alter their operation mode or technique by means of software. Thus this technique is known as Software Defined Radio (SDR). The desired cognitive radio system should have the ability to freely switch between the techniques.

Thus, an SDR with all the latest communication techniques is the core of cognitive radio[3].

Two types of users are defined in CR: the licensed users which are referred to as **primary users (PUs)** and unlicensed users which are referred to as **secondary users (SUs).** The PUs get the spectrum bands from their service providers and then they have the ability of using the bands whenever they want while the SUs detect the absence/presence of PUs in their spectrum bands in order to use them.

2.2 Cognitive Cycle

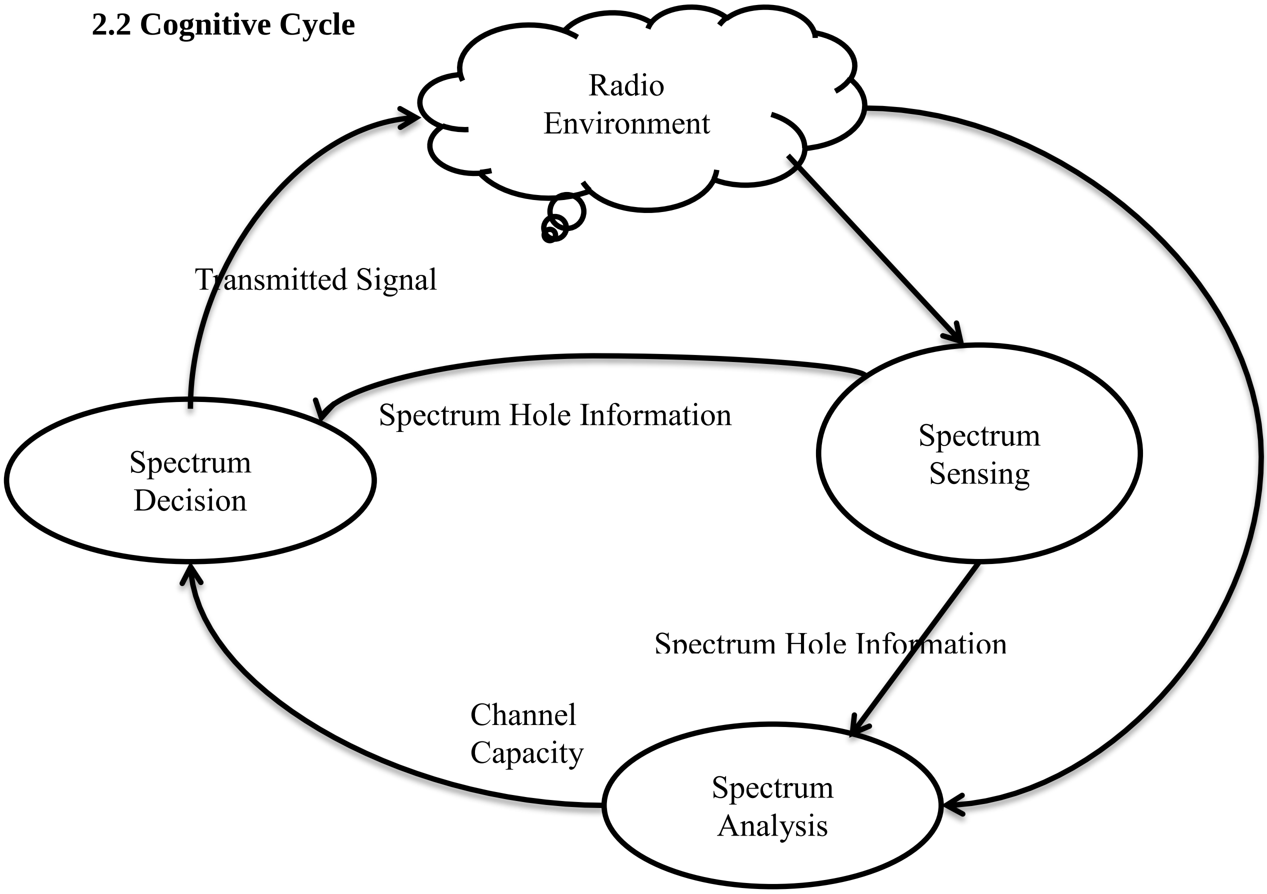

Fig.2.2 Cognitive cycle

The cognitive capability of a cognitive radio enables real time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. The tasks required for adaptive operation in open spectrum are shown in Fig. 2.2 which is referred to as the cognitive cycle.[1,17] Three main steps of the cognitive cycle:

- spectrum sensing
- spectrum analysis
- spectrum decision

2.2.1 Spectrum Sensing

The first integral of cognitive radio task is spectrum sensing. The cognitive radio monitors the spectrum bands, captures information and detects spectrum holes In cognitive radio parlance, spectrum holes are sub-bands of the electromagnetic spectrum assigned to primary users, but can be exploited by secondary users when partially or fully underutilised at various times and locations as shown in Fig. 2.3 [13].

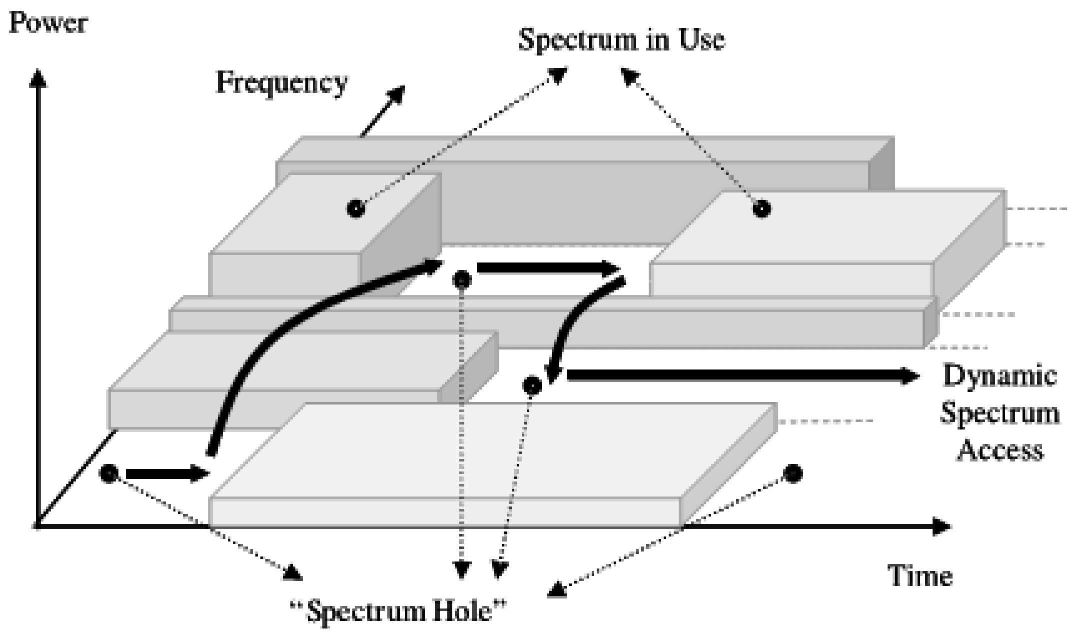

Fig.2.3 Spectrum hole concept.

Sensed spectra can be classified into the following [1]:

- **Black Spectrum Holes:** These are spectra that are fully occupied and are to be avoided when their emitters are ON.

- **Gray Spectrum Holes:** These are spectra that are partially occupied and are candidates for use by prospective service operators.
- **White Spectrum Holes:** These are spectra that are free and are also candidates for use by prospective service operators.

Spectrum sensing can broadly be classified either based on the architecture of the sensing nodes or on the kind of information to be sensed. Fig.2.4 is showing the various sensing categorizations [18].

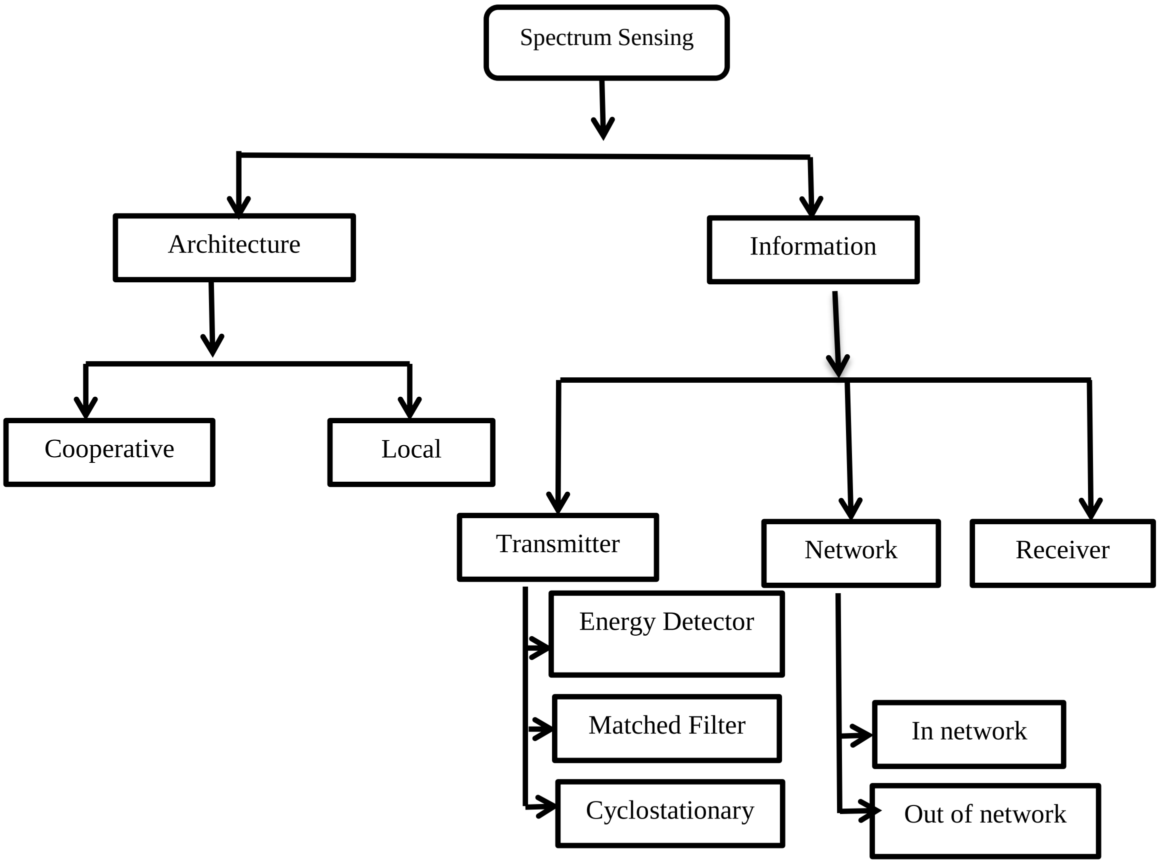

Fig. 2.4 Spectrum sensing options

2.2.1.1 Architecture-Based Sensing

Architecture-based sensing can either be cooperative or local based spectrum sensing.

- Cooperative Spectrum Sensing: Cooperative spectrum sensing refers to spectrum sensing method where multiple cognitive radios cooperate towards the detection of a primary user's spectrum holes.
- Local Spectrum Sensing: In local spectrum sensing, each user makes decision on the presence of a primary user's spectrum holes based on its local sensing measurements

2.2.1.2 Information Detection

Transmitter detection, receiver detection and network-based detection are three types of information detection.

- ***Transmitter Detection:*** Transmitter detection techniques are used to determine if the signals from a primary transmitter are present in a certain spectrum. The approaches of transmitter detection techniques are stated below [13]

1. Energy Detection: The energy detection method is a means of detecting signals overshadowed by Gaussian noise and the receiver cannot get enough information about the primary user's signal. The major drawbacks of this method is that it cannot distinguish interference from the user signal.

2. Match-Filter Detection: Match-filter detection is a method of signal detection done by maximizing the received SNR in the presence of Gaussian noise. The matched-filter works by correlating a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal.

3. Cyclostationary Detection: The cyclostationary detection technique is a method of detecting modulated signals, characterized as being cyclic, at low SNR. This form of detection is used where energy

detection is ineffective. However, it requires a long observation time and large computational capacity [13].

- ***Receiver Detection:*** Secondary users in cognitive networks need to be able to detect other receivers in the network to avoid interfering with their communications. The first way to achieve this is to ensure the cooperation of the sensed receivers. The second way of achieving this is by interference-based detection technique, which derives from the measurement of the collective interference temperature from surrounding transmission in the cognitive network. Communication is allowed at the participating receiver when the summation of interference received is below a certain threshold.

- ***Network Detection:*** Network detection can be regarded as the sensing of information from the network, beyond the domain of the sensing cognitive user. It can be categorized under two subdivisions, namely in-network detection and out-network detection. By in-network detection, a cognitive user monitors information from neighboring nodes in the network, both from cooperative and distributed nodes. Monitoring information from other nodes in the network will assist the sensing node to find a channel that is optimal for communication. Out-network monitoring can be regarded as the gathering of information related to higher layers the communication protocol stack. Such information includes routing protocol messages, beacons sent by the MAC protocol, applications that are currently in use, and so forth.[13]

2.2.1.3 Sensing modes:

In general, there are two sensing modes, reactive sensing and proactive sensing, depending on the way to initiate the sensing. These two modes can be defined as follows:

Reactive sensing: This sensing is on-demand sensing and is initiated only when the user has data to send. If during sensing no usable channel was found, the user will wait in this sensing for a predefined period and then will restart sensing again until all the data that was intended to be sent, is not sent.

Advantage: Sensing overheads are decreased as there is no continuous spectrum sensing.

Disadvantage: The delay is introduced in data. Because sensing is continued until the sensing is performed with a great accuracy.

Proactive sensing: In this sensing mode even when the user is not intending to send any data**,** sensing is done periodically. The sensing period is the time between the sensing iteration and as each channel has its own unique behavior, these sensing periods may differ between the channels. The optimization of the sensing periods should be done separately for each channel.

Advantage: As compare to reactive sensing the delay is decreased in this mode because the users will have knowledge about the holes even before they need them.

Disadvantage: There is increase in sensing overheads as a lot of time and effort is wasted on sensing even when it was not needed exactly.

2.2.2. Spectrum Analysis

After spectrum sensing, the secondary users would have obtained certain measurements to build a model of the wireless communication scene. This process is called channel-state estimation. Main aim of this operation is analysing the channel behaviour and its effects on the transmitted signal and estimating the impulse response of the channel. If channel impulse response is known, its effects can be neutralized on the receiver by using an equalizer or on the transmitter by transmitting a signal that can absorb those effects. [1] The two perspective of channel identification are

- Estimation of Channel State Information (CSI)
- Predictive modeling

2.2.2.1 Estimation of Channel State Information (CSI):

Channel State Information (CSI) is Channel's Impulse Response .when a signal is transmitted by transmitter and propagated through the channel then from transmitter to receiver it is subject to fading , scattering, distance varying power decay etc. If CSI is available, the transmitter and receiver can be fine-tuned to nullify negative channel impulse response characteristics.

2.2.2.2 Predictive modeling:

As we know that the environment and the channel behavior is not static in nature. So if we will analyze only the current channel and if upon this analysis the results obtained are used directly then it may lead to an inefficient use of the available resources. So predictive modeling is used. It aims on finding models that will predict the behavior of the channels on the future. For finding out the model that will suit the channel or the traffic in the future, it uses both the current observations as well as previous observations. [1]

2.2.3 Spectrum Decision:

Decision making is the core of the cognitive radio, because main task of the cognitive radio is to decide the best configuration for both transmitter and receiver for efficient utilization of resources. The operation of finding the best decisions can be considered a sort of optimization. The main decision making tasks are

Dynamic Spectrum Allocation

Distributed Power Control

Adaptive Modulation

2.2.3.1 Dynamic Spectrum Allocation

In cognitive radio the spectrum allocation process is performed by the radios themselves in an ad-hoc manner without the need for core network containing special equipment. The complexity of the spectrum allocation process is that the allocation process must be dynamic. The dynamic spectrum allocation is distributing the traffic demanded by the users in the spectrum holes which were found during the spectrum sensing procedure. During spectrum allocation users generally try increase their own benefit but there should be some general rules to keep some fairness between the users to ensure that overall high benefit is obtained.

2.2.3.2 Distributed Power Control

This process is centralized in conventional radios. The power control process can be done in a distributed manner. In cognitive radio, each user must make sure that the signal that he transmits will reach the receiver and in a certain level it is high enough to be detected by the receiver , but low enough to avoid interfering with other users. At the same time each user has to inform the other users, which are transmitting to it, about the signal level reception. Actually the power control plays a crucial part in minimizing the interference and in respecting the quality of service in many communication systems.

2.2.3.3 Adaptive Modulation

Some modulation techniques are suitable for some conditions but not suitable for others. So cognitive radio should be able to switch between different modulations techniques to compensate for variation in the communication channel and the traffic characteristics. For example, if the available bandwidth decreases the system should be able to switch to a modulation scheme which has better bandwidth efficiency. This modulation switching process should be highly dynamic. This process will also provide the system with the capability to maintain the required quality of service in different environmental and thus improves the system efficiency.

2.2.3.4 OFDM Channel Filling

As discussed before, the cognitive radio system should be able to switch to a new modulation technique to avoid the drawbacks of the old modulation. The Orthogonal Frequency Division Multiplexing (OFDM) implies a high set of different characteristics. For example, using OFDM the symbols constellation, channels size can be changed along with the modulation. So, OFDM is very promising to use in cognitive radios. The use of OFDM in cognitive radio requires dynamic and accurate management of the channels. Managing the channels in OFDM is called channel filling, which is aiming to fill the channel without causing it to overflow.[1]

2.3 Applications of Cognitive Radio:

More efficient and flexible use of spectrum in the near future will open up exciting opportunities for cognitive radio to support a variety of applications, ranging from public safety and broadband cellular, to medical applications. Some of the applications are given below and a brief view on how cognitive radio would support such applications, the benefits that cognitive radio would bring, and also some challenges that are yet to be resolved are explained.

2.3.1 Public Safety networks:

We know that wireless communication system is being widely used by the emergency responders e.g., fire, police, and emergency medical services. This wireless service is not limited to the voice or messaging. It has extended to web browsing, email, picture and video transfer etc. The radio frequencies being used in the public safety environment have become congested. This congestion is more in urban areas. Sometime the agencies and first responders from different jurisdictions are not able to communicate during the emergency. This hampering in interoperability is because of by the use of multiple frequency bands, lack of standardization and incompatible radio equipment.

Cognitive radio is the best technology that can overcome all the above challenges and can increase the efficiency of spectrum usage. With CR additional spectrum such as license-exempt TV band can be used by the public safety users. But to access licensed spectrum of commercial operator there is a need of appropriate spectr.um sharing partnerships. For example, the public safety community will be allowed to roam on the commercial networks in 700 MHz in the areas where public safety broadband wireless networks will be unavailable or there will be requirement of more capacity to respond to an emergency. [19]

During natural disasters, existing communication infrastructure may get destroyed. In such situations emergency personnel and public safety user working in the disaster areas needs immediate established emergency networks. As these emergency networks deal with the critical information, so there is need of reliable communication with minimum latency. Also there is requirement of a significant amount of radio spectrum for handling huge volume of traffic including voice, video and data. Cognitive radio networks are capable of enabling the usage of the existing spectrum without the need for an infrastructure. [20,21]

2.3.2 Wireless Medical Networks (Mbans)

In recent years interest for the implementation of ubiquitous monitoring of patients in hospitals is increasing mainly for vital signs such as temperature, pressure, blood oxygen, and electrocardiogram (ECG) etc. This monitoring is done using the on-body sensors that are connected by wires to a bedside monitor. The MBANs are used in eliminating the wires. So the MBANs would help in increasing the patient comfort and mobility, and improve quality of medical decision making.

The main priority for MBAN’s is to maintain quality of service, this can be possibly attained if spectrum is not more crowded. For medical applications usually WMTS band is used but due to bandwidth scarcity the desired need cannot be met. As there is a lot of interference present in the ISM band it is not suitable to use it for the applications where QoS is a critical factor. There is one more option i.e. the 2.4 GHz industrial, scientific, and medical (ISM) band but it is not suitable for life-critical medical applications. The reason is the interference and congestion from IT wireless networks in hospitals.

By using the 2360–2400 band allocated for MBANs on a secondary basis, Qos for these monitoring applications can be respected. Also the 2360–2400 MHz band is immediately adjacent to the 2400 MHz band for which there exist many devices today that could easily be reused for MBANS, such as IEEE 802.15.4 radios and it makes low-cost implementations easy which leads to wider deployment of MBANs.[20]

2.3.3 Cellular Networks

There have been lots of changes in the use of cellular in recent years. Because the expectation of consumer of being connected always, anywhere and anytime is high. The popularity of smartphones, social networks, growing media sites such as YouTube, devices such as e-readers, is responsible for the addition to the already high and growing use of cellular networks that was needed for conventional data services such as email and web-browsing. This can be taken as opportunity as well as a challenge for cellular operators. This is opportunity because it will lead to increased average revenue per user due to added data services and it is challenge is because in certain geographical areas, cellular networks are overloaded, due partly to limited spectrum resources owned by the cellular operator

With the ruling FCC's TVWS, the new spectrum becomes available to cellular operators. In near future television band spectrum which is not declared white space yet, may also become available to cellular operators according to National Broadband Plan. This plan discusses the possibility of voluntarily auction of their licenses by current license holders of television spectrum, in return for part of the proceeds from the auction. The vision of the plan is to use this newly freed spectrum for cellular broadband applications.

Rural areas i.e. areas with low population density distribution are known for poor coverage. Cellular operators have been given rights to use their spectrum nationwide, but they choose not to deploy their networks in rural areas. The reason is that infrastructure costs is a significant part of the costs of a cellular operator. It is not possible to recover this cost in rural areas because of lack of number of subscribers in a given area. With white space spectrum, the problem can be solved.

For example, by making white space spectrum available for unlicensed use, this white space spectrum can be used by cellular operators for backhaul, for connecting their cell towers to their backbone networks, and thus provide coverage to more customers in unserved and underserved areas. For using additional spectrum some design considerations should be kept in mind given that the transmission requirements associated with the additional spectrum are varying significantly from that of the primary cellular spectrum. [20]

2.3.4 Military network: Cognitive radio can play an interesting role in military application especially in a military radio environment [21]. It can be used to enable the military radio to choose arbitrary modulation scheme, coding scheme, intermediate frequency according to the variable radio environment of battlefield. Military networks need security and protection of communication in hostile environment. Cognitive radio network will allow the spectrum handoff to find secure spectrum.

2.4 Challenges in Cognitive Radio:

There exist several open research challenges that need to be investigated for the development of cognitive radio

- Spectrum sensing challenges
- Spectrum decision challenges
- Spectrum sharing challenges
- Routing challenges
- Transport layer challenges

2.4.1 Spectrum sensing challenges

Support of asynchronous sensing: Each user has independent and asynchronous sensing and transmission schedules in CRAHNs. So it can detect the transmissions of other CR users as well as PUs during its sensing period. With the energy detection, which is mostly used for spectrum sensing, CR user cannot distinguish the transmission of CR and PUs, and can detect only the presence of a transmission. As a result, the transmission of CR users detected during sensing operations causes false alarm in spectrum sensing. So to coordinate the sensing cooperation of each CR user to reduce these false alarms is the most important issue in spectrum sensing.

Optimization of cooperative sensing: Cooperative sensing has another crucial issue. By requesting the sensing information from several CR users, accuracy is improved but also increases in the network traffic. This result in higher latency in collecting this information due to channel contention and packet re-transmissions. Thus, CRAHNs are required to optimize all these factors. [23]

2.4.2 Spectrum decision challenges

PU activity modeling: A simple ON–OFF model for PU activities is mostly used for spectrum sensing which cannot capture the diverse characteristics of all existing primary networks. This inaccurate model for primary networks leads to an adverse effect on spectrum sensing resulting in either lower spectrum utilization or higher interference to the primary networks. Some of the empirical models on PU activities are not computationally efficient in practical situations. Thus, there is need to develop more practical PU activity models by considering the characteristics of access technologies as well as traffic types.

Joint spectrum decision and reconfiguration framework: After characterization of the available spectrum bands, by considering the QoS requirements i.e. delay, jitter, average session time, acceptable loss rate etc., the most appropriate spectrum band should be selected. However, as we are using the reconfigurable transmission parameters such as modulation scheme, so according to these parameters there is a significant change in the spectrum characteristics. With only reconfiguration, CR users will be able to maintain the quality of the current session, but not always. It may happen sometime. For example, SNR and BER are dependent. So if SNR is changed, and we still want to maintain bit rate and bit error rate (BER) then it can be done by exploiting an adaptive modulation scheme, instead of changing the route and spectrum. So we need joint spectrum decision and reconfiguration framework [23]

2.4.3. Spectrum sharing challenges

Spectrum sharing and sensing share some of functionalities so most of the issues are similar to those of spectrum sensing.

Distributed power allocation: The CRAHN user determines the transmission power in a distributed manner without support of the central entity, which may cause interference due to the limitation of sensing area even if it does not detect any transmission in its observation range. Thus, spectrum sharing requires the sophisticated power control methods for adapting to the time-varying radio environment so as to maximize capacity with the protection of the transmissions of PUs.

Spectrum access and coordination: In classical ad hoc networks, the request to send (RTS) and clear to send (CTS) mechanism is used to reduce simultaneous transmissions to an extent. In CR the available spectrum is dynamic and users may switch the channel. Thus, a fresh set of RTS-CTS exchange may need to be undertaken in the new channel to enforce a silence zone among the neighboring CR users in the new spectrum. Moreover, the CR users monitoring the earlier channel are not aware to the spectrum change on the link. They still continue to maintain their timers and wait for the duration needed to complete the entire data transfer before initiating their own transmission. This leads to inefficient spectrum use, and new coordination mechanisms among the CR users is necessary whenever the spectrum access conditions change

Evolution and learning: The occupancy history of the spectrum bands by the PUs may vary with the time of the day and location. It is desired that the MAC protocol learns the characteristic PU activity and accordingly alters its spectrum selection and data transmission strategy. [23]

2.4.4 Routing challenges

Routing constitutes a rather important but yet unexplored problem in cognitive radio networks. So far, the research on cognitive radio networks is primarily on spectrum sensing techniques and spectrum sharing solutions. [21]

Intermittent connectivity: In cognitive radio networks, the reachable neighbors of a node may change rapidly. This is due to two reasons. First, the available spectrum may change or vanish as licensed users exploit the network. Moreover, once a node selects a channel for communication it is no longer reachable through other channels. As a result, the connectivity concept used for wireless networks is different in cognitive networks and depends on the spectrum. For this purpose channel-based model with time-based solutions is required.

Re-routing: In cognitive radio networks, due to the intermittent connectivity, a route established for a flow can change due to the available spectrum in addition to mobility. Hence, the re-routing algorithms considering the dynamic spectrum is necessary for routing in cognitive radio networks. A spectrum-aware routing adapts route selection to spectrum fluctuations.

Queue management: The queue management in cognitive radio networks is another challenge which has not been addressed to date. A cognitive radio terminal may have multiple interfaces for communication with different nodes. Since the available spectrum varies over time, these interfaces may become unavailable requiring the packets served through that interface moved to other interfaces. In addition, the quality of service requirements may deploy various priorities on different traffic types. Hence, the implementation of a single queue or multiple queues for each traffic type of each interface needs to be investigated. [21]

2.4.5. Transport layer challenges

Several solutions have been proposed to improve the performance of TCP and UDP in Conventional wireless networks. These studies focus on mechanisms to limit the performance degradation of TCP and UDP that arise because of wireless link errors and access delays. However, the cognitive radio networks impose unique challenges for transport protocols. The performance of TCP in case of cognitive radio depends on the packet loss probability and the round trip time (RTT).The packet loss probability not only depends on the access technology, but also on the frequency in use, interference level, and the available bandwidth. Therefore, the wireless TCP and UDP protocols that are designed for existing wireless access technologies cannot be used in cognitive radio networks. [21]

CHAPTER 3

GAME THEORY

3.1. Introduction

Game theory can be viewed as a branch of applied science as well as of applied mathematics. It has been mostly used in economics, but has also penetrated into a variety of other disciplines such as political science, biology, computer science, philosophy, and, recently, wireless and communication networks, social sciences. [24] Game theory can be defined as following

"The Game Theory is a collection of models and analytic tools used to study interactive decision-making processes"

As the games usually do, there are also rules that define what is going to be the outcome when every player takes its action. In this scenario the decisions that every player makes will influence the rest of them, or from another point of view, the behavior of every subject depend on the behavior of the rest of them. So the basic assumptions of the game theory are that decision-makers are rational i.e. they pursue well-defined exogenous objectives and whatever they do, they do have strategic reason i.e. take into account their knowledge or expectations of other decision-makers' behavior.[25]

3.2. History

After the publication of von Neumann and Morgenstern's book, and the seminal work of John Nash, game theory has enjoyed over 65 years of scientific development. It has experienced exponential growth in both the number of theoretical results and the scope and variety of applications. Three Nobel have been given in the economic sciences for work primarily in game theory. The first Nobel Prize was given in 1994 to John Harsanyi, John Nash, and Reinhard Selten "for their pioneering analysis of equilibrium in the theory of non-cooperative games." The second Nobel Prize went to Robert Aumann and Thomas Schelling in 2005, "for having enhanced our understanding of conflict and cooperation through game-theory analysis." And most recently it has been given in 2007, recognizing Leonid Hurwicz, Eric Maskin, and Roger Myerson, "for having laid the foundations of mechanism design theory." The biggest achievement is Crafoord Prize i.e. the highest prize in the biological sciences was given to John Maynard Smith, Ernst Mayr and G. Williams in 1991 "for developing the concept of evolutionary biology." Smith got recognition through his work on evolutionary games and evolutionarily stable equilibrium.[24 25]

3.3. Game Components

A game is the description of interactions that includes the players, their strategies and constraint on their actions. Solution is description of the outcomes in the game. So in brief we can say that game theory suggests the solutions of games and examine their properties. The main application of the game theory is to find the conditions under which the game achieves equilibrium. [24 – 25]

A Game is a tuple composed by three elements: the set of players, a set of strategies to follow, and the payoff functions i.e.

$$G = \langle I, (S_i)_{i\in I}, (u_i)_{i\in I} \rangle. \quad (3.1)$$

Decision Makers (I): Each game is assumed to have a finite number of decision makers or players I.

Action Space (S_i): Every player (i) has its own action space (S_i) which is the set of actions which includes all possible actions that player can choose. The total action space (S) is calculated by multiplying all action sets. $s_i \in S_i$ an action for player I, $s_{-i} = [s_j]_{j\neq i}$ is a vector of actions for all players except I, $S = \prod_i s_i$ is set of all profiles of actions, $S_{-i} = \prod_{j!=i} s_i$ is the set of all profiles of actions for all players except I.[26]

Utility Set (U): It is a set consists of utility or payoff functions for all players. $(u_i)_{i\in I}$ is a set of payoff functions.

Nash Equilibrium: The main task in game theory is to find the Nash equilibrium. The steady state of the play of a Game in which each player holds the correct expectation about the other players' behavior and acts rationally is called Nash equilibrium. Nash equilibrium of a game G= <I, $(S_i)_{i\in I}$, $(u_i)_{i\in I}$ > is a strategy profile $s^* \in S$ such that $\forall i \in I$ we have the following

$$u_i(s_i^*, s_{-i}^* \geq u_i(s_i, s_{-i}^*), \forall s_i \in S_i, s_i \neq s_i^*, \forall i \in I \tag{3.2}$$

In other words a strategy profile is Nash equilibrium if no player has incentive to unilaterally deviate to another strategy.[24 ,26]

3.4. Example of Game Theory

The classical example of game theory is the so-called "Prisoner's Dilemma." This game introduces a scenario where because of the requirement of independent decision-making, conflict of interest arises. The Prisoner's Dilemma helps in analyzing the decision-making process in the following hypothetical setting. Two criminals are arrested after being suspected of a crime in unison. But the problem is that the police do not have enough evidence to convict either of them. So to deal with this situation the police decided to play a trick. They decided to separate the two and offer them a deal.

The deal is

- If one testifies against the other, he will get a reduced sentence or set free. In this situation the prisoners do not have information about each other's "moves," .It is the same situation as they would have in some social games such as chess.
- If they both don't say anything i.e. they cooperate with each other, the payoff is somewhat favorable. Because in this situation neither can be convicted of the real crime without further proof. Though they will be convicted of a lesser crime.
- If one of them betrays i.e. testify against 2nd prisoner but the other one does not, then the betrayer is going to get benefits. Because he

goes free while the other one is imprisoned, since there is now sufficient evidence to convict the silent one.

- If they both confess, they both get reduced sentences, which can be viewed as a null result.

The obvious dilemma in above situation is the choice between two options, where a favorable decision, acceptable to both, cannot be made without cooperation. A representative Prisoner's Dilemma is depicted in Table I

One player acts as the row player and the other the column player, and both have the action options of cooperating (C) or defecting (D).

Table I Prisoner's Dilemma

P1/P2	**Cooperate**	**Defect**
Cooperate	(3,3)	(0,5)
Defect	(5,0)	(1,1)

Thus, there are four possible outcomes to the game:

{(C,C),(D,D),(C,D),(D,C)}.

- Under mutual cooperation,{(C,C)}, both players will receive a reward payoff of 3.
- Under mutual defection,{(D,D)}, both players receive the punishment of defection, 1.
- When one player cooperates while the other one defects, {(C,D),(D,C)}, the cooperating player receives a payoff of, 0, and the defecting player receives the temptation to defect, 5.

In The Prisoner’s Dilemma example, if one player cooperates, the other player will have a better payoff (5 instead of 3) if he or she defects; if one player defects, the other player will still have a better payoff (1 instead of 0) if he or she also defects. Regardless of the other player’s strategy, a player in The Prisoner’s Dilemma has an incentive to always select defection, and {(D,D)} is an equilibrium. Although cooperation will give each player a better payoff of 3, greediness and lack of trust leads to an inefficient outcome. This simple example shows how the game-theoretic concept of equilibrium can provide a lot of insight into the outcome of decision-making in an adversarial or conflicting situation.

3.5. Nash Equilibrium

John Nash’s work on the concept of equilibrium for non-cooperative games introduced the concept of an equilibrium of a game, which later became known as the Nash equilibrium. The Nash equilibrium defines fair-sharing approaches and outcomes of selfish interactions in a game, and is regarded as the most important solution concept in game theory.

The Nash equilibrium of a strategic-form game is a mixed strategy profile wherein every player is playing a best response to the strategy choices of his opponents. A player’s best action depends on the opponents chosen actions. When players in a game apply their best strategies, the game ultimately reaches the Nash equilibrium point.

The Nash Equilibrium is based on two assumptions:

- The choice of strategy adopted by each player is a rational in nature. It is best response strategy based on impressions or beliefs formed by analyzing the actions of his opponents
- Every player's belief about the other players' actions is correct.

From these underlining assumptions, there exist two philosophical motivations for adopting the Nash equilibrium as a solution concept. These are

- No-regret: This concept of no-regret is based on the fact that no player can do strictly better by deviating from the best response strategy. But with condition that the other players also follow the equilibrium policy.
- Self-fulfilling beliefs: Players in a game of Nash equilibrium form self-fulfilling beliefs about their adopted strategy, because it is the best response to the other opponents strategies.

The relevance of the Nash equilibrium to cognitive radio networks is best understood when we consider the following example [27] [28]:

Consider a multiple-access game, as illustrated by Table II. It involves two transmitters, which has been denoted as p1and p2, who want to send data packets over a shared channel to their receivers, r1 and r2 respectively. There are two strategies in the game that the players can use. Each can decide to transmit a packet or do not transmit i.e. remain quiet denoted by T and Q respectively.

The payoffs of their actions are defined in the corresponding columns and rows. The cost earned by transmitting a packet is denoted by c, where c lies between 0 and 1 i.e. $0 < c < 1$. Since the channel is shared, the transmission by both players results in a collision, which results in the loss of packets.

Table II: Tabular representation of the multiple-access game.

P1/P2	Q	T
Q	(0,0)	(0,1-c)
T	(1-c,0)	(0,0)

From above table it is clear that the optimal solution to the multiple-access game is as follows:

- If player p1 chooses to transmit, then the best response for player p2 will be to remain quiet.
- Also, if player p2 chooses to transmit, the best response for player p1 will be to remain quiet.

So we can conclude that in the Nash equilibrium points, there is no incentive for any player involved in the game to deviate from the best response strategies.

3.5.1. Inefficiency of the Nash Concept and Equilibrium Selection

There exist the exceptional cases where the Nash equilibrium leads to unstable outcomes. Since the Nash equilibrium is the most widely used solution concept in game theory. So it is important to discuss these exceptions.

- Nash equilibrium need not exist in a game: The Nash equilibrium does not give information of how to attain the equilibrium state, it only gives us the equilibrium value
- Existence of many Nash equilibrium in a game: In some circumstances, multiple Nash equilibrium could exist in a game and so, there is the challenge of choosing the appropriate solution.
- Inadequate deductive intelligence: The Nash equilibrium assumes that players have unlimited computing capabilities and hence, can resolve infinite loops from logical reasoning. In practice, players do not have such ability.
- A Nash equilibrium may involve a weakly dominated strategy by some players: The Nash equilibrium is engendered by the use of best response strategies against an opponent with a similar goal. However, rational decisions are not always suitable in a game. For example, in the two-player game represented by Table II, when a player changes strategy and adopts a non-equilibrium strategy, the optimal response of his opponent would be a relative non-equilibrium strategy too. Hence, in such circumstance, the Nash equilibrium does not apply. [28, 29]

3.6. Types of Games

The games are generally divided into two types

- Cooperative
- Competitive games

Cooperative Games: This is the game where all players are concerned about the overall benefits. They are not very worried about their own personal benefit. So for overall benefit, players fully cooperate with each other like football players in a team.

Competitive Games: This is a game where every user is mainly concerned about his personal payoff and therefore all its decisions are made competitively and moreover selfishly. Thus, it is called non-cooperative games. Most of the two players' games are good example of this type. Normally most games and applications cannot be viewed as cooperative games but can be viewed as competitive non cooperative game.

3.7. Game models

Game theory has many game models. The choice of the model depends on the problem in hand and its characteristics. The different game models are shown in the Fig. 3.1.

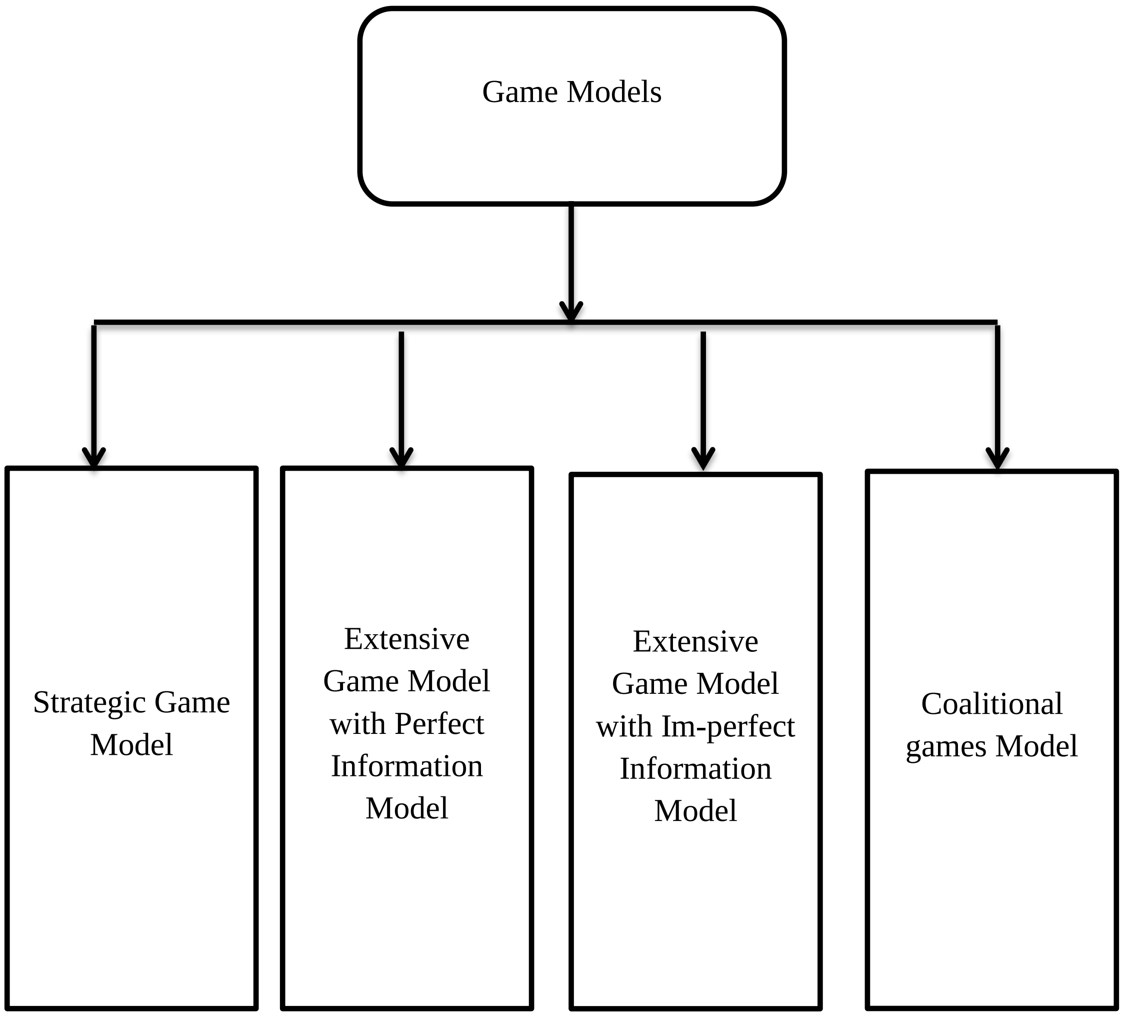

Fig. 3.1 Game models

3.7.1 Strategic game Model: Strategic game is "a game in normal form" according to Von Neumann and Morgenstern (1944). In this for each player there is a set of possible actions and a preference over the set of possible action profiles. It is a model of interactive decision-making. In the beginning of game each decision-maker chooses his plan of action once and for all, and these choices are made simultaneously. The model consists of a finite set N of players and, for each player i, a set A_i of actions and a preference relation on the set of action profiles.[30]

To summarize, the definition is the following.

A strategic game consists of

- a finite set N (the set of players)
- for each player $i \epsilon N$ a nonempty set A_i (the set of actions available to player i)
- for each player $i \epsilon N$ a preference relation

If the set A_i of actions of every player i is finite then the game is finite

In this game model a high level of abstraction exists which allows it to be applied to a wide variety of situations. A player may be an individual human being or any other decision-making entity like a government, a board of directors, the leadership of a revolutionary movement, or even a flower or an animal. There are no restrictions on the set of actions available to a player, which may, for example, contain just a few elements or be huge set containing complicated plans that cover a variety of contingencies. However, the range of application of the model is limited by the requirement that we associate with each player a preference relation. A player's preference relation may simply reflect the player's feelings about the possible outcomes or, in the case of an organism that does not act consciously, the chances of its reproductive success.

The fact that the model is so abstract is a merit to the extent that it allows applications in a wide range of situations, but is a drawback to the extent that the implications of the model cannot depend on any specific features of a situation. Indeed, very few conclusions can be reached about the outcome of a game at this level of abstraction; one needs to be much more specific to derive interesting results.

Nash equilibrium of a strategic game: The steady state of the play of a Game in which each player holds the correct expectation about the other players' behavior and acts rationally is called Nash equilibrium.

Nash equilibrium of a game G is a strategy profile $s^* \in S$ such that $\forall i \in I$ we have the following;

$$u_i(s_i^*, s_{-i}^* \geq u_i(s_i, s_{-i}^*), \forall s_i \in S_i, s_i \neq s_i^*, \forall i \in I \qquad (3.3)$$

In other words a strategy profile is Nash equilibrium if no player has incentive to unilaterally deviate to another strategy.[27]

Examples: The Prisoner's Dilemma, Matching Pennies.

3.7.2. Extensive game with Perfect Information

In a strategic situation an extensive game with perfect information gives the description of the sequential structure of a problem where decision is to be taken**.** It is called a game with perfect information, because each player is perfectly informed during the decision making about the events that have previously occurred. For simplicity we initially restrict attention to games in which no two players make decisions at the same time and all relevant moves are made by the players .[30]

An extensive game with perfect information has the following components

- The set of players (N)
- A set of sequences (H). Each member of H is a history and is an action taken by a player. A history $(a^k)_{k=1,\dots k+1} \in$ H is terminal if it is finite or if there is no a^{k+1} such that $(a^k)_{k=1,\dots k+1} \in$ H. The set of terminal histories is denoted by Z
- A function P that assigns to each nonterminal history (each member of H/Z) a member of N. If P is a player function , P(h)will be the player who take an action after history h)
- For each player $i \in N$ a preference relation on Z

Sometimes specifying the structure of an extensive game is more important as compare to specifying the players' preferences. The game is finite, if the set H of possible histories is finite. A strategy in an extensive game is the plan specifying the action chosen by the player according to every history after which it is his turn to move.[30]

Nash equilibrium of an extensive game: A Nash equilibrium of an extensive game with perfect information < *N*, *H*, *P* > is a strategy profile s^* such that for every player $i \in N$ we have

$$u_i(s_i^*, s_{-i}^* \geq u_i(s_i, s_{-i}^*), \forall s_i \in S_i, s_i \neq s_i^*, \forall i \in I \quad (3.4)$$

If Nash equilibrium were the only solution we defined for extensive games, we could define a strategy more restrictively. we can define a reduced strategy of player.[27,24]

Example:

- **Bargaining Games :**

  Game theory deals with situations in which people's interests' conflict. The people involved may try to resolve the conflict by committing themselves voluntarily to a course of action that is beneficial to all of them. If there is more than one course of action more desirable than disagreement for all individuals and there is conflict over which course of action to pursue then some form of negotiation over how to resolve the conflict is necessary. The negotiation process may be modeled using the tools of game theory.

- **Repeated game** :

  The model of a repeated game is designed to examine the logic of long term interaction. It captures the idea that a player will take into account the effect of his current behavior on the other players' future behavior, and aims to explain phenomena like cooperation, revenge, and threats.[30,31]

3.7.3. Extensive game with imperfect information

The model of an extensive game with imperfect information allows a player, when taking an action, to have only partial information about the actions taken previously. The model is rich; it encompasses not only situations in which a player is imperfectly informed about the other players' previous actions, but also, for example, situations in which during the course of the game a player forgets an action that he previously took and situations in which a player is uncertain about whether another player has acted. We analyze the model by assuming, as we did previously, that each player, when choosing an action, forms an expectation about the unknowns. However, these expectations differ from those we considered before. Unlike those in strategic games, they are not derived solely from the players' equilibrium behavior, since the players may face situations inconsistent with that behavior. Unlike those in Bayesian games, they are not deduced solely from the equilibrium behavior and the exogenous information about the moves of chance. Finally, unlike those in extensive games with perfect information, they relate not only to the other players' future behavior but also to events that happened in the past.[30.32]

The following definition generalizes that of an extensive game with perfect information to allow players to be imperfectly informed about past events when taking actions. It has following components

- The set of players (N)
- A set of sequences (H). Each member of H is a history and is an action taken by a player. A history $(a^k)_{k=1,\ldots k+1} \in$ H is terminal if it is finite or if there is no a^{k+1} such that $(a^k)_{k=1,\ldots k+1} \in$ H. The set of terminal histories is denoted by Z
- A function P that assigns to each nonterminal history (each member of H/Z) a member of N. If P is a player function , P(h)will be the player who take an action after history h)
- A function f_c that associates with every history h for which P(h)=c a probability

measure $f_c(.|h)$ on A(h), where each such probability measure is independent of every other such measure. ($f_c(a|h)$ is the probability that a occurs after the history h.)

- For each player $i \in N$ a preference relation on Z

3.7.4. Coalitional Games

The previous models are often referred to as noncooperative" games. In these games each action is taken by a single player autonomously. One primitive of coalitional model is the collection of sets of joint actions that each group of players (coalition) can take independently of the remaining players. An outcome of a coalitional game is a specification of the coalition that forms and the joint action it takes. The other primitive of the model of a coalitional game is the profile of the players' preferences over the set of all possible outcomes. Thus although actions are taken by coalitions, the theory is based on the individual's preferences. A solution concept for coalitional games assigns to each game a set of outcomes. As before, each solution concept we study captures the consequences of a natural line of reasoning for the participants in a game;

It defines a set of arrangements that are stable in some sense. In general the stability requirement is that the outcome be immune to deviations of a certain sort by groups of players; by contrast, most (though not all) solutions for noncooperative games require immunity to deviations by individual players. A coalitional model is distinguished from a noncooperative model primarily by its focus on what groups of players can achieve rather than on what individual players can do and by the fact that it does not consider the details of how groups of players function internally. If we wish to model the possibility of coalition formation in a noncooperative game then we must specify how coalitions form and how their members choose joint actions. These details are absent from a coalitional game, so that the outcome of such a game does not depend on them.

To illustrate the differences between the two modeling approaches, consider the following situation. Each of a group of individuals owns a bundle of inputs and has access to a technology for producing a valuable single output. Each individual's inputs are unproductive in his own technology but productive in some other individual's technology. A noncooperative model of this situation specifies precisely the set of actions that is available to each individual: perhaps each individual can announce a price vector at which he is willing to trade inputs, or perhaps he can propose a distribution of inputs for the whole of the society. A coalitional model, by contrast, starts from the sets of payoff vectors that each group of individuals can jointly achieve. A coalition may use contracts, threats, or promises to achieve a high level of production; these institutions are not modeled explicitly in a coalitional game. We do not view either of the two approaches as superior or more basic. Each of them reflects different kinds of strategic considerations and contributes to our understanding of strategic reasoning. The study of the interconnections between noncooperative and cooperative models can also be illuminating.

A coalitional game with transferable payoff consists of

- a finite set N (the set of players)
- a function v that associates with every nonempty subset S of N (a coalition) a real number v(S) (the worth of S). For each coalition S the number v(S) is the total payoff that is available for division among the members of S.[30]

3.8 Repeated games

Repeated games have been studied extensively. Repeated game is the stage game and is played repeatedly by the same set of players. After each play of the stage game, all of the players have knowledge about what strategies were chosen by their opponents in the last round. As a result, players can change their choice of strategies based on past actions of their opponents [6]. Repeated games are of three types.

- Repeated games with complete information: A repeated game is of complete information if each player is aware of all other players, the set of strategies and payoff.
- Repeated games with perfect information : In repeated game with

perfect information each player knows every action of the players that moved before him or her.

- Repeated games with imperfect information. : Repeated game with imperfect information is quite different. In such games player does not know exactly what action other players took up to this point. [33]

For power optimization in this dissertation we have used the repeated games with perfect information.

3.9 Applications of game theory in communications and networking:

Because of the recent advances in technology there is a need of novel analytical frameworks that can be suited to tackle the numerous technical challenges accompanying current and future wireless and communication networks. Thus, in recent years game theory has been widely used as a central tool for the design of future wireless and communication networks. The reason is the need of incorporating decision-making rules and techniques into next-generation wireless and communication nodes that enable them to operate efficiently and meet the users' needs in terms of communication services [24]

Example:

The most popular examples of game theory is modeling the problem of power control in cellular networks using non-cooperative games. For example there exists the near – far problem in uplink CDMA system. So there is need of designing a mechanism that allows the users to regulate their transmit power, given the interference that they cause in the network. In doing so, wireless researchers were able to found a similarity between the problems of power control and non-cooperative game theory.

In a non-cooperative game, there is a competition between numbers of players and whenever a player makes a move i.e. it chooses its strategy this move has an impact that may be positive or negative on the utility of the other players. Similarly, in a power control game, we have a competitive situation in which the transmit power level (strategy) of a wireless user can impact positively or negatively (because of interference) on the transmission rate and quality of service (QoS) of the other users. As a result, solving a power control game has been shown to be equivalent to solving a non-cooperative game. It is not the only application. In fact game theory have emerged in the wireless, communications, and signal processing communities.[24]

3.10 Challenge

The game theory was initially developed as a tool to be used in economics and the social sciences. Hence, use of game theory in engineering applications is accompanied by many difficulties. For instance, researchers interested in applying game-theoretic models to problems in wireless and communication networks face many hurdles in finding accurate models and solutions. This is due to the fact that existing game-theoretic models are not tailored to cope with engineering- specific issues such as modeling time varying wireless channels, developing performance functions (i.e., utilities) that depend on restrictive communication metrics (e.g., transmission rate, queuing delay, signal to-noise ratio), and conforming to certain standards (e.g., IEEE 802.16, LTE). This has necessitated a timely, comprehensive reference source that can guide researchers and communications engineers in their quest to find effective analytical models from game theory that can be applied to the design of future wireless and communication networks. [24]

3.11 Applications of game theory in Cognitive Radio

Almost all optimization problems in cognitive radio can be mapped into games. In cognitive radio networks game theory can be naturally applied to achieve the decentralized operation and self-configuration features. In game theory, cognitive radios can be viewed as selfish rational players and is seeking to optimize its own utility. The interest of an individual cognitive radio may conflict with that of the network, in which case game theory can be straightforwardly applied, as it traditionally analyzes situations where player objectives are in conflict. [34]

Each node in the network that is involved in the decision step is a player in the game. The node's action set is the various alternatives available to a node, and the action space is formed from the Cartesian product of the radios' alternatives. A cognitive radio's observation and orientation steps combine to form a player's utility function. [35]

- **Game theory in spectrum sensing:**

In local sensing each secondary user does its own sensing, and decides on the presence or absence of the PU using energy detector, matched filter etc. In fading environments, local sensing suffers from hidden terminal problem. Solution to the hidden terminal problem is collaborative spectrum sensing. In such scenario there exist a Fusion Center and it makes final decision i.e. PU present or not. All the SUs perform local Sensing of PU signal and send their data to Fusion Center. But this centralized approach results in more overheads. So there is need of distributed collaborative sensing between the users with no centralized fusion center. Distributed collaborative sensing can be modeled as Coalitional games. [33]

- **Game theory in dynamic spectrum allocation:**

DSA process is distributing the traffic demanded by the users in the spectrum holes which were found by the spectrum sensing procedure. In this operation users are generally interested in increase their own benefit but they should obey some general rules to keep some fairness between the users and to ensure obtaining a high overall benefit. The user behaviors along with those general rules are called user strategies. The decision making process then can be seen similar to playing a game. Each user represents a player in that game and the strategies represent the rules of the game. This concept is formulated on a mathematical theory called the game theory. DSA can be modeled using exact potential game model. A game is said to be potential when there is a function V: {A}, and any independent variation in V (ΔV) is seen by the corresponding independent player as (ΔUi). And if $\Delta V = \Delta Ui$ the game is called exact potential game. It was also proved that any potential game has at least one steady state, and all states that maximize V are Nash equilibrium states. [35]

- **Distributed Power Control:**

Each secondary user has a certain power budget available for transmission. More power is used; higher will be end to end throughput of cognitive radio network. But at the same time, interference toward the primary network will also increase. So the main objective of distributed power control is optimal power allocation at the secondary user nodes leading end to end throughput maximization, while satisfying the interference constraint of primary user network. There exist the centralized power control scheme where each node in the network has to follow the instructions of central manager. But it results in more overheads. So distributed power control can be used. But in distributed power control all the users try to maximize their own payoff that results in non-co-operative behavior. The solution to this problem is Game Theory. Distributed power control problem can be modeled using the super-modular game and repeated game model.

- **OFDM channel filling**

OFDM is very promising technique which can be used in cognitive radios. The use of OFDM in cognitive radio requires dynamic and accurate management of the channels. Managing the channels in OFDM is called channel filling, which is aiming to fill the channel without causing it to overflow. The OFDM channel filling can also be examined using game theory. The resulting problem is similar to the spectrum allocation. It is modeled using exact potential game

CHAPTER 4

POWER CONTROL

4.1. Transmit power control

There are two categories of cognitive radio operations: opportunistic spectrum access and spectrum sharing. Opportunistic spectrum allow secondary user (SU) to access frequency band that was allocated to primary user (PU) when primary user is inactive. In spectrum sharing secondary users are allowed to transmit simultaneously with primary user even when primary user is active as long as quality of service (QOS) of PU transmission is not degraded to an acceptable level [36]. In spectrum sharing environment the coexistence of primary users and secondary users in the same spectrum network will inevitably introduce interference. Hence, a critical design challenge for cognitive networks is to establish a balance between transmit power and interference. So, for the efficient use of resources in any wireless network it is mandatory to maintain a balance between them. Interference management is possible through the transmit power control. The amount of transmission power should be such that it is sufficient to be received at the receiver and do not create interference to other user The essence of spectrum decision is transmit-power control. In Cognitive Radio networks, power control deals with the selection of proper transmit power for CR users' transmissions that achieves high spectrum efficiency by enabling CR users to reuse the PUs' spectrum bands under the interference constraints imposed by PUs. [21]

4.2. Challenges of Transmit-Power Control

Challenges of Transmit-Power Control are described below:

4.2.1. Opportunistic access to unstable spectrum holes:

There is competition among the secondary users in cognitive radio networks for accessing the available limited resources. The availability of spectrum holes for opportunistic access by competing nodes varies with time and location. It leads to the concept of dynamic cognitive network. Nodes participating in competition have to exploit unstable spectrum holes. But they should also ensure that their individual activities do not cause distribution of network resources, and hence leads to instability of the network. Therefore, fundamental requirement is the design of suitable algorithms capable of driving the cognitive users to adopt rational behavioral tendencies.

4.2.2. Balance between transmit power, bandwidth and interference:

In wireless communication systems, three fundamentally connected, but conflicting theoretical concepts are transmit power, bandwidth, and interference. It is impossible to increase any in a network without causing conflicts in the others. Hence, a criterion for the efficient use of resources in any wireless network is to maintain a balance between them. The cognitive network is complicated by the existence of two types of users, namely primary and secondary users. The traditional problem of interference management through power control is quite different in cognitive radio because of the existence of two types of users, namely primary and secondary users. Secondary users have conflicting interests. Cognitive radio users are engaged in maximizing their data rate, while minimizing the interference to the active primary users and other secondary users Hence, a critical design challenge for cognitive radio is to establish a balance between transmit power, bandwidth and interference.[21]

4.2.3. Autonomous Operability:

Cognitive networks is of dynamic in nature, and it demands that cognitive radios are autonomous and independent in their operational functions such as self-organization mechanisms to perceive the radio environment, to establish links and cooperation with neighbouring peer nodes and to keep track of historical decisions on spectrum holes and interference . Hence, autonomous operability is considered a fundamental design criterion of cognitive networks. [29]

4.3. Transmit-Power Control Techniques

The implementation of power control in cognitive radio networks can be done in two ways.

- Centralised power control scheme
- Distributed power control scheme

4.3.1 Centralised Power-Control Scheme:

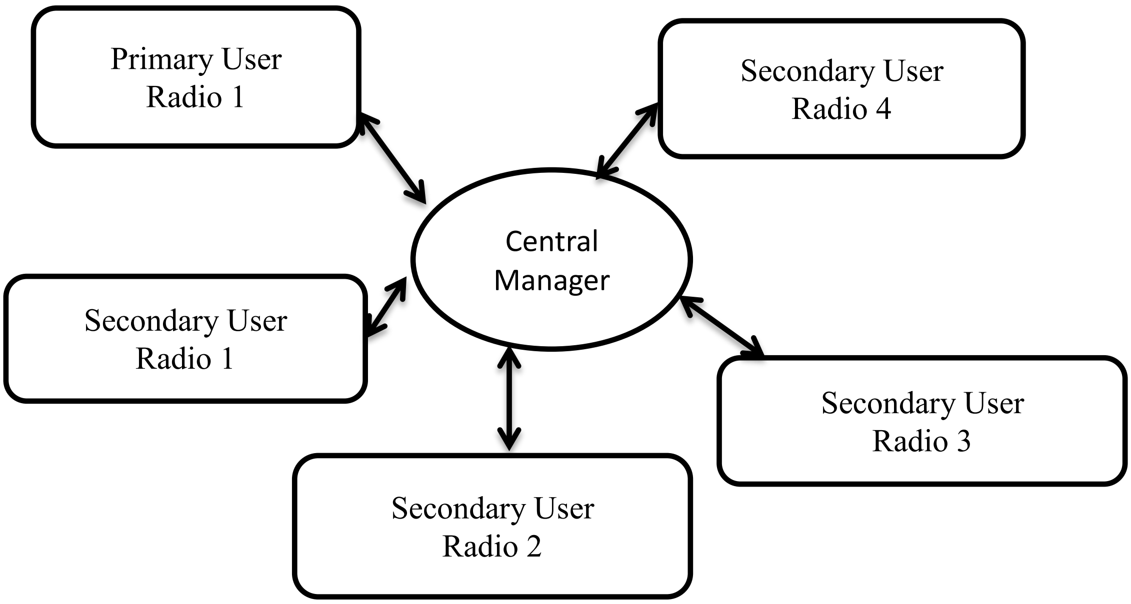

Fig.4.1 Centralized power control scheme.

In centralised cognitive radio networks, there exists a central manager in the network as shown in Fig. 4.1. The Centralized Manager is responsible for exchanging information and control the transmission power of all secondary users within its coverage area. When secondary users are authorized by the central manager through information exchange only then transmission by secondary users in the network can take place. The problem with the Centralised Power-Control Scheme is overhead generated when users communicate with the central manager. [37,38]

Distributed Power-Control Scheme:

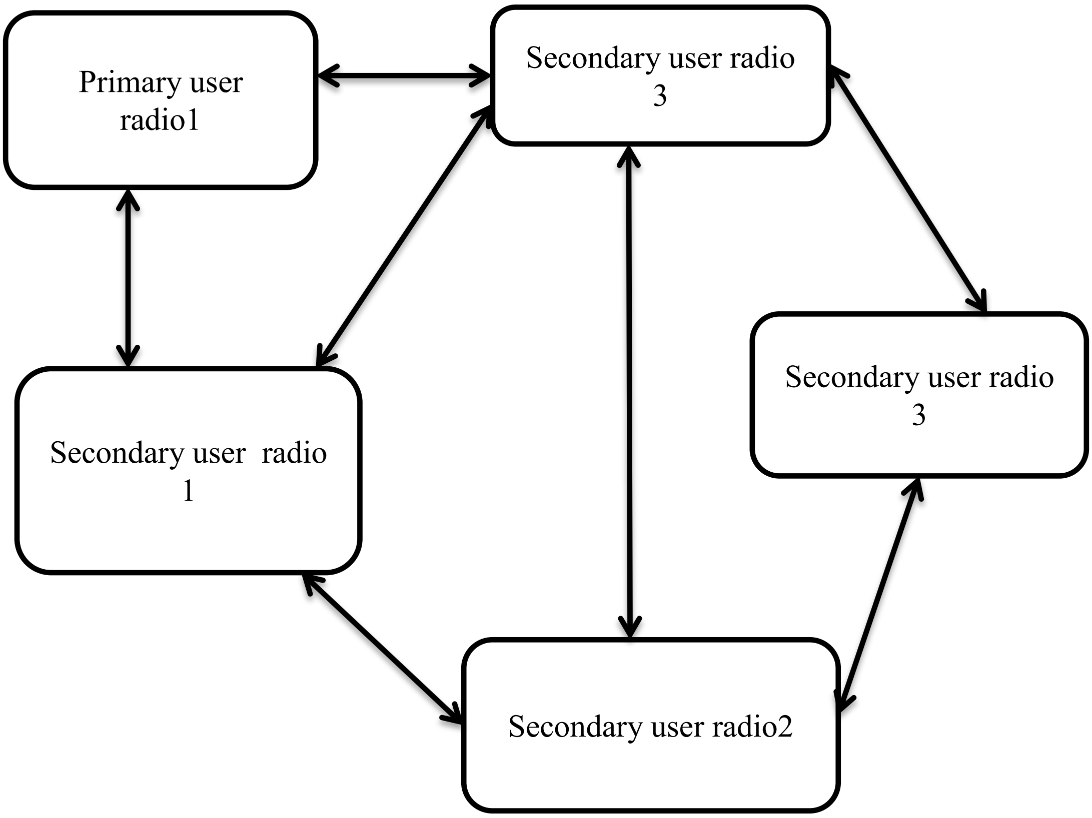

Fig. 4.2 Distributed power control scheme

Fig. 4.2 given illustrates the distributed power control scheme. In the distributed power control scheme, there exists no centralised server or moderator. Each user controls it's transmit power by itself. For controlling power it uses only local information.

In Centralised power control scheme there was a problem of signaling bottlenecks and information overheads that were because of the communication with centralised manager.

Distributed power control avoids this problem. However, even in the distributed power-control scheme the problems exists and are due to,

- The severe non-cooperation of the secondary users
- The interference from the transmit power of the all distributed secondary users being above the interference temperature threshold.

The problem of non-cooperation can be solved by the use of game theoretic concepts.[39]

4.4 RELATED WORK:

Since cognitive radio is a new technology many researchers are working on this. Some of the related work is mentioned below.

In case of centralized approach a lot of work has been done. [37] Uses the Fuzzy logic to control the transmit power in centralized manner. This fuzzy logic helps the SUs to dynamically adjust their power according to the interference caused to the PUs. The problem with this method is excessive signaling and overheads. To improve the efficiency of centralized scheme [40] uses the linear programing concept. Ensuring fairness in frequency distribution was also considered. But even this method had not addressed the overhead problem.

Distributed power control is the alternate for removing excessive overhead problem. But there exists the problem of non-co-operation in such scenario as every user wants to increase its benefit. This problem has been addressed using game theory. In [11] power allocation with interference is proposed but without the consideration on the protection of primary (licensed) users. In [41] a power control algorithm has been proposed with a new pricing function with interference temperature constrains to control the network's power consumption in a distributed cognitive radio network game model. In [12] Instead of applying interference power constraint at the primary user (PU) receiver for the secondary user (SU) to protect the primary transmission, constraint on the maximum tolerable outage probability for the PU due to the SU transmission is proposed, but with the assumption that perfect instantaneous channel state information (CSI) is available on the SU channel. In both [12, 41] the decision is taken with assumption that local information is available. In [42] to improve the secondary system's performance, a pricing function based on Signal-to-Interference and Noise Ratio (SINR) is incorporated into the non-cooperative power control game model. The power control in multi-antenna cognitive radio system has been researched with the idea of game theory in [43]. In [44] PU adjusts their power in renting the spectrum to secondary users. The secondary users adjust their power by observing the changes in the price and the quality of the spectrum. PUs power adjustment is modeled using Bertrand game and SUs adjustment has been modeled using Stackelberg game. Distributed power control is investigated in [45] for cognitive radio networks (CRNs) based on a cooperative game theoretic framework. Taking into consideration both network efficiency and user fairness.

Nash bargaining power control game (NBPCG) model is formulated which is cooperative in nature. Interference power constraints (IPCs) are imposed to protect the primary users' (PUs') transmissions, and minimum signal-to-interference plus-noise ratio (SINR) requirements. Kalai–Smorodinsky (KS) bargaining solution and a Nash bargaining solution (NBS) have been developed. In [48] Power control in CDMA environment with Rayleigh fading is explained. But in case of cognitive radio this approach is difficult to implement. [49] Analyzes the outage probability in cognitive radio networks. The analysis is based on the Poisson point process model of node spatial distribution and the standard propagation path loss model, including Rayleigh and log-normal fading. A discounted distributed power control algorithm [50] is used to achieve non-intrusive secondary spectrum access without either a centralized controller or active PU cooperation. This paper has provided the more fundamental capacity analysis, e.g., outage capacity. In [51] the authors have considered a cognitive radio relay networks in which the secondary transmitter communicates with receiver through a best relay node under the peak power constraint at the primary user receiver. [52] focus on the outage probability analysis of cognitive transmissions by considering the impact of spectrum sensing overhead on system performance. [53] presents a study on the interference caused by Secondary Users (SUs) due to miss-detection and its effects on the capacity-outage performance of the Primary User (PU) in a cognitive network with beacon. An adaptive power control scheme [54] for cognitive radio system (CRS) in Rayleigh fading channel is proposed. The transmit power of a secondary user (SU) is adjusted in Rayleigh fading to maximize the constant output signal-to-noise ratio (SNR) at an SU receiver while keeping the interference to a primary user (PU) under given constraints.

4.5 System model

There are two categories of cognitive radio operations: opportunistic spectrum access which allow secondary user (SU) to access frequency band that was allocated to primary user (PU) when primary user is inactive and spectrum sharing which allow secondary user to transmit simultaneously with primary user even when primary user is active as long as quality of service (QOS) of PU transmission is not degraded to an acceptable level. For the spectrum sharing environment power control is essential. In spectrum sharing scenario SUs can access the radio frequency spectrum simultaneously with primary user. The system model for spectrum sharing environment is given in the next page. Solid line indicates the intended communication link while the dotted line indicates the interference. A cognitive SU is interfered by other SUs as well as by the PUs with interference link gains as shown in Fig. 4.3.

In this dissertation we are considering a scenario in which SUs are trying to transmit data in the uplink to the BS. As SUs are sharing the spectrum with PUs, SUs will cause interference to PUs [36]. The QoS of primary user i.e. signal to interference ratio will vary according to the channel model.

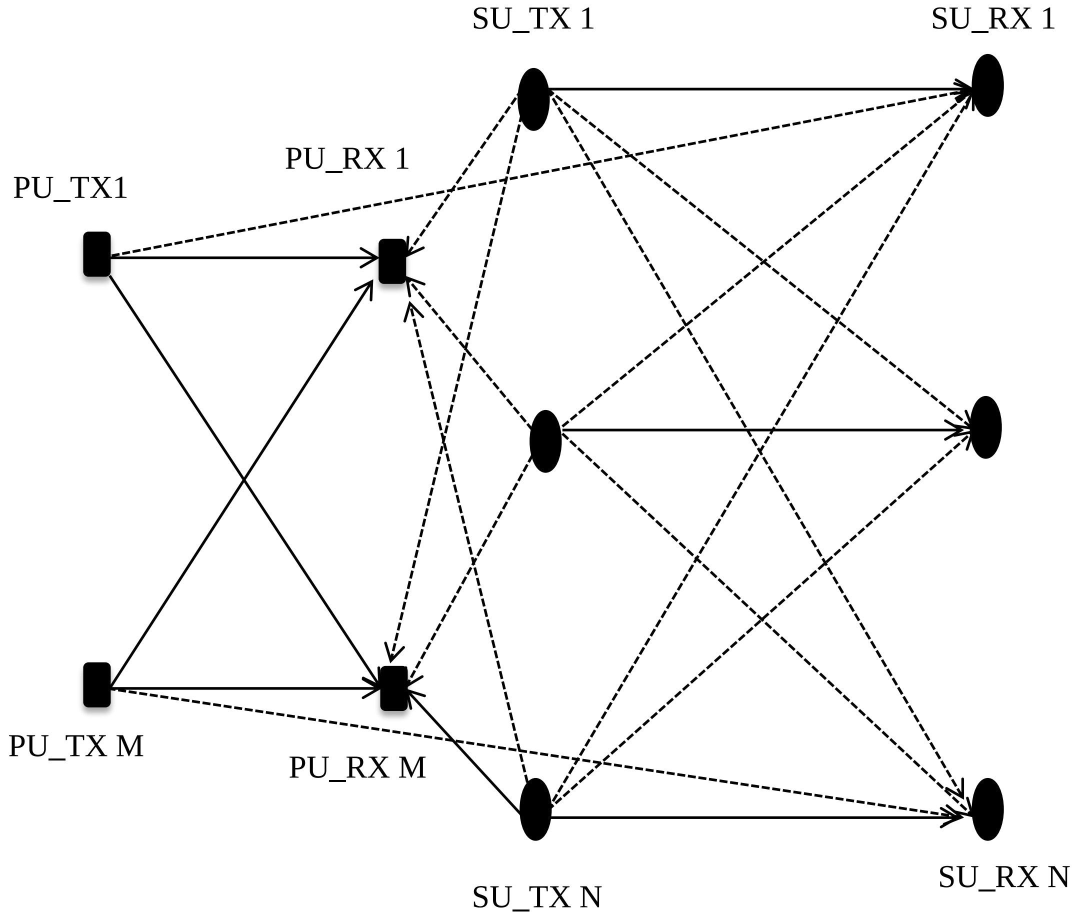

Fig. 4.3 System model for M PUs and N SUs

4.5.1 Path loss impact

Signal to interference and noise ratio of primary user is

$$\left(SINR_{pu}\right)_i = \left(\frac{P_i G_{k,i}}{\sum_{k=1,k\neq i}^{N} P_k G_{k,i} + \sum_{j=1}^{M} P_j G_{j,i} + \sigma^2}\right) \tag{4.1}$$

$\left(SINR_{pu}\right)_i$ is instantaneous signal to interference ratio of multi-primary system with N PUs and M SUs. P_i is the transmit power of the ith primary user .$\sum_{k=1,k\neq i}^{N} P_k G_{k,i}$ represents the interference caused by other primary user except ith user, $\sum_{j=1}^{M} P_j G_{j,i}$ is the interference caused by M secondary users and σ^2 is noise power.[46]

In this dissertation we have considered one PU and M SUs scenario. Thus the previous expression is transformed into

$$SINR_{pu}=\left(\frac{P_{pu}G_{pu,pu}}{\sum_{j=1}^{M}P_jG_{j,pu}+\sigma^2}\right) \tag{4.2}$$

G is the path gain that depends on the channel characteristics. For pathloss the following simplified model as a function of distance is used

$$G = K\left(\frac{d_0}{d}\right)^{\gamma} \tag{4.3}$$

In this model, K is a unit less constant which depends on the antenna characteristics and the average channel attenuation and under approximation is

$$KdB = 20\log_{10}\left(\frac{\lambda}{4\pi d_0}\right) \tag{4.4}$$

d_0 is a reference distance for the antenna far-field, and γ is the pathloss exponent. The value of γ depends on the propagation environment. For propagation that approximately follows a free-space or two-ray model γ is set to 2 or 4, respectively. The value of γ can be obtained via a minimum mean square error (MMSE) fit to empirical measurements for more complex environments. From (4.3) it is clear that the link gain will vary with the distance. So according to the distance SUs will have to control their transmitting power so that threshold ($SINR_{pu}$) required by PU is always greater than some threshold. [46, 47].

4.5.2 Impact of Combined Pathloss and Shadowing:

There will be random variation in the received power at a given distance due to blockage from objects in the signal path, changes in reflecting surfaces and scattering objects. This random variation in received power is called shadowing. Since the changes in reflecting surfaces and scattering objects cause the random attenuation so some statistical model must be used. The most common method is the log-normal shadowing. The ratio of transmit-to-receive power i.e. $\varphi = \left(\frac{P_t}{P_r}\right)$ is a random variable with lognormal distribution as

$$p(\varphi) = \frac{\xi}{\sqrt{2\pi}\sigma_{\varphi dB}} exp\left[-\frac{\left(10\log_{10}\varphi - \mu_{\varphi dB}\right)^2}{2\sigma_{\varphi dB}^2}\right] \qquad (4.5)$$

Where $= \frac{10}{ln10}$, $\mu_{\varphi dB}$ is the mean and $\sigma_{\varphi dB}$ is the standard deviation of φ_{dB}

Now this shadowing impact and pathloss impact can be superimposed to find the path gain or to find random fluctuation in received power. For this combined model the ratio of received to transmit power in dB is given by

$$P_r/P_t(dB) = 10\log_{10} K - 10\gamma \log_{10}\left(\frac{d}{d0}\right) - \varphi dB$$

$$P_r/p_t = K\left(\frac{d_0}{d}\right)^{\gamma} . (\varphi) \qquad (4.6)$$

φdB is a Gauss-distributed random variable with mean zero and variance $\sigma_{\varphi dB}^2$.

The combined effects of path loss and shadowing have important implications for the system design. It introduces the concept of outage probability. In systems there is a minimum received power i.e. P_{min} below which performance of system is not acceptable. Outage probability $p_{out}(P_{min}, d)$ under path loss and shadowing is the probability that the received power P_r at a given distanced, falls belowP_{min} : $p_{out}(P_{min}, d) = p(P_r(d) < P_{min})$.

$$p(P_r(d) \leq P_{min}) = 1 - Q\left(\frac{P_{min} - (P_t + 10log_{10}K - 10\gamma \log_{10}(\frac{d}{d_0})}{\sigma_{\varphi dB}}\right) \qquad (4.7)$$

Where the Q function is defined as

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} (e^{-\frac{z^2}{2}})\, dz$$

So from equation number 11 we can find the transmit power for a given outage probability. Solving equation 11 we have transmit power

$$P_t = -\sigma_{\varphi dB} Q^{-1}(1 - P_{out}) + P_{min} - 10\log_{10} K + 10\gamma \log_{10}(\frac{d}{d_0}) \quad (4.8)$$

And using equation 10 we can calculate $SINR_{PU}$ and according to this threshold SUs will control their transmit power using game theory. QoS requirement of PU is also going to vary with outage probability.[46,47]

4.5.3. Impact of Rayleigh Fading:

The probability of error depends on the received SINR (γ_s) in AWGN. Received signal power varies randomly over distance or time. This variation is due to shadowing, multipath fading. So SINR (γ_s) is a random variables, probability of symbol error is also random. It also introduces the outage probability concept. If γ_0 is the minimum SINR required for acceptable performance then outage probability is given by following equation

$$p_{out} = \int_0^{\gamma_0} p_{\gamma_s}(\gamma) d\gamma \quad (4.9)$$

$p_{\gamma_s}(\gamma)$ is the distribution of random variable γ_s. Solving above equation the required SINR under fading environment for a given outage probability is given by

$$\gamma_s = \frac{\gamma_0}{-\ln(1-p_{out})} \quad (4.10)$$

For a given probability of error there is requirement of minimum SINR. This SINR (threshold) will vary in fading environment.[16] The probability of error will be different for different modulation scheme. And according to that probability of error there will be minimum SINR requirement (γ_0). This threshold will further vary with outage probability. So for a given outage probability $SINR_{PU}$ threshold can be calculated using equation 14 and according to threshold required SUs will control their transmit power using repeated game model described in next section.[47]

CHAPTER 5

SIMULATION AND RESULTS

5.1. Introduction

This chapter deals with the methodology and simulation results for the two techniques, namely the centralized and the distributed using game theory. It defines the approaches adopted, the scenarios set-up, the assumptions made and the methods used. Comprehensive simulation results derived using MATLAB to simulate these two technique. The convergence of game theory is also shown.

5.2 Methodology

The formulation of the centralized and the repeated game theory for power control is performed using the step-by-step approach, as discussed in chapter 4. The simulations were conducted using MATLAB software. Firstly the centralized technique is simulated and results are derived. Secondly the distributed power control using game theory is simulated.

5.2.1 Centralized power control

As explained earlier centralised cognitive radio networks, there exists a central manager in the network that is responsible for exchanging information and control the transmission power of all secondary users within its coverage area. Flowchart is given in the next page. SU has to follow the instructions of the central manager. SUs will send their transmit power information to central manager that will find out the interference caused to PU. As we are taking the spectrum sharing scenario i.e. secondary users are allowed to transmit simultaneously with primary user even when primary user is active as long as quality of service (QOS) of PU transmission is not degraded to an acceptable level. So if the interference is less than bearable threshold then SU is allowed to transmit at that power, otherwise central manager will ask SU to step down their power.

5.2.1.1 Flowchart

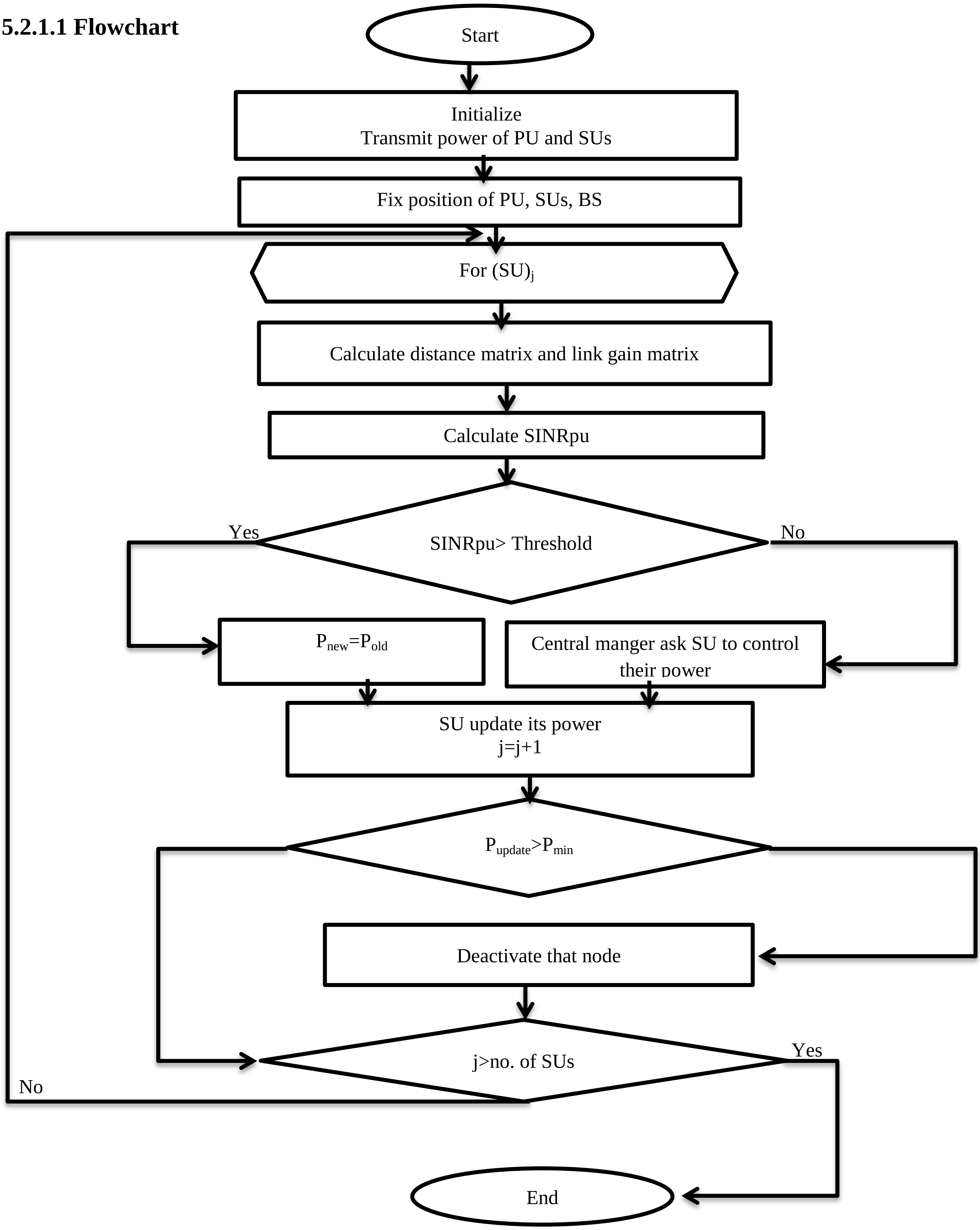

Fig.5.1 Flowchart for centralized power control

5.2.1.2 Simulation and Results:

The simulation for the centralized power control is set up using MATLAB and according to the procedure described in the flow chart of Fig. 5.1 . The following parameters and assumptions used for the simulation.

Assumptions and parameters:

The assumption is that every SU is transmitting with same power.

Link gain calculated using pathloss model

Table III: System Parameters for centralized power control

Parameters	Values
Number of secondary users, M	9
Number of Primary users, N	1
Distance of PU from BS, *d_pu*	0.04 km
Distance of SUs from BS, *d_su*	(0.31, 0.46, 0.57, 0.66, 0.74, 0.81, 0.88, 0.94, 1.00) km
Minimum transmit power, P_{min}	0.001 W
Maximum transmit power, P_{max}	1 W
K	$0.097*10^{-3}$
Background system noise, σ^2	$5*10^{-15}$ W
Link gain, G	$k * d\_pu^{-\gamma}$ *for primary user* $k * d\_su^{-\gamma}$ *for secondary users*
Path loss exponent(γ)	*4 in urban scenario*

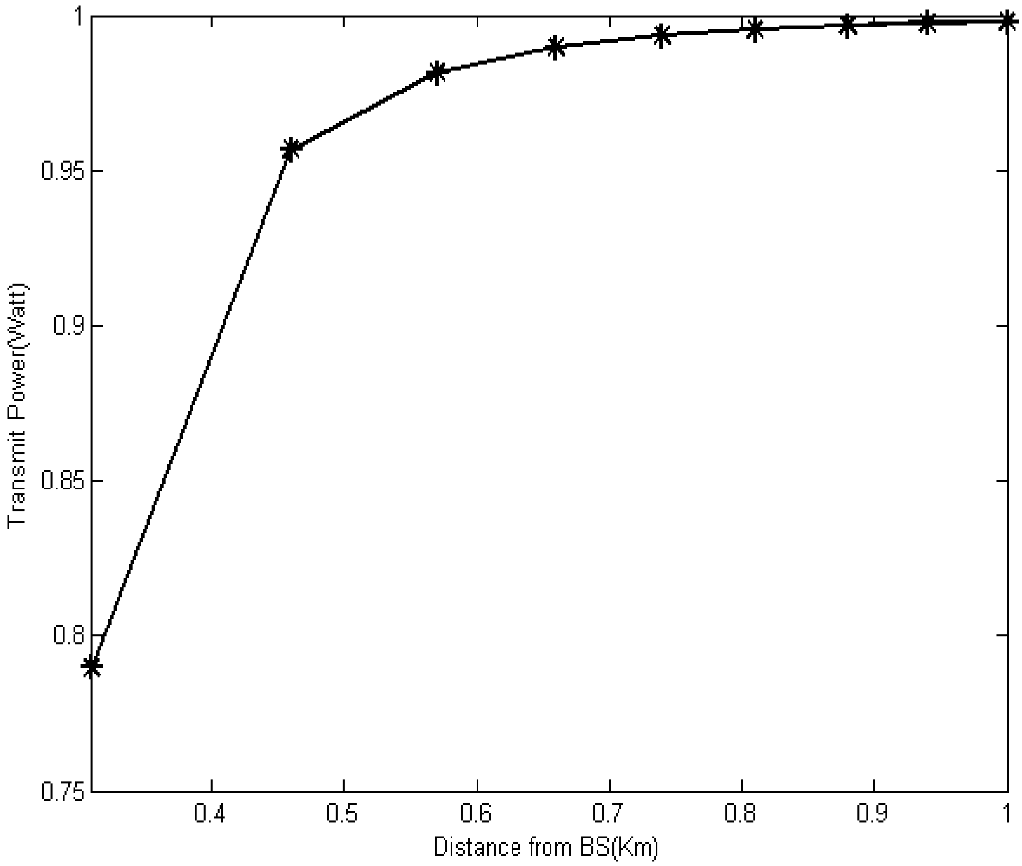

Fig. 5.2 Transmit power of SUs vs. Distance from base station using centralized power control

In Fig. 5.2 the power controlled after getting power control signal from central manager is shown. The result is quite obvious. The closest user has controlled its power more as compare to farthest user. The only problem is of overheads that are associated with this approach because of the communication of every SU with central manger. This problem has been solved in the next section using game theory where there exists no central manager.

5.2.2. Distributed power control:

A Game Theory Formulation: As discussed in chapter 5 in centralised power control scheme there was a problem of signaling bottlenecks and information overheads that were because of the communication with centralised manager. Distributed power control avoids this problem. However, even in the distributed power-control scheme the problems exists and are due to, the non-cooperation of the secondary users. The problem of non-cooperation can be solved by the use of game theoretic concepts

The power allocation problem can be modeled according to the game theory in the mathematical form as a triplet with Players(I), Action Profile(S_i) and Payoff(U_i).

$$G =< I, (S_i)_{i\in I}, (u_i)_{i\in I}$$

In this power allocation game the players are the SUs. Their actions are the choice of transmit power. The payoff function u_i will denote the reward received by player i when select action $s_i$while the other player's choice is s_{-i}.For player in this game, its action can be expressed as s_i= {P_{min}:*delta*:P_{max}} i.e. the power has been quantized between P_{min} and P_{max} with some step size delta. So players have choice to choose any power within the range of P_{max} and $P_{min..}$ Main aim will be to find that transmit power for each SU for which $SINR_{pu}$ is always greater than some threshold. To solve this problem repeated game has been played. The flowchart is given below.

The problem is modeled using repeated game with perfect information, i.e. each player knows every action of the players that moved before him or her. Instead of transmitting or not transmitting i.e. binary power control the SU will choose that power i.e. choose that strategy for which $SINR_{pu}$ is always greater than some threshold. When first SU has taken its move now the second SU will make its move by considering the move taken by first user, i.e. for calculation of $SINR_{pu}$ it will now use the updated power. This process will go on until the stable or equilibrium point is not achieved. Equilibrium point is that point where there is no change in the strategy. Any player deviating from equilibrium point will not get better result.

5.2.2.1 Flowchart: Flowchart of the repeated game model is shown in Fig. 5.3

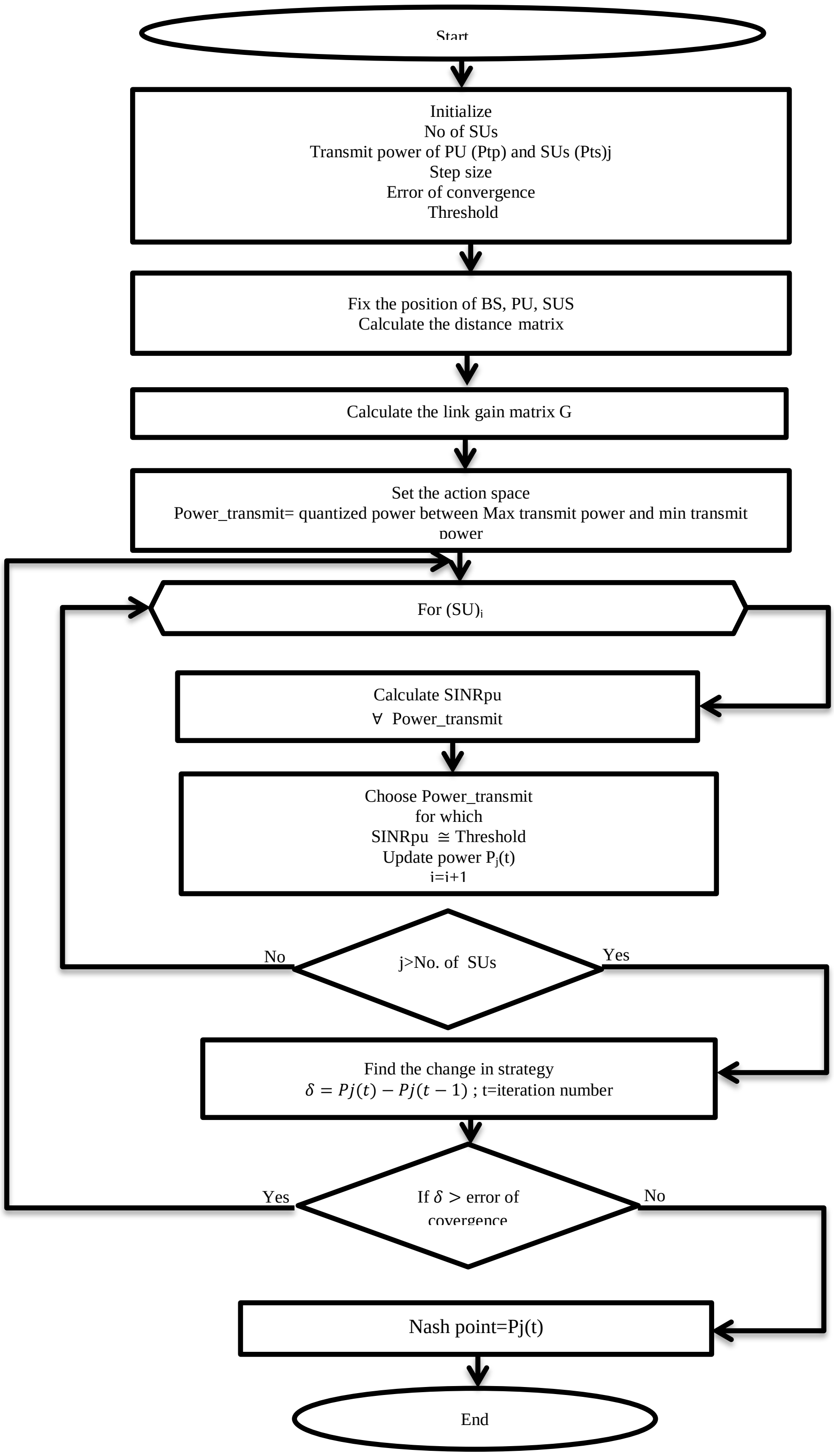

Fig. 5.3 Flowchart for power control using repeated game.

5.2.2.2 **Simulation and Results**

In this dissertation we are using MATLAB software for simulation of repeated game. To explain the problem conveniently, the system parameters for our simulation are given in table IV.

Table IV: System Parameters for distributed power control

Parameters	**Values**
Number of secondary users, M	9
Number of Primary users, N	1
Distance of PU from BS, *d_pu*	0.04 km
Distance of SUs from BS, *d_su*	(0.31, 0.46, 0.57, 0.66, 0.74, 0.81, 0.88, 0.94, 1.00) km
Minimum transmit power, P_{min}	0.001 W
Maximum transmit power, P_{max}	1 W
Step size, Δ	0.001
Error of convergence, δ	0.0001
K	$0.097*10^{-3}$
Background system noise, σ^2	$5*10^{-15}$ W
Link gain, G	$k * d\_pu^{-\gamma}$ *for primary user* $k * d\_su^{-\gamma}$ *for secondary users*
Path loss exponent(γ)	*4 in urban scenario*

Applying the algorithm on this data we have obtained the following results. Initially it has been assumed that each SU is transmitting with the same power.

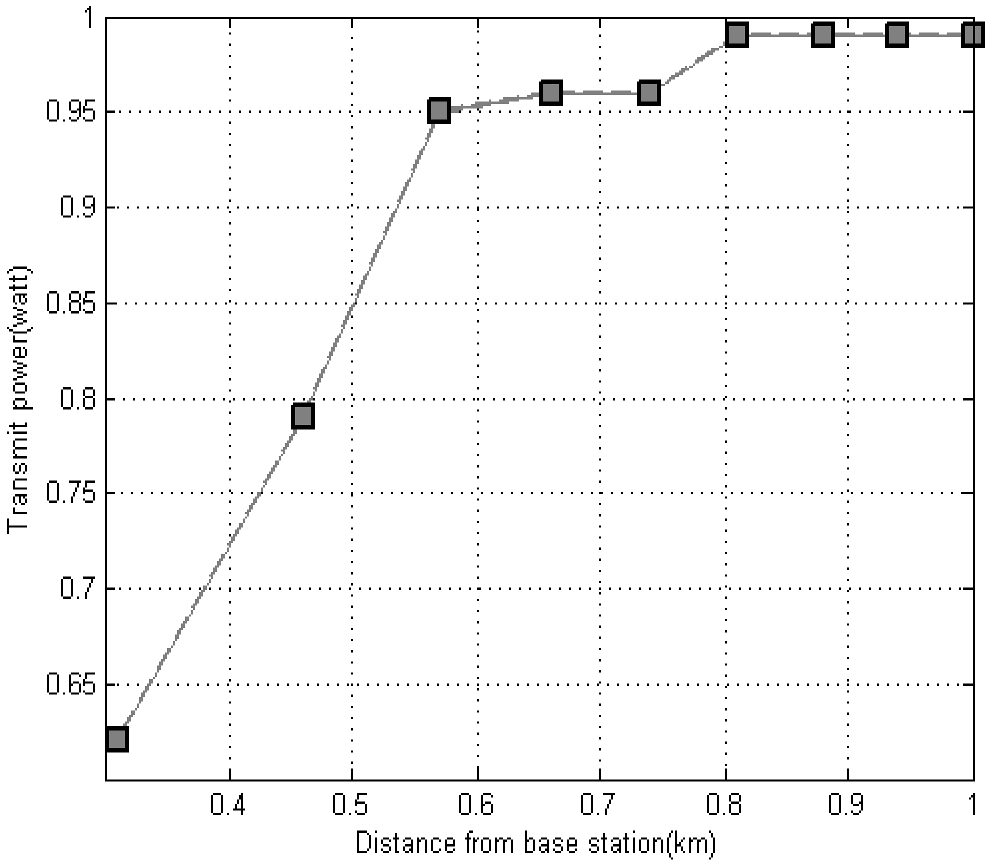

Fig. 5.4 Transmit power of SUs vs. Distance from base station

From Fig. 5.4 it is clear that SU close to base station is transmitting with less power as compare to farthest SU. In Fig. 5.5 the no of iteration vs. transmit power of each user is plotted. In 1^{st} iteration each SU was assumed to be transmitting with the same power and then each SU updates power in every iteration until Nash point was achieved i.e. 9^{th} iteration.

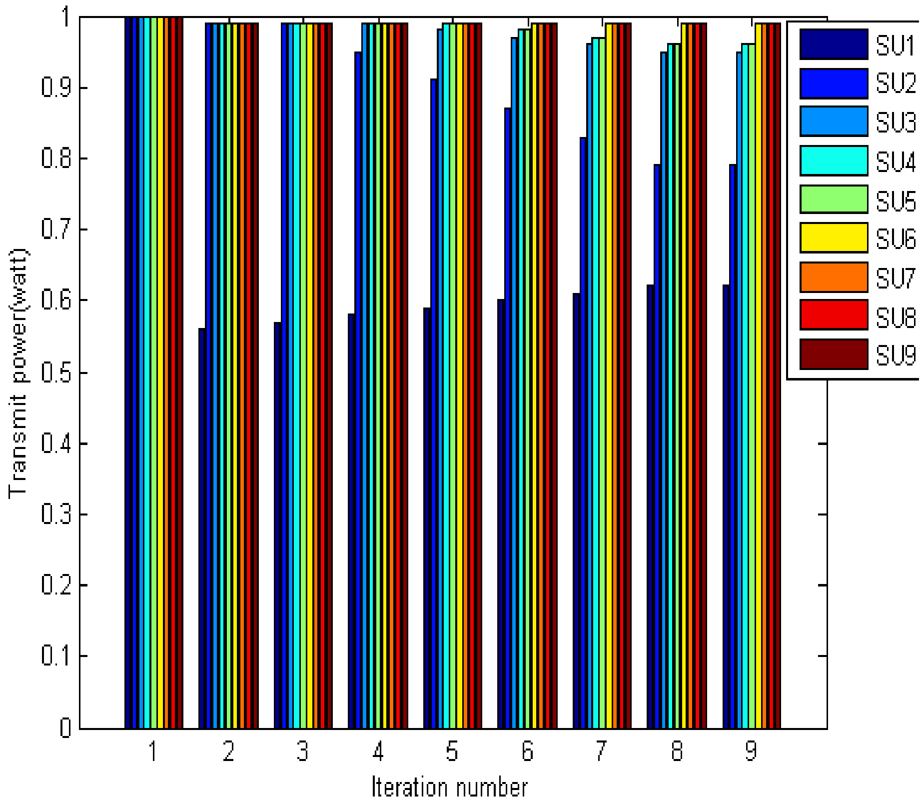

Fig.5.5 Convergence evaluation

Nash point is the equilibrium point. At this point no player (SU) will change its strategy. At Nash point the $SINR_{pu}$ should be greater than or equal to the threshold. In Fig. 5.6 the variation of SINR for the PU due to the SU1 , SU3, SU6, and SU9 with respect to number of iterations is shown. It can be clearly seen that as the number of iterations increases $SINR_{pu}$ approaches the predefined threshold value and thus minimizing the interference level for PU.

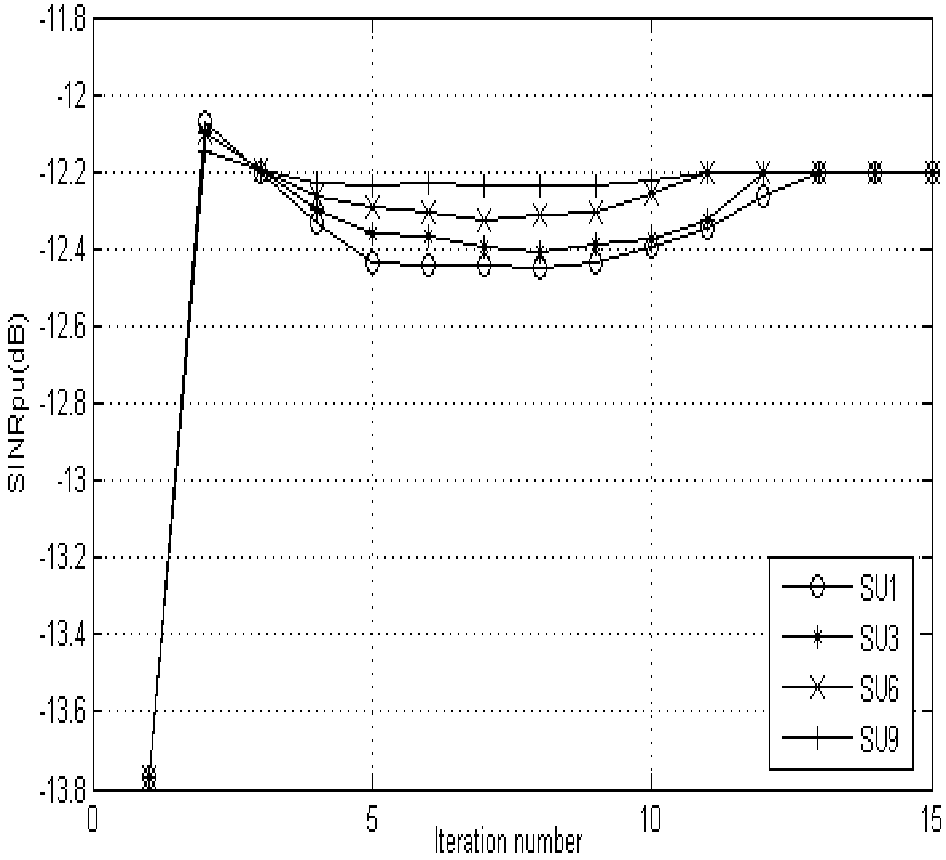

Fig.5.6. QOS convergence

- **Impact of shadowing:**

For modeling shadowing lognormal distribution with mean zero and standard deviation 10dB is used. The plot of transmit power vs. distance from base station is given in Fig. 5.7. Transmit power is calculated using (4.7) for outage probability .012 , p_{min} =-110.5dB. This transmit power is further controlled by SUs to achieve the desired QoS i.e. $SINR_{pu.}$ For controlling power same repeated game model is used. Channel is modelled using (4.6)

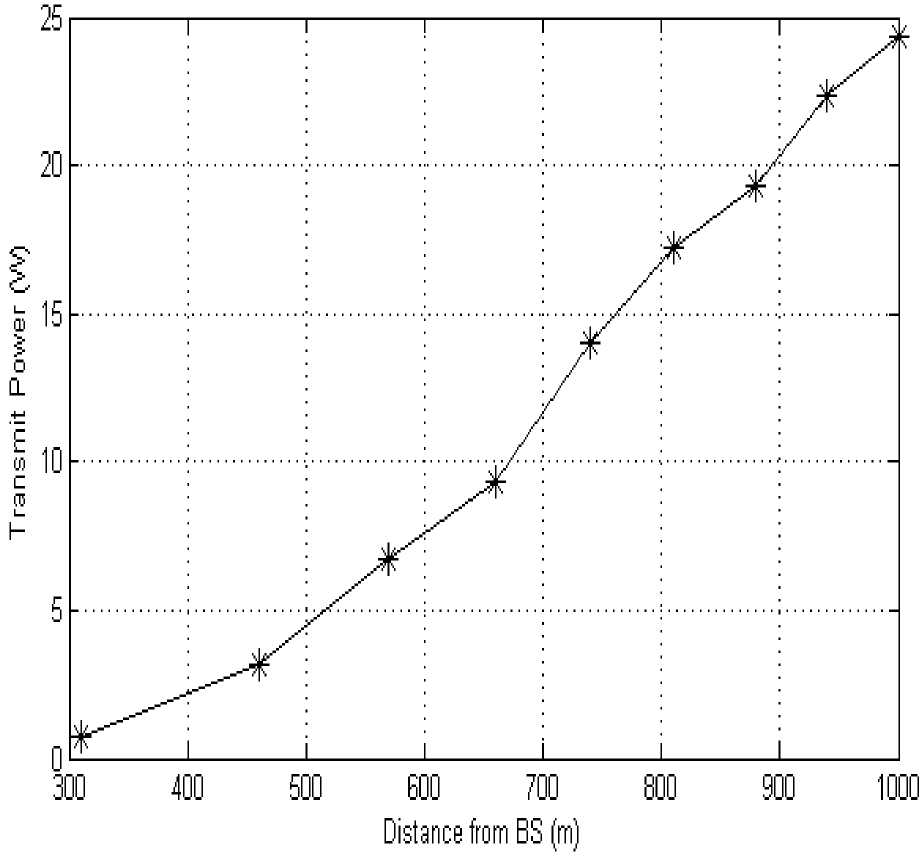

Fig. 5.7 Transmit power vs distance for log-normal shadowing

Fig. 5.7 shows the transmit power of each SU after playing repeated game. The farthest node have the maximum power while the nearest node has minimum, which is quite fair. After controlling the power the farthest node is having more outage probability i.e. clear from Fig. 5.8

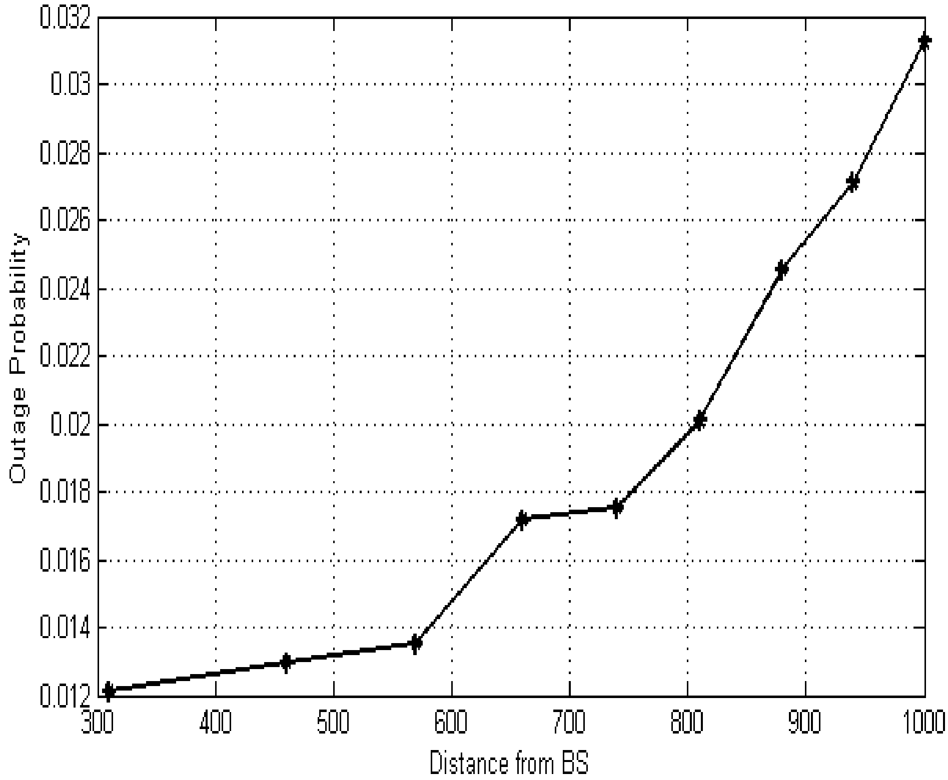

Fig. 5.8 Outage probability of SUs after playing game.

- **Impact of Rayleigh fading**:

As we have discussed earlier that in a fading environment the received signal power varies randomly over distance due to shadowing and/or multipath fading. The impact of shadowing on power control is discussed already. Now the impact of multipath fading is cosidered. Rayleigh multipath fading is taken into consideration. The QoS requirement or the threshold i.e. minimum SINRpu required will vary with outage probability according to (4.10). This variation is shown in Fig. 5.9

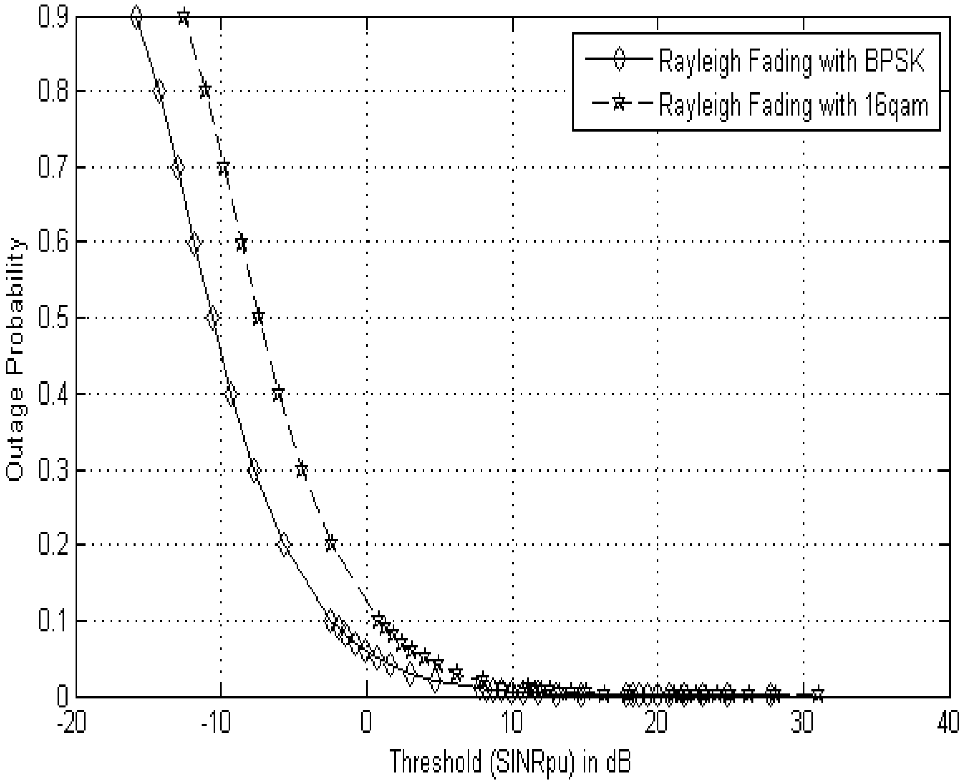

Fig. 5.9 Threshold variation with outage probability

For example the PU is using BPSK and in slow Rayleigh fading the minimum requirement of the system is to achieve a BER= 10^{-4}. Using BER and SNR relationship we can find out the SNR required to achieve this BER and is 8.5dB. But with different outage this SINR will be different. If it can tolerate some outage it needs less SINRpu while for 0 outage it needs very high SINR i.e. clear from Fig. 5.9. The modulation scheme will also affect the performance. Using 16QAM for the above example the SNR required is 12.37 dB. i.e. more SNR required to achieve the same performance. The impact of modulation scheme is also clear from Fig.5.9 .

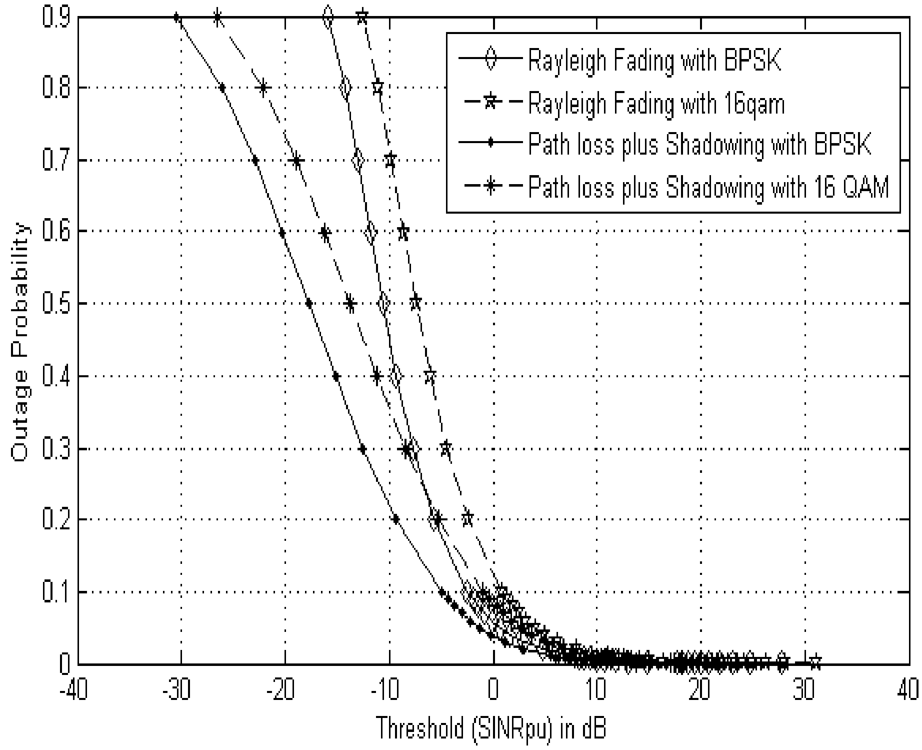

Fig. 5.10. Comparison of combined pathloss shadowing model and multipath fading with different modulation scheme.

Finally the comparative analysis of combined pathloss shadowing model and multipath fading is shown in Fig. 5.10. Multipath fading is having the worse impact on QoS of PU. So SUs will have to decrease more power as compare to pathloss plus shadowing impact.

CHAPTER 6
CONCLUSION

In wireless communication, cognitive radio technology is generally perceived as the next disruptive technology, because of its ability to autonomously adapt to changing network conditions in order to ensure a more flexible and spectrally efficient wireless network. The flexibility of cognitive radio comes with the problem of dynamic control of transmit power. In recent years, enormous research studies have been made to different algorithms for the control of transmit power in cognitive radio networks. In this dissertation, we have studied power control and interference analysis for cognitive radio networks. Different challenges have been studied. We have taken into account the spectrum sharing scenario where SUs can transmit simultaneously with PUs. So interference constraint has been imposed to protect the PUs. We have shown that game theory is an appropriate tool for analyzing the problem of power control in cognitive radio. Repeated game model has been used to solve the problem. The proposed method protects the PU by ensuring that the SINR drop of the PU due to the SU transmission is not larger than a predefined threshold. The number of iterative computational procedures of the algorithm, is a function of the number of secondary users in the network and error of convergence only. Hence, the algorithm has a low computational complexity as compare to other algorithm. In this dissertation we have considered the 1 PU and M SUs scenario. This work can be extended for M PUs and N SUs scenario. Also we have used the repeated game with perfect information i.e. every SU is fully aware about the actions taken into past by the other SUs. But it may not be the case always. So in future such situation can be considered. Solution to such problem is repeated game with imperfect information . In such games player does not know exactly what action other players took up to this point. So they make some beliefs or expectations about the other player’s move.

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LIST OF PUBLICATIONS

A.Sharma, D.S.Saini, “Transmit Power Optimization in Cognitive Radio Networks using Game Theoretic Approach,” International Conference on Signal Propagation and Computer Technology (ICSPCT 2014). (accepted)

RESUME

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Objective

Quest to work in a professional atmosphere, which will help me to explore my potential by virtue of my sincerity and dedication. I intend to contribute positively towards the growth and prosperity of the organization.

Education

M.Tech. in **Electronics and Communication** from **Jaypee University of Information Technology**

Academic Profile

M.Tech.

Year	University	Percentage/CGPA
2012-2014	Jaypee University of Information Technology	9.2(till 3rd Sem.)

B.Tech.

Year	University	Percentage/CGPA
2007-2011	Lovely Professional University	9.57

10+2

Year	Board	Percentage
2007	HP Board	84.6%

10th

Year	Board	Percentage
2005	HP Board	90%

Trainings and Workshops

- Duration- 2 weeks, Training in **Lovely Professional University**, “PCB Making**”**.
- Duration-6 weeks, Industrial Training in **CSIO Chandigarh.**
- Seminar by Microsoft i.e. “Microsoft Yatra” in **Lovely Professional University**.
- Seminar and workshop on ‘'Hamm Radio’’ in **Jaypee University of Information Technology**

Projects

<u>M.Tech Project</u>

Project Title : Game theory application in Cognitive Radio
Duration : 1 Year
Team size : Individual Project
Organization : Jaypee University of Information Technology

B.Tech Project

Project Title	: Iris recognition system for personal identification using image processing
Duration	: 6 Month
Team size	: Two
Organization	: Lovely Professional University

Training Project

Project Title	: Automatic page orientation in Portable reading Machine for Blind
Duration	: 6 Month
Team size	: Individual Project
Organization	: CSIO Chandigarh

Skill Set

Languages	**: C, C++, VHDL, VERILOG**
Software	**: MATLAB, XILINX, OrCAD, LabVIEW**
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Achievements and Extra-Curricular Activities

- Awarded with Gold Medal in B.Tech.
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