SPECTRUM SHARING IN COGNITIVE NETWORKS

By

Maida Hafeez Abbasi

A Thesis Submitted to the Faculty of Electrical Engineering Department Military College of Signals, National University of Sciences & Technology, Rawalpindi in partial fulfillment of the requirements for the degree of

MS in Electrical (Telecom) Engineering

August 2018

In The name of Allah the most Beneficent and the most Merciful

DEDICATION

Dedicated to my family who has always been a source of motivation for me and also to my supervisor Col Dr Adnan Rashdi for being forthcoming and helping in fulfillment of this research work.

ABSTRACT

Cognitive Radio Networks (CRNs) provide an efficient solution to address the increasing demand for spectrum resources. The cooperation among Secondary Users (SUs) improves the sensing performance and spectrum efficiency. A traffic-demand based cooperation strategy of SUs in multichannel cognitive networks is analysed.When a SU has high traffic demand it can choose to sense multiple channels in the sensing period and obtain more chances to use spectrum resources. This problem has been formulated as a non-transferable utility (NTU) overlapping coalitional game. In this game each SU implements a cooperation strategy according to its expected payoff, which takes into account the expected throughput and energy efficency.Two algorithms Overlapping coalitional game (OCF) and Sequential coalition game (SCF) have been analyzed and a proposed algorithm has been introduced. In proposed coalition formation algorithm SUs are given priority according to data in the buffer and a coalition is developed based on the channel conditions. Each SU chooses a coalition based on its utility history and based on largest uncertainty reduction the SU joins the coalition. Proposed algorithm guarantees less complexity and more expected throughput than all other algorithms. Simulation results prove that our proposed coalition formation algorithm provides better throughput than OCF and SCF algorithms.

DECLARATION

No content of work presented in this thesis has been submitted in support of another award of qualification or degree either in this institution or anywhere else.

ACKNOWLEDGEMENTS

With profound humility, I pay my gratitude to Allah Almighty for enabling me to achieve another astounding milestone in my literary career. I would like to extend my special thanks to the faculty and administration of Military College of Signals and NUST, for proffering a commendable research environment at the institute. This arduous work would have not possible without the support of my supervisor Col. Dr. Adnan Rashdi who not only provided timely guidance, profound encouragement and positive criticism but also ensured that I complete the assigned tasks in stipulated time. His affectionate and kind consideration towards my research helped me to carry on with my project in odd circumstances. I am also very obliged to my committee members, Brig Dr. Imran Rashid, Col (R) Dr. Imran Touqir and Lt. Col. Dr. Adil Masood, for their intimate help in fulfillment of this research work.

I am deeply indebted to my great parents for their encouragement and affectionate selfless prayers. Most importantly I would like to thank my dear friends Aqib, Soban and Umair for always appreciating my hardwork.Without their continuous support and dialogues of encouragement this would not have been possible.

LIST OF ACRONYMS

1.	Cognitive Radio	**CR**
2.	Cognitive Radio Network	**CRN**
3.	Dynamic Spectrum Access	**DSA**
4.	Frequency Allotment Board	**FBA**
5.	Primary User	**PU**
6.	Secondary User	**SU**
7.	Transmitter	**TX**
8.	Receiver	**RX**
9.	Spectrum Sensing	**SS**
10.	Cooperative Spectrum Sensing	**CSS**
11.	Federal Communication Commission	**FCC**
12.	Energy Detection	**ED**
13.	Analog to Digital Converter	**ADC**
14.	Media Access Control	**MAC**
15.	Gel’fand-Pinsker	**GP**
16.	Nash equilibrium	**NE**
17.	Circular Symmetric Complex Gaussian	**CSCG**
18.	Cross-Entropy	**CE**
19.	Associated Stochastic Problem	**ASP**
20.	Overlapping Coalition Formation	**OCF**
21.	Sequential Coalition Formation	**SCF**
22.	Base Station	**BS**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter-1

Introduction

1.1 Background

The emergence of new wireless technologies has paved the way for communications. This advancement in wireless communication leads to the spectrum efficiency. Rapid growth and development in mobile communications, satellite communications and other wireless communication systems require advanced spectrum sources. The radio spectrum for different technologies has been densely allocated. Heavily populated radio spectrum due to increased wireless communication has raised the spectrum scarcity problem. To come up with the spectrum shortage, there is a need for efficient spectrum utilization.

Frequency is a limited natural resource and it is very important to use such vital resource efficiently in order to meet the requirements of current wireless communication systems. Within the current spectrum framework, different spectrum bands are allocated to specified licensed users. The licensed users of the spectrum are known as primary users, who possess the legacy right to use the frequency bands allocated to them. The licensing process of the spectrum and allocating fixed ranges of spectrum to the licensed user results in congestion in those bands, while lot of spectrum bands are under-utilized and apparently causes spectrum scarcity. The spaces in the spectrum bands which are not being actively used by the licensed users are called spectral holes.

Latest research work has revealed that large portion of allocated frequency bands are not used by the licensed user's frequently. Therefore, in order to efficiently utilize the frequency spectrum Cognitive Radio Networks have been introduced. [1]

For opportunistic use of spectrum Cognitive radio has emerged to be a technology that has obtained interest from a lot of researchers in the past because previously dynamic allocation of spectrum was done by signal processing technqiues.Wireless communication has been revolutionised by the emergence of cognitive radio. [2]

Spectrum utilization can be made efficient, when secondary users sense the spectrum and detect the spectral holes accurately and utilize them efficiently without causing any interference to the transmission of other users. Thus secondary users must possess cognitive capabilities to sense the spectrum reliably and detect the spectral holes in it.

The emerging paradigm of Dynamic Spectrum Access (DSA) [3] makes sure that the spectrum scarcity problem is solved by allowing secondary/unlicensed users to utilize the already allocated spectrum dynamically using spectrum agile wireless networks [4]. The key component to DSA paradigm is CR which senses its environment and performs such functions to serve its users, without causing any harmful interference to the neighbouring authorized users [5]. With the use of CR, secondary users coexist with the licensed users without causing any interference in their transmission to increase the efficiency of the spectrum. Thus CR provides an opportunistic sharing of the spectrum. Dynamic allocation of the spectrum via CR has made advancement in signal processing capabilities and wireless technology. To sense the spectrum in minimum possible time is a critical issue faced by CR in spectrum sensing.

1.2 Research motivation

During last few years detection and false alarm probability has gained much concern. Detection probability is defined as the expectation that PU is found as idle when it is actually idle. False alarm probability occurs when PU is actually absent but is declared present by the cognitive receiver. Researchers have tried a lot to improve the detection probability and false alarm probability. Several techniques have been proposed for this issue. Keeping in mind the literature it has been observed that some of the algorithms are difficult to implement and require more time resulting into more complexity.

When SNR is low we require high accuracy regarding detection of PUs and during the current wireless communication system where everything is converging towards software defined adaption and adaptation so these factors motivated towards research on this area. Another motivation behind this topic was the need for an efficient and quick algorithm that can provide best and accurate results.

1.3 Problem Statement

Frequency is a natural limited resource and there is an immense need to use frequency spectrum efficiently to fulfill all requirements. Static allocation of frequency bands does not fulfill the requirements of present wireless technology. So, dynamic spectrum utilization is required for wireless communication in order to enhance capacity of the channel.

Usage characteristics for various channels are different and each SU has different detection performance. As a result performance of the Primary users is severely degraded which consequently degrades the expected available time of the Secondary user.

Traffic demand of different secondary users varies. Due to this cooperation among SUs decrease and sensing performance is greatly reduced consequently limiting the system utility.

1.4 Proposed Solution

Cognitive Radio Networks is a need of time. It is very important to efficiently utilize the frequency bands that are useful in wireless communication. Static allocation of frequency bands does not fulfill the requirements of present wireless technology so dynamic spectrum utilization is required for wireless communication. Cognitive radios is a strong nominee to efficiently use the valuable limited natural resource frequency to increase spectrum efficiency which in turn gives better data rates, service quality and capacity.

To accommodate Dynamic Spectrum Access (DSA) in Cognitive Radio Networks spectrum sensing holds immense importance. Spectrum sensing is performed by the SU's to identify and explore all the available idle spectrum bands. Idle bands needs to be explored before starting any transmission. When PU's are not available in the band of interest then only the SU can use the band for transfer of data. [6] The harmful effects of shadowing and fading degrade the performance of spectrum sensing. This afterwards causes interference for the PU's. [7]Cooperative spectrum sensing has been suggested as a solution after addressing these issues. It will give better sensing results and the interference with the primary user will be greatly reduced. In cooperative sensing a combined decision about availability of PU's is made by sharing of the sensing results by multiple SU's.Detection performance can be greatly increased by cooperative spectrum sensing based on spatial diversity and multiuser diversity. It will increase the probability of detection and the probability of false alarm will be reduced. [8]

Cooperative spectrum sensing has been massively studied in literature for the case of single channel. But usually we have to deal with multiple channels rather than single channel so DSA in multi-channel CRNs has gained a lot of attention nowadays. It is more challenging because of many channels and various SU's. [9]

A traffic demand based approach is introduced in order to cater the varying needs of all the SUs which increases the cooperation among them as a result energy efficiency and throughput is improved.

1.5 Relevance to National Needs

It is the responsibility of government agencies to allocate the frequency spectrum to the licensed users. As the natural frequency resource is limited so current allocation of frequency spectrum cannot meet all useful wireless communication requirements. Moreover, the frequency spectrum allotted to primary users are not completely used by them so most of the frequency spectrum is wasted. Cognitive radios increase the spectral efficiency and fulfil certain wireless communication requirements within the limited natural frequency resource. In Pakistan FAB (Frequency allotment board) is the regulatory authority to allot frequency bands to licensed users.CRN can help FAB in the allocation of frequency bands useful for wireless communication.

When the frequency is same then spectrum that is allocated to various service providers is not used properly. This issue is being handled by Cognitive Radios by making spectrum sharing possible so that licensed spectrum can be used by the Sus.

This is quite economical for the service providers as they are also paid by the shared secondary users.

Spectrum Sharing methodologies provide best utilization of resources to operate in packed spectral environment. Spectrum sharing also reduces the amount by which calls are blocked and utilization of spectrum is further enhanced. Military spectrum may be best utilized and planned with spectrum sharing capabilities in software defined radios. Different military systems may share same spectrum for different communication and surveillance/intelligence systems used by military.

1.6 Thesis Objective

- Coordinate SUs for multi-channel sensing
- All the available channels needs to be shared which corresponds to spectrum sensing and sharing respectively.[10]
- Satisfying secondary user's requirement on the expected access time.
- Expected available time will be maximized as much as possible keeping a check on interference of the PU.Interference should be under a predefined level.
- Increase cooperation among SUs by forming coalitions according to traffic demand of SUs.
- To compare the output of our proposed technique with other existing techniques.

Chapter-2

Literature Review

2.1 Cognitive Radio

CR is an emerging technology which has attracted a lot of researchers towards itself. It is because of this technology that cognitive wireless terminals can access the available spectrum opportunities dynamically. The definition of CR was given by Mitola. He defined CR as an intelligent system or radio which can sense its environment dynamically and change or adjust its operating parameters according to the requirement autonomously [11].The definition given by Mitola was further generalized by FCC.It is a radio or system which has the ability to sense the electromagnetic environment and it can change dynamically according to the environment in order to modify the operations of system. It can change to increase the throughput, cancel the interference, facilitate interoperability and reach to secondary markets [12].The two attractive and main features which distinguish CR from all other traditional radios are capability of cognition and reconfigurability.Fig.1.1 illustrates how these unique features of a CR conceptually interact with the radio environment.

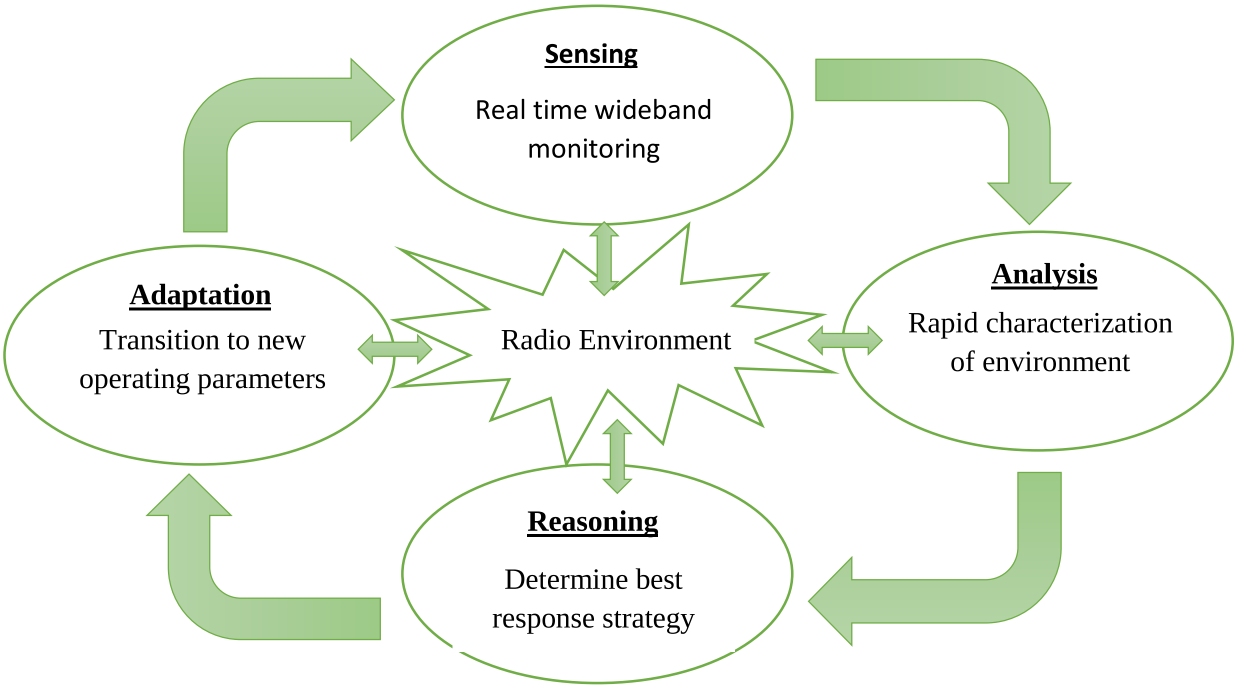

Figure 2.1: Functional Architecture of a CR. [13]

When a CR transceiver has the capability to sense its surrounding environment and it can analyze the information that has been captured in the best possible way so that spectrum bands can be used and best strategy can be adopted for the transmission this is known as the cognition capability of a CR.Due to this capability of CR it can observe all the changes that radio environment is going through in order to make some appropriate plans for transmission.

Cognitive radio comprises of PUs.These users do not have any license whereas the PUs have licensed band.SUs make use of that part of frequency band which is not being utilized by the primary users. It the responsibility of CRs to check the Spectrum Sensing (SS) results in order to ensure the reliability of the outcome. If the output is highly reliable then collision with the primary user can be avoided easily. Black spaces are those part of the frequency bands which are in possession whereas the portion of frequency bands not being occupied are known as white spaces or spectrum holes.CRs search for "white spaces" in the spectrum and use them to their own advantage till PU's reclaim these spaces. The detection performance of spectrum sensing can be primarily determined on the basis of three metrics: Detection probability (P_d), False alarm probability (P_f), and missed detection probability(P_m). P_f depicts the likeliness of a CR user claiming that a PU is available when the portion of frequency band is actually free, and P_d represents the chances of a CR user saying that a PU exists when the portion of band is in real possessed by PU.is indeed occupied by the PU.A collision with PU will take place if a wrong detection is being made whereas false alarm will cause reduction is spectral efficiency. So in order to make optimal detection P_d should be maximized subject to the constraint of P_f.

In CR network SS performance is notably and critically affected by the receiver (RX) uncertainty issue, signal fading caused by the multipath propagations and the effects of obstacles shadowing. The CR network scenario with shadowing, RX uncertainty issue and multipath propagations is shown in Fig.1.2.

It can be seen from the figure below that CR3 is outside the transmission scope of PU transmitter (TX) and CR1 and CR2 are sited inside its range. It is visible in the figure that CR2 is experiencing severe effects of multipath propagations and is under the effect of obstacle shadowing because of reception of delayed diminished replicas of PU signal and the presence of a house in between the direct line of sight to CR2.Hence it is justified that the CR2 is unable to sense the PU

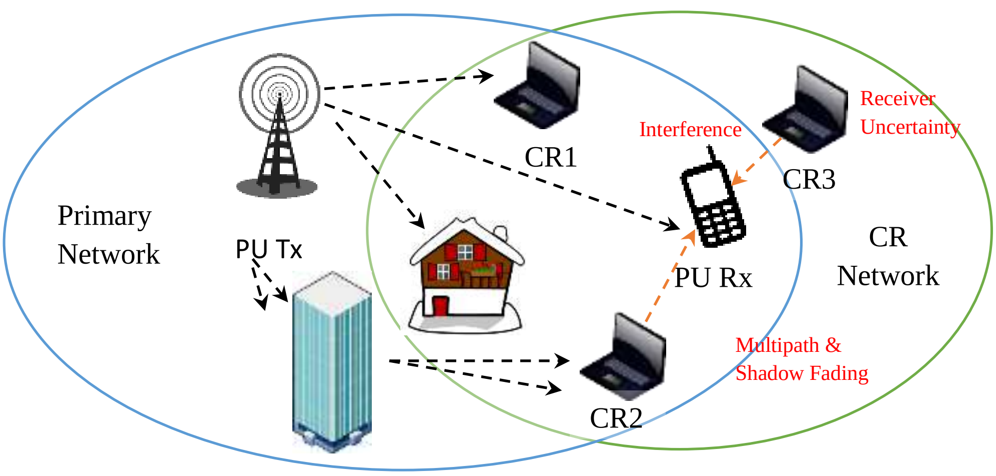

Figure 2.2: RX uncertainty and multipath/shadow fading. [14]

TX signal successfully. The issue of RX unpredictability is also shown in the figure as CR3 is totally ignorant of signal transmission of PU and from the attendance of a PU RX.Because of this scenario the CR3 will have high miss detection results of spectrum and due to which CR3 will try to access the spectrum. This transmission from CR3 will hinder the PU RX signal reception significantly. In whatever way, because of geographical diversity, it is improbable for all geographically distributed CRs to coincidentally undergo the effect of multipath propagation, shadowing and RX unpredictability issue in a CR network. The SS performance can be improved if maximum number of CRs, present at the direct line of sight with PU TXs or are receiving the higher power signal (like CR1 in the figure),can collaborate and cooperate with other CRs present in the environment by sharing their sensing results. The problem of inadequacy of discrete and independent sensing results of each CR user can be resolved by the merged collaborated decisions derived from geographically collected sensing results. Therefore, on the whole, SS performance can be significantly enhanced. The process of collaborating CR users is called Cooperative SS (CSS).CSS is an appealing and efficacious procedure to alleviate the RX unpredictability issue and to impede effects of shadowing and multipath propogation.To enhance the SS performance of CR network by exploring dimensional diversity in observations of geographically located CRs is the main idea behind CSS technique.CRs can exchange their SS results, by collaborating with each other ,for providing a more precise merged decision than the independent decisions.

2.2 Spectrum Sensing

Cognitive Radio Network comprises of primary users and secondary users. Users which have been given access through license are categorized as Primary users whereas the other are known as Secondary users. Cognitive radio has surprising ability to sense the PU channel usability. When it detects that PU is not transmitting and the channel is idle it enables secondary users to start transmission consequently enhancing spectrum efficiency. Therefore, SS is a very serious factors in the implementation of CRN. Therefore, cognitive users termed as secondary users, tend to coexist with primary users, which have the right to use the spectrum and thus must have a guarantee not to be interfered by secondary users.

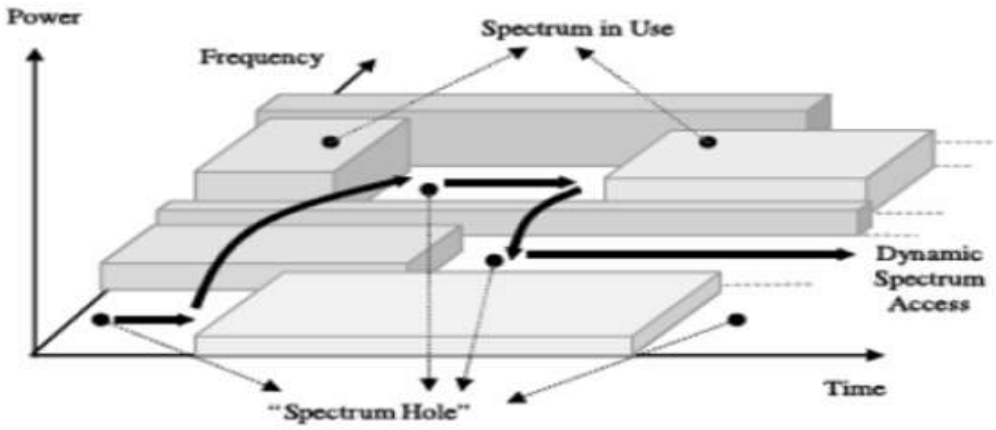

Figure 2.3: Spectrum Sensing

As a consequence of these facts, need to enhance the spectrum efficiency and lack of spectrum utilization is inspiring researchers to exploit the wireless means. In this regard, FCC has published a report in 2002, which examines the lack of spectrum usage. CRNs are considered to be capable of utilizing those "spectrum holes", by the acknowledgment of the environment and cognitive capability, to adjust their radio parameters accordingly. Spectrum sensing is the basic step that will allow cognitive radio networks to meet this target. Fundamentally, a device which can sense spectrum must be capable of giving an overview on the medium over the whole radio spectrum. This enables the cognitive radio network to investigate all features such as space, time and frequency to estimate the utilization of spectrum.

2.3 Features of Spectrum Sensing

The basis of SS depends on a renowned approach known as signal detection. Recognition of signal is defined as a process for detecting the availability of a signal in a disturbing environment. Signal identification can be summarized analytically as an easy identification problem that can be expressed as hypothesis.

$$H_1: y(n) = x(n)h + w(n) \tag{2.1}$$

$$H_0: y(n) = w(n) \tag{2.2}$$

Here, y (n) is the signal collected by SU,x (n) is the signal sent by the primary user, h is the channel coefficient matrix; and w (n) is the additive white Gaussian noise having varianceσ_w^2.H_1 and H_0 are the hypothesis also known as sensing states for presence and absence of signal respectively.H_1 is the alternative hypothesis that points towards the existence of the primary user and H_0 is the null hypothesis that shows that the primary user does not start communication. There are four possible states for the signal that is recognized:

1. Claiming H_1 under the assumption H_1 which points towards the Detection Probability (P_d).

2. Declaring H_0 under the hypothesis H_1 which points towards the Missed Detection Probability (P_m).

3. Stating H_1 under the supposition H_0 which points towards the Probability of False Alarm (P_f).

4. Declaring H_0 under the hypothesis H_0.

If H_0 is declared under hypothesis H_1,then it points towards the probability of missed detection, P_m, which is probability of declaring that primary signal is absent where as it is present actually. It is also defined as the probability that the transmitted signal is missing. If H_1 is declared under the hypothesis H_0 then it points to the false alarm probability which is the expectation deciding that primary signal is available whereas no primary user is actually transmitting. Thus incorrect alarm likeliness is the error that consequently leads to underutilization of the spectrum. Therefore, the basic target of the signal detector is to always attain correct identification, but this can never be achieved practically because of certain limitations. Therefore signal detectors are intended to work inside certain minimized error levels. One of the greatest issues for spectrum sensing is missed detection, since it results in interference with the primary user transmission. However, it is convenient to maintain least false alarm probability, so the system can utilize all available transmission resources. Since, it is assumed that in a wireless radio network the spectrum sensing device is unaware of the transmitter's location, there are two cases to be considered:

1. Path loss between the transmitter and the equipment which is sensing is the main cause of low h.This indicates that observing device is far away and it can transmit easily.

2. A lesser h is because of multipath or shadowing, which represents that the sensing gadget can be within the transmitter's range and can cause interference.

In addition with the fading effects, there are also other challenges that cognitive radio networks may encounter while spectrum sensing. Some of the challenges are shortly described below.

2.4 Spectrum Sensing Challenges

2.4.1 Hidden Node Problem

In wireless channel. Fading plays a specifically negative role in the renowned "hidden node" issue which also indicates towards the hidden primary user. This trouble states that the spectrum sensing device/terminal is in deep fade regarding the communication with receiving point. Therefore, a free medium is sensed by the spectrum sensing node and it starts the transmission eventually, consequently interference is induced on the primary transmission. So, fading results in ambiguity concerning the estimation problem. To address this problem, cooperative sensing is introduced.

2.4.2 Limited Sensing Ability

Recent research has revealed that cognitive radios have only a fundamental "sense of hearing" to notice the spectrum holes that is why its capability is restricted. This depicts that there is only a single sense available to cognitive radios to detect its multidimensional environment. For example; let's consider a blind man trying to go across the road in a busy traffic only utilizes hearing sense just like a cognitive radio. Many open issues are related to the performance and sensing ability in wider bandwidths. Advanced techniques are needed to overcome this issue and sense a wide range of bandwidths rapidly and reliably.

2.4.3 Wideband Sensing

While performing spectrum sensing one of the most challenging task is to explore a way so that boundaries can be adjusted regarding which spectrum to sense. As an alternative of wideband detection, limited spectrum can be exploited for spectrum sensing. Received signal can be sampled at or above Nyquist rate with existing technology while working in the limited spectrum. Additionally; the computational complexity that comes can be bounded to a feasible level. Moreover; costly analog front-end needed for a wide spectrum can also be avoided. [15]

2.4.4 Spectrum Sensing in Multi-Dimensional Environment

Systems which operate on cognitive radios work in the environment that generally comprises of multiple licensed users and multiple unlicensed users. Due to the presence of multiple secondary users (unlicensed users) spectrum sensing is challenged, as some of the SU can result in distortion with the other SUs in the environment that makes it hard to sense primary users precisely. To solve this issue, some features of cooperation in SS must be taken into consideration like information (transmitted power, frequency of other users, transmitted power, location, etc.), the approach to collaborate with other secondary users.

2.4.5 Sensing Time

Cognitive radios are used to assure that primary or licensed users can utilize the frequency bands any time so that collision can be avoided and to enhance the capacity of the spectrum; spectrum gaps must be sensed rapidly to accommodate the secondary users. So, it is very important to perform spectrum sensing algorithm within a certain limited time period. It is also very essential to consider that how frequently cognitive radio performs the spectrum sensing. It must sense very often to avoid missing any opportunity.

2.5 Spectrum Sensing Technique

Spectrum sensing is to find out the signals that are available in frequency spectrum. Whenever we come across a white space in frequency spectrum this means that a new link can be established by allocating a candidate. In primary and secondary users the SU must search for the available primary signals and move to the empty location. In order to achieve this task an efficient allocation of spectrum is required. Some techniques which work on the concept of centralized unit need to be implemented. The central unit will hold and change any information regarding spectrum utilization [16].One way to address this task is to implement some sensing algorithms or receive data through other mobile units. The spectrum sensing device should have the capability to detect the availability of signals even when the SNR is very low and the location of device should not be important.

Spectrum sensing demands the signal to be detected on time and should be accurate. This is an important requirement of spectrum sensing. Regardless of the method used for detection some relaxation should be given in scanning and signal processing. Out of band performance is done so that any kind of interference in transmission and reception is avoided. Several methods are available for the detection of primary signals but every technique has some drawbacks.

Few spectrum sensing techniques are energy detection, cyclo-stationary detection, matched filtering, Detection based on eigen value and channel estimation using random matrix theory. The method used for spectrum sensing is dependent on the requirement of the application for which it is used. There are some applications which require few signals to be identified, some applications demand totally blind spectrum sensing and some want just a little knowledge of the signal.

Figure 2.4 shows the different types of spectrum sensing techniques.

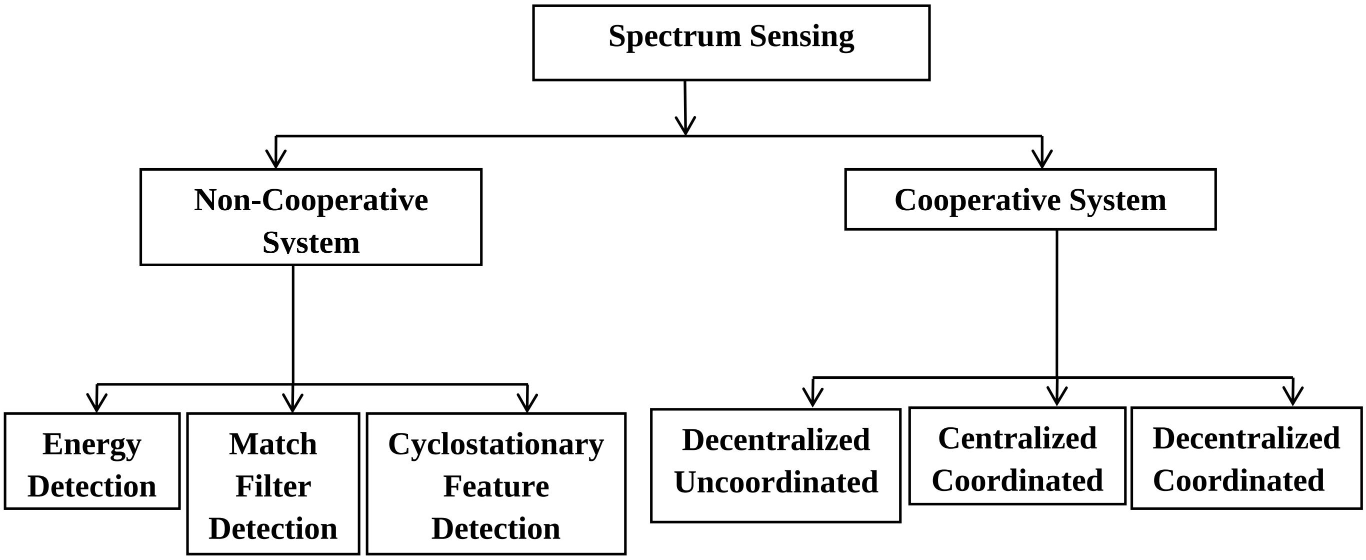

Figure 2.4: Different types of Spectrum Sensing approaches

2.5.1 Non-Cooperative System

2.5.1.1 Energy Detection

Energy detection (ED) is a method which is commonly adopted for spectrum sensing.ED is simpler to implement as the complexity level of this algorithm is very less. There is a pre-defined threshold which is compared with the energy that is being detected. Frequency and time domain both can be used for detection. When time domain is adopted then we need to obtain the average of the squared energy whereas for frequency domain FFT is required. The algorithm is greatly improved after the implementation of FFT as it provides a degree of freedom which has 2nd order. In both frequency and time domain the comparison of energy with the threshold is required.

The detection of primary signal in energy detection is done with the help of energy obtained from the sensed signal [17].The reasons behind ED being the most suitable and feasible technique in cooperative sensing are

i. Easy and simple to implement.
ii. No information required regarding the Primary user signal.

In ED method first of all a band pass filter is required through which signal is passed. Band passed signal then goes through integration process that is performed over time interval and in the end output obtained after integration is correlated with the predefined threshold. In order to determine the availability of PU this comparison is required. The value of threshold can be fixed or it can be changed according to the condition of channel. This technique has been widely used for sensing the spectrum but some of the factors are not being considered by this technique.

In some conditions the noise floor varies and when noise floor changes adaptive threshold needs to be used as implemented by few algorithms which implement ED.Energy detector cannot differentiate between the interferences caused by in-bands. One of the drawback of energy detection is that it cannot differentiate between the signal, noise or interference. Due to this reason few applications avoid the use of energy detection. Energy detection is simpler and easier to implement but whenever SNR is low then the performance of ED is not guaranteed. Complete method of the method is given below.

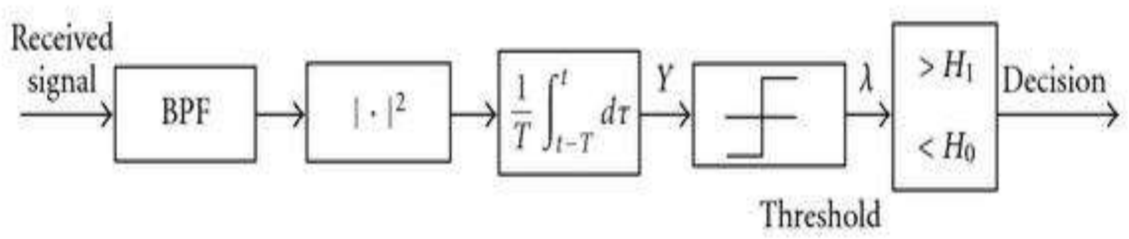

Figure 2.5: Block Diagram of Energy Detector

Energy detector consists of few elements like filter which will be used to remove all adjacent interferences and noise, an Analog to Digital Converter (ADC) which will convert an analog signal to digital signal. After ADC a square law device is placed in order to calculate the energy. The purpose of integrator and differentiator is to determine about measured energy.

Signal energy is compared with the threshold E_d.This energy is known as test metric. The energy is given by

$$E_d = \frac{1}{s} \sum_{l=1}^{S} |r(l)|^2 \tag{2.3}$$

Where, S is the amount of samples that are used for sensing. Test metric E_d is a chi-square distributed random variable. The detection probability is defined as

$$P_d = P_r(E_d > \Upsilon/H_1) \tag{2.4}$$

The probability of false alarm can be expressed as shown below. This is a closed form expression.

$$P_{fa} = \frac{\Gamma(S,\Upsilon/2}{\Gamma(s)} \tag{2.5}$$

Where, $\Gamma(.)$ and $\Gamma(.,.)$ are the incomplete and complete gamma functions.

We conclude our discussion on energy detection by giving probability of miss detection as

$$P_m = 1 - P_d \tag{2.6}$$

2.5.1.2 Matched Filtering

In order to identify the signal pattern one of the famous technique is matched filter detection [18].Whenever additive stochastic noise will come an optimal linear filter will be required to reduce the SNR.This function will be accomplished with the help of a matched filter. Figure 2.6 shows the steps followed in this method. The signal r (t) received by the secondary user is sent inside the matched filter and is written as

$$r(t) = hs(t) + n(t) \tag{2.7}$$

where r (t) is the signal obtained by cognitive user, s(t) is the primary signal transmitted,n(t) represents AWGN noise, and h is the amplitude gain of the channel. The primary user is inactive if s (t) is 0.

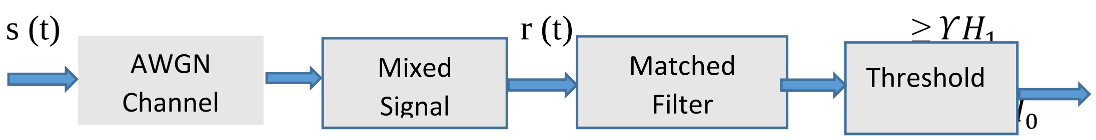

Figure 2.6: Matched Filter based spectrum sensing

At the end a comparison of matched filter outcome is made with the threshold factor which makes decision about the availability of the PU on the range of frequency sensed. [19]

The probability of detection, P_d, and false alarm, P_{fa}, of a matched filter are given as

$$P_d = Q\left(\frac{\Upsilon - E}{\sigma_n\sqrt{E}}\right) \quad (2.8)$$

$$P_{fa} = Q\left(\frac{\Upsilon}{\sigma_n\sqrt{E}}\right) \quad (2.9)$$

Where Q is the Gaussian complexity distribution function, E is the energy of the deterministic signal of interest, and ${\sigma_n}^2$ is the noise variance.

Whenever SU has beforehand knowledge of the PU then only Matched Filter method can be used. Its benefits are

i. In order to achieve the given detection probability the time required is very less.
ii. In stationary Gaussian noise SU has knowledge of the PU so this matched filter method is only optimal in this case.[20]

Its drawbacks are

i. Knowledge about PU needs to be known beforehand.
ii. The performance can be severely degraded if the information with SU about the PU is not correct.
iii. Every primary user requires a dedicated receiver for a cognitive radio.

2.5.1.3 Cyclostationary Feature Detection

When received primary signal is checked periodically then the presence of the PU can be detected with the help of this method. Periodicity can be introduced in the primary signal through many ways.

The features included by cyclostationary signals are periodicity and spectral correlation by it also carries the stationary noise and interference. [21]

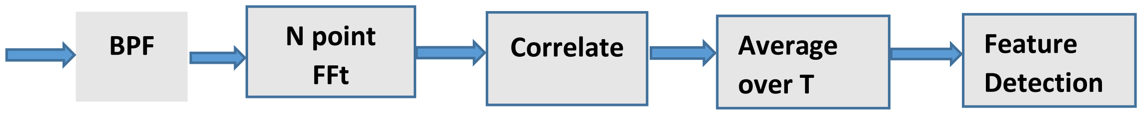

Figure 2.7: Cyclostationary Feature Detector Block Diagram

Advantages of Cyclostationary Feature detection are

i. Noise unpredictability can be easily controlled by this method.
ii. When the SNR is low then the performance of this method is much better than the ED method.
iii. This method allows transmissions of cognitive radio to be easily differentiated from various types of PU signals.
iv. In case of ED synchronization is not required during cooperative sensing whereas synchronization is must in cooperative sensing.
v. The throughput of the overall cognitive radio system is improved through this method.

Its drawbacks are

i. Difficult to compute. Complex in nature.
ii. More time is required for sensing.

Observing these negative aspects of cyclostationary feature detection this approach is not used commonly in cooperative sensing as compared to ED.So whenever cooperative sensing is done ED technique is adopted.

2.5.2 Cooperative Techniques

High sensitivity for secondary users was required previously but due to cooperative techniques this requirement has reduced. Multiple SUs cooperate together to sense the channel. Cooperative techniques comprises of various topologies. According to the level of cooperation these topologies are further divided into three parts. [22]

2.5.2.1 Decentralized Uncoordinated Technique

In this technique different SUs donot coordinate with each other. The channel is being discovered separately by each SU.No cooperation is made between each other. The SU will move out of the channel and leave it without informing any other SU whenever PU wants to use the same channel. Coordinated techniques are much more beneficial than uncoordinated techniques. Since there is no cooperation among different SUs and if a SU finds a channel idle but came to know that channel is being used by PU so this will cause distortion at the primary end.

2.5.2.2 Centralized Coordinated Technique

Secondary users have an infrastructure for this centralized coordinated technique. Secondary user informs the secondary user controller about the presence of primary transmitter or receiver. Any other SU can be secondary user controller. All the information about SU in the range are informed by the controller using control message.

Cooperation level can be used to divide the centralized technique into partial cooperative. In partial cooperative various network nodes are available and they will cooperate only in sensing. The channel is being detected by the SU and updated result is passed on to the SU controller which then broadcasts the information to all SUs as demonstrated in figure 2.8.

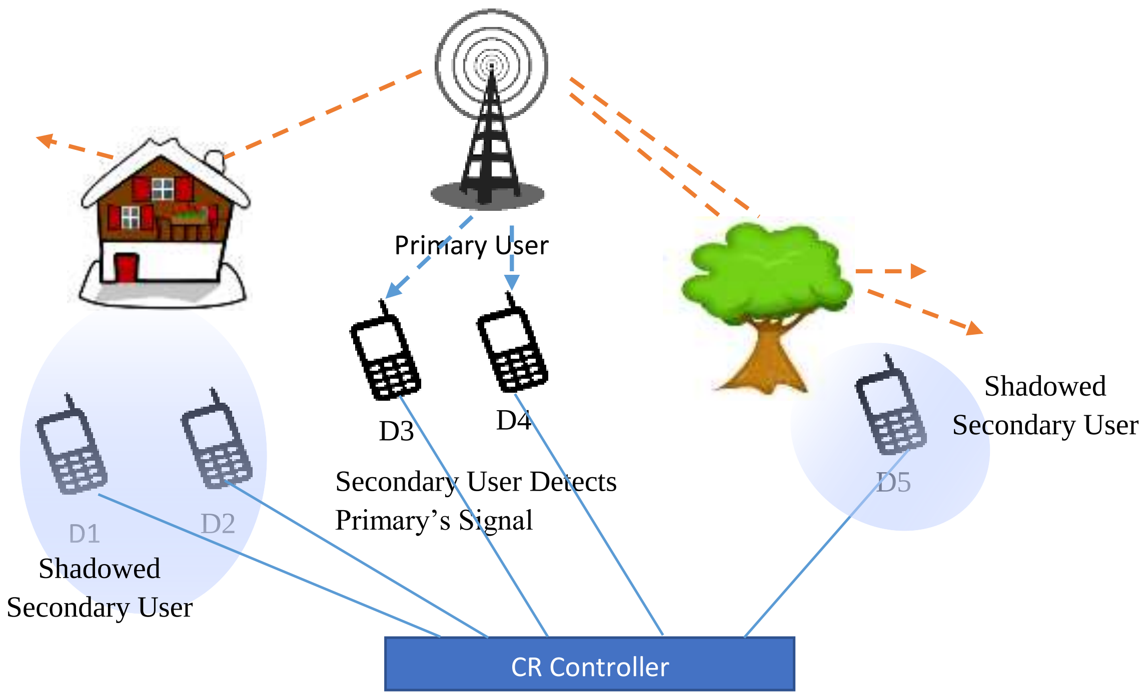

Figure 2.8: Centralized Coordinated Technique as Partial Cooperative [23]

It can be clearly seen in figure 2.8 that SU individually detects the channels and then after detections informs cognitive radio controller about the results and then controller broadcasts this information to all the SUs available. SUs donot cooperative with each other. There is no cooperation in case of partial cooperation.

When network nodes completely cooperate with each other in passing information to each other as well as in sensing the channel this is known as total cooperative. The phenomena is demonstrated in figure 2.9.

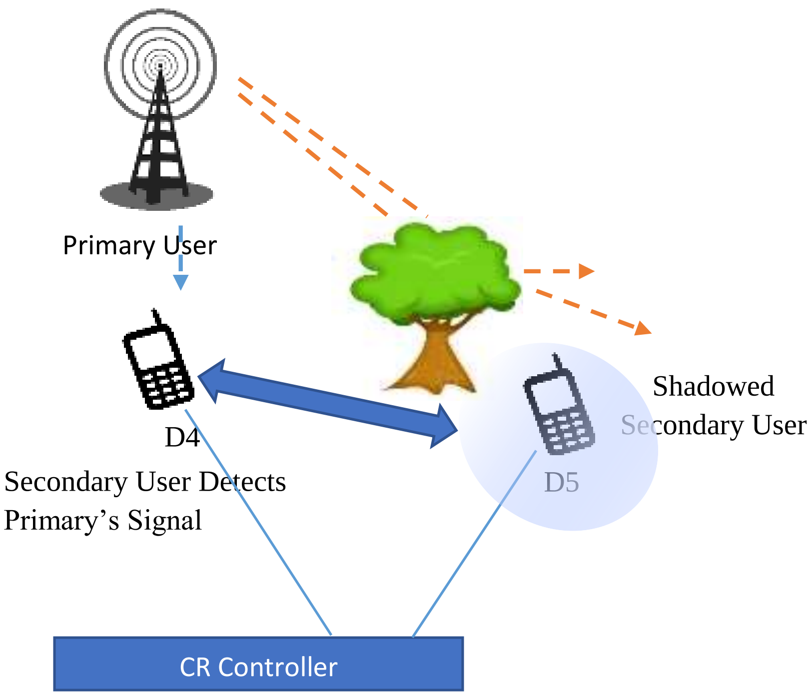

Figure 2.9: Centralized Coordinated Technique as Total Cooperative

It can be observed from the figure above that SUs cooperate with each other in case of total cooperation. They communicate with each other and share the sensing information. They also convey this information to the cognitive radio controller which then conveys to all the SUs.

2.5.2.3 Decentralized Coordinated Techniques

In decentralized coordinated technique, there is no cognitive radio controller. No coordination is done between SUs through cognitive radio controller. Decentralized technique has further two types of algorithms listed below.

i. Gossip Algorithms
ii. Clustering Techniques

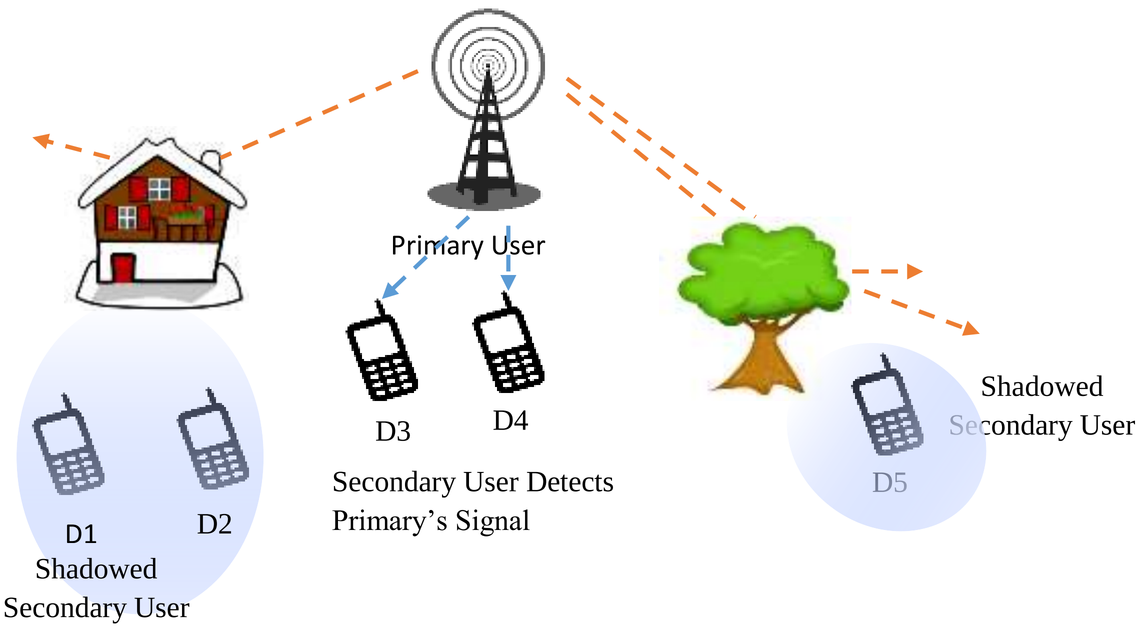

Figure 2.10: Decentralized Coordinated Technique

2.5.2.4 Benefits of Cooperation

Cooperation of SUs among each other results in various advantages which are listed below.

i. Sensitivity is very high.
ii. In cooperative networks detection time is greatly reduced as compared to uncoordinated networks.

2.5.2.5 Drawbacks of Cooperation

Cooperation technique has several negative points such as

i. Sensitivity requirements, energy consumption and data throughput are not much efficient in this technique.
ii. This technique does not have the capability to quickly change according to the demand of users for the spectrum [24].

Chapter-3

Spectrum Sharing

3.1 Introduction

Spectrum Sharing is an important part of the cognitive cycle. It allows sharing of the spectrum holes with the secondary users depending on their requirement. When it comes to save energy spectrum sharing will turn to be beneficial. It will reduce the transmitting power by utilizing the frequency bands which are low. Capacity can be greatly increased when some unused part of the spectrum will be utilized. System power efficiency can also be enhanced by decreasing the amount of base stations.Communication is necessary so that automatically makes spectrum important. All global communications are dominated by the wireless and mobile communications. [25]

Communication spectrum is becoming scarce with the passage of time. Scarcity of spectrum leads to the importance of spectrum sharing. Demand for the spectrum is increasing rapidly as billions of users are trying to access the spectrum and more and more bandwidth is being utilized.

In CR networks since a lot of SUs compete with each other in order to access the unused spectrums so access coordination of transmission attempts between SUs is required so that interference can be prevented. The proposed solution for this problem is spectrum sharing. Previously in traditional wireless networks Media Access Control Protocol (MAC) was used but this technique has similar features to MAC.Since there are some advanced and unique features of CR networks like change in available spectrum resources dynamically and co-existence with primary users, the spectrum sharing policy in cognitive radio networks faces many new challenges. A lot of research has been carries out on this area of interest.

The rapidly developing technology of cognitive radio is giving a lot of advantages to every radio community member. Spectrum sharing can provide many profits. Spectrum will be used efficiently due to sharing of spectrum and the spectrum regulators will obtain many benefits as gains will increase. Previously centralized (command and control style) approach was used for spectrum management but due to spectrum sharing the need for this approach will reduce massively. Cognitive radio will also make spectrum management possible through the use of automatic (seamless) approach. Spectrum sharing will allow new and current service providers to increase their business without bothering about spectrum scarcity. Some of the applications are promising as far as spectrum sensing is concerned.e.g downloading multimedia, emergency communications, multimedia wireless networking with high data rates. Spectrum sharing can also take place for several applications which operate in bands between ~140MHz-11GHz.On the other hand there are several technological and practical issues that need to be addressed. Keeping in mind the constraints imposed by regulatory authorities and other information cognitive radio systems provide underlay, overlay or interweave spectrum sharing.

The existing proposed spectrum sharing algorithms can be categorised into different types.

1. Centralized and Distributed Spectrum Sharing
2. Cooperative and Non-Cooperative Spectrum Sharing
3. Overlay and Underlay Spectrum Sharing
4. Intra-Network and Inter-Network Spectrum Sharing

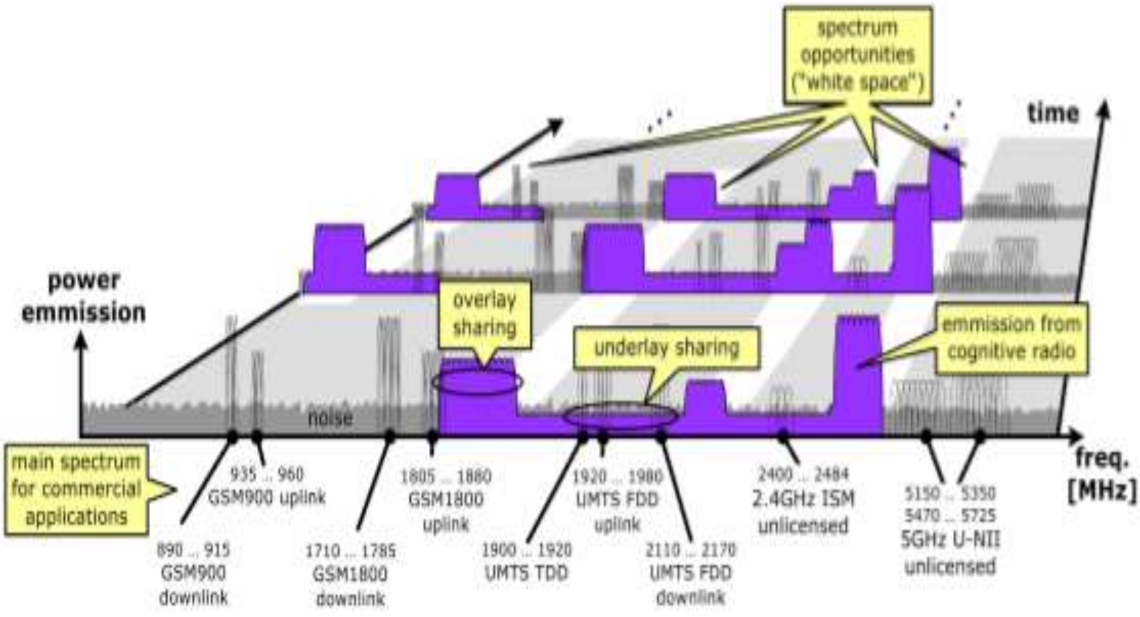

Figure 3.1: Cognitive Radio Paradigm

3.2 Underlay Spectrum Sharing

In this model both the SUs and PUs are allowed to transmit data simultaneously keeping the interference caused by secondary user under a predefined threshold so that performance of primary user is not degraded. If the predefined threshold limit is exceeded then the primary signal can be distorted. In literature many techniques and approaches have been explored which help to avoid and stop interference so that primary user is protected. Beam forming and spread spectrum are few of those methods.

Figure 3.2 below illustrates the underlay approach.

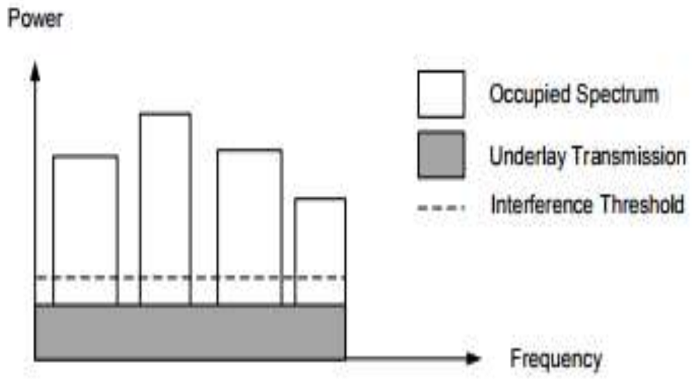

Figure 3.2: Interference Threshold and spectrum occupied by Underlay scheme

In this approach spread spectrum technique is used and complete spectrum is available for the secondary users which can turn out to be a disadvantage as interference could be caused for the licensed users. In both the frequency and time domain the spectrum is used concurrently and without coordination by all the users. In order to implement underlay spectrum sharing it is assumed by the cognitive radio that it has all the knowledge about the distortion caused by the non-cognitive users for the primary users. This scheme calls the cognitive radio as the secondary user. The primary systems are not changed at all as they are the main systems and difficult to change. Communication of PU is protected from the disturbance of SU. An interference constraint should be there for the protection of the licensed or existing users. This constraint needs to give at least two parameters {Q, ε} [26].The first parameter Q denotes the maximum interference power that can be observed by an active primary user. It is also known as noise floor. The second symbol highlights the maximum outage probability. It tells the probability by which the interference at primary receiver is exceeding the noise floor Q [27].In this approach the cognitive radio is only allowed to transmit in the common spectrum when the interference at the primary receiver is below an acceptable level.

Figure 3.3 below gives the model of underlay spectrum sharing approach. In this model the communication of the SU-Tx with the SU-Rx is through the wireless link. The channel power gain of the link is g_1.When the secondary transmitter will interfere with the primary receiver that link will be known as interfering link and its channel power gain is expressed by g_0.No interference is caused by the primary transmitter in the communication of secondary network as it is assumed to be placed far away the secondary users.

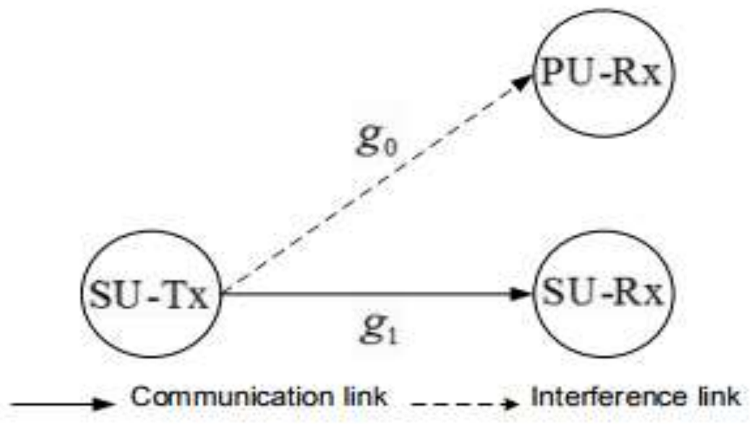

Figure 3.3: Basic Underlay Cognitive Radio Network where PU-Tx is far away from the secondary network

Another scenario for the underlay cognitive radio network is when the secondary users and primary transmitter are in range of each other i.e they are close from one another. Figure 3.4 illustrates this scenario. The channel that is interfering with the primary user is going from primary transmitter PU-Tx to the secondary receiver SU-Rx and its channel power gain is represented by h_p.Primary transmitter PU-Tx and primary receiver PU-Rx have their channel power gain as g_p.In literature for this type of scenario a system outage analysis has been conducted.[28]

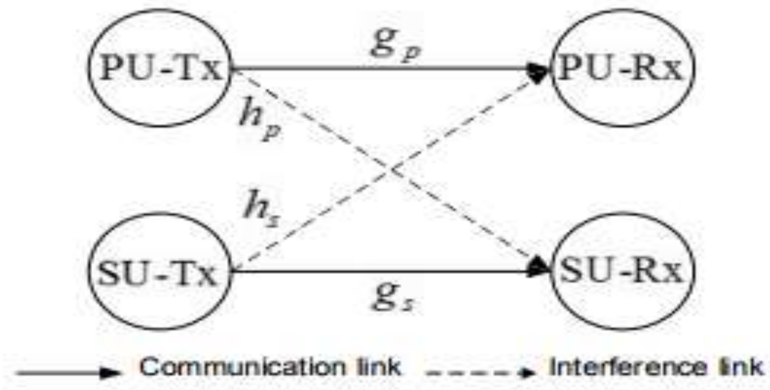

Figure 3.4: Basic Underlay Cognitive Radio Network where PU-Tx is in the proximity of the secondary network

3.3 Overlay Spectrum Sharing

This approach also allows secondary and primary users to transmit simultaneously. But in this approach knowledge about signal codebooks and messages of primary user is required. Primary user needs to give this information to the secondary transmitter in overlay method. This material will be used by the secondary user to either reduce or mitigate the interference caused by them. Primary user's messages will be used by the secondary transmitter to improve its own and PU's data rate. Data rate will be improved with the help of encoding scheme that is implemented by secondary transmitter [29].In literature various encoding and decoding techniques have been introduced which implement overlay spectrum sharing [30].Few encoding techniques are

1. Rate Splitting
2. Gel'fand-Pinsker (GP) Binning
3. Cooperation
4. Superposition Coding

Encoding strategies for interference and multi-access channels are used to derive all these techniques. Rate-splitting is famous as the best encoding technique and it improves the rates by cancelling the interference partially at the decoders. Recoding against the interference is done by the GP binning in order to enhance the code rate. If your channel is Gaussian then you can use dirty paper coding. In case of encoding cooperation secondary user makes the rate better by relaying the primary user message partially. Finally superposition coding is used which is a mixture of all the coding mentioned above [31].

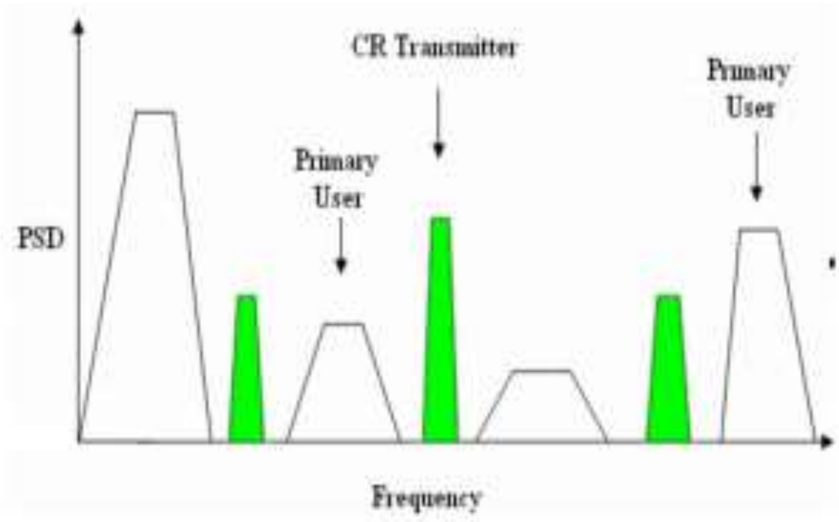

Figure 3.5: Overlay Spectrum Sharing

3.4 Centralized Spectrum Sharing

Centralized spectrum sharing technique is based on the architecture of cognitive radio network. A centric spectrum management entity is available in this technique. This entity is important for the management of the spectrum allocation and access of the spectrum. All allocations of the spectrum and access of the spectrum is administered by this center. Each member of the CRN sends the results of spectrum allotment to this main center which then decides about spectrum allocation map. All decisions related to allocation of spectrum are done by this entity [32]. First sensing is done to determine the spectrum demands of all the available users and the information related to the network is obtained. After receiving this information this centric entity will propose a spectrum sharing objective keeping in mind the demands of the users and the status of the network. Now after this all secondary users will be provided by the real time results of spectrum allocation. [33]

3.5 Distributed Spectrum Sharing

Distributed Spectrum Sharing is also related with the architecture of the cognitive radio network. In this method each cognitive user will access the spectrum individually and obtained information about the wireless network. There will be no centralized entity as in centralized spectrum sharing. All the decisions will be based on the local policies without consulting any centralized authority. After realizing the spectrum each user will decide for the spectrum access in a distributed manner. This approach basically focuses on the simple and flexible operations of dynamic spectrum sharing that are being used by the real world. If we compare this method with the centralized spectrum sharing approach this technique turns out to be a bit complicated. As high sensing ability of each individual user is required and dynamic approaches also needs to be flexible so that this approach can be implemented successfully. Distributed spectrum sharing is used in the cases where we do not need to construct any type of infrastructure.

3.6 Cooperative Spectrum Sharing

Collaborative Spectrum Sharing is another name of Cooperative spectrum sharing. When one node communicates with the other node an effect is produced that effect is being monitored by this technique. The interference measurements made by each and every point will be shared with all the other nodes. So for this approach these measurements are important. Solutions which are for centralized spectrum sharing they can also be used as a solution for cooperative spectrum sharing.

3.7 Non-Cooperative Spectrum Sharing

Non-Cooperative spectrum sharing technique is also known as Non-collaborative spectrum sharing technique. It is a selfish method of spectrum sharing because it only considers the node that is available at the moment. The nodes will not share any type of information with each other. Use of spectrum can be decreased if this approach is adopted.

Three factors which are considered for the comparison of cooperative and non-cooperative solutions include fairness, spectrum usage and throughput. After investigating both the techniques with these factors it was observed that non-cooperative technique is much better than cooperative spectrum sharing.

3.8 Centralized-Intra Network Spectrum Sharing

In centralized-intra network spectrum sharing technique we have a centric entity known as the spectrum server as shown in figure 3.6.All cognitive users are being coordinated by this main server. All the users in this technique work using the cooperative approach.

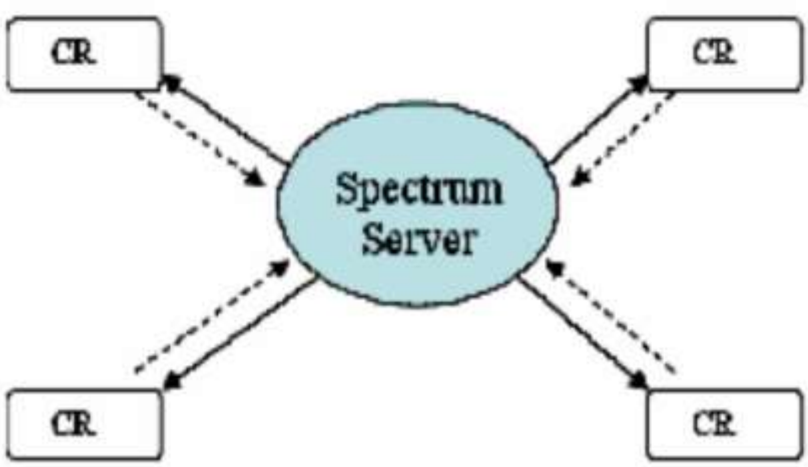

Figure 3.6: Centralized-Intra Network Spectrum Sharing

3.9 Distributed-Intra Network Spectrum Sharing

In distributed spectrum sharing technique there is no centre entity or spectrum server that is available in the centralized-intra network approach. The decision regarding spectrum sharing is not made by any single body. Individual cognitive user makes their decision by themselves not depending on anyone else.

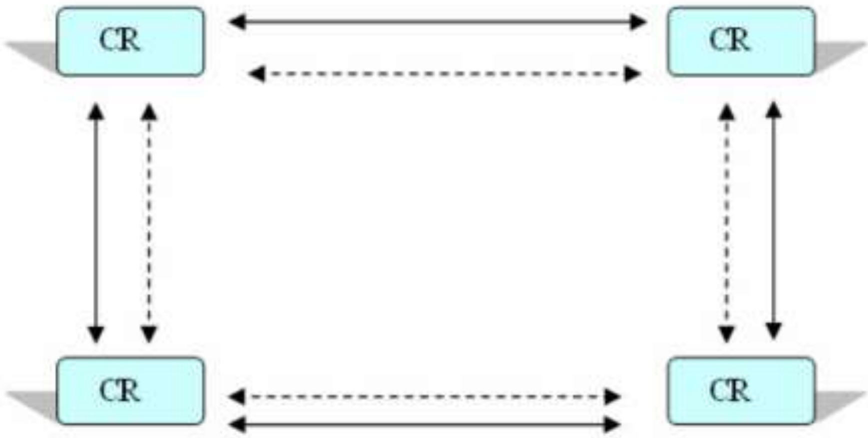

Figure 3.7: Distributed-Intra Network Spectrum Sharing

3.10 Centralized-Inter Network Spectrum Sharing

Centralized-inter network are very similar to intra networks as far as dynamics are concerned. But in case of centralized-inter network spectrum sharing approach we have a spectrum broker. This broker manages all the cognitive users and shares spectrum among them.

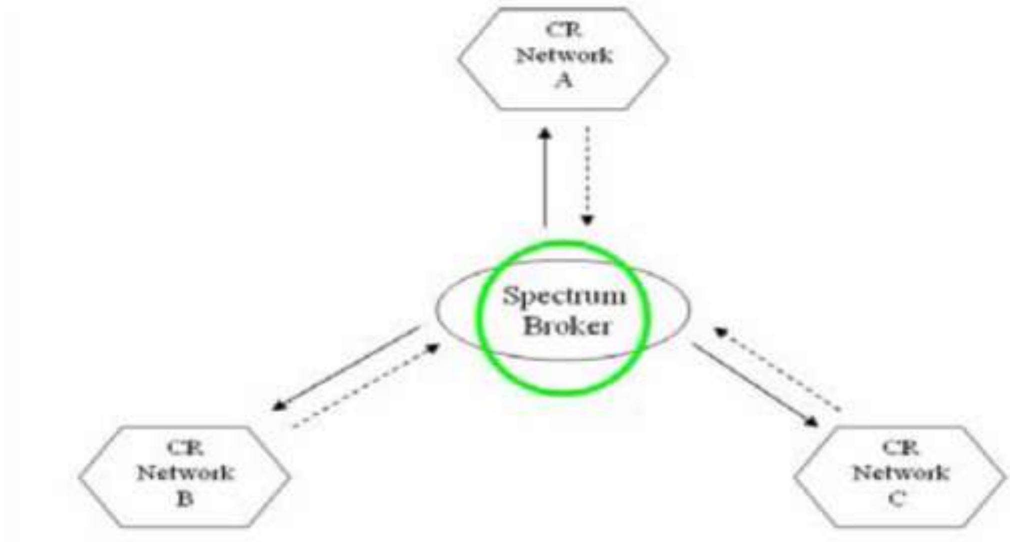

Figure 3.8: Centralized-Inter Network Spectrum Sharing

3.11 Distributed-Inter Network Spectrum Sharing

In distributed-inter network approach there is no centre entity and each user makes its decision itself without depending on any other component. Spectrum sharing is done by all the cognitive users.

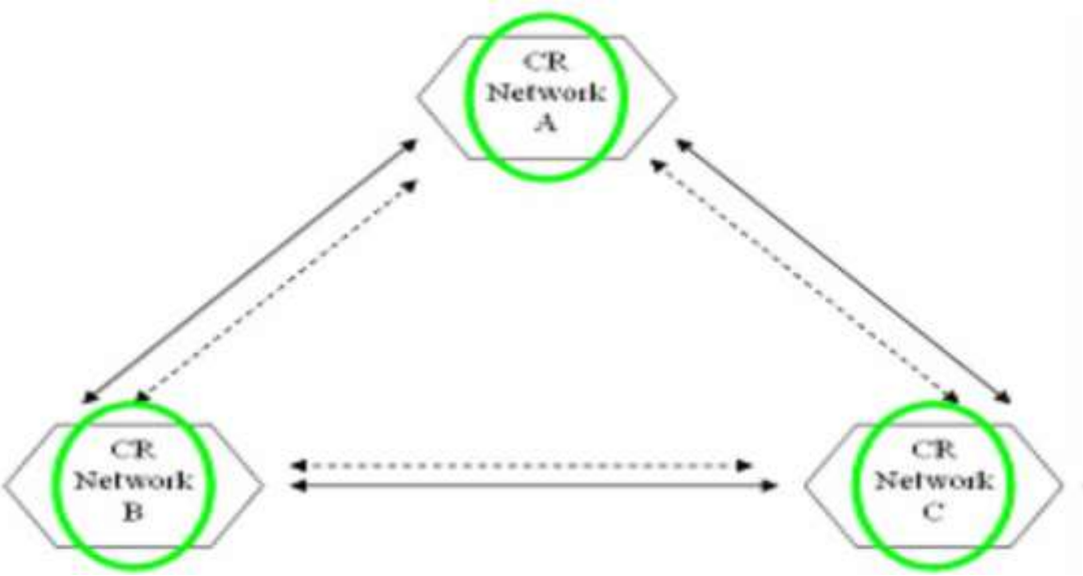

Figure 3.9: Distributed-Inter Network Spectrum Sharing

Chapter-4

Dynamic Spectrum Access in Multi-Channel CRNS

4.1 Introduction

In multichannel cognitive radio networks dynamic spectrum access has gained a lot of attention with the passage of time. But this is more difficult then single channel as here we have multiple channels and multiple secondary users. There are two main problems that we need to solve while this method of access. Main problems are mentioned below.

1. Coordination of the secondary users while sensing multiple channels.
2. Sharing of all the vacant channels.

Cooperative spectrum sensing is performed for the case of multi-channel cognitive radio networks. The limitation of hardware allows each secondary user to select single channel only while performing spectrum sensing and access only single channel at a certain instant while performing share of spectrum [34].For spectrum sensing two aspects have been discussed for the channel selection problem. Primary user's point of interest and secondary user's point of interest have been taken into consideration.

i. From primary user's perspective: In this case secondary user's act conservatively while performing spectrum sensing. The goal is to reduce the interference of primary user. The motive is to reduce the interference to primary user. Demand of SU regarding available time that they want to achieve is also required to be fulfilled.
ii. From secondary user's perspective: In this case the behavior of secondary user is aggressive during spectrum sensing. Their main objective is to increase the expected available time as much as possible but keeping a check on the interference so that PUs are protected.

The channel to be sensed is decided by the secondary user in order to fulfill these aims. A general approach is adopted where the common difference are:

i. Individual secondary user's detection performance is totally based on channel condition. These conditions can vary from one user to another.
ii. Usage characteristics like the average sojourn idle time and the expectation of idleness are different for all the channels.

All these factors make the selection of channel a challenging task. So the selection of channel is considered as a nonlinear integer programming problem. Various approaches are being used depending on the type of problem. To solve the problem efficiently from primary user's perspective the problem was investigated in detail and by making a bipartite graph and weight vectors a transformation was made for convex bipartite matching problem. Based on this transformation an algorithm was introduced as the channel selection algorithm. A stochastic optimization problem was introduced for the other case. Afterwards cross-entropy optimization technique was used to find the solution for channel selection. In the end spectrum sharing was studied.Modelling of spectrum sharing was done using a very general game which is using the concept on weights in congestion games. Separate weights are assigned to individual secondary users who have different conditions of the channel. In this way all the secondary user's which have better channels can be favored. An algorithm was introduced due to which secondary user's can achieve Nash equilibrium (NE).

4.2 System Model

A cognitive radio has two types of user's primary user's (PU) and secondary user's (SU).We also have considered such a CR network which has both PU's and SU's.The primary users are also known as the licensed user's because they have a license of certain portion of spectrum band where they can operate. On the other hand secondary users are not the licensed users and they have not purchased any portion of the spectrum. They only access the spectrum whenever they get a free spectrum to transmit. The part of spectrum which can be accessed by the SU's is further partitioned into set of channels. Every channel has a certain fix portion of the bandwidth.

In the network that we have considered we have K licensed bands (channels).They have allowed PU's to transmit at the same time. We assume that the PU is operating in such a channel which can be either on or off. In identical vicinity there can be N SU's which will try to access the spectrum and start transmission. In this way there are chances of interference between the primary user and the secondary user. To avoid interference spectrum sensing needs to be performed by the secondary user. Spectrum Sensing will detect all the unused spectrum that are not being accommodated by the PU's.

To explore the status of each channel a method known as the ON-OFF channel usage model is being considered. Condition of the channels keeps on changing between busy and idle. Busy is considered as the ON state and idle as OFF. Whenever the channel is not being used or it is in OFF state then only it can be accessed by the SU.We make an assumption that the state of the channel is changing without depending on anything and PU_j is using the channel j.The figure below further highlights the status of the channel.

α_j = Transition rate from ON to OFF state of channel j.

β_j = Transition rate from OFF to ON state of channel j.

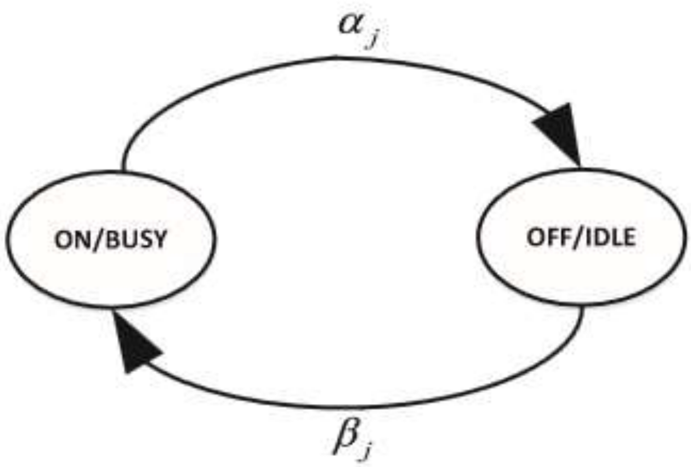

Figure 4.1: ON-OFF Model for a given channel

The usage characteristics of all the channels may not be same. Different channels may have different usage characteristics. It not necessary that α_j and β_j for channel j are going to be same as α_i and β_i for channel i.

4.3 Spectrum Sensing

4.3.1 Individual Spectrum Sensing

In order to determine the status of the channel whether it is in OFF state or ON spectrum sensing is performed. Suppose

H_1 = ON state or PU is available in our channel of interest.

H_0=OFF state or PU is not available in our channel of interest.

There are several techniques that have been commonly used in literature for spectrum sensing e.g. energy detection, cyclostationary detection and matched filtering. All the methods have few advantages and few disadvantages. But we have used the energy detection technique because it is simple and easy to implement. Its overhead time is also very less (almost 1ms).The probability of detection and probability of false alarm in energy detection is represented as

$$p_d = Pr(D > \delta|H_1) \quad (4.1)$$

$$p_f = Pr(D > \delta|H_0) \quad (4.2)$$

where,

δ = Detection Threshold

D = Test Statistic

$$D = \frac{1}{M}\sum_{n=1}^{M} |y(n)|^2 \quad (4.3)$$

M= Quantity of samples during the period of observation.

y (n) = nth sample of the received signal.

According to this the likeliness of wrong indication of SU_i for channel j is represented below

$$p_f(i,j) = Q\left(\left(\frac{\delta}{\sigma^2} - 1\right)\sqrt{M}\right) \quad (4.4)$$

Q (.)= Complementary Distribution Function of standard Gaussian.

Neyman-Pearson criterion is adopted so probability of false alarm is considered as fixed. The probability of false alarm is same for all the SU's and is expressed as p_f.In this way the detection threshold for all the SU's will also become same and all SU's have exactly identical value of δ.

The detection probability of SU_i for channel j is given by

$$p_d(i,j) = Q\left(\left(\frac{\delta}{\sigma^2} - \Upsilon_{i,j} - 1\right)\sqrt{\frac{M}{2\Upsilon_{i,j}+1}}\right) \tag{4.5}$$

$\Upsilon_{i,j}$ = Average received signal-to-noise- ratio (SNR) from PU_j to SU_i.

$$\Upsilon_{i,j} = \frac{P_{PU} h_{i,j}}{\sigma^2} \tag{4.6}$$

P_{PU} = Transmission power of the PU.

$h_{i,j}$ = Average channel gain from PU_j to SU_i

σ^2=Variance of the Gaussian Noise.

Depending on the probability of false alarm the probability of detection is expressed as

$$p_d(i,j) = Q\left(\frac{1}{2\Upsilon_{i,j}+1}\left(Q^{-1}(p_f(i,j)) - \sqrt{M}\Upsilon_{i,j}\right)\right) \tag{4.7}$$

4.3.2 Cooperative Spectrum Sensing

The problems that we face due to low SNR, shadowing and hidden terminal can be addressed through cooperative spectrum sensing. In this approach all SU's cooperative with each other so that the results of sensing can be improved. All SU's share their results of sensing and make a conclusion together about the presence or absence of PU.This decision is based on the decision fusion rule. In this rule all the cooperative SU's individually sense the spectrum and sends their decision to the central body. After this the final judgment is made by decision center after combining all the decision of SU's.Two main decision fusion rules are focused which are

1. Logic-OR rule

2. Logic-AND rule

4.3.2.1 Logic-OR Rule

In this rule if any of the SU claims that PU is present then the final decision says that the primary user is present in the spectrum. According to this regulation the probability of false alarm and expectation of missed-detection is given as

$$P_i^f(k_i, \tau, \varepsilon_i) = 1 - [1 - P_i^f(\tau, \varepsilon_i)]^{k_i} \quad (4.8)$$

$$P_i^d(k_i, \tau, \varepsilon_i) = 1 - [1 - P_i^d(\tau, \varepsilon_i)]^{k_i} \quad (4.9)$$

k_i = Number of secondary users appointed for sensing channel i.

4.3.2.2 Logic-AND Rule

Logic-AND rule decides about the absence or presence of the PU based on the decision of all the secondary users. If all the SU's says that PU is present then the final decision declares PU as present else if any one of the SU says that PU is absent then the final decision is also absent. Keeping in mind this logic-AND rule the probability of missed detection and probability of false alarm is defined as

$$P_i^f(k_i, \tau, \varepsilon_i) = [P_i^f(\tau, \varepsilon_i)]^{k_i} \quad (4.10)$$

$$P_i^d(k_i, \tau, \varepsilon_i) = [P_i^d(\tau, \varepsilon_i)]^{k_i} \quad (4.11)$$

4.3.3 Optimization Algorithms

The problem of secondary user assignment and spectrum sensing parameters adjustment on multichannel cooperative spectrum sensing have been jointly considered. This is done to enhance the throughput of the SUs. Decision fusion rule is used for the optimization of problem.

For a given channel i, $P\,(H_i^o)$ is the probability that PU is absent. The two cases which can exist for CR to operate on channel i are mentioned below.

1. PU is not available and fusion center does not gave any wrong indication.

2. PU is available but it is not identified by the base station (BS).

It is assumed that whenever the PU is absent on channel i then only throughput will be obtained. The average throughput of channel i can be expressed as

$$R_i(k_i,\tau,\varepsilon_i) = \frac{T-\tau}{T} P(H_i^o)\,[1 - P_i^f(k_i,\tau,\varepsilon_i)] \log(1+r_i) \qquad (4.12)$$

r_i = SNR of SU from its transmitter to receiver on channel i.

The main objective is to increase the throughput using decision fusion rule of the CR network as much as possible but keeping a check on the detection probability. For each channel it should be less than the predefined threshold.

Using decision Fusion Rule a problem has been optimized which is expressed below.

Problem P1:

$$\max_{\{k_i\},\,\tau,\{\varepsilon_i\}} \quad R(\{k_i\},\tau,\{\varepsilon_i\}) = \sum_{i=1}^{N} R_i(k_i,\tau,\varepsilon_i) \qquad (4.13)$$

$$\text{s.t.} \quad P_i^d(k_i,\tau,\varepsilon_i) \geq P_{th}^i,\; i=1, 2,\ldots, N \qquad (4.14)$$

$$0 \leq \tau \leq T \qquad (4.15)$$

$$\sum_{i=1}^{N} k_i = K \qquad (4.16)$$

$$k_i > 0,\; k_i \in I \; i = 1,2,\ldots,N \qquad (4.17)$$

$P_i^f(k_i,\tau,\varepsilon_i)$ is represented by equation 4.8 under "Logic-OR" rule and equation 4.10 under "Logic-AND" rule.

$P_i^d(k_i,\tau,\varepsilon_i)$ is represented by equation 4.9 under "Logic-OR rule" and equation 4.11 for "Logic-AND rule".

P_{th}^i is the least probability that must be satisfied by the fusion center so that PU can be protected.

It is very difficult to solve the above problem because both functions are non-convex. So problem P1 is transformed to

$$max \qquad R(\{k_i\})=C^*(\{k_i\}) \tag{4.18}$$

$\{k_i\}$

$$s.t. \qquad \sum_{i=1}^{N} k_i = K \tag{4.19}$$

$$k_i > 0, k_i \in I \; i = 1,2,\dots,N \tag{4.20}$$

$C^*(\{k_i\})$ is the optimal objective value of the following problem P2 with specific $\{k_i\}$ values.

Problem P2 (with some $\{k_i\}$ values):

$$max \qquad C(\tau,\{\varepsilon_i\})=\sum_{i=1}^{N} R_i(k_i,\tau,\varepsilon_i) \tag{4.21}$$

$\tau,\{\varepsilon_i\}$

$$s.t. \qquad P_i^d(k_i,\tau,\varepsilon_i) \geq P_{th}^i \qquad i=1, 2,\dots, N \tag{4.22}$$

$$0\leq\tau\leq T \tag{4.23}$$

The best solution of problem P2 exists when the limitations of equation 4.21 are at equality. The values of $P_i^f(k_i,\tau,\varepsilon_i)$ and $P_i^d(k_i,\tau,\varepsilon_i)$ are inversely proportional to the threshold of sensing ε_i.The above problem P2 can be changed into problem P3.

$$max \qquad C(\tau) = \sum_{i=1}^{N} R_i(k_i,\tau,\varepsilon_i(k_i,\tau)) \tag{4.24}$$

τ

$$s.t. \qquad 0\leq\tau\leq T \tag{4.25}$$

Under "Logic-OR" $\varepsilon_i(k_i,\tau)$ and $P_i^f(k_i,\tau,\varepsilon_i((k_i,\tau)))$ of problem P3 are expressed as

$$\varepsilon_i(k_i,\tau) = \sigma^2\left(\sqrt{\frac{2\Upsilon_i+1}{\tau f_s}}\, Q^{-1}\left(1\text{-}(1-P_{th}^i)^{\frac{1}{k_i}}\right) + \Upsilon_i + 1\right) \tag{4.26}$$

$$P_i^f\left(k_i,\tau,\varepsilon_i\left((k_i,\tau)\right)\right) = 1 - [1 - Q(\sqrt{2\Upsilon_i+1}\, Q^{-1}(1-(1-P_{th}^i)^{\frac{1}{k_i}}) + \Upsilon_i\sqrt{\tau f_s}\;]^{k_i} \tag{4.27}$$

Under "Logic-AND" rule $\varepsilon_i(k_i, \tau)$ and $P_i^f(k_i, \tau, \varepsilon_i((k_i, \tau)))$ of problem P3 are given by

$$\varepsilon_i(k_i, \tau) = \sigma^2 \left(\sqrt{\frac{2\Upsilon_i + 1}{\tau f_s}} Q^{-1}\left((P_{th}^i)^{\frac{1}{k_i}}\right) + \Upsilon_i + 1 \right) \quad (4.28)$$

$$P_i^f\left(k_i, \tau, \varepsilon_i\left((k_i, \tau)\right)\right) = [Q(\sqrt{2\Upsilon_i + 1}\, Q^{-1}((P_{th}^i)^{\frac{1}{k_i}}) + \Upsilon_i\sqrt{\tau f_s}\ ]^{k_i} \quad (4.29)$$

It can be proved that C (τ) of problem P3 is unimodal and can be easily solved using numerous search methods.

4.3.3.1 Exhaustive Algorithm

The exhaustive algorithm is explained in Table 1 below. The number of combinations of $\{k_i\}$ correlates with K-M.It also increases rapidly as K-N is increased.

Find the optimal $\{k_i\}$, τ, $\{\varepsilon_i\}$ that maximize R
1.Search all possible combinations of $\{k_i\}$; 2.Solve the optimization problem P3 for each combination, and find the optimal R of each combination; 3.Compare the optimal R of different combination, and choose the maximal R; 4.Get the optimal $\{k_i\}$, τ, $\{\varepsilon_i\}$ corresponded to the maximal R.

Table 4.1: Exhaustive Algorithm

4.3.3.2 Greedy Algorithm

Table 2 gives the greedy algorithm. This algorithm is much simpler in terms of complexity when K-N is very big as compared to exhaustive algorithm.

Find the optimal $\{k_i\}, \tau, \{\varepsilon_i\}$ that gives the maximum value of R
1.Initialization: j $\longleftarrow$ 0; $k^j = \{k_i\}^j = \{1,1,\ldots,1\}$ 2.Repeat for $i = 1,2,\ldots,N$ $k^{j+1} = k^j$ $k^{j+1}(i) = k^j(i)+1$ Find the optimal $R_i = R(k^{j+1})$ through solving the optimization problem P3 end Find $i^* = \arg\max \{R_i\}$, then let $k^{j+1} = k^j$ and $k^{j+1}(i^*) = k^j(i^*)+1$ $j=j+1$ 3.Until $\sum_{i=1}^{N} k^j(i) = \mathrm{K}$ 4. Output: $\{k_i\} = \{k_i\}^j$, and get the optimal $\tau, \{\varepsilon_i\}$ corresponded to $\{k_i\}$ through solving the optimization problem P3.

Table 4.2: Greedy Algorithm

4.3.4 Spectrum Sensing in Multi-Channel CRNs

In multi-channel CRNs spectrum sensing has been explored for two cases. For the first scenario Logic-OR rule is being adopted and SU behaves conservatively. SU tries to reduce the collisions of the PU while fulfilling the SU's requirement of access time that is available. For the next part behavior of SU is aggressive in spectrum sensing. The aim is to increase for all the channels the expected available time while protecting the PU's.For different objectives different channel selection approaches have been formulated.

4.3.4.1 PU's interest perspective

When PU's interest are concerned Logic-OR rule is followed by the SU.The task is to reduce the collisions of the PU while fulfilling the demand of SU on available time they wish to obtain for sensing. So first channel selection problem is done and afterwards proposed approach of bipartite matching.

- Problem Formulation :

  T_{ON}^{j} and T_{OFF}^{j} are the sojourn times of ON state and OFF state for channel j respectively. Exponential distributions with mean are given below

$$T_{ON}^{j} = \frac{1}{\alpha_j} \quad , \quad T_{OFF}^{j} = \frac{1}{\beta_j} \tag{4.30}$$

  P_{ON}^{j} and P_{OFF}^{j} are the probabilities that the channel j is in ON state and OFF state respectively. They are expressed as

$$P_{ON}^{j} = \frac{\beta_j}{\alpha_j+\beta_j}, \; P_{OFF}^{j} = \frac{\alpha_j}{\alpha_j+\beta_j} \tag{4.31}$$

  If the channel j is idle and it is sensed to be in OFF state then the SU will have an average period of T_{OFF}^{j} to use. If the channel j is busy in real but it is being sensed as idle or in OFF state then the SU will access the channel and interference will be produced with the PU.Since PU are very sensitive towards the interference they face from the SU as a result of miss detection so a detection threshold P_{rm} has been defined. Satisfaction is introduced in order to measure the experience feeling of PU's.The miss detection probability and satisfaction are inversely proportional to each other. The conditions of channel and the number of secondary users sensing the channel are two parameters which determine the misdetection probability. Satisfaction is determined by

$$s =: log\frac{P_{rm}}{F_m(j)} \tag{4.32}$$

The value of satisfaction is positive when $F_m(j) < P_{rm}$ and its negative when $F_m(j) > P_{rm}$.

The main objective behind the channel selection problem is to fulfill the PU's satisfaction as much as we can while maintaining the demands of the SU's.

The channel selection problem is given below

$$\text{(P1):} \quad max \sum_{j=1}^{K} log \frac{P_{rm}}{F_m(j)} \tag{4.33}$$

$$s.t. \quad \sum_{j=1}^{j=K} I_{i,j} \leq 1, i \in \{1, 2,...., N\}$$

$$T_{OFF}^{j} \; P_{OFF}^{j} \; (1 - F_f(j)) \geq T_r$$

$$I_{i,j} = \{0, 1\}.$$

The above channel selection problem can be solved using convex bipartite matching problem.

- Non-Linear Bipartite Matching

For changing the channel selection problem into convex bipartite matching approach, bipartite graph is being formulated. There are K channels and N SU's and n=NK.

Figure below shows the bipartite graph E_{nxn} that was made with vertex A ⊎ B.

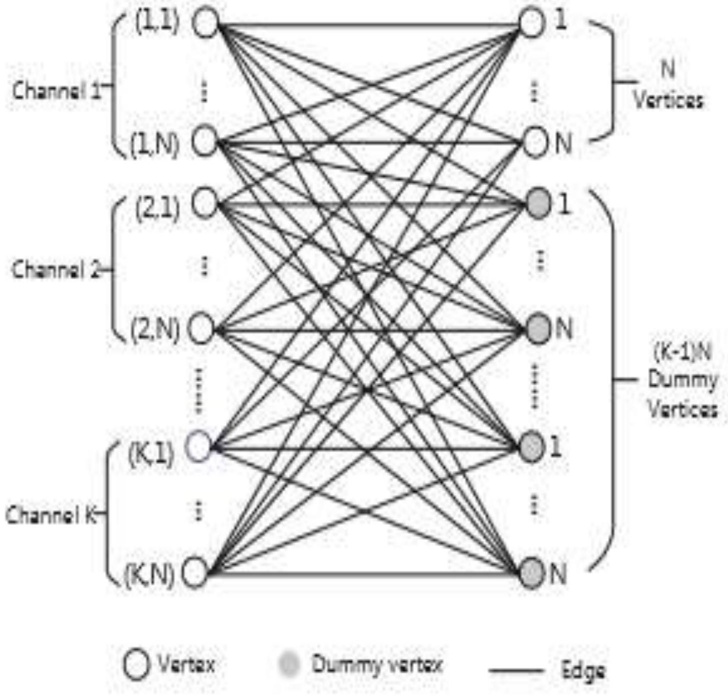

Figure 4.2: The complete bipartite graph

The K weight vectors $w^1, w^2, \dots, w^K$ on the edges of E_{nxn} are defined as

$$w^j(a, b) = \begin{Bmatrix} log \frac{1}{1-p_d(i,j)} & , if\ a = \{j, i\}\ and\ b = i \\ 0 & otherwise \end{Bmatrix} \tag{4.34}$$

The vectors w^j is given as:

$$\begin{pmatrix} 0 & \cdots & \cdots & \cdots \\ \vdots & \ddots & \ddots & \vdots \\ \log \frac{1}{1-p_d(1,j)} & 0 & 0 & \cdots \\ 0 & \log \frac{1}{1-p_d(2,j)} & 0 & \cdots \\ 0 & 0 & \log \frac{1}{1-p_d(3,j)} & \cdots \\ \vdots & \ddots & \ddots & \cdots \end{pmatrix}$$

Using the constructed bipartite matching graph the channel selection problem is transformed into another problem given below.

(P2): $max \sum_{j=1}^{j=K} w^j \boldsymbol{x}$ (4.35)

$s.t. \sum_{i=1}^{n} x_{i,j} = 1 , \sum_{j=1}^{n} x_{i,j} = 1$

` $T_{OFF}^{j} \; P_{OFF}^{j} \; (1 - F_f(j)) \geq T_r$

$x_{i,j} = \{0, 1\}.$

- Channel Selection Algorithm

To solve the above problem a technique is invented to select the channel efficiently based on convex bipartite matching. The central approach is to explore the least grid which contains vertex, order the grid points, obtain the fiber vertex and afterwards see whether the obtained fiber fulfills the conditions of the permutation matrix.

Table 4.3 below gives the channel selection algorithm.

1.Solve the following two linear programs to find b_j and d_j for $j=1,2,..,K$ $b_j := \min\{w^j x : \sum_i x_{i,j} = \sum_j x_{i,j} = 1, x \geq 0\}$ $d_j := \max\{w^j x : \sum_i x_{i,j} = \sum_j x_{i,j} = 1, x \geq 0\}$ Then we define a grid G := $\{y \in \mathbb{Z}^K : b_j \leq y_j \leq d_j , j = 1,2, \ldots K\}$ where y:=$\{y_{1,} y_2, \ldots , y_K\}$
2. Calculate the values of f for all the possible y.Arrange all the possible y in a nonincreasing order according to the values of f,i.e. $y^1, y^2, \ldots, y^{\lvert G \rvert}$ where $f(y^1) \geq f(y^2) \geq \cdots \geq f(y^{\lvert G \rvert})$
3.Check the fibers of each y^i in order to find the first y^k such that vertex **x** of fiber $\Pi^n \cap \boldsymbol{w}^{-1}(y^k)$ is a permutation matrix and satisfies $T_{OFF}^{j} \; P_{OFF}^{j} \Pi_{i=1}^{N} w_t^{j,i} . \boldsymbol{x} \geq T_r$,where $w_t^{j,i}$ is given by

$w_t^{j,i}(a,b) = \begin{cases} 1 - p_f(i,j) & \text{if } a = \{j,i\} \text{ and } b = i \\ 1 & \text{if } a = \{j,i\} \text{ and } b = k \neq i \\ 0 & \text{otherwise} \end{cases}$	
4. Return the perfect matching corresponding to the permutation matrix **x** as the optimal channel selection.	

Table 4.3: Channel Selection Algorithm

4.3.4.2 SU's interest perspective

When SU's interest are concerned Logic-AND is implemented. Goal is to increase the time of all the channels during which they are idle while protecting the PU's.First of all formulation of channel selection problem is done and then it is solved using cross-entropy (CE) method.

- Problem Formulation :

  If channel j is actually free but it is detected to be in OFF state then the SU's have on average T_{OFF}^{j} to access. Basically the objective is to increase the total average time as much as possible. It is formulated below.

(P3): $$max \sum_{j=1}^{K} T_{OFF}^{j} \; P_{OFF}^{j} \; (1 - \; F_f(j)) \quad (4.36)$$

$$s.t. \quad \sum_{j=1}^{j=K} I_{i,j} \leq 1, i \; \in \{1, 2, ..., N\}$$

$$(1 - F_d(j)) \, P_{ON}^{j} \leq P_i$$

$$I_{i,j} = \{0, 1\}.$$

Since the solution of exterior point allows the variables to disobey the inequality restriction during the iterations so this method is sued to remove the constraint $(1 - F_d(j)) \, P_{ON}^{j} \leq P_i$.The problem P3 can be changed into another format shown below.

$$max \sum_{j=1}^{j=K} [T_{OFF}^{j}\ P_{OFF}^{j}\ (1 - \ F_f(j)) - A(F_d(j)U_o\ (1 - F_d(j))\ P_{ON}^{j}] \quad (4.37)$$

$$s.t. \quad \sum_{j=1}^{j=K} I_{i,j} \leq 1, i\ \in \{1, 2,...., N\}$$

$$I_{i,j}\ =\ \{0, 1\}.$$

Where U_o is a linear penalty factor, A $(F_d(j)U_o$ is the indicator function. This indicator function is 1 if (1 - $F_d(j)$) $P_{ON}^{j} \leq P_i$ else its 0.

The above issue is a non-convex integer programing problem which is not solvable using convex bipartite matching problem so C-E method will be used to obtain an efficient solution.

- Cross-Entropy Based Approach :

  This method is used in complex stochastic networks to calculate the probabilities of rare events. In C-E method the problem is transformed from deterministic optimization problem to stochastic optimization problem. The main idea behind this technique is to define an associated stochastic problem (ASP) for the original optimization problem. Then afterwards solve the transformed problem using some adaptive technique. Some random solutions are generated sequentially which converge to an optimal or sub-optimal one.
- C-E Algorithm :

  Central concept behind this scheme is to produce some random data samples using some stochastic policy. The stochastic policy is being updated depending on the result of the sample so that some improved sample can be produced when next iteration is performed. This algorithm consists of five main steps described in the table below.

The strategy space S for the SU's is given as

$$S := \{ch_1, ch_2, ..., ch_K\}$$

From the strategy space a single medium for transfer of data will be selected by each SU. The probability vector related with the strategy space is given can be derived using C-E algorithm.

4.3.5 Spectrum Sharing in Multi-Channel CRNS

After SS the process of spectrum sharing is started. The behavior of SU's during spectrum sharing is analyzed using weighted congestion game by formulating a channel access game. An efficient approach for accessing the channel is also invented for the SU's so that Nash equilibrium can be achieved during spectrum sharing.

4.3.5.1 Congestion Game

When same resources are being shared by various users then that scenario can be visualized with the help of congestion game. In congestion game every single player selects its own resources and then tries to maximize its utility. Sharing of every resource is a function which does not increase along with the number of players.

Congestion game is defined by the tuple

$$\{N, R, (\sum i)_{i \in N}, (U_j^r)_{j \in R}\}$$

Where $N= \{1, 2,..., N\}$ represents the players set, $R= \{1,2, ...,R\}$ represents the set of resources, $\sum i$ denotes the strategy space of player *i* and U_j^r is the payoff associated with resource $j. U_j^r$ has decreasing nature because of congestion or competition between players.e.g. U_j^r=1/n_j, where n_j is the total quantity of members choosing resource *i*. The strategy profile of the game is expressed as $S= (s_1, s_2, \ldots\ldots, s_N)$ where $s_i \in \sum i_{i \in R}$ and s_i is actually the strategy of player *i*. The congestion vector is denoted by $n = (n_1, n_2, \ldots\ldots, n_R)$, total amount of players sharing resource *j* is represented by n_j .The utility of player *i* is given as below

$$U_i = \sum_{j \in s_i} U_j^r \, (n_j(S)) \tag{4.40}$$

Congestion game has a more general version which is known as the weighted congestion game. Each member is given a specific weight in weighted congestion game. The weight vector of the players is represented by $w= (w_1, w_2, \ldots\ldots, w_N)$ where w_i is the weight of player *i*. In this game the payoff associated with the resource *j* is a function of the total weights of player sharing resource *I* but this is not the case in standard congestion game.

4.3.5.2 Channel Access Game

Weighted congestion game is used to model the channel access behavior of SU's.In this approach the SU's which have good channel conditions are appointed with more weights. The channel access game Γ is defined by

$$\{N, K, (w_i)_{i\in N}, (\sum i)_{i\in N}, (U_j^i)_{i\in N, j\in K})\}$$

where *N={1,2,...,N}* represents the set of SU's, *K={1,2,...,K}* which represents the set of channels, weight associated with the SU_i is represented by w_i,$\sum i$ denotes the strategy space of SU_i and the utility function of SU_i for selecting channel j is U_j^i .

U_j^i is a decreasing function of the sum of weights of SU's choosing the same channel. Each secondary user decides which channel to access and tries to maximize its utility. The utility function of SU_i is given by

$$U_j^i = \frac{w_i \Psi_j}{\sum j \in s_i w_i} = w_i \zeta_j(W_j) \tag{4.41}$$

Where Ψ_j is the average sojourn time of state OFF of channel j is, W_j is the total weights of SU's adopting channel j and the payoff function of resource j is $\zeta_j(W_j) = \frac{w_i \Psi_j}{\sum j \in s_i w_i}$.This payoff function leans on the total weights of the channel j.So access time that SU_i can obtain is represented by U_j^i.When w_i=1 for all SU's then this game becomes a standard congestion game. In standard congestion game all SU's are treated equally so that they can share the resources and choose the channel according to their personal requirement. The level of fairness achieved is much higher in this type of congestion game. When the available channels are being shared throughout of the secondary network needs to be considered. The users with good channel conditions are being favored by assigning them more weights so that they have higher priority in the process of resource sharing. The average time for transmission will be longer for the users which have higher weights results in an increase in the utility of the secondary network. The channel is compared with a predefined threshold and considered to be in best or worse state. The SU's with good channel conditions are assigned weight $w^{'}$ and the one with bad conditions are assigned weight w ($w^{'} > w$).In this game single channel is being used by each secondary user to access. Nash equilibrium is the solution of this game. If each SU has selected a strategy and utility cannot be increased by varying the strategy whereas the strategies of others is not varied then a NE is constituted by the existing set of strategies.

A channel access approach is being explored to access the channel efficiently. The main concept behind this algorithm is that all SUs wants to improve their individual utility and afterwards in the end the overall utility is optimized.

Chapter 5

Overlapping Coalitional Game for Cooperative Spectrum Sensing and Access in CRN

5.1 Introduction

In developing SS and spectrum access strategies in CRNs Coalitional game theory has been used widely. Most of the previous works have formulated a non-overlapping coalitional structure where a SU has the permission to associate with only one coalition and use that group for spectrum sensing. Because of this limitation the cooperation among SUs and system utility is greatly affected. Due to this limitation overlapping coalitional game theory is considered. In overlapping coalitional structure SUs can join multiple coalitions. In this game SUs can sense multiple channels resulting in an increase of channel access probability.

We have analyzed a joint CSS and access strategy in CRNs which is based on traffic demand. A coalitional game theory is implemented to develop some cooperation among SUs.Whenever a SU decides to form a coalition it takes care of the expected throughput and energy efficiency.

In overlapping coalitional strategy during a sensing period SU can detect various mediums and can accompany many coalitions in order to upgrade its payoff. If a SU has less traffic demand then it can choose to go in quit sensing mode without joining any coalition.

5.2 System Model

A CRN comprises of M PUs, N SUs and a base station for these SUs is considered. All primary users use a licensed channel to transmit data. The number of licensed channels are M.

Let

M = Set of PUs where M= {1,...., M}

N = Set of SUs where N= {1,...., N}

The working of CRNs is done is a way where time is divided in parts and the time of each slot is T.If a SU has decided to perform cooperative spectrum sensing and access then sensing will be performed first and after that channel will be accessed. The sensing period is denoted by τ.There are multiple energy detectors for a single SU to sense multiple channels. We have assumed that for every channel a detector is available. There are multiple groups and each group has all the SU's which sense the same channel. Whenever a channel is identified as free the BS allocates that channel to a group member. To stop collisions among SUs a free channel can only be used by one SU at a certain instant.The amount of data to be transmitted is different for every SU and SU which chooses to participate in cooperative sensing can only get channel access. Traffic demand and channel capacity are two key parameters used by SUs to decide about participation in cooperative sensing.

The detection probability of SU $i \in N$ after sensing channel $j \in M$ is written as

$$p_{d,i,j}(\varepsilon, \gamma_{i,j}) = \text{Q}\left(\left(\frac{\delta}{\sigma_n^2} - \Upsilon_{i,j} - 1\right)\sqrt{\frac{N_S}{2\Upsilon_{i,j}+1}}\right) \quad (5.1)$$

Where Q (.) is the tail probability for the standard normal distribution. ε is the detection threshold. σ_n^2 denotes noise power, $\Upsilon_{i,j}$ is the received SNR at SU i when it senses channel j and N_s is the quantity of sensing specimens during the duration of sensing in a time slot.

The false alarm expectation of SU *i* at channel *j* is expressed below

$$P_{f,i,j}\left(P_{d,i,j}, \Upsilon_{i,j}\right) = Q\left(\sqrt{2\Upsilon_{i,j} + 1}\, Q^{-1}(P_{d,i,j}) + \sqrt{N_s \Upsilon_{i,j}}\right) \quad (5.2)$$

The transmit power of SU *i* when it performs transmission on channel *j* is given by $W_{t,i,j}$.The rate of transmission of SU *i* over channel *j* is given by

$$R_{i,j} = B_j \log_2\left(1 + |g_i|^2 \frac{W_{t,i,j}}{\sigma_n^2}\right) \quad (5.3)$$

where B_j represents the bandwidth of channel j and g_i represents the channel gain of transmission link of SU i.

The throughput that SU i can achieve in the time slot is

$$U_{i,j} = \frac{R_{i,j} t_{i,j}}{T} \tag{5.4}$$

Multiple channels can be sensed by SU during the interval of sensing. We represent the set of channels that SU i chooses to sense as A_i.The expected throughput that SU i can obtain is represented by the following function of channel set A_i.

$$U_i(\, A_i) = \sum_{k \subseteq A_i} ((\, \prod_{j \in k} P^E_{i,j} \prod_{j \in A_{i \setminus k}} (1 - P^E_{i,j}) \text{ x} \frac{P^U_{i,argmax\ j \in k\{U_i,j\}}}{P^E_{i,argmax\ j \in k\{U_i,j\}}} \max\{U_i, j\} \tag{5.5}$$

The expected throughput of SU i rises with the size of A_i .This happens because when SU chooses more channels to sense it has more chances of accessing the channel.

In case of energy-constrained SU it should control the energy spent on sensing so the energy could be saved for sending data. Thus the expected power consumption of SU i as a function of the set of channel A_i which it chooses to sense is given by

$$E_i(\, A_i) = \frac{1}{T} (\sum_{k \subseteq A_i} ((\prod_{j \in k} P^E_{i,j} \prod_{j \in A_{i \setminus k}} (1 - P^E_{i,j})) \text{ x } E^t_{i,argmax_{j \in k}\{U_{i,j}\}}) + \sum_{j \subseteq A_i} E^S_{i,j}) \tag{5.6}$$

In order to maintain a balance between throughput and power consumption energy efficiency has been used as a key factor. This factor decides about the decision of SU it makes about cooperation. Expected energy efficiency of SU i is expressed as

$$n_i(A_i) = \frac{U_i(A_i)}{E_i(A_i)} \tag{5.7}$$

The main aim of SU is to make sure that its utility is maximum considering the constraint on energy efficiency. This means that in a certain time period SU should transfer as much data as possible but the energy efficiency should be kept above a predefined threshold. In some case when SU has very less data to transmit it can should not to perform sensing and join quit sensing mode in order to save energy for data transmission in future.

5.3 Overlapping Coalitional Game For Cooperation Strategy

5.3.1 Non-Transferable Utility Overlapping Coalitional Game Formation

In CSS and access approach different channels are being used by the SU to maximize their throughput while keeping in mind the limitation of energy efficiency. All the SUs which choose to participate in spectrum sensing form a coalition to improve the sensing performance. In this way each channel in set M has a coalitional game. Whereas SUs in set N can choose multiple channels and associate with many coalitions at same instant.Payoff of SU depends on its traffic demand and its utility cannot be transferred to other SUs that's why it's known as an NTU game.

An NTU overlapping coalitional game is defined by *G* where

$$G = (N, v) \tag{5.8}$$

Where *N* refers to the players of the game or SUs and *v* being the value function.

An overlapping coalitional structure Π over a set of players N is given as

$$\Pi = \{S_1, \dots \dots, S_K\} \tag{5.9}$$

K=Number of coalitions

There may be few SUs which have low traffic demand as a result they decide not to perform sensing and go in quit sensing mode. The set of Su that go in quite sensing mode are represented by S_{M+1}.

There may be greater than single channel for a SU in a given time duration but it can only send data over one channel only. Due to this we cannot calculate the total payoff of a SU by adding off its payoff from all groups that it is associated with. The total payoff of SU I is expressed as

$$p_i(\Pi) = \begin{cases} U_i\,(A_i) & if\; n_i(A_i) \geq n_{min} \\ -\infty & \text{otherwise} \end{cases} \tag{5.10}$$

This definition of payoff proves that expected energy efficiency of the SU will not be lower than the threshold during the process of coalition formation. The payoff of all the SUs which are in set S_{M+1} is zero.

In some cases the SU may become selfish and tries to maximize its own payoff without considering any benefits of other SUs.As a result the SU with low traffic demand may occupy the channel and the one with high traffic demand remain deprived of the channel. This will result in low utilization of the channel. We have considered a preference order where we consider both the social welfare as well as the individual payoff at a single moment. Social welfare of a coalition structure Π is defined as

$$u\,(\Pi) = \sum_{i \in N} p_i(\Pi) \tag{5.11}$$

The social welfare u (Π) is the addition of the payoff of each member. A coalition structure is preferred by a SU over another if and only if the total outcome of the coalition group and the individual performance of SU are both greater than the other coalition.

5.3.2 Coalition Formation Algorithms

When coalition formation is going on the SU makes its own decision about joining or leaving a certain group according to the preference orders defined. There are basically three rules on which movement of a SU depends from one coalition to another. The three rules are defined as

1. Join Rule
2. Quit Rule
3. Switch Rule

In join rule SU will join a certain coalition if its own outcome and the value of group is improved by his move. This rule takes both social welfare and individual payoff into consideration. In quit rule SU disconnects with one of its available coalition. This happens in two cases if there are plenty of SUs in a certain group to sense a particular channel so there are less chances of a SU to get access of that channel or if the SU has very few information bits to transfer so it will leave that coalition in order to give a negative payoff. During switch rule SU *i* moves from one of the present group to another new group if that group is given preference over the present one.

- **OCF Algorithm**

In order to construct a stable coalition structure an OCF algorithm has been proposed. This algorithm is executed by each SU $i \in N$ since it's a distributed algorithm. Complete OCF algorithm is given below.

Initialization: S_{M+1} **:=**N ; $S_J \coloneqq \phi$ for $j \in M$; Π:={ $S_1, \dots., S_{M+1}$};Π_l:=Π For each SU $\in N$.
SU *i* executes *i*.broadcast (i, D_i).
SU *i* executes *i*.receive (l, D_l) for each SU $l \in N\{i\}$
Repeat
SU *i* randomly selects $k \in A_i \cup \{M+1\}$ and $j \in M \setminus A_i$
$\Pi_{Quit} \coloneqq \{\Pi \setminus S_k\} \cup \{S_k \setminus \{i\}\}$
SU i calculates $u(\Pi_{Quit})$ and $p_i(\Pi_{Quit})$
$\Pi_{join} \coloneqq \{\Pi \setminus S_j\} \cup \{S_j \cup \{i\}\}$.
SU i calculates $u(\Pi_{join})$ and $p_i(\Pi_{join})$
$\Pi_{Switch} \coloneqq \{\Pi \setminus \{S_j, S_k\}\} \cup \{S_j \cup \{i\}\} \cup \{S_k \setminus \{i\}\}\}$
SU i calculates u (Π_{Switch}) and $p_i(\Pi_{Switch})$
if $\Pi_{Quit} \succ_i \Pi$ **then**
$\Pi_i \coloneqq \Pi_{Quit}$; u (Π_i) := u (Π_{Quit})
else if $\Pi_{join} \succ_i \Pi$ **then**
$\Pi_i \coloneqq \Pi_{join}$; u (Π_i) := u (Π_{join})
else if $\Pi_{Switch} \succ_i \Pi$ **then**
$\Pi_i \coloneqq \Pi_{Switch}$; u (Π_i) := u (Π_{Switch})
end if
SU *i* executes *i*.broadcast $(i, \Pi_i, u\ (\Pi_i)\ )$.
SU *i* executes *i*.receive $(l, \Pi_l, u\ (\Pi_i))$ for each SU $l \in N\{i\}$
$T_{info} := \{\Pi_1, \dots..\Pi_N\}$.

22:	Π:=$argmax_{\Pi_l \in T_{info}} \{u\ (\Pi_l)\ \}$
23:	**Until** ∀ $i \in N, \forall\ k \in A_i \cup \{M+1\}$ and $j \in M \backslash A_i$,$\Pi_{Quit} \forall_i$ Π
24:	SU *i* executes *i*.sense(Π)
25:	**If** SU *i* is appointed channel *j* then
26:	SU *i* calculates $W_{t,i,j}^{opt}$ and sends data with power $W_{t,i,j}^{opt}$
27:	**end if**

Table 5.1: The Overlapping Coalition Formation (OCF) algorithm in CRN for SU $\boldsymbol{i} \in \boldsymbol{N}$

After a limited number of tries the overlapping coalition structure converges to a stable structure. If we have M channels and N players and both M and N are finite then the amount of overlapping structures is 2^{MN}.In OCF algorithm in table 5.1 during the process of coalition formation SU tries to improve its own utility while improving the value of the coalition structure. After each repetition the moves made by SU lead to a new coalition structure Π.In this way a larger payoff is obtained every time the coalition structure changes. This algorithm is adaptive to the changes in cognitive radio networks. It can change its cooperation strategy according to the SU can form new coalition structures.

- **Sequential Coalition Formation (SCF)**

Although in our previous OCF algorithm stability can be reached but the number of iterations increases dramatically. In order to reach a stable coalition structure the number of iterations increases exponentially with the amount of SUs.Therefore another algorithm is proposed which is known as SCF.The computational complication of SCF method is less and less information is required to be exchanged among SUs to construct a coalition structure.

In SCF technique the structure of coalition is constructed one by one. In every stage a single SU can update the group. Moves are made by each player gradually using the rule of order *h*.If a player has tied with a certain coalition it has to stay in that group.

Traffic demands of SUs are used to determine the rule of order h.The SU which has the most traffic is the first one to join a coalition as it is given preference.

Table 5.2 shows the SCF algorithm. In this algorithm the decision of SU about coalition formation is distributed. The behaviors of SU are controlled by a central coordinator. The traffic demands of each SU are conveyed to the central coordinator.

for every $i \in N$ **do**
SU *i* performs *i*.broadcast (i, D_i).
end for
$D := (D_1, D_2, \ldots\ldots, D_N)$
Coordinator calculates $p := H(D)$ and sends *p* to all SUs.
for *i*=1 to N **do**
if *i*=1 **then**
SU $p(i)$ initializes $S_{M+1} := N$; $S_J := \phi$,$\forall_J \in M$ and $\Pi := \{S_1, S_2, \ldots\ldots S_{M+1}\}$
Else
SU *i* executes *i*.receive $(p(i\text{-}1), \Pi)$
end if
for each $j \in M$ **do**
$\Pi_{join} \coloneqq \{\Pi \backslash S_j\} \cup \{S_j \cup \{p(i)\}\}$.
SU p(i) calculates $u(\Pi_{join})$ and $p_{p(i)}(\Pi_{join})$
SU $p(i)$ randomly selects $k \in A_{p(i)} \cup \{M+1\}$
$\Pi_{Switch} \coloneqq \{\Pi \backslash \{S_j, S_k\}\} \cup \{S_j \cup \{p(i)\}\} \cup \{S_k \backslash \{p(i)\}\}$
SU p(i) calculates $u(\Pi_{Switch})$ and $p_{p(i)}(\Pi_{Switch})$
if $\Pi_{Join} \succ_{p(i)} \Pi$ **then**
$\Pi \coloneqq \Pi_{Join}$

else if $\Pi_{Switch} \succ_{p(i)} \Pi$ **then**
$\Pi := \Pi_{Switch}$
end if
end for
if $i=N$ **then**
SU *p(i)* executes *p(i)*.broadcast (*p(i)*,Π)
Else
SU *p(i)* executes *p(i)*.send (*p(i)*,*p(i+1)*,Π)
end if
end for
for each $i \in N \setminus \{p(N)\}$ **do**
SU *i* executes *i*.receive (*p(N)*,Π)
end for
for each $i \in N$ **do**
SU *i* executes *i*.sense (Π)
if SU *i* is appointed channel *j* **then**
SU *i* calculates $W_{t,i,j}^{opt}$ and transmit data with power $W_{t,i,j}^{opt}$.
end if
end for

Table 5.2: The Sequential Coalition Formation (SCF) algorithm in CRN

The SCF scheme does not provide guarantee about the stability of the coalition formation but its results area as good as that of OCF approach in terms of the throughput obtained. The SCF method has less computational complexity as compared to the OCF algorithm.SU in SCF Algorithm makes only one move on each channel to obtain the coalition structure and it only requires MN number of iterations during this algorithm whereas the number of coalition formation structure in OCF algorithm are much more than this. Besides this less information exchange is requires in SCF algorithm as compared to OCF algorithm where the SU is supposed to share the updated coalition structure information with each other after every iteration. Due to this the OCF algorithm consumes more energy than SCF.

5.4 Adaptive Transmission Power Control

When a SU has been assigned a channel adaptive transmission power control scheme has been adopted. This scheme achieves the optimal transmission power for a SU which minimizes the energy consumed in transmission and maximizes the throughput achieved.

The throughput $R_{i,j}$ that a SU can achieve over a channel depends upon the transmission power $W_{t,i,j}$ and the number of information bits D_i in the buffer. If the amount of data in the buffer is not large and it can be sent easily in a given duration with low data rate then increasing its transmission power will consume more energy since throughput of SU cannot increase further. So SU should change its power of transmission adaptively to balance the transfer data rate and consumption of energy. To find the optimal transmission power of a SU two steps need to be adopted which are

1. Determine the set of transmission powers that will cause the SU to achieve maximum throughput.

2. From these set of powers determine the value that will minimize the energy consumption for the SU.

Let's assume SU *i* has been assigned $j \in M$ for data transmission. The throughout maximization problem can be considered as follows:

$$maximize_{W_{t,i,j}} \; U_{i,j} W_{t,i,j} \tag{5.12}$$

$$\text{Subject to } W_{t,i}^{min} \leq W_{t,i,j} \leq W_{t,i}^{max}$$

The main function is expressed as

$$U_{i,j}W_{t,i,j} = \begin{cases} \frac{B_j \log_2\left(1+|g_i|^2\frac{W_{t,i,j}}{\sigma_n^2}\right)(T-\tau)}{T} & if\ W_{t,i,j} \leq W_{t,i,j}^h \\ \frac{D_i}{T} & otherwise \end{cases} \quad (5.13)$$

where $W_{t,i,j}^h > 0$ is a threshold of transmission power that satisfies

$$B_j \log_2\left(1 + |g_i|^2 \frac{W_{t,i,j}}{\sigma_n^2}\right)(T-\tau)=D_i \quad (5.14)$$

A SU can set its transmission power to be equal to any value or it can choose any of the value between an interval to maximize the throughput. In order to save the energy spent on data transmission and maximize the throughput an minimized optimization problem is considered which maximized the throughput.

The optimization problem is given as

$$minimize_{W_{t,i,j}}\ E_{i,j}^t(W_{t,i,j}) \quad (5.15)$$

$$\text{Subject to } U_{i,j}(W_{t,i,j}) \geq U_{i,j}^{max}$$

$U_{i,j}^{max}$ is the maximum value of $U_{i,j}(W_{t,i,j})$.

Chapter 6

Proposed Algorithm

6.1 Introduction

Spectrum sensing plays a vital role as it identifies the spectrum holes from which available channels for SUs communication can be separated. Performance of spectrum sensing depends on various factors like shadowing, multipath fading and receiver uncertainty. To cater these problems, Cooperative spectrum sensing is an emerging solution where different SU collaborate with each other to enhance sensing results.

Currently most of the research techniques mainly focus on fully cooperative environment. Fully cooperative means all SUs participate in joint activity to sense surrounding areas to identify PU presence or absence and share their results with fusion center. Fusion center concludes final decision based on received data. Fully cooperative spectrum sensing is not always essential and useful. Because as number of SUs increase it decreases the transmission time of SUs. To tackle this tradeoff, we have introduced partial spectrum sensing approach in our proposed algorithm.

In partial spectrum sensing (PSS) approach, SUs first has to select among option of taking part in sensing or staying without it.If SU decided to sense channel it is called Participator (P) and if SU decided not to sense channel it is termed as Free Rider (F). Another approach introduced in our proposed algorithm is the use of utility history to decide whether SU is suitable to become Participator (P) or Free Rider (F). PSS approach solves the question that which action of SU is more suitable to maximize the energy efficiency.

Uncertainty Based Coalition Formation (UCF) is another technique introduced in our proposed algorithm. UCF aids each Participator (P) to make decision about which channel to sense. UCF is dependent on measure of uncertainty of channel. As channel uncertainty gives more accurate measure of channel status. In this algorithm main goal is to reduce uncertainty difference for each channel when Participator (P) decides which channel to sense.

Another main approach is to reduced iterations and coalition convergence time. Unlike SCF it does not require calculations for utility and energy efficiency equations for each step. In our proposed algorithm we first check SU to be Participator (P) or Free Rider (F) based on utility history so it has self-learning capability which improves results with the passage of time, afterwards using UCF algorithm we can select efficient channel by reducing uncertainty up to maximum and then calculate throughput.

6.2 System Model

We consider a 100x100KM square region covered by M primary channels M={1,2,..,M} and secondary users N={1,2,…,N}. Primary users are licensed users which have specific spectrum band to communicate and SU's are unlicensed users which sneak on primary user to evaluate whether primary user is busy or idle using spectrum sensing. When PU is idle and channel is free, SU communicates.

We assume that system is divided into portions of time. At every slot of time PUs are synchronously sensed. Our algorithm helps SUs make an opinion about taking part in SS or quitting it based on their utility history. Then based on channel uncertainty reduction we divide SU into C coalitions. Each coalition checking one channel. The final transmission approval of SU is decided by coalition head depending on majority rule and broadcasted within a coalition. Another assumption is that in our system the user can be selfish but not malicious. It means SU can be selfish to save their own energy by not participating in CSS but it will not manipulate the sensing results.

Spectrum sensing problem can be formulated as binary hypothesis

$$x(t) = \begin{cases} n(t) & H_0 \\ hs(t) + n(t) & H_1 \end{cases}$$

Where

$x(t)$ = Signal obtained by SU

$s(t)$ = Signal sent by PU

$n(t)$ = Additive White Gaussian Noise

h = Amplitude gain of channel

H_0 = Hypothesis about absence of PU

H_1 = Hypothesis about presence of PU

There are different techniques to sense the presence or absence of channel like Energy detection, Cyclostationary and Matched filter. We choose Energy detection technique because of its simplicity and low overhead design. In Energy detection technique received signal $x(t)$ is transformed to normalized output Y. Normalized output is than compared to threshold θ, if normalized value is below the threshold θ than PU is absent and if normalized value is above the threshold θ than PU is present.

The accuracy of the spectrum sensing is based on two basic metrics:

1. **Detection Probability:** Probability that PU is reported to be present and PU is indeed using that spectrum.

$$P_{d,i,j} = P\{Y_{i,j} > \theta_j | H_1\}$$

$$= e^{-\frac{\theta_j}{2}} \sum_{n=0}^{m-2} \frac{1}{n!}\left(\frac{\theta_j}{2}\right)^n + \left(\frac{1+\gamma_{i,j}}{\gamma_{i,j}}\right)^{m-1} \times \left[e^{-\frac{\theta_j}{2(1+\gamma_{i,j})}} - e^{-\frac{\theta_j}{2}} \sum_{n=0}^{m-2} \frac{1}{n!}\left(\frac{\theta_j \gamma_{i,j}}{2(1+\gamma_{i,j})}\right)^n\right]$$

And

$$\gamma_{i,j} = \frac{P_j h_{j,i}}{\sigma^2}$$

$$h_{j,i} = \frac{k}{d_{j,i}^{v}}$$

2. **False Alarm Probability:** Probability that PU is reported to be present but PU does not occupy that spectrum.

$$P_{f,i,j} = P\{Y_{i,j} > \theta_j | H_0\} = \frac{\Gamma\left(m, \frac{\theta_j}{2}\right)}{\Gamma\,(m)}$$

We will evaluate the likeliness of detection and probability of incorrect alarm under Rayleigh fading channel. SU i detecting the status of channel j.

Where

$Y_{i,j}$ = Normalized output of SU i sensing the status of PU j

θ_j = Detection threshold for PU j

m = Time Bandwidth product

$\gamma_{i,j}$ = Average signal to noise ratio of received signal from PU to SU

P_j = Transmission power of PU j

σ^2 = Gaussian noise variance

$h_{j,i}$ = Path loss between PU j and SU i

k = path loss constant

v = path loss exponent

$d_{j,i}$ = Distance between PU j and SU i

$\Gamma(.)$ = Gamma function

6.2.1 Partial Spectrum Sensing (PSS)

In Partial Spectrum Sensing (PSS) SU selects to be a Participator (P) or a Free Rider (F) based on their utility history. Unlike in Fully Cooperative Spectrum Sensing all SU participate in spectrum sensing but in PSS SU’s have a choice.SU’s can be selfish to conserve their energy by not participating in SS. In this way to decide which option to opt for SU follows PSS algorithm.

1. Initially all SU's takes part in Spectrum Sensing (SS).If they lie in the range of energy efficiency threshold they will sense the channel and calculate the throughput else quit sensing.
2. At every time interval t, each SU chooses the movement $e \in \{P, F\}$ with probability $p_{n_i}(e,t)$. Then every SU computes its utility $U_{n_i}(e,t)$ for the selection of action e at time slot t.
3. Each SU approximates the average utility for action e within the past T time slots which is denoted by $U_{n_i}(e)$. And also approximates the average utility of mixed actions denoted by U_{n_i}.
4. Probability that SU selects the action $e \in \{P, F\}$ for the next time slot is

$$p_{n_i}\big(e,(t+1)\big) = p_{n_i}(e,t) + \eta_{n_i}[U_{n_i}(e) - U_{n_i}]p_{n_i}(e,t)$$

As the above equation gives the probability of action taken by SU at specific time slot, Growth rate gives us the answer that whether to continue with current strategy or change strategy.

$$p_e = \frac{p(e,t+1) - p(e,t)}{p(e,t)} = \eta[U(e) - U]$$

If rate of growth increases same strategy will be followed, if growth rate decreases SU will change strategy and shift from participator (P) to free rider (R) or vice versa.

6.3 Uncertainty Based Coalition Formation (UCF):

When SU decides to be a participator (P) it joins the coalitions which gives the least channel uncertainty. To derive channel uncertainty, we refer to it as Entropy. Entropy is the measure of uncertainty associated with a random value. It usually refers to the Shannon entropy, which quantifies the expected value of the information in a message, usually in units such as bits.

The equation for Entropy is:

$$H(X) = \sum_{i=1}^{n} p(x_i) \log_b \frac{1}{p(x_i)} = -\sum_{i=1}^{n} p(x_i) \log_b p(x_i)$$

X is a discrete random variable with possible values $x_i, \ldots\ldots, x_n$ and probability mass function is $p(X)$. In our case, random values are the condition of each channel. H_0 denotes the absence of PU in the considered channel. H_1 denotes the presence of PU in the considered channel. So X can be expressed as X^i for channel i. For channel uncertainty prediction we evaluate two probabilities $p_1^i = p(x_1^i = 1|H_1)$ and $p_2^i = p(x_2^i = 0|H_0)$. Hence higher values of these two probabilities gives more accuracy of channel estimation. Entropy equation can be expressed as

$$H(X^i) = \sum_{z=1}^{2} p_z^i \log_b \frac{1}{p_z^i} = -\sum_{i=1}^{n} p_z^i \log_b p_z^i$$

SU's are dispersed into M channels. SU that are participating for cooperative spectrum sensing for channel i form a coalition which is denoted by S_c^i.

Calculate p_1^i:

p_1^i is the detection probability of SU, as there are multiple SU which are sensing the same channel so final decision will be made by majority rule. If more than 50% SU's report that channel is busy then the final decision will conclude about the presence of PU.

$$p_1^i = p(x_1^i = 1|H_1)$$

$$P_r\ (more\ than\ half\ nodes\ in\ S_c^i\ report\ H_1|H_1)$$

$$= \sum_{k=\left\lceil \frac{1+|S_c^i|}{2} \right\rceil}^{|S_c^i|} P_r\ (k\ SUs\ in\ S_c^i\ report\ H_1|H_1)$$

There are k SUs from S_c^i that detect the presence of a PU and report H_1. Those k SUs form S_d^i. $P_r\ (k\ SUs\ in\ S_c^i\ report\ H_1\big|H_1)$ can be expressed as

$$= \sum_{w=1}^{K} \prod_{\substack{\forall a, n_a \in S_{d,w}^k \\ \forall b, n_b \in S_c^i \& n_b \notin S_{d,w}^k}} P_{d,n_a,i}(1 - P_{d,n_b,i})$$

Thus

$p_1^i = p(x_1^i = 1|H_1)$

$$= \sum_{k=\left\lceil\frac{1+|S_c^i|}{2}\right\rceil}^{|S_c^i|} \sum_{w=1}^{K} \left\{ \prod_{\substack{\forall a, n_a \in S_{d,w}^k \\ \forall b, n_b \in S_c^i \& n_b \notin S_{d,w}^k}} P_{d,n_a,i}(1 - P_{d,n_b,i}) \right\}$$

Where $P_{d,n_a,i}$ and $P_{d,n_b,i}$ denote the detection probabilities of coalition members n_a and n_b for channel i.

Calculate p_2^i:

Now we will calculate the probability that channel is idle. Probability of the false alarm rate for channel i denoted by P_F^i.

$p_2^i = p(x_2^i = 0|H_0) = 1 - P_F^i$

$= 1 - P_r\ (more\ than\ half\ nodes\ in\ S_c^i\ raises\ false\ alarm)$

So,

$$P_F^i = \sum_{k=\left\lceil\frac{1+|S_c^i|}{2}\right\rceil}^{|S_c^i|} P_r\ (k\ SUs\ in\ S_c^i\ raises\ false\ alarm)$$

We assume that the local false alarm probabilities computed by the SUs within the coalition for channel i are the same, denoted by $P_{f,i}$. After coalition fusion the false alarm probability for channel i can be expressed as

$$P_F^i = \sum_{k=\left\lceil\frac{1+|S_c^i|}{2}\right\rceil}^{|S_c^i|} (P_{f,i})^k (1 - P_{f,i})^{|S_c^i|-k}$$

So

$p_2^i = p(x_2^i = 0|H_0)$

$$= 1 - P_F^i$$

$$= 1 - \sum_{k=\left\lceil \frac{1+|S_C^i|}{2} \right\rceil}^{|S_C^i|} \left(P_{f,i}\right)^k \left(1 - P_{f,i}\right)^{|S_C^i| - k}$$

As we can calculate $H(X^i)$, which is uncertainty of channel i. Participator (P) will join coalition which will reduce uncertainty up to maximum and is denoted by $H(X^i, n_V)$. Thus the main equation for Uncertainty based Coalition Formation is

1. Calculate uncertainty difference for all channels

$$\Delta H(n_V) = H(X^i) - H(X^i, n_V)$$

2. Select channel which gives maximum uncertainty difference

$$\hat{\imath} = arg \max_{i \epsilon M} (H(X^i) - H(X^i, n_V))$$

As PSS algorithm gives us the SUs which are eligible to be Participator (P).Then UCF gives us the Coalition formation of UCF based on uncertainty. Main key features of this algorithm are its speedy convergence and reduced iterations along with the improved throughput and energy efficiency.

Table 6.1 below highlights the parameters and the values used for our proposed UCF algorithm.

Parameter	**Value**
Quantity of SUs N	10
Amount of PUs (licensed channels) M	6
Path Loss exponent n	2
Bandwidth of channel j B_j	100 KHz
Probability that channel j is being free $P_{I,j}$	[0.5, 1]
Target detection probability $P_{d,i,j}$	0.99
Noise power σ_n^2	0.01 mW
Maximum transmission power of SU i $W_{t,i}^{max}$	150 mW
Minimum transmission power of SU I $W_{t,i}^{min}$	50 mW
Received SNR at each SU during the sensing stage $\gamma_{i,j}$	-15 dB
Sensing power of SU I on channel j $W_{s,i,j}$	50 mW

Slot duration T	100 ms
Sensing duration T	5 ms
Number of sensing samples during the sensing stage N_s	5000
Average number of packets generated by SU during a time slot λ	0.5 packet per time slot
Size of packet	20 kbit
Size of Buffer of each SU	200 kbit
Lower bound of the energy efficiency η_{min}	500 kbit/Joule
Time bandwidth product m	5
Path loss constant κ	1
Energy consumption for spectrum sensing per slot ξ	1
Equivalent revenue per unit energy ω	10
Adjustment step size η	0.06

Table 6.1: Parameters of proposed algorithm

The technique proposed follows several steps to obtain the desired output. The detailed algorithm is described in figure 6.1 below.

1.For each SU do
2.SU i executes i.broadcast(i,D_i)
3. D :=($D_1, D_2, \ldots \ldots . D_N$)
4. Coordinator calculates p: = H (D) and broadcasts p to all SUs.
5.SU p(i) initializes S_{M+1} := N ; Sj = 0, all j ∈ M and
6.Π := {S_1,S_2, …., S_{M+1} }
7.SU i executes i.receive (p(i-1),Π)
8.For each channel j ∈ M
9.Calculate the uncertainty Hz using $\Delta H(n_V) = H(X^i) - H(X^i, n_V)$
10.Selects channel j that brings the largest uncertainty reduction
11.Π p(i) calculates u(Π) and $P_{p(i)}$ (Π)
12.Update Π
13.calculate throughput of coalition

14.if i=N
15.SU p(i) executes p(i).broadcast (p(i), Π)
16.else
17. SU p(i) executes p(i).send (p(i+1), Π)

Figure 6.1: Proposed algorithm in CRN

Chapter 7

Results and Simulations

7.1 Overview

Various algorithms have been implemented to confirm the effectiveness of our suggested technique. Simulations are carried out to check the validity of our channel assignment algorithm. Exhaustive and greedy algorithms are also implemented to see their role on the throughput of the system. The two algorithms are checked implemented for the Logic-OR and Logic-AND approaches. A comparison is also made to analyze which of them is better in terms of the throughput. Simulation has also been performed to see the effect of sensing time on greedy algorithm with both Logic-OR and Logic-AND. A C-E design is suggested to check the performance of secondary network as the quantity of SUs are increased. A comparison of formulated C-E approach is made with the greedy technique to explore which algorithm achieves the better utility. Weighted congestion game and standard congestion game is also implemented to explore the effects of both on the throughput of the SU's.In the end a comparison is made between our proposed approach and random channel selection and simulations are made to highlight the effect on the throughput.

Another traffic demand based algorithm is also proposed to improve the cooperation among SUs.It increases the throughput along with spectrum efficiency when comparison was made with other techniques.

7.2 Simulations

We have considered a 2 km x 2km area where we have 4 primary users occupying 4 channels. A group of secondary users are looking for transmission opportunities which are placed randomly outside the circle of radius 1 km.PU's have a transmission power of 10mw, whereas the noise variance is fixed as -80dB.The channel gain between any PU and SU can be obtained using $h = \frac{k}{d^{\mu}}$, where k=1 and μ=3.5.The probability of false alarm for all SU's is set as 0.1 and P_{rm} = 0.1.We need to round off the components in

w_j to 2 decimal places and then the outcome is multiplied by hundred in order to maintain a good symmetry between accuracy and complexity of channel assignment. Table below highlights the detailed simulation parameters.

Parameters	Value
Number of SU's	[4,5,6,7]
Number of Channels	4
Number of Samples	6000
Transmission power of PU's	10mw
Variance of Noise	-80dB
Path loss exponent μ	3.5
P_{rm}	0.1
p_f	0.1
T_r	[1,2]
T_{ON}	[4,4,5,5]
α	[0.6,0.8,1,1.2]
Simulation times	200

Table 7.1: Parameters for Channel Selection Algorithm

Figure 7.1 below shows the network topology assumed for the simulation.

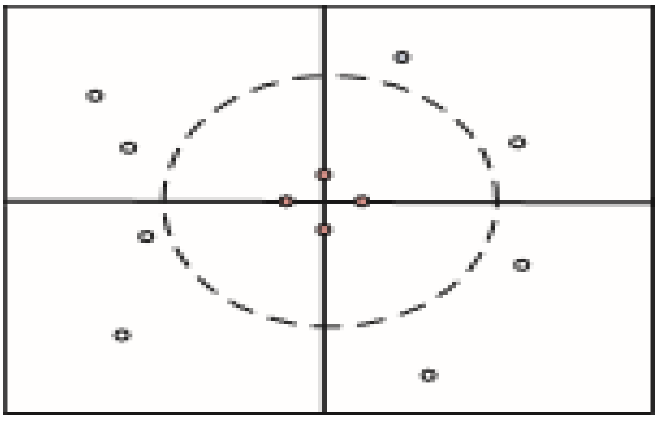

Figure 7.1: The network topology for simulation

The average misdetection probability of PU's along with the count of SU is plotted as shown in figure 7.2 below.

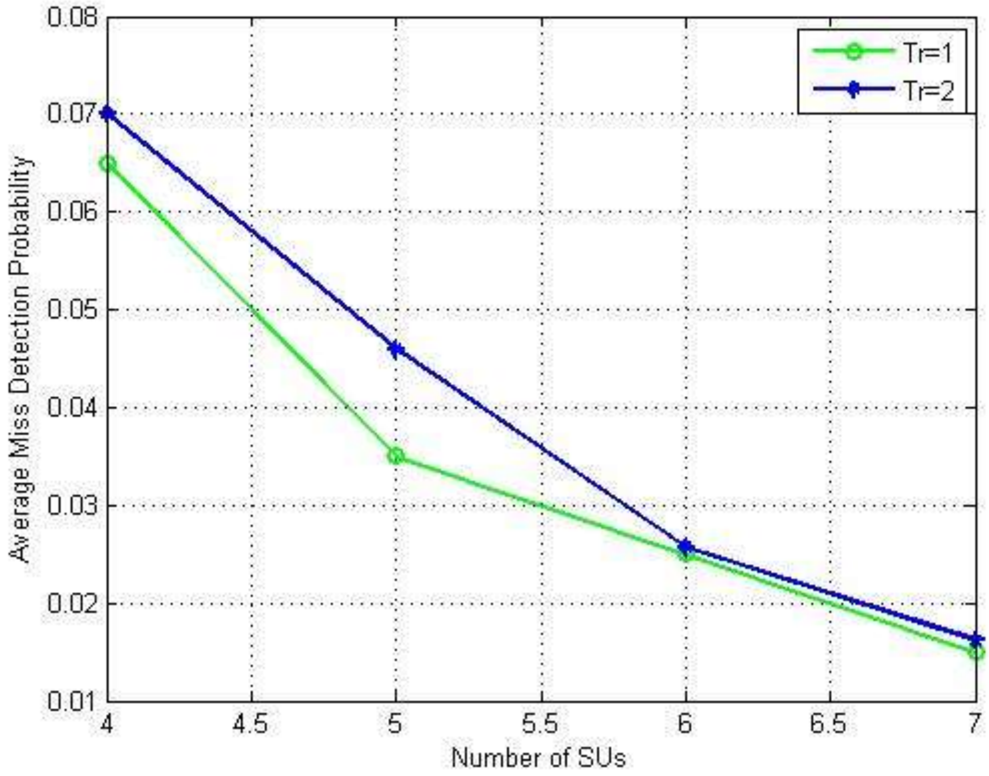

Figure 7.2: Average misdetection probability against the number of SU's

We analyzed from the figure above that average miss detection probability decrease as the number of SU's are increased. This decrease in probability is mainly due to the OR-rule which is used in cooperative spectrum sensing. In OR-rule when all the SU's report about the absence of PU then only PU will be considered to be absent. When the average available time of sensing is reduced then also lower misdetection probability can be obtained whereas when available time increase then miss detection probability increases.

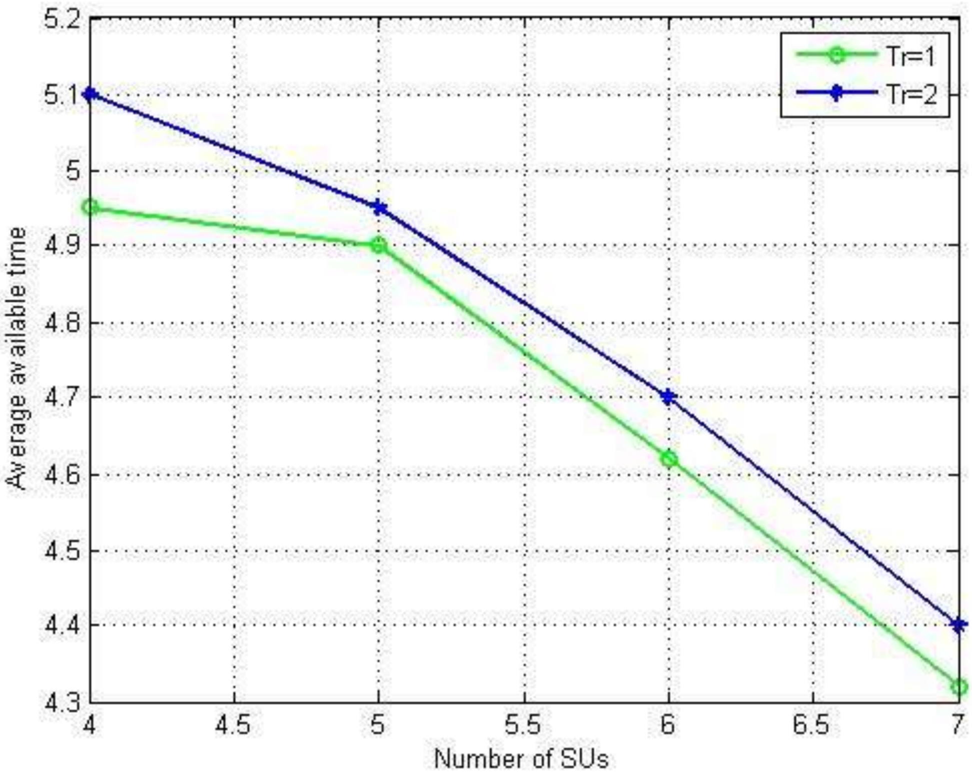

Figure 7.3: Average available time against the quantity of SU's

The graph in above image highlights the average available time of SU's against amount of secondary user's available for sensing. It is analyzed that the time for which channel is present on average drops down as the count of SU's are increasing. This decrease is due to the OR rule used for sensing. The expectation of wrong indication increases since the count of SU's are increasing so due to this the chance to detect the available channels also decreases. If the requirement of available time is more then as a result available time attained by the SU's will be much higher.

After observing the misdetection probability and average available time two optimization algorithms were developed to analyze the optimal SU assignment, the best time for sensing and the optimal sensing thresholds.

Parameters	Value
Narrowband Channels N	5
T	100ms
Sampling frequency	6MHz

σ^2	1
P(H_i^0)	[0.7,0.5,0.8,0.3,0.6]
P_{th}^i	0.9
γ_i	[-20,-19,-18,-17,-16] dB
Number of Simulations	10,000
Ergodic mean	20dB

Table 7.2: Parameters for Exhaustive and Greedy Algorithm

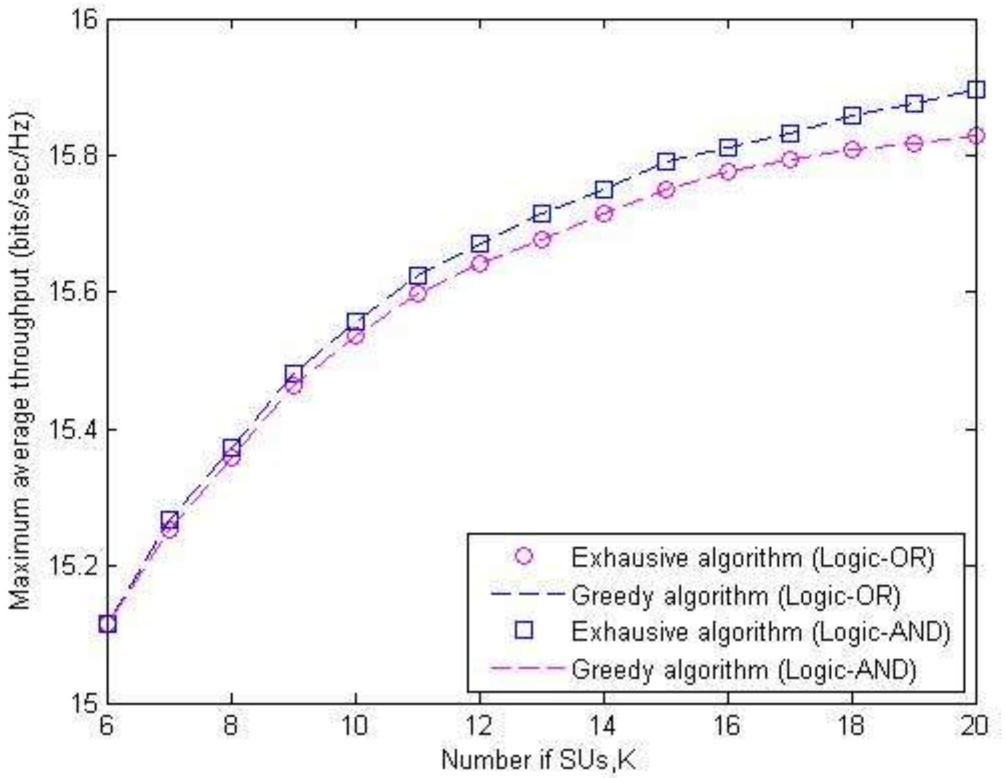

Figure 7.4: Maximum average throughput against the number of SU's

Figure 7.4 above represents the maximum average throughput of the CR network on y-axis with the number of SU's on x-axis under exhaustive approach and greedy technique. It can be observed from the graph that throughput of both greedy and exhaustive algorithms have much similarity with each other. Maximum average throughput increases as the quantity of secondary users are increased. Maximum average throughput under the Logic-AND is a bit higher than Logic-OR rule.

Figure 7.5 below shows the maximum average throughput of the CR networks for different sensing times under Logic-OR rule. Different values of sensing times are used to check the effect on maximum average throughput using Logic-OR. It is observed from the result that the maximum average throughput with optimal sensing time is comparatively greater than with fixed sensing time. Increasing the number of SU's has a very slight effect on the maximum average throughput because it hardly changes with the increase in number of SU's when sensing time leaves the optimal sensing time.

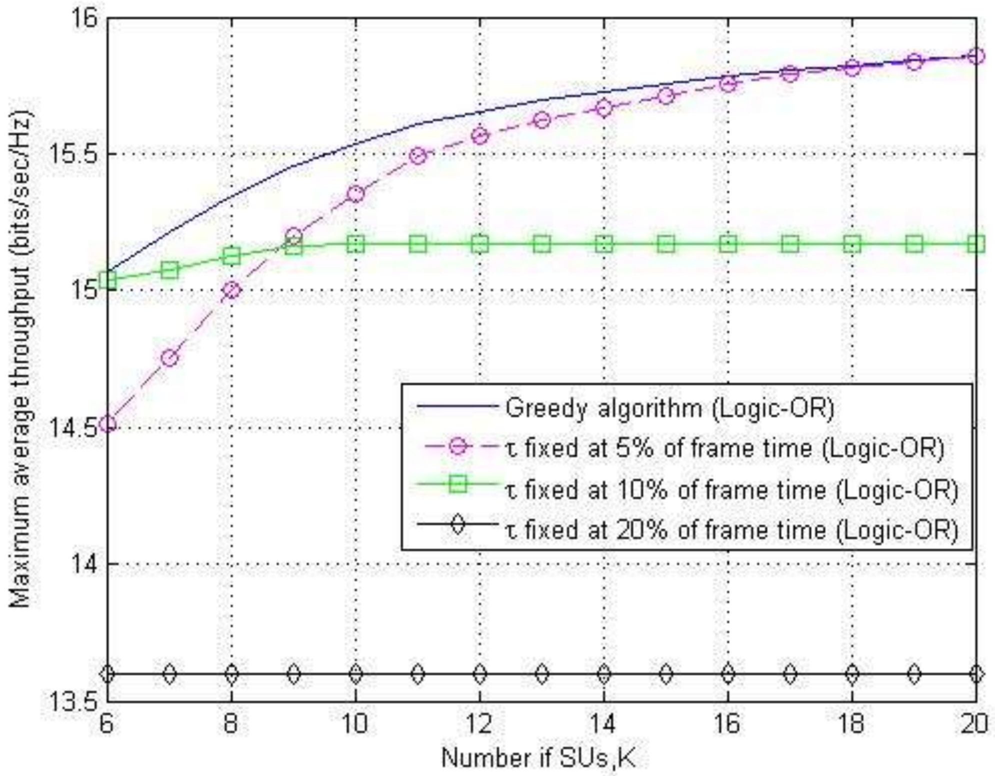

Figure 7.5: Maximum average throughput for various sensing time

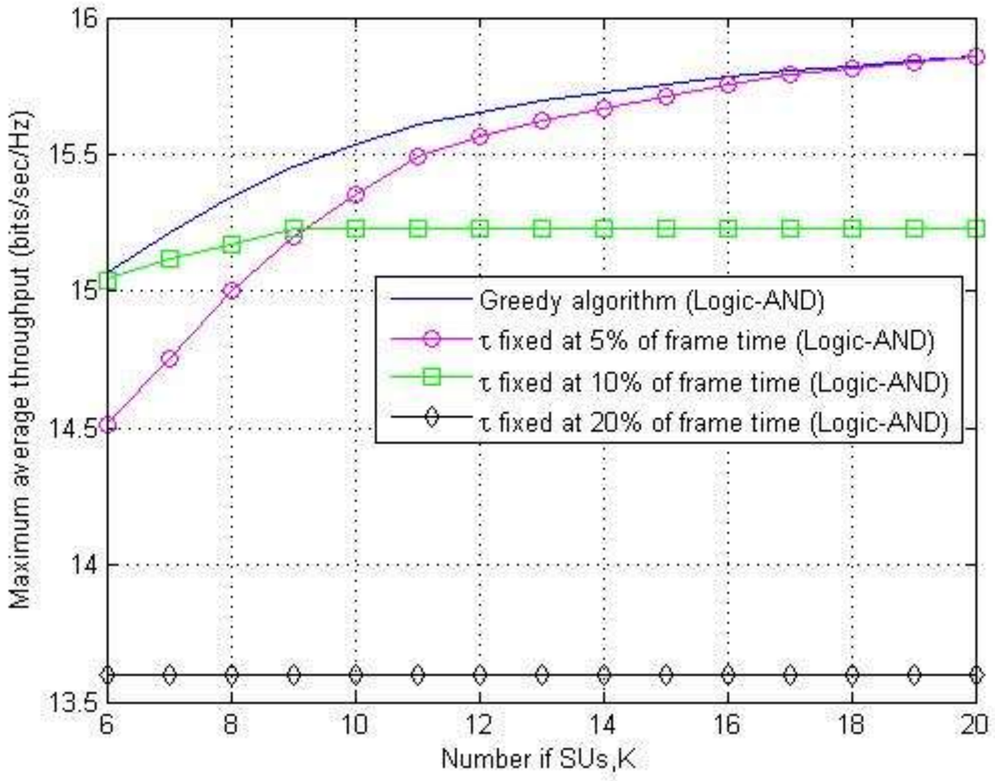

Figure 7.6: Maximum average throughput for various sensing time

Figure 7.6 shows the maximum average throughput of the CR network for distinct sensing time when Logic-AND approach is adopted. Now Logic-AND rule is used to observe the effect on maximum average throughput. It can be seen that the throughput with optimal sensing time is higher in Logic-AND as compared to fixed sensing time.

After this the utility of secondary networks was analyzed along with the count of SU's using various methods. Greedy algorithm was compared with our proposed C-E algorithm and the utility of secondary user's was observed.

Parameters	Value
Number of Channels	4
P	0.2
Z	100

Table 7.3: Parameters for C-E Algorithm

Figure 7.7 highlights the performance of secondary network against the statistics of secondary user's for diverse approaches. A comparison is made between C-E algorithm, Greedy-1 and Greedy-2 method. The difference between greedy-1 and greedy-2 technique is that greedy-1 method has no consideration about channel dynamics and it does not bothers about probability of detection whereas greedy-2 technique keeps a check of all these aspects.

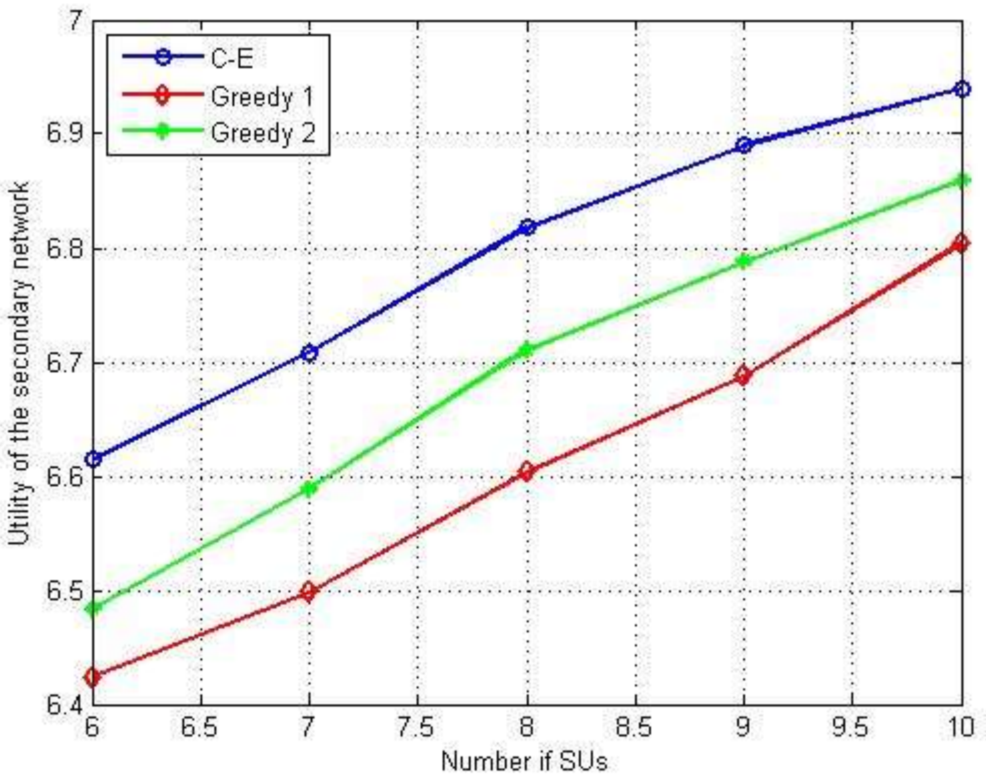

Figure 7.7: Utility of SU's versus the number of SU's

The above graph highlights that greedy-2 provides us with more utility in comparison to greedy-1 approach whereas the C-E method provides the greatest performance in all the greedy techniques. In all of the three schemes as the number of secondary user's increase the utility also increases.

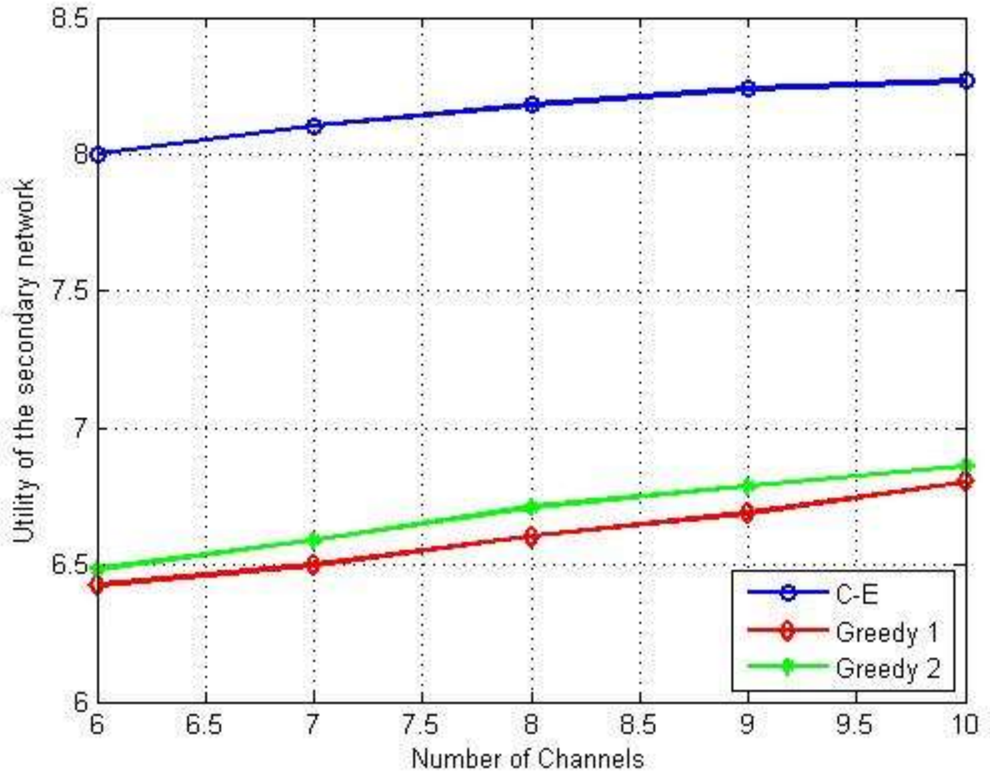

Figure 7.8: Utility of SU's versus the number of channels

In figure 7.8 above the utility of SU's is observed against the number of channels using various techniques with the quantity of secondary user's taken as 10.The quantity of channels and the throughput of secondary network is directly proportional to each other because an increment in the amount of channels results in an increase in utility of secondary network. It can be observed that greedy-2 approach has much reliable performance as compared to greedy-1 technique and C-E algorithm provides the best results. It has the highest utility among all other techniques.

Figure 7.9 shows the throughput of the secondary network in comparison to amount of SU's by making use of congestion games which works based on weights and some standards respectively. The quantity of channels are fixed as five. Shannon capacity formula is used to determine exact throughput. The channel conditions are randomly generated for each SU.Values of channel conditions are obtained using uniform distribution which lies between fifteen and thirty-five decibels. The threshold is set at Twenty-Five decibels. The medium is considered as a good channel if it gives gain greater than the threshold else the channel is considered as bad. The SU will be given a higher value in weighted congestion game. In image 7.9 this is quite clear that a larger throughput is obtained using weighted congestion game as compared to standard congestion game. The throughput is higher is case of weighted congestion game because SU's having better conditions of medium will receive a bigger part of the vacant channels.

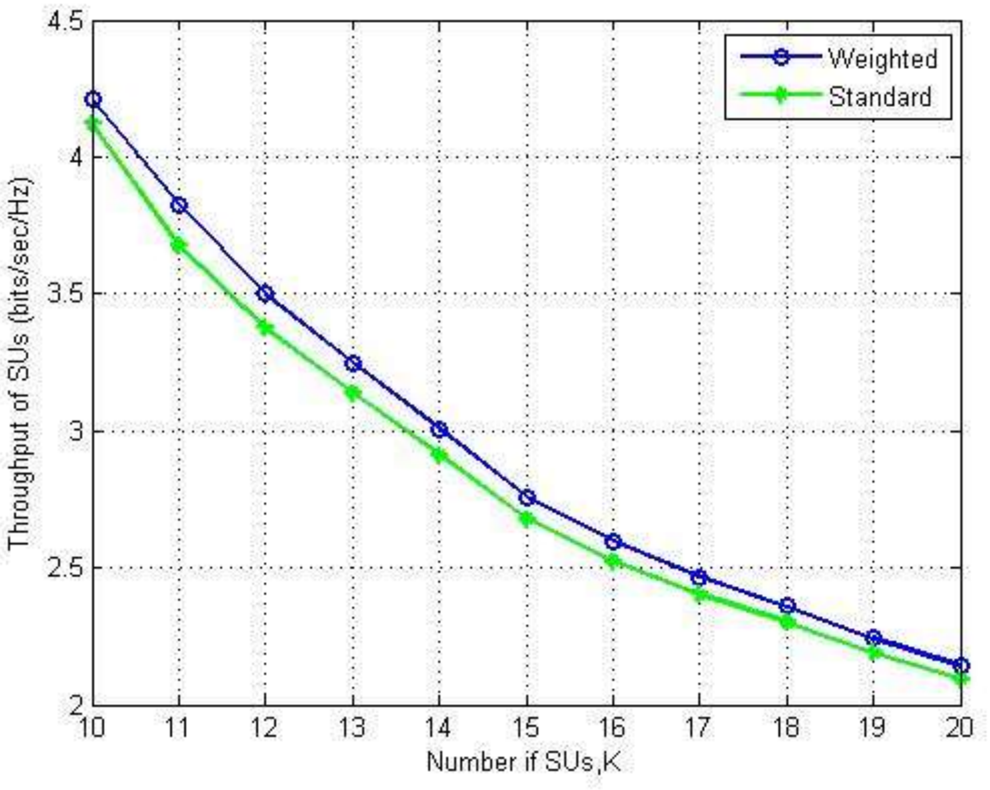

Figure 7.9: Throughput of SU's against the quantity of SU's

Figure 7.10 below shows the throughput averaged for every user for the channel access approach and the random access approach when the amount of channels are considered as five. In random access strategy the SU's randomly sense the channel and it is accessed whenever sensed as idle. It can be seen from the figure that channel access scheme provides with a higher throughout per user as compared to random access strategy. It means that SU's can achieve higher utility in the channel sensing and access strategy.

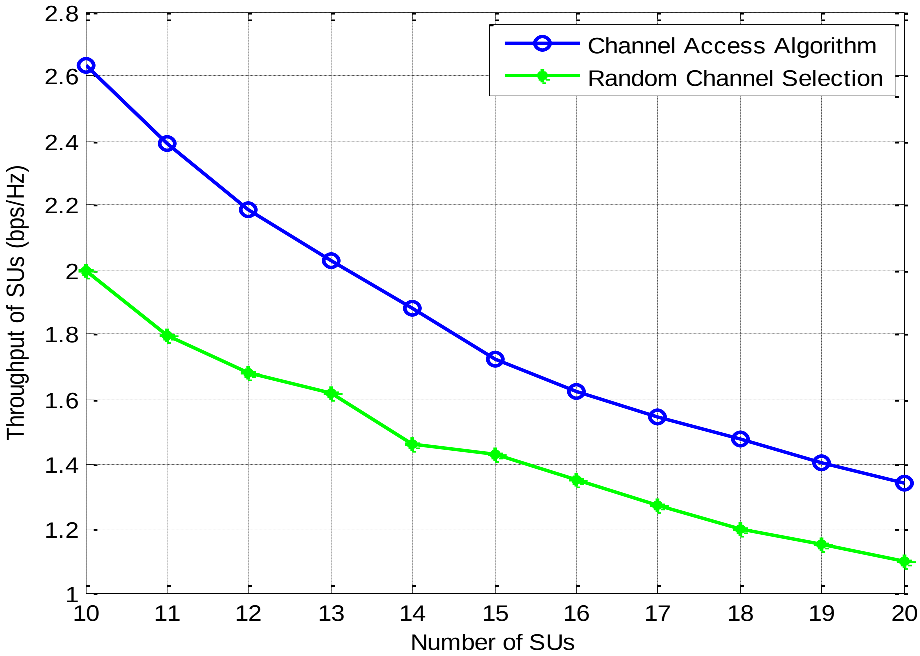

Figure 7.10: The channel access approach against random channel access

7.3 Simulations of OCF, SCF and our proposed algorithm

We have compared the performance of OCF, SCF and our proposed algorithm from the aspect of aggregate throughput.

We have considered a CRN with N SUs and M PUs.There is a 100mX100m square region where SUs are placed randomly. The base station is placed at the mid of the region. The channel gain of the link of SU i is modelled as $|g_i|^2 = 1/d_i^n$ .d_i is the distance of SU from the base station and path loss exponent is expressed by n. Parameters used in these algorithms are given in the table below.

Parameter	**Value**
Number of SUs N	10
Number of PUs M	6
Path loss Exponent *n*	2
Bandwidth of channel *j* B_j	100 kHz
Probability that channel *j* is being idle $P_{I,j}$	[0.5,1]
Target Detection Probability $P_{d,i,j}$	0.99

Noise power σ_n^2	0.01 mW
Maximum transmission power of SU i $W_{t,i}^{max}$	150mW
Minimum transmission power of SU i $W_{t,i}^{min}$	50mW
Received SNR at each SU during the sensing stage $\gamma_{i,j}$	-15dB
Sensing power of SU i on channel j $W_{s,i,j}$	50mW
Slot duration T	100ms
Sensing duration τ	5ms
Number of sensing samples during the sensing stage N_s	5000
Buffer size of each SU	200kbit
Lower bound of the energy efficiency η_{min}	500kbit/Joule

Table 7.4: Parameters for OCF, SCF algorithm

Figure 7.11 below shows the aggregate throughput of SUs when the quantity of SUs N increases from 2 to 20.This shows that our proposed scheme outperforms the OCF and SCF algorithm.

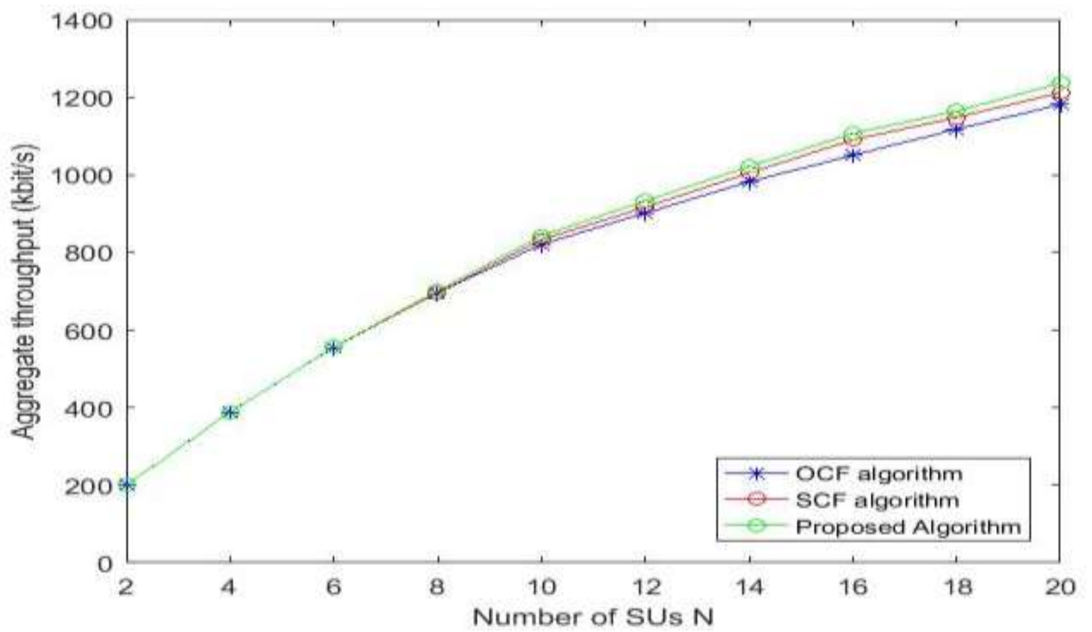

Figure 7.11: Average throughput along with the number of SUs

Figure 7.12 shows the aggregate throughput of SUs when the count of PUs rises from 1 to 10.The graph clearly highlights that our suggested scheme provides an improved throughput as compared to other two algorithms.

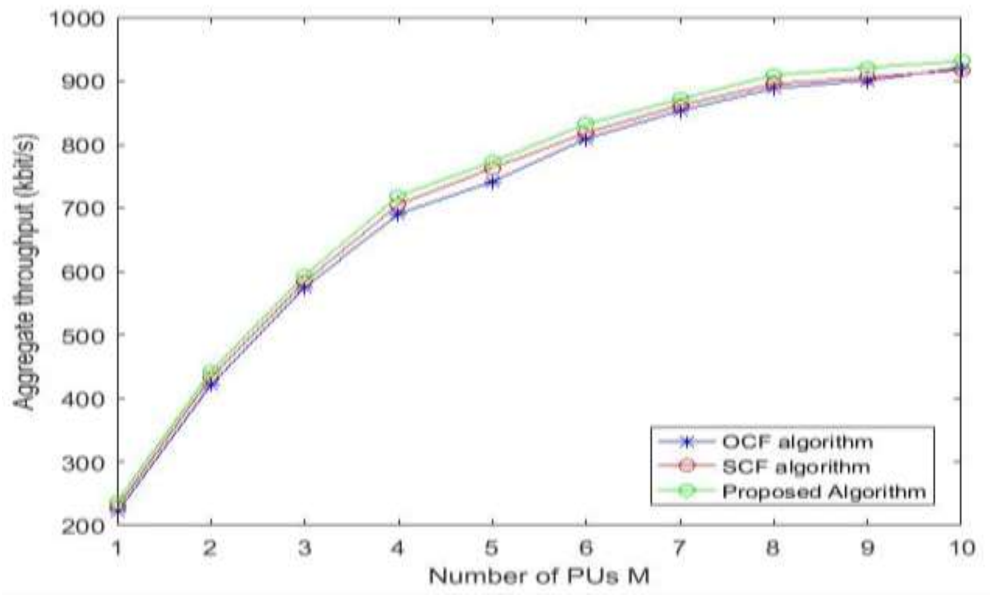

Figure 7.12: Average throughput against the number of PUs

Figure 7.13 shows the number of iterations along with the SUs.As the number of SUs increase the iterations decrease but the number of iterations of SCF and our proposed technique are approximately equal with our technique giving better throughput and efficiency.

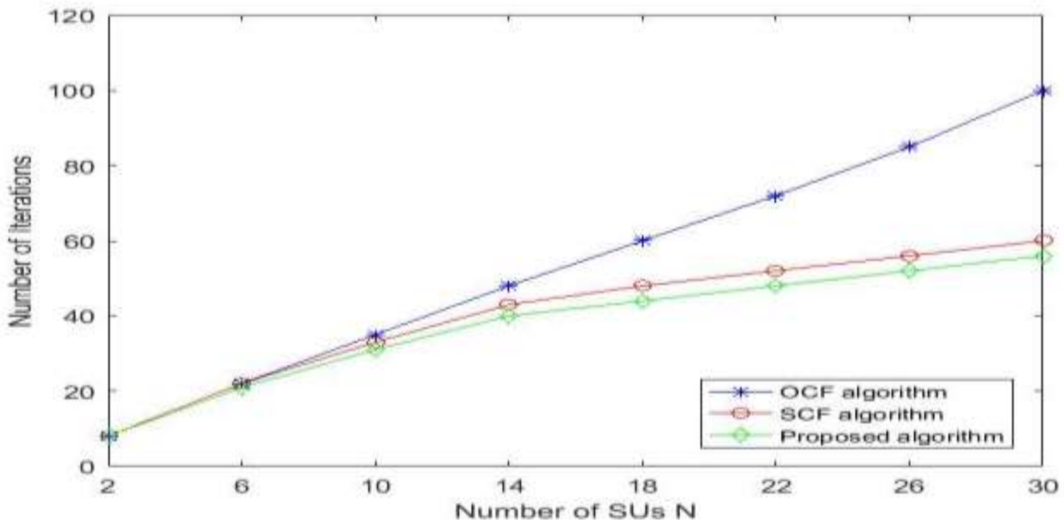

Figure 7.13: Number of Iterations along with Number of SUs

Chapter 8

Conclusion and Future Work

Accessing the spectrum dynamically in cognitive radio networks with multiple channels has been investigated. Spectrum sensing is performed considering the usage characteristics of various channels and the varying achievements of different SUs.An algorithm has been proposed which is capable enough to select the channel easily. This algorithm will make sure that collision for PUs are minimized and the constraint of access time is achieved. A cross-entropy based approach has been formulated in order to increase for all the channels the expected time for which channel is available. For sharing the spectrum a channel access game is implemented which is based on the weighted congestion game. Nash equilibrium has been achieved by channel access algorithm.

An Uncertainty based cooperation strategy is proposed in CRN with multiple channels. We proposed a scheme where maximum throughput is obtained while maintaining the energy efficiency. We have proved that our proposed algorithm provides better throughput as channel conditions are prioritized and the amount of data in buffer of SU is also given preference.

Adaptive transmission power control scheme is considered as a future work in the proposed UCF algorithm to further enhance the capability of our scheme. Along with these a general setting may also be adopted so that SU can automatically adjust with the system according to its sensing time and power.

References

1. J. Mitola III, “Cognitive radio for flexible multimedia communications,” IEEE International Workshop on Mobile Multimedia Communications, 1999, (MoMuC '99), pp. 3–10, November 1999.

2. J.Mitola and G.Q Maguire, “Cognitive radio: making software radios more personal,” IEEE personal communications Vol, 6, pp, 13-18, 1999.

3. I. F. Akyildiz, W. Y. Lee and M. C. Varun, “NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey,” Computer Networks Journal, pp. 2127-2159, September 2006

4. Y. Xing, R. Chandramouli, S. Mangold and S. Shankar, “Dynamic spectrum access to open spectrum wireless networks,” IEEE Journal on Selected Areas in Communications, pp. 626-637, March 2006

5. S. Haykin, “Cognitive radio: brain empowered wireless communication,” IEEE Journal on Selected Areas in Communications, vol. 23, no 2, pp. 201-220, February 2005

6. P. Cheng, R. Deng, and J. Chen, “Energy-efficient cooperative spec- trum sensing in sensor-aided cognitive radio networks,” IEEE Wireless Commun., vol. 19, pp. 100–105, 2012.

7. N. Zhang, N. Lu, N. Cheng, J. W. Mark, and X. Shen, “Cooperative Spectrum Access Towards Secure Information Transfer for CRNs,” IEEE J. Sel. Areas Commun., vol. 31, no. 11, pp. 2453–2464, 2013.

8. I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, “Cooperative spectrum sensing in cognitive radio networks: A survey,” Physical Communica- tion, vol. 4, no. 1, pp. 40–62, 2011.

9. E. C. Y. Peh, Y.-C. Liang, Y. L. Guan, and Y. Zeng, “Optimization of cooperative sensing in cognitive radio networks: a sensing-throughput tradeoff view,” IEEE Trans. Veh. Technol., vol. 58, no. 9, pp. 5294–5299, 2009.

10. I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “A survey on spectrum management in cognitive radio networks,” IEEE Commun. Mag., vol. 46, no. 4, pp. 40–48, 2008.

11. Mitola III, J.Cognitive radio: An Integrated Agent Architecture for Software Defined Radio.Ph.D.thesis,KTH Royal Institute of Technology. 2000.

12. FCC.Notice of proposed rule making and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies.FCC, 2005.ET Docket No 03-108

13. Singh, Manwinder, Manoj Kumar, and Jyoteesh Malhotra. "Review on Cognitive Radios: A revolutionary idea behind optimum spectrum utilization." (2013).

14. Akyildiz I.F.,Lo B.F.,Balakrishnan R.Cooperative spectrum sensing in cognitive radio networks:A survey.*Physical Communication.* 2011, vol. 4. P.40-62.

15. Zarrin, S., Lim, T.J.Belief propogation on factor graphs for cooperative spectrum sensing in cognitive radio.In proceedings of IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN).Chicago (USA), 2008.

16. Qing Zhao, Anathram Swami,"A survey of Dynamic Spectrum Access: Signal Processing and Networking Perspectives" ICASSP 2007

17. B.Rawat, G.Yan, and C.Bajracharya,"Signal processing techniques for spectrum sensing in cognititve radio networks,"international journal of ultra wideband communications and systems, vol.x(x), pp.1-10, 2010.

18. D.Cabric, A.Tkachenko and R.W.Brodersen,"Spectrum Sensing measuements of pilot,energy, and collaborative detection,"IEEE Military Communications Conference (MILCOM) 2006,Washington,DC,pp.1-7,October 2006

19. D, Bhargavi and C.R.Murthy,"Performance comparison of energy,matched-filter and cyclo-stationary-based spectrum sensing," IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC) 2010,pp.1-5,June 2010.

20. A.Shahzad,"Comparative analysis of primary transmitter detection based spectrum sensing techniques in cognitive radio systems,"Australian journal of basic and applied sciences INSINET publications, vol.4 (9), pp.4522-4531, 2010.

21.A.Tkanchenko,D.Cabric,and R.W.Brodersen,"Cyclostationary feature detector experiments using reconfigurable BEE2," in proceedings IEEE symposium on new frontiers in dynamic spectrum access networks,Dublin,Ireland,pp.216-219,April 2007.

22. F.Zeng, Z.Tian, and C.Li,"Distributed compressive wideband spectrum sensing in cooperative multi-hop cognitive networks", in proceedings of IEEE ICC, pp.1-5, 2010.

23. V.Orani,"Wavelet spectrum sensing and transmission system based on WPDM," 2003.

24. Y.Zeng, Y.Liang, A.Hoang and R.Zhang,"A review on spectrum leasing for cognitive radio: challenges and solutions," EURASIP journal on advances in signal processing, 2010.

25. http://scholarworks.uaeu.ac.ae/cgi/viewcontent.cgi?article=1047&context=all_theses

26. Abdoulaye Bagayoko. Spectrum Sharing under Interference Constraints. Signal and Image Processing. Universit´e de Cergy Pontoise, 2010. English

27. W. Ren, Q. Zhao and A. Swami, "Power Control in Cognitive Radio Networks: How to Cross a Multi-Lane Highway," IEEE journal on selected areas in communications, vol. 27, No.7, September 2009.

28. C. Kabiri, H.-J. Zepernick, L. Sibomana, and H. Tran, "On the performance of cognitive radio networks with DF relay assistance under primary outage constraint using SC and MRC," in Proc. IEEE International Conference on Advanced Technologies for Communications, Ho Chi Minh City, Vietnam, Oct. 2013, pp. 12–17.

29. http://cognitive-radio-networks.blogspot.com/2014/05/cognitive-radio-underlay-overlay-or.html.

30. A. Goldsmith, S. Jafar, I. Maric, and S. Srinivasa, “Breaking spectrum gridlock with cognitive radios: An information theoretic perspective,” Proc. IEEE, vol. 97, no. 5, pp. 894–914, May 2009.

31. https://www.diva-portal.org/smash/get/diva2:833885/FULLTEXT01.pdf

32. file:///C:/Users/Maida%20Hafeez/Downloads/9783319450766-c2.pdf

33. http://www.ijettjournal.org/volume-4/issue-4/IJETT-V4I4P333.pdf

34. Zhang, Ning, et al. "Dynamic spectrum access in multi-channel cognitive radio networks." *IEEE Journal on Selected Areas in Communications* 32.11 (2014): 2053-2064.