Analytical Study of Spectrum Sharing In Cognitive Radio

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May 2011

submitted in partial fulfillment of the requirement for the degree of

Bachelor of Technology

in

Electronics and Communication Engineering

Jaypee University of Information Technology
Waknaghat, Solan - 173 234, Himachal Pradesh

Certificate

This is to certify that the project report entitled "An Analytical study of spectrum sharing in Cognitive Radio ", submitted by Ritu, Neena Dadhwal and Tanmay Khatri in partial fulfillment for the award of degree of Bachelor of Technology in Electronics and Communication Engineering to Jaypee University of Information Technology, Waknaghat, Solan has been carried out under my supervision.

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It is certified that this work has not been submitted partially or fully to any other University or Institute for the award of this or any other degree or diploma.

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Acknowledgement

As we conclude our project with the God's grace, we have many people to thank; for all the help, guidance and support they lent us, throughout the course of our endeavor.

First and foremost, we thank Dr Ghanshyam Singh, our Project Guide, who has always encouraged us to put in our best efforts and deliver a quality and professional output. His methodology of making the system strong from inside has taught us that output is not the END of project. We really thank him for his time & efforts.

Secondly, we thank Dr. Rao and Miss Shipra kapoor for their patient hearing of our ideas and opening up our minds to newer horizons by pointing out our flaws, providing critical comments and suggestions to improve the quality of our work and appreciating our efforts.

Apart from these, countless events, countless people & several incidents have made a contribution to this project that is indescribable.

Tanmay Neena Dadhwal Ritu

(Tanmay Khatri) (Neena Dadhwal) (Ritu)

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List of Abbreviations

AACR - Aware and Adaptive Cognitive Radio

ADC - Analog to Digital converter

AI – Artificial Intelligence

BBU – Base band Unit

BER – Bit Error Rate

CDMA – Code Division Multiplex Access

CR – Cognitive radio

CSB -- Coarse Sensing Blocks

DAC – Digital to Analog Converter

DARPA – Defense Advanced Research Projects Agency

DDC – Digital to Digital Converter

DSA -- Dynamic Spectrum Access

DSP -- Digital Signal Processor

DMSS – Demand Matching Spectrum Sharing

DBSG – Dynamic Bandwidth Selection Game

DSR -- Dedicated Sensing Receiver

FCC -- Federal Commission on Communication

FFT – Fast Fourier Transform

FRS -- Fine Resolution Sensing

GSC -- Global Standards Collaboration

GSM – Global System for Mobiles

GUI -- Graphic User Interface

IF – Intermediate Frequency

IFU – Intermediate Frequency Unit

ISM – Industrial Scientific and Medical

LO – Local Oscillator

LORAN – Long Range Navigation

MAC – Medium Access Control

NC – Non- Cooperative

NIST – National Institute of Standards And Technology

OR-- Omni Directional

PA -- Power Amplifier

PLL – Phase Locked Loop

QoS -- Quality of Service

QoI -- Quality of Information

RF – Radio Frequency

RFU – Radio Frequency Unit

SDR – Software defined Radio

SINR -- Signal to Interference and Noise Ratio

SNR -- Signal to Noise Ratio

VCO – Voltage Controlled Oscillator

WRC -- World Radio Communication Conferences

xG – Next Generation

Abstract

Opportunistic unlicensed access to the (temporarily) unused frequency bands across the licensed radio spectrum is currently being investigated as a means to increase the efficiency of spectrum usage. The sophistication possible in a software defined radio has now reached a level where each radio can conceivably perform many beneficial tasks that help the user and network. It minimizes the spectrum congestion and also eradicates the problem of spectrum scarcity.

If a radio could use favorable frequencies and choose waveforms that would minimize and avoid interference with existing communication systems; it would be an ideal software defined radio. But a software defined radio must support three major intelligent applications that can raise its capabilities and ultimately make it into a cognitive radio, namely, (i) spectrum management and optimization (ii) interference with wide variety of networks and optimization of network resources (iii) interface with humans and providing electromagnetic resources.

In a cognitive radio network, the secondary users are allowed to utilize the frequency bands of the primary users when these bands are not currently being used. To support this spectrum reuse functionality, the secondary users are required to vacate the channel within a certain amount of time. Therefore spectrum access is of significant importance in cognitive radio networks. There are two parameters associated with spectrum sensing: probability of detection and probability of false alarm. The higher the probabilities of detection, the better the primary users are protected. However, from the secondary users' perspective, the lower the probability of false alarm, the more chances the channel can be reused when it is available, thus the higher the achievable throughput for the secondary network.

In this paper we have designed a flowchart for the spectrum access considering the economic aspect of the same. Also an algorithm and a code for the spectrum access are advised.

CHAPTER 1

Cognitive Radio: A Brief Overview

1.1 What cognitive radio is all about?

The dictionary meaning of Cognitive is perception. It means the process of acquiring knowledge by reasoning or by intuition or through the senses [1]. Cognitive Radio is a radio or a system that is aware of its operational environment and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly [2].

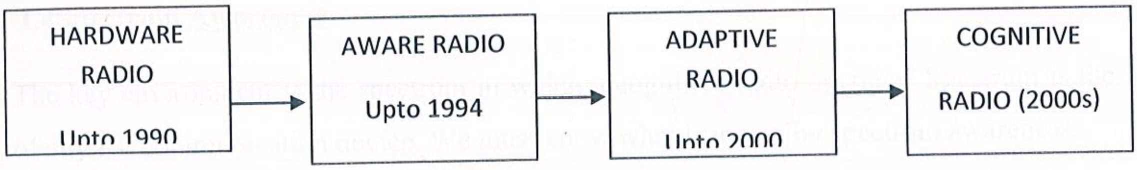

Figure 1.1 the journey towards cognitive radio.

1.2 Characteristics of Cognitive Radio

1.2.1 Cognitive capability: Cognitive capability refers to the ability of the radio technology to capture or sense the information from its environment. This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portion of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.

1.2.2 Re configurability: The cognitive capability provides spectrum awareness whereas re configurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design.

1.3Need of Cognitive Radio

Today's wireless networks are characterized by fixed spectrum assignment policy. However a large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time.

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically.

This new networking paradigm is referred to as cognitive radio networks.

1.4Spectrum Awareness

The key environment is the spectrum in which a cognitive radio operates. Spectrum is the "lifeblood' of any RF communication device. We must know what is meant by spectrum awareness.

Spectrum aware radios offer the opportunities to fundamentally change how we manage interference and thus transit the allocation and utilization of spectrum from a command and control structure that is embedded within the radio. Spectrum and frequency managers assign discrete frequencies to individual radios or networks and attempt to ensure that the emissions from one do not adversely impact others . Such planners are inherently disadvantaged by number of factors.

- Interfering signals will propagate to the maximum possible range.
- Desired signals will be received without un acceptable link margin degradation.

1.5 How do We Create Awareness?

Table 1.1 shows the ways of creating awareness with focus and stress on certain aspects like speed (lower sensing time), power etc.

We can achieve this task by following methods:

- One method could be by neighbors informing as mentioned above.
- Spectrum sensing methods, this method has become easier and faster with the development of efficient analog to digital convertors, which intern have made faster FFTs possible.

Table 1.1 Comparison of spectrum sensing approaches.

Technology	***Spectrum analyzer***	***Wideband FFT***
Complexity	Lower complexity if it can share receiver components.	Adds requirement for wideband ADC and extensive DSP.
Short signal detection	Low dwell time on each frequency can fail to see short, pulsed signals. Typical dwell is only microseconds to milliseconds, and below 1%.	Higher probability of detecting short signals, based on duty cycle of the sensing, which could reach 50%.
Bandwidth	Can scan large ranges of signal.	Limitations in ADC constrain instantaneous bandwidth.
Speed	Slower, based on dwell time on each channel. May be difficult to interleave "listen through" without penalty to the node performance.	With appropriate filters, sample sub-Nyquist to minimize time delay and interleaving time. These short intervals can be compatible with MAC layer timing.
Power	Mostly classical analog components, potentially shared with the mission receiver.	Digital processing adds to the inherent analog energy usage.

1.6 Potential Interference Analysis

We can consider interference in two categories. The first category is the direct interference with ongoing communication of primary user, resulting in degraded communication functionality. The second is the interference to the channel, when it is not in use; causing the primary user to "think" there is something wrong with the channel or equipment [5,6]. The figure below gives us the details.

Table 1.2 Interference effects on digital processing layers.

Layer	***Impact***	***Mitigation***
PHY	Creation of higher uncorrected BER	Allow higher layers to resolve a short interval of interference adjust coding dynamically
MAC	Complete and uncorrectable blockage of a packet	MAC layer acknowledgment retransmits. Blocked RTS are automatically retried
NETWORK	Complete and uncorrectable blockage of a packet	Protocol operates effectively with missing data. For example, VoIP can suffer some loss as long as it is not correlated
TRANSPORT	Network fails to route packet	Transport layer recognizes missing sequence and requests retransmission

1.7 Position Awareness

For cognitive radio (CR) to reach its full potential as an efficient member of a network or as an aid in users' daily tasks, and even to conserve the precious spectrum resource, a radio must primarily know its position and what time it is. From position and time, a radio can:

1. Calculate the antenna pointing angle that best connects to another member of the network.
2. Place a transmit packet on the air so that it arrives at the receiver of another network member at precisely the proper time slot to minimize interference with other users.
3. Guide its user in his or her daily tasks to help achieve the user's objectives, whether it is to get travel directions, accomplish tasks on schedule, or any of a myriad of other purposes.

Position and time are essential elements to a smart radio. Furthermore, from position and time, velocity and acceleration can be inferred, giving the radio some idea about its environment. Geo-location applications are also a key enabling technology for such applications as spatially variant advertisement, spatially aware routing, boundary-aware policy deployment, and space- and time-aware scheduling of tasks. These capabilities enable a CR to assist its user to conveniently acquire goods and services as well as to communicate with other systems using minimal energy (short hops) and low latency (efficient directional propagation of packets through a network). Geo-location applications in a CR enable the radio to be carried throughout the world and used without any manual adjustment or modification to maintain compliance with local regulations [6]. Finally, space- and time-aware scheduling of tasks improves the efficiency of CR operations by managing vital resources and accomplishing goals "at the right place" and "just in time."

The National Institute of Standards and Technology (NIST) radio station, call sign WWV, which continuously broadcasts time with high accuracy, is somewhat well known in the Western Hemisphere. (WWV consists of stations call signs WWVB and WWVH). However, without knowing position, it is difficult to determine how long the transmission took to propagate to the receiver, and thus it renders only a coarse time. Some other examples are **V**ery high frequency (VHF) **O**mnidirectional **R**anging (VOR) transmitters used by aircraft to locate current position [7], **LO**ng **R**ange **N**avigation (LORAN) used by ships at sea to calculate position, and the geo-positional services of cellular telephone system [8].

1.8 Physical Architecture of the Cognitive Radio

Architecture is a comprehensive, consistent set of design rules by which a specified set of components achieves a specified set of functions in products and services that evolve through multiple design points over time. The project develops a CR model by which Software Defined Radio, sensors, perception and intelligence may be integrated to create a AACR with better QoS and QoI through capabilities to observe (sense, perceive), orient, plan, decide, act and learn in RF and user domains, transitioning from merely aware or adaptive to demonstrably cognitive radio [9].

The generic architecture of cognitive radio is as shown in the figure given below:

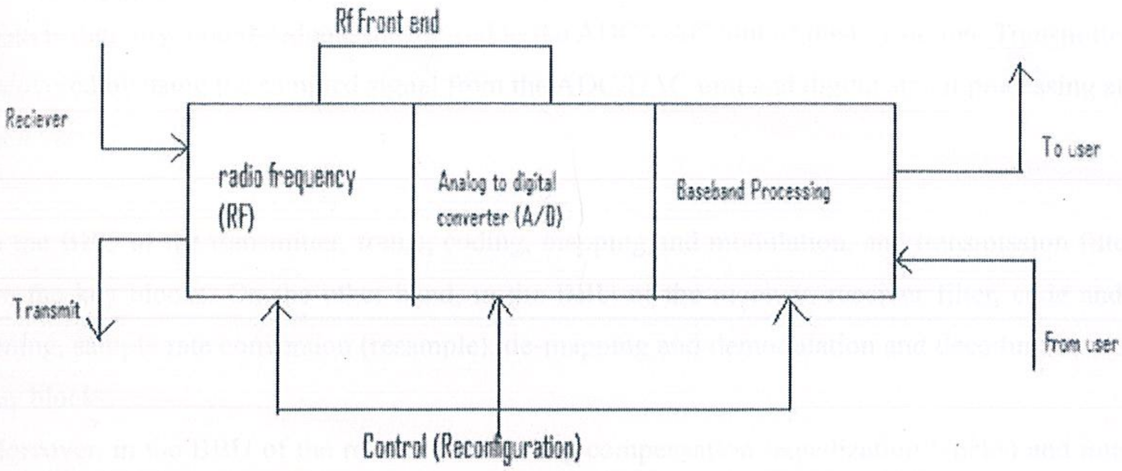

Fig 1.2 Physical architecture of cognitive radio [9,10]

The main components of a cognitive radio transceiver are:

1. Radio front end
2. Baseband processing unit

1.8.1 The RF Front End

At the transmitter end, the signals coming from IF unit or BBU are up-converted to the radio frequency band signals, amplified and transmitted to the antenna unit [9].

At Receivers RFU, the signal received by the antenna unit are amplified to a constant level that is suitable for signal processing and directly down-converted to a lower frequency band such as IF band or base band.

The signal processing is done by an analog circuit. The linearity or efficiency of the RF amplifier and the conversion method to the lower frequency band at the receiver will be main discussion point.

1.8.2 The Baseband Region

Data is digitally modulated and transferred to the ADC/DAC unit of the transmitter. Transmitted data is recovered by using the sampled signal from the ADC/DAC unit and digital signal processing at the reciever

In the BBU of the transmitter, frame, coding, mapping and modulation, and transmission filter blocks are the key blocks. On the other hand, in the BBU of the receiver, receiver filter, code and symbol timing, sample rate conversion (resample), de-mapping and demodulation and decoding blocks are the key blocks.

Moreover, in the BBU of the receiver, the fading compensation (equalization blocks) and interference cancellation blocks for eliminating undesired signal are present. In most cases, BBU is configured by several DSPH such as DSP, FPGA or ASIC. The BBU configuration can be changed by changing DSPS.

1.9 Framework of Cognitive Radio

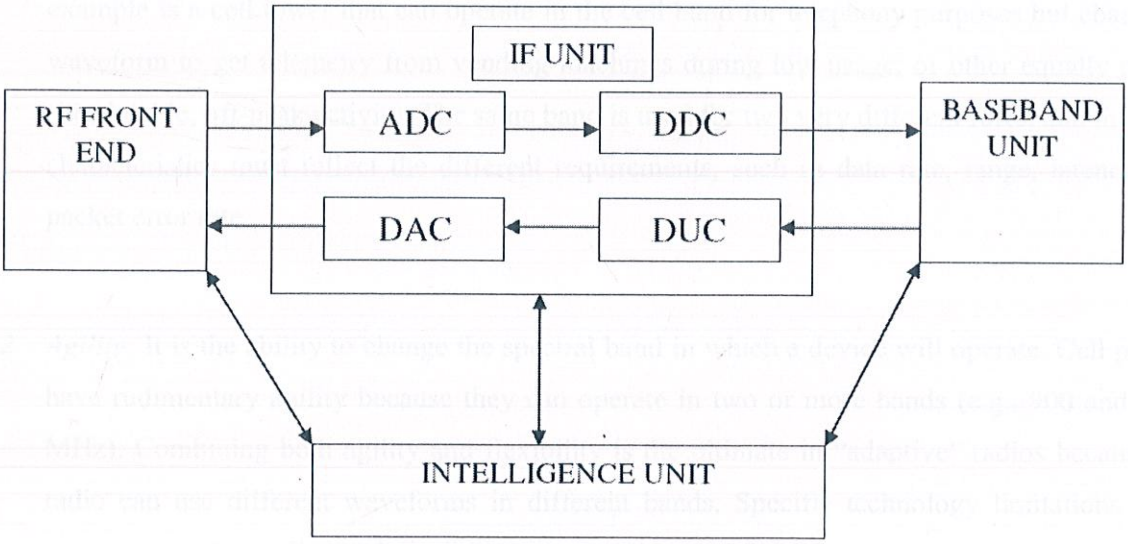

Fig 1.3Framework of a Cognitive Radio [12]

As above we have seen the physical architecture of cognitive radio, now we will have a look on the frame of a cognitive radio.

We will discuss different parts of the cognitive radio other than RF front end and baseband processing unit as they are already discussed.

The diagram shown above is the framework of cognitive radio.

1.9.1 The IF Part

The signal from the ADC/DAC unit are up-converted to the IF band signal, amplified and transferred to the RFU of the transmitter. At receiver, the signal from the RFU are amplified to an adequate level for signal processing in the IFU and directly down converted to a suitable frequency for the ADC/DAC unit or base band unit. When the signals of several systems are received at receiver, the required frequency band must be selected by using a filter.

1.9.2 Intelligence Unit

This section consists of the dedicated sensing receiver and the reasoning agent. These components help in cognitive radio achieve the following four traits, through Dynamic Spectrum Access (DSA).

1. *Flexibility:* It is the ability to change the waveform and the configuration of a device. An example is a cell tower that can operate in the cell band for telephony purposes but change its waveform to get telemetry from vending machines during low usage, or other equally useful, schedulable, off-peak activity. The same band is used for two very different roles, and the radio characteristics must reflect the different requirements, such as data rate, range, latency, and packet error rate.

2. *Agility:* It is the ability to change the spectral band in which a device will operate. Cell phones have rudimentary agility because they can operate in two or more bands (e.g., 900 and 1900 MHz). Combining both agility and flexibility is the ultimate in "adaptive" radios because the radio can use different waveforms in different bands. Specific technology limitations exist, however, to the agility and flexibility that can be afforded by current technology. The time scale of these adaptations is a function of the state of technology both in the components for adaptation as well as the capacity to sense the state of the system. These are classically denoted as the observable/controllable requirements of control systems.

3. *Sensing:* It is the ability to observe the state of the system, which includes the radio and, more importantly, the environment. It is the next logical component in enabling dynamics. Sensing

allows a radio to be self-aware, and thus it can measure its environment and potentially measure its impact to its environment. Sensing is necessary if a device is to change in operation due to location, state, condition, or RF environment.

4. *Networking:* It is the ability to communicate between multiple nodes and thus facilitate combining the sensing and control capacity of those nodes. Networking, specifically wireless networking, enables group-wise interactions between radios. Those interactions can be useful for sensing where the combination of many measurements can provide a better understanding of the environment. They can also be useful for adaptation where the group can determine a more optimal use of the spectrum resource over an individual radio.

Future wireless communication systems are expected to have the intelligence to perform tradeoffs between user Quality of Service (QoS) requirements and scarce radio resources constraints. This intelligence will be based on the innovative CR design philosophy, which allows for devices to make clever decisions on spectrum usage, power allocation, type of network services to access/subscribe, and collaboration with other devices, while meeting QoS requirements [12, 13].

1.10Regulatory Issues in Cognitive Radio:

There are various mechanisms for regulating the spectrum allotment and their usage. They can be broadly categorized into three categories as shown in the figure below [14].

There are many regulating bodies such as:

- Federal commission on communications (FCC)
- DARPA – Defense Advanced Research Projects Agency, USA's military wing for communication research.
- The government bodies periodically meet at World Radio Communication Conferences (WRCs)

- Global Standards Collaboration (GSC) group within the ITU

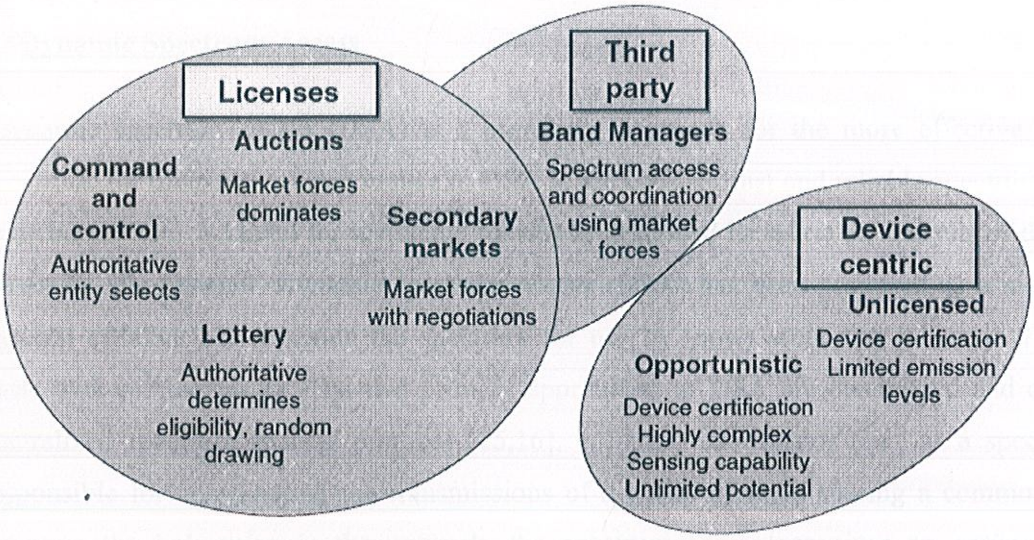

Fig 1.4 Spectrum Access Regimes [14]

1.11 Cognitive Radio Technologies of Today and The Future

Software-defined cognitive radios (CRs) use voice as a primary input/output modality and are expected to have substantial computational resources capable of supporting advanced speech- and audio-processing applications. We also have cognitive-like services that enhance military mission capability by capitalizing on automatic processes, such as speech-information extraction and understanding the environment. Some examples in the filed of Speech and Language Processing would be Speaker Recognition, Language Identification, Text-to-Speech Conversion, Speech-to-Text Conversion, Machine Translation, Background Noise Suppression, Speech Coding and Speaker Stress Characterization.

Some of the Available Technologies for Cognitive radios are as follows; Geo location which is an important CR enabling technology due to the wide range of applications that may result from a radio being aware of its current location and possibly being aware of its planned path and destination. Another technology is in the field of Biometrics. A CR can learn the identity of its user(s), enabled by one or more biometric sensors.

CHAPTER 2

DYNAMIC SPECTRUM ACCESS

2.1Dynamic Spectrum Access

Dynamic spectrum access (DSA) is a promising approach for the more effective use of existing spectrum. Of fundamental importance to DSA is the need for fast and reliable spectrum sensing over a wide bandwidth. A model for two-stage sensing is described based on an analysis of the mean time to detect an idle channel. Dynamic spectrum access (DSA) has been proposed as a means to improve spectral efficiency by opening the spectrum for use by (new) secondary users on a non-interfering basis with primary users. The two primary approaches to DSA are centralized and distributed. In a centralized spectrum sharing protocol [15,16], a central coordinator (i.e., as a spectrum server) is responsible for coordinating the transmissions of a group of links sharing a common spectrum. By knowing the link gains in the network, the spectrum server organizes an optimal schedule that maximizes the average throughput of the network. In distributed systems, each transmitter/receiver pair must find an idle channel in which to communicate. Several studies have shown that varying levels of cooperation can increase the overall throughput of the network.

A two stage DSA approach comprises of preliminary coarse resolution sensing (CRS) followed by fine resolution sensing (FRS). The total spectrum is first partitioned into several contiguous coarse sensing blocks (CSB) of equal bandwidth; each is denoted as either CSBW with or CSBN without idle channels, respectively. In CRS, the first CSBW is located; thereafter, FRS attempts to detect an idle channel within it. A random search is used in CRS with a detection bandwidth equal to that of he CSB; i.e., $B_{sense} = B_{csb}$. Although both random and serial searches exhibit similar detection time performance, random search provides a better fairness to allocate a potential free channel, whether it is at the beginning or end of the channel sequence. In contrast, because random search can cause unnecessary death lock, FRS employs a serial search within a CSB with $B_{sense} = B_c$. This occurs if a false alarm in CRS occurs (i.e., the detector indicates an idle channel in the CSB when all are actually busy); a random search during the subsequent FRS would continue to try but fail to locate this nonexistent free channel – a death lock. However, the use of a serial search in FRS easily avoids the death lock because it evaluates all channels only once. If no idle channel is detected during FRS, the device returns to the CRS mode .

If a false alarm (detecting a busy channel as idle) occurs during FRS, a penalty equal to J integration periods is incurred for recovery from the error before scanning is resumed. Inherent in the two-stage sensing algorithm is the need to quickly and efficiently jump from one channel frequency to another as the maximum frequency hop in either the CRS or FRS stage may span the entire frequency spectrum of interest. The settling time required for such frequency hopping is primarily determined by the design of the phase locked loop (PLL) used in the frequency synthesizer that generates the channel carrier frequencies. It is well known that a conventional PLL designed with a wider bandwidth achieves a faster settling time. However, its phase noise is increased resulting in increased reciprocal mixing and decreased SNR with a corresponding increase in detection errors. Although a conventional PLL cannot simultaneously achieve fast settling and low phase noise with low power dissipation, more sophisticated architectures overcome these tradeoffs [18,19].

2.2Spectrum Utilization and its different aspects

Today's wireless networks are characterized by a fixed spectrum assignment policy. However, a large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time [20]. The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. This new networking paradigm is referred to as Dynamic spectrum Access and cognitive radio networks.

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. Dynamic spectrum access is proposed to solve these current spectrum inefficiency problems.

Dynamic Spectrum Access Networks (DSANs) as well as cognitive radio networks, will provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques. The inefficient usage of the existing spectrum can be improved through opportunistic access to the licensed bands without interfering with the existing users. Dynamic spectrum access techniques allow the cognitive radio to operate in the best available channel. More specifically, the cognitive radio technology will enable the users to

(1) determine which portions of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing),

(2) Capturing the best available spectrum to meet user communication requirements.(spectrum management),

(3) coordinate access to this channel with other users (spectrum sharing),

(4) vacate the channel when a licensed user is detected (spectrum mobility).

Once a cognitive radio supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum.

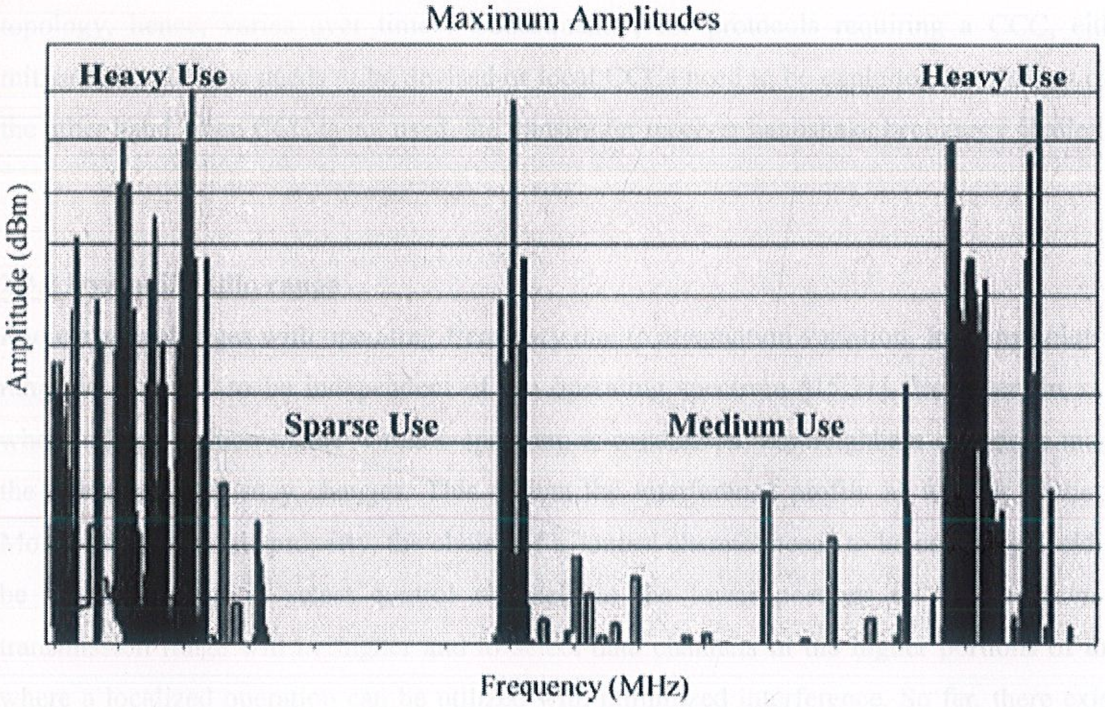

Fig 2.1 Spectrum Utilization [20]

2.3 Spectrum Sharing Challenges

In the previous sections, the theoretical findings and solutions for spectrum sharing in xG networks are investigated. In the following, we detail the challenges for spectrum sharing in xG networks along with some possible solutions.

2.3.1 Common control channel (CCC)

Many spectrum sharing solutions, either centralized or distributed, assume a CCC for spectrum sharing. It is clear that a CCC facilitates many spectrum sharing functionalities such as transmitter receiver handshake , communication with a central entity , or sensing information exchange. However, due to the fact that xG network users are regarded as visitors to the spectrum they allocate, when a primary user chooses a channel, this channel has to be vacated without interfering. This is also true for the CCC. As a result, implementation of a fixed CCC is infeasible in xG networks. Moreover, in a network with primary users, a channel common for all users is shown to be highly dependent on the topology, hence, varies over time . Consequently, for protocols requiring a CCC, either a CCC mitigation technique needs to be devised or local CCCs need to be exploited for clusters of nodes .On the other hand when CCC is not used, the transmitter receiver handshake becomes a challenge

2.3.2 Dynamic radio range

Radio range changes with operating frequency due to attenuation variation. In many solutions, a fixed range is assumed to be independent of the operating spectrum [15,71]. However, in xG networks, where a large portion of the wireless spectrum is considered, the neighbors of a node may change as the operating frequency changes. This effects the interference profile as well as routing decisions. Moreover, due to this property, the choice of a control channel needs to be carefully decided. It would be much efficient to select control channels in the lower portions of the spectrum where the transmission range will be higher and to select data channels in the higher portions of the spectrum where a localized operation can be utilized with minimized interference. So far, there exists no work addressing this important challenge in xG networks and we advocate operation frequency aware spectrum sharing techniques due the direct interdependency between interference and radio range.

xG networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in the spectrum usage by exploiting the existing wireless spectrum opportunistically. xG networks, equipped with the intrinsic capabilities of the cognitive radio, will provide an ultimate spectrum-aware communication paradigm in wireless communications.

Chapter 3

Spectrum Sensing in Cognitive Radio Networks: Techniques and Challenges.

3.1 Introduction

Opportunistic unlicensed access to the (temporarily) unused frequency bands across the licensed radio spectrum is currently being investigated as a means to increase the efficiency of spectrum usage. Such opportunistic access calls for implementation of safeguards so that ongoing licensed operations are not compromised. Among different candidates, sensing-based access, where the unlicensed users transmit if they sense the licensed band to be free, is particularly appealing due to its low deployment cost and its compatibility with the legacy licensed systems. The ability to reliably and autonomously identify unused frequency bands is envisaged as one of the main functionalities of *cognitive radios*. Here we provide an overview of the regulatory requirements and major challenges associated with the practical implementation of spectrum sensing functionality in cognitive radio systems. Furthermore, we outline different design trade-offs that have to be made in order to enhance various aspects of the system's performance.

With the emerging concept of Cognitive Radio and opportunistic spectrum access, spectrum sensing has gained new aspects since it is the main task on which the entire operation of cognitive radio rests. It is identified as the key requirement and is one of the most challenging issues in cognitive radio system. A hybrid model for transmitter based spectrum sensing has been presented, in which various aspects of spectrum sensing problem under transmitter based detection are studied with a cognitive radio perspective. The presented approach helps in detecting the idle spectrum bands (spectrum holes that is the underutilized sub bands of the radio spectrum) opportunistically with better utilization of the spectrum under non cooperative sensing with increase in the overall spectrum efficiency.

Driven by consumers' increasing interest in wireless services, demand for radio spectrum has increased dramatically. Moreover, with the emergence of new wireless devices and applications, and the compelling need for broadband wireless access, this trend is expected to continue in the coming years. The conventional approach to spectrum management is very inflexible in the sense that each operator is granted an exclusive license to operate in a certain frequency band. However, with most of the useful radio spectrum already allocated, it is becoming exceedingly hard to find vacant bands to either deploy new services or enhance existing ones. On the other hand, as evidenced in recent measurements, the licensed spectrum is rarely utilized continuously across time and space. The relatively low utilization of the licensed spectrum suggests that spectrum scarcity, as perceived today, is largely due to inefficient fixed frequency allocations rather than any physical shortage of spectrum. The various observation has prompted the regulatory bodies to investigate a radically different access paradigm where secondary (unlicensed) systems are allowed to *opportunistically* utilize the unused primary (licensed) bands, commonly referred to as *white spaces*. In particular, the Federal Communications Commission (FCC) has already expressed its interest in permitting unlicensed access to white spaces in the TV bands. This interest stems in part from the great propagation characteristics of the TV bands and their relatively predictable spatiotemporal usage characteristics.

3.2 Spectrum sensing methods for Cognitive Radio

The most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of an xG (next generation) user. In reality, however, it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter. Thus, the most recent work focuses on primary transmitter detection based on local observations of the xG users. In general, various spectrum sensing techniques has been shown in the figure given below.

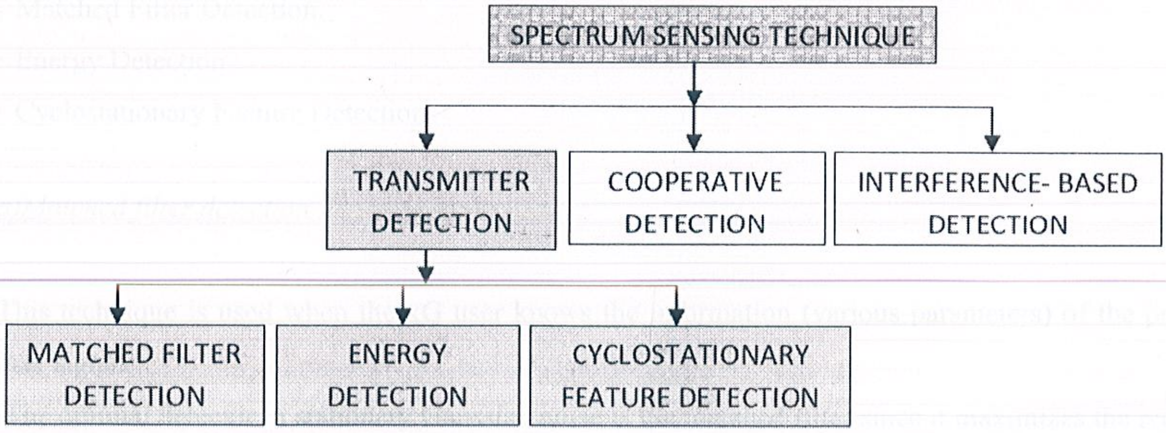

Fig 3.1 Different spectrum sensing techniques [27]

3.3 **Transmitter detection (non-cooperative detection)**

The main aim of cognitive radio should be to distinguish between used and unused spectrum bands. Thus, it should exhibit ability to determine whether a signal is from a primary transmitter which is locally present in a certain spectrum or not. In order to cope up with this problem, the transmitter detection approach is implemented which is based on the detection of the weak signal from a primary transmitter through the local observations of the xG users. The basic hypothesis model [3] for transmitter detection is defined as follows:

If $x(t) = n(t)$ then H_0

If $x(t)=hs(t)+n(t)$ then H_1

where x(t) is the signal received by the xG user, s(t) is the transmitted signal of the primary user, n(t) is the AWGN (additive white Gaussian noise) and h is the amplitude gain of the channel. H0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H1 is an alternative hypothesis, which indicates that there exists some licensed user signal. This model only helps to identify whether there is any local (primary) user present in the particular focused area for further processing or not.

Under transmitter detection technique, three different schemes are generally used. In the following subsections, we thereby investigate the detection techniques proposed for transmitter detection in the xG networks by as shown in Figure1 which are enumerated as:

- Matched Filter Detection.
- Energy Detection.
- Cyclostationary Feature Detection.

a)Matched filter detection

This technique is used when the xG user knows the information (various parameters) of the primary user signal.

The optimal detector in stationary Gaussian noise is the matched filter since it maximizes the received signal-to-noise ratio (SNR).While the main advantage of the matched filter detector is that it requires less time to achieve high processing gain due to coherency. It requires a priori knowledge of the primary user signal such as the modulation type and order, the pulse shape, and the packet format. Alternately, if this information is not accurate, then the matched filter performs poorly. However, since most wireless network systems have pilot, preambles, synchronization word or spreading codes, these can be used for the coherent detection.

limitation of this technique is that the matched filter cannot differentiate between the signal been received by the receiver of the secondary user.

The flow sequence of the matched filter is shown in figure 3.2.

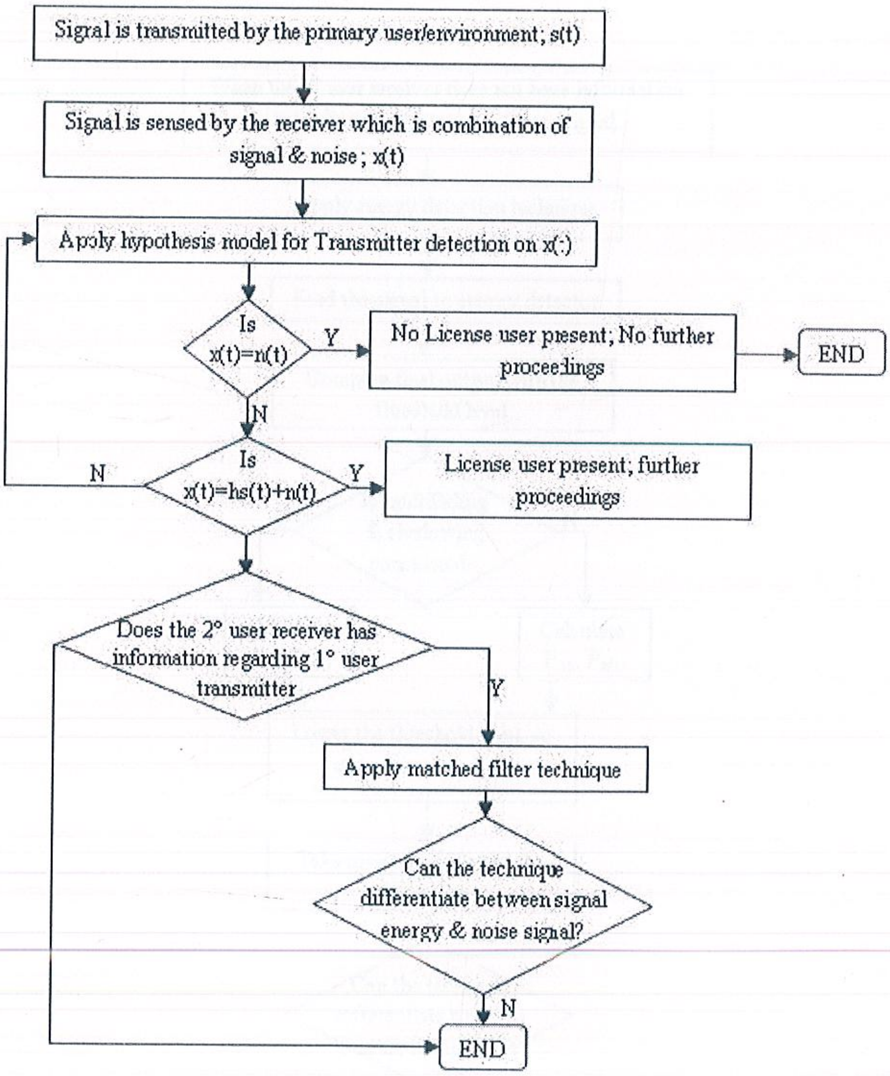

Fig 3.2 Matched Filter detection[27]

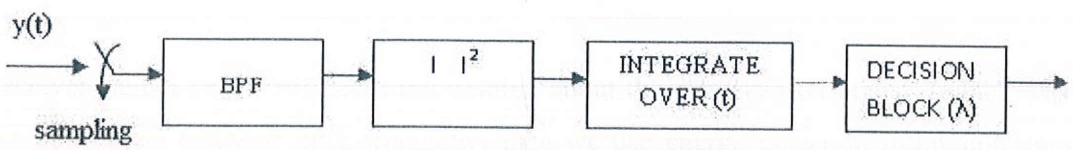

Fig 3.3 Schematic representation of the energy detector over a spectrum subband of interest [3,27].

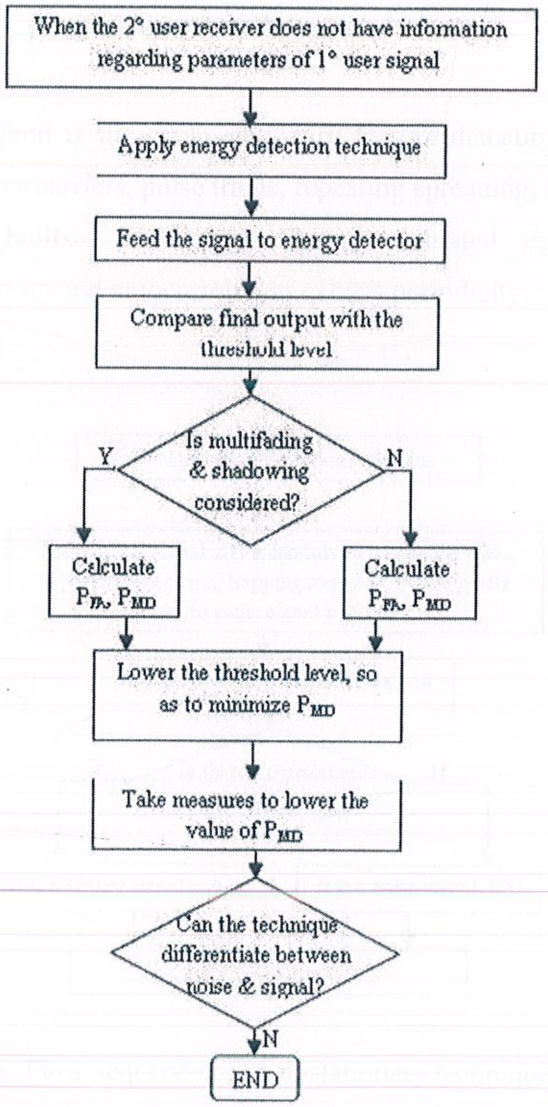

Fig 3.4 Flow sequence of the energy detection technique [27].

b)Energy detection

If the receiver cannot gather sufficient information about the primary user signal, (which was one of the limitation of the matched filter technique) then we use energy detection technique, the optimal detector is an energy detector. It is shown in figure 3.3.In order to measure the energy of the received signal, the output signal of band-pass filter with bandwidth W is squared and integrated over the observation interval T. Finally, the output of the integrator, Y, is compared with a threshold to decide whether a licensed user is present or not. Figure given below helps in explains the above concept. The flow sequence of energy detection is shown in figure 3.4.

c) Cyclo-stationary feature detection

An alternative detection method is the cyclo-stationary feature detection. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. These modulated signals are characterized as cyclostationarity since their mean and autocorrelation exhibit periodicity.

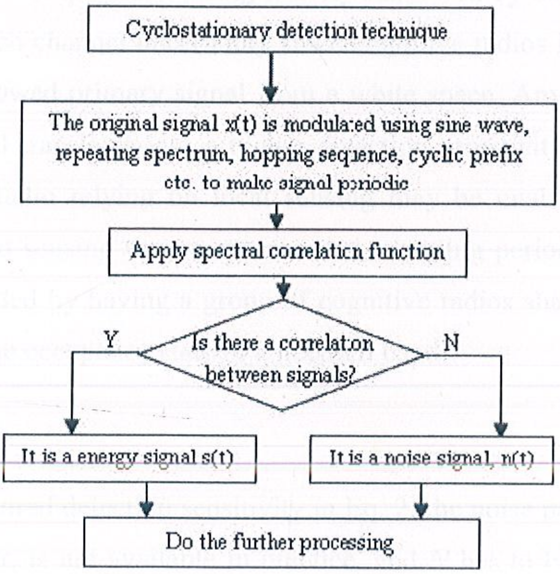

Fig 3.5 Flow sequence of cyclostationary technique[27]

These features are detected by analyzing a spectral correlation function as shown in Figure 5. The main advantage of the spectral correlation function is that it differentiates the noise energy from modulated signal energy, which is a result of the fact that the noise is a wide-sense stationary signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity. Therefore, a cyclostationary feature detector can perform better than the energy detector in discriminating against noise due to its robustness to the uncertainty in noise power.

3.4 Spectrum Sensing Challenges

Spectrum sensing in cognitive radio networks is challenged by several sources of uncertainty ranging from channel randomness to device level and network-level uncertainties. Since spectrum sensing should perform robustly even under worst case conditions, such uncertainties usually have implications in terms of the required detection sensitivity, as discussed below.

3.4.1 Channel Uncertainty

Under channel fading or shadowing, a low received signal strength does not necessarily imply that the primary system is located out of the secondary user's interference range, as the primary signal may be experiencing a deep fade or being heavily shadowed by obstacles. Therefore, spectrum sensing is challenged by such channel uncertainty since cognitive radios have to be more sensitive to distinguish a faded or shadowed primary signal from a white space. Any uncertainty in the received power of the primary signal translates into a higher detection sensitivity requirement. Under severe fading, a single cognitive radio relying on local sensing may be unable to achieve this increased sensitivity since the required sensing time may exceed the sensing period, *Tp*. As we shall illustrate later, this issue may be tackled by having a group of cognitive radios share their local measurements and collectively decide on the occupancy state of a licensed band.

3.4.2 Noise Uncertainty

In order to calculate the required detection sensitivity in Eq. 2, the noise power has to be known. Such a priori knowledge, however, is not available in practice, and N has to be estimated by the receiver. Unfortunately, calibration errors as well as changes in thermal noise caused by temperature variations limit the accuracy with which noise power can be estimated. Since a cognitive radio may violate the sensitivity requirement due to an underestimate of *N*, gmin should be calculated with the worst case noise assumption, thereby necessitating a more sensitive detector.

Spectrum sensing is further challenged by noise uncertainty when energy detection is used as the underlying sensing technique. More specifically, a very weak primary signal will be indistinguishable from noise if its SNR falls below a certain threshold determined by the level of noise uncertainty [8]. Feature detectors, on the other hand, are not susceptible to this limitation due to their ability to differentiate between signal and noise.

3.5 Conclusion

In cognitive radio networks, the interests of primary users and secondary users are contradictory. In this chapter we studied different sensing techniques, using which secondary users can find the white holes and utilize them in the way they want. Using energy detection scheme, we have proved that there indeed exists an optimal sensing time which achieves the best tradeoff. Cooperative sensing has also been studied based on the proposed tradeoff methodology.

Chapter4

Cognitive radio spectrum access using different techniques

RECENTLY, the technology of cognitive radios has captured the attention of many research in that it promises an effective way of enhancing spectrum usage and solving the problem of heterogeneity of radio devices [28-30]. A Markov chain model was proposed to predict the behavior of open spectrum access in unlicensed bands [29]. For spectrum accessing licensed bands, two Markov chain models were investigated in[31] .In a radio network consisting of primary users (licensed users) and cognitive users (unlicensed users), the primary users do not always fully utilize their spectrum. The cognitive users may therefore temporally occupy the unused sub-bands. However, the cognitive users need to vacant these sub-bands when primary users want to use them. When this occurs, the affected communication links of the cognitive users will be lost. But if the cognitive users can sense idle sub-bands they can reconstruct the communication links to them. This is called spectrum hand-off. Here we present a general model for cognitive radios access in licensed bands. Furthermore, we propose the use of channel reservation to tradeoff the forced termination probability. Significant higher throughput could be achieved if a proper number of channels were reserved [32].

4.1 System Modeling

Let there be two types of radio users , the primary users and the cognitive users , operating in the same spectrum. The spectrum consists of M primary bands nd each primary band is divided into N sub-bands. The cognitive users can be channel A1 to Anm while the primary users can be through B1 to Bm . The A and B channel overlap each other s indicated in the figure . The primary users have the priority to use the spectrum and can reclaim any sub-bands temporarily used by cognitive users . Therefore the presence of cognitive users is entirely transparent to the primary users.

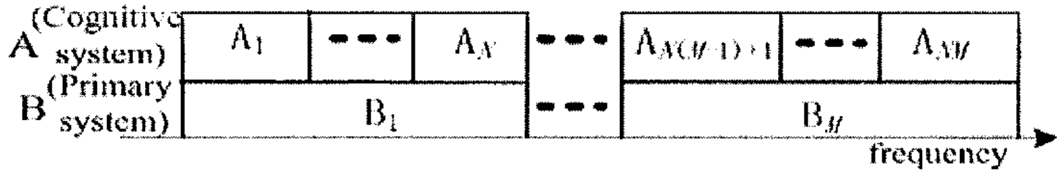

Fig 4.1Frequency bands used by two types of radio systems [33].

4.2 Spectrum Handoff

Before proposing this model, we will discuss spectrum handoff in cognitive radio systems, spectrum handoff occurs when a secondary user changes frequency due to the appearance of a primary user. Spectrum handoff may result in degraded system performance because of the different propagation loss of the different frequency. In this case, data transmission is disrupted and it is more difficult to provide seamless service [33].

4.2.1 Types of Spectrum Handoff

Hard Handoff is one in which the channel in the source cell is released and only then the channel in the target cell is engaged. Thus the connection to the source is broken before or 'as' the connection to the target is made for this reason such handovers are also known as break before make. Hard handovers are intended to be instantaneous in order to minimize the disruption to the call. A hard handover is perceived by network engineers as an event during the call. It requires least processing by the network providing service. When mobile is between base stations, then mobile can switch with any of base stations. So, base stations bounce the link with mobile back and forth. This is called ping-ponging.

Soft Handoff is one in which the channel in the source cell is retained and used for a while in parallel with the channel in the target cell. In this case the connection to the target is established before the connection to the source is broken, hence this handovers is called make before break. The interval, during which the two connections are used in parallel, may be brief or substantial. For this reason the soft handovers is perceived by network engineers as a state of the call, rather than a brief event. Soft handovers may involve using connections to more than two cells, e.g. connections to three, four or more cells can be maintained by one phone at the same time. When a call is in a state of soft handovers the signal of the best of all used channels can be utilized for the call at a given moment or all the signals can be combined to produce a clearer copy of the signal. The latter is more advantageous, and when such combining is performed both in the downlink (forward link) and the uplink (reverse link) the handover is termed as softer. Softer handovers are possible when the cells involved in the handovers have a single cell site .

4.3 Comparison of Hand-offs

An advantage of the hard handover is that at any moment in time one call uses only one channel. The hard handover event is indeed very short and usually is not perceptible by the user. In the old analog systems it could be heard as a click or a very short beep, in digital systems it is unnoticeable. Another advantage of the hard handoff is that the phone's hardware does not need to be capable of receiving two or more channels in parallel, which makes it cheaper and simpler. A disadvantage is that if a handover fails the call may be temporarily disrupted or even terminated abnormally. Technologies, which utilize hard handovers, usually have procedures which can re-establish the connection to the source cell if the connection to the target cell cannot be made. However re-establishing this connection may not always be possible (in which case the call will be terminated) and even when possible the procedure may cause a temporary interruption to the call [34].

One advantage of the soft handovers is that the connection to the source cell is broken only when a reliable connection to the target cell has been established and therefore the chances that the call will be terminated abnormally due to failed handovers are lower. However, by far a bigger advantage comes from the mere fact that simultaneously channels in multiple cells are maintained and the call could only fail if all of the channels are interfered or fade at the same time. Fading and interference in different channels are unrelated and therefore the probability of them taking place at the same moment in all channels is very low. Thus the reliability of the connection becomes higher when the call is in a soft handover. Because in a cellular network the majority of the handovers occur in places of poor coverage, where calls would frequently become unreliable when their channel is interfered or fading, soft handovers bring a significant improvement to the reliability of the calls in these places by making the interference or the fading in a single channel not critical. This advantage comes at the cost of more complex hardware in the phone, which must be capable of processing several channels in parallel. Another price to pay for soft handovers is use of several channels in the network to support just a single call. This reduces the number of remaining free channels and thus reduces the capacity of the network. By adjusting the duration of soft handovers and the size of the areas, in which they occur, the network engineers can balance the benefit of extra call reliability against the price of reduced capacity [34].

Now sharing of BW between primary users nd secondary users can take place in two ways:

Cognitive Radio with spectrum handoff

Cognitive Radio without spectrum handoff

4.4 Cognitive Radio without spectrum-handoff

The process of spectrum occupation is modeled as a continuous time Markov chain. It is characterized by its states and transition rates. The NM sub-bands are shared by the primary users and cognitive users. In this case states are described by an integer pair (i ,j), where i is the total number of sub-bands used by cognitive users nd j is the total number of primary bands used by the primary users. We assume the arrivals of cognitive users and primary users are both Poisson processes with arrival rates λ_a *and* λ_b. *The corresponding service times are exponentially distributed with rates* μ_a and μ_b.

As the primary users have the priority to use the spectrum, the cognitive users can be preempted by primary users. Depending on the number of sub-bands occupied by the cognitive users in the newly preempted primary band, a forced termination in state (i, j) will move the state to one of $(i, j+1)$, $(i-1, j+1)$, $(i-2, j+1)$, . . . , $(i-(N-1), j+1)$, and$(i-N, j+1)$ as shown in Fig.2. The transition rate of a forced termination depends on the number of sub-bands k used by the cognitive users in this primary band. Let $\gamma(i,j)$ $(i-k,j+1)$ denote the transition rate from state (i, j) to state $(i-k, j+1)$. This transition occurs when the k sub-bands are in the same primary band while the residual $(i - k)$ sub-bands are distributed in the other $(M - j - 1)$ primary bands as shown in Fig given below

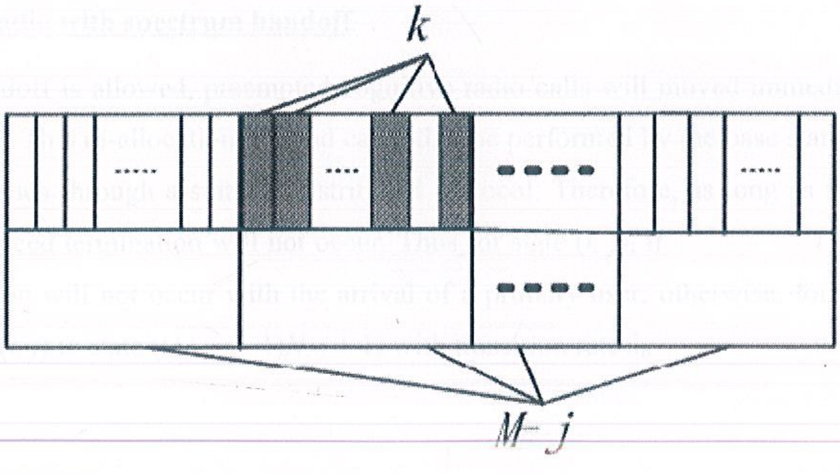

Fig 4.2 Sub-bands occupied in the forced termination state[33].

Forced termination represents a disruption of service and should be kept below a tolerable level. When the state transition is from state (i, j) to state $(i - k, j + 1)$, k out of i cognitive users will experience forced termination.

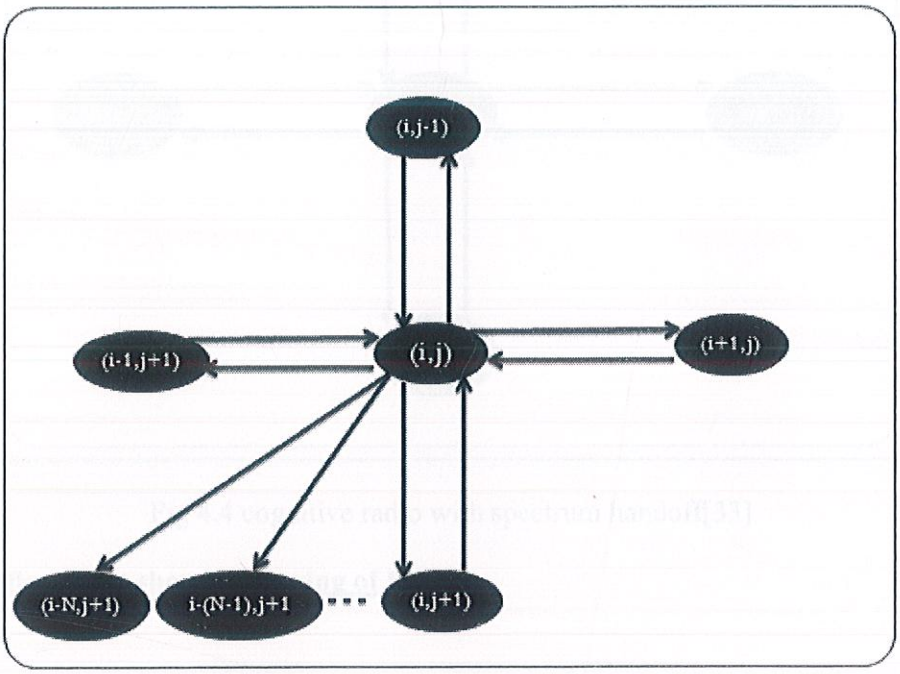

Fig 4.3 cognitive radio without spectrum handoff [33]

4.5 Cognitive radio with spectrum handoff

If spectrum handoff is allowed, preempted cognitive radio calls will moved immediately to idle sub-bands elsewhere. This re-allocation of band can either be performed by the base station centrally or by the cognitive radios through a suitable distributed protocol. Therefore, as long as there are idle sub-bands around forced termination will not occur. Thus for state (i, j), if $i + jM \le (N - 1)M$, forced termination will not occur with the arrival of a primary user; otherwise, forced termination(s) will move state (i, j) to state $((M - j - 1)N, j + 1)$ with transition rate λ_b..

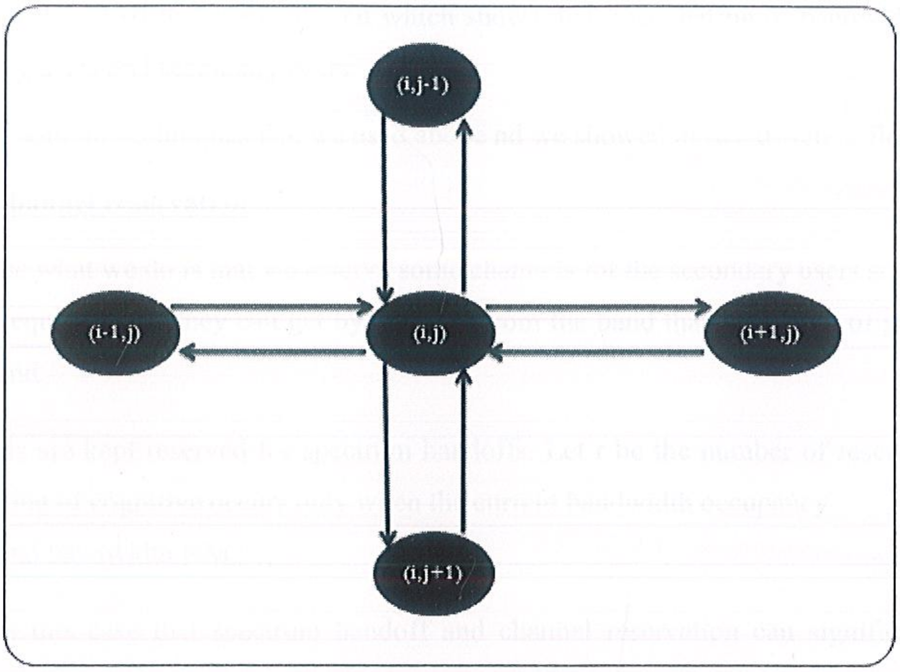

Fig 4.4 cognitive radio with spectrum handoff[33]

4.6 Complete flowchart showing sharing of BW

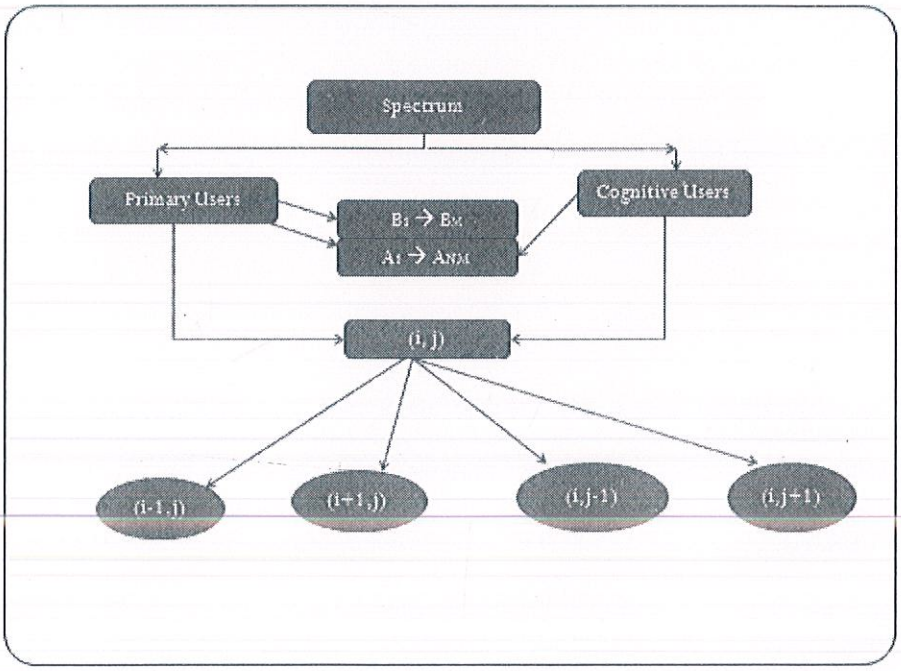

fig 4.5

This is the final flowchart that we made out which shows that how sharing of bandwidth takes place between primary users and secondary users.

It comprises of both the techniques that we used above nd we showed in two different flowcharts.

4.7 Optimal Channel reservation

In this technique what we do is that we reserve some channels for the secondary users so that whenever they need the required BW, they can get by jumping from the band that it is using of primary user to the reserved band.

Some sub bands are kept reserved for spectrum handoffs. Let r be the number of reserved sub bands .Now the blocking of cognitive occurs only when the current bandwidth occupancy (i + Nj) plus r equals to the total bandwidth NM.

It is seen from this case that spectrum handoff and channel reservation can significantly increase throughput.

Chapter 5

Cognitive Radio Bandwidth Sharing Scheme Based on the Two-Way Matching game

5.1Introduction

Bandwidth is the scarcest resource for wireless communications and may become congested to accommodate diverse types of applications. Currently, wireless network systems suffer from insufficient bandwidth utilization. To enhance the efficiency of bandwidth usage, the concept of cognitive radio has emerged as a new design paradigm. CR has been proposed as an emerging technique for the dynamic bandwidth sharing. By detecting unoccupied bandwidth holes as long as they cause no intolerable interference to licensed users (i.e. primary users).so we can make a new Dynamic bandwidth sharing strategy between primary and secondary users, the bandwidth utilization and users satisfaction can be enhanced dramatically.

So we tried to develop a new bandwidth sharing algorithm for cognitive radio networks. Here we did two things:

First is we formulate the bandwidth sharing problem as a two sided matching model. Secondly, we use a game to reach a new optimal solution.

We tried to propose a new adaptive BW sharing scheme for cognitive radio networks. Usually most previous works in the area of cognitive radio emphasized the technical aspect of BW sharing like as BW sensing technique or dynamic access protocol. However the proposed scheme focuses on the economic aspect of BW sharing. It refers to the bargaining process of selling and buying bandwidth in a cognitive radio environment. The main objective of the proposed scheme is to maximize the revenue of primary users while maximizing the satisfaction of secondary users. To satisfy this goal, users have to dynamically adapt their actions. To model the dynamic behavior of each user, the methodologies that we adopt is the two sided matching game and modified game theory.

To design a two sided matching problem, two set of individuals are given nd asked to form pairs consisting of one member from each set. For the cognitive radio game model, one side set consists of primary users, who offer the amount of sharing bandwidth to maximize their revenues. The other side set consists of secondary users, who can purchase BW to improve the QoS satisfactions.

In the proposed scheme, primary and secondary users are assumed to be self-regarding game players and select their strategies to maximize their perceived payoffs. Each player's behavior might affect the behavior of the other players. Therefore, player's decisions are coupled with one another. The dynamics of this interactive mechanism can cause cascade interactions of players nd lead the network system to an efficient state.

The proposed scheme includes the following important features:

i) ability to maintain bandwidth efficiency as high as possible.

ii) Maximizing the network revenue during the network operation.

iii)A practical and suitable approach in real world.

iv)Adaptive process to make control decision under diversified network situations.

v) Ability to estimate individual users' payoffs in a distributed manner.

5.2 Earlier evolved sharing schemes

Recently, several bandwidth sharing schemes for CR networks have been presented.

a) DMSS (Demand-Matching Spectrum Sharing) [3]

b) DBSG (Dynamic Bandwidth Selection Game) [10]

DMSS is a non-cooperative game model for CR bandwidth sharing problems. This game enables each licensed users to access appropriate bandwidth by using some method.

DBSG is a game theoretic framework to evaluate bandwidth management functionalities in CR networks. In this scheme, different quality measures are considered to select the best bandwidth opportunities under the tight constraint.

Compared to these schemes, the proposed scheme attains better performance for wireless networks.

5.3 MATCHING GAME MODEL

The two way matching game was developed for special matching problems. In two way matching problem, players on each side have preferences over player on the other side. And have enough information to rank players on the other side. The player on one side should be matched with the player on the other side so as to satisfy both the players as much as possible. A presumption in cognitive radio matching game is that both sides consists of multiple sellers and multiple buyers who have interests of their own and capacities to act upon them. When the bandwidths of Primary Users re not fully utilized, PU's have an opportunity to sell their spare bandwidth for the revenue maximization. Secondary Users want to buy bandwidth to improve their QoS satisfaction. The proposed algorithm focuses on the economic aspect of spectrum sharing. Bandwidth sharing problem in a cognitive radio can be performed based on the exchange between bandwidth and money.

From the economic viewpoint, supply function for PUs determines the amount of selling bandwidth; bandwidth selling can generate the more revenue for bandwidth owners. Similarly, demand function for SUs determines the amount of purchasing bandwidth; bandwidth purchasing can enhance the satisfaction of secondary users. Supply function is derived from the payoff gained by the primary service and the revenue received from selling bandwidth to the secondary services [39]. The profit function of the primary user i is defined as follows.

$$\mathbf{P\_Ui = [\alpha_i \times u(B_i)] + [(1-\alpha_i) \times P_i Q_i] \quad where\ u(B_i) = ln(W_i - Q_i)\ [39]}$$

where B_i , P_i are the actually allocated bandwidth for users i's primary service and the price charged for the bandwidth selling, respectively.

$u(B_i)$ is the Qos satisfaction function of user i.

W_i is the total bandwidth amount for user i

Q_i is the selling bandwidth amount to the secondary user, i.e., $B_i = W_i - Q_i$[39].

The parameter $\boldsymbol{\alpha_i}$ controls the relative weights given to QoS satisfaction($u(B_i)$) and revenue (P_iQ_i). Under diverse network environments, each user has different preference between QoS satisfaction and revenue.

Profit Function of secondary user

$$\mathbf{S\_Uj = [\beta_j \times u(Q_j)] - [(1-\beta_j) \times P_j Q_j]\ where\ u(Q_j) = ln(Q_j)}\ [39]$$

Q_j- Purchasing bandwidth amount of user j

β_j- controls the relative weights like α

Finally we have the supply function (S_i) of primary user i and the demand function (D_j) of secondary user j are defined as follows [38,39].

$$S_i = Q_i = W - [(\alpha_i/1-\alpha_i) \times 1/P_i]$$

$$D_j = Q_j = [(\beta_j/1-\beta_j) \times 1/P_j]$$

In matching game model players have their own expectations. PU player I (i € M ={m_1,…….m_g}, where g is the total number of PUs

PUS has two bargaining terms ; the selling bandwidth amount (S_i) and expected revenue(P_iQ_i). At the same time, SU plyer j (j € N = {n_1,……..n_f}), where f is the total number of SUs has two bargaining terms; the demanding bandwidth amount(D_j) and budget(P_jQ_j).

5.4 Proposed Bandwidth Sharing Algorithm(Economic factor)

In this scheme, we only took care of cost of the bandwidth at which different primary users want to sell their bandwidth and at what cost secondary users want to buy the bandwidth.

Step 1 - At the initial time, primary user set M and secondary user set N are established. The members of sets are assumed as players of the matching game using 4.

Step 2 – Each player in M has his own supply(S) function and price (P) for the bandwidth selling. In a distributed manner, players estimate the amount of selling bandwidth using 4.

Step 3 – Each player in has his own demand (D) function and price(P) for the bandwidth buying. In a distributed manner, players estimate the amount of purchasing bandwidth using 4.

Step 4 – All possible PU-SU player's matching pairs estimate the supply and demand functions and the other profit functions.

Step 5 – Player i ranks each player in N according to the functions calculated and proposes to its most preferred player j. If player j gets more than one proposal, player j retains all these proposals.

Step 6 – If all players in M offer their preference partners in N, swapping process is triggered to find the best matching for all individuals.

Step 7 – The SU player in N, who has more than one proposal, selects its most preferred PU player. Finally an effective matching pair is decided.

Step 8 – If a matching pair is finally decided, the players of decided pairs are removed in M and N sets.

Step 9 – If M and N sets are not empty, proceed to step 5 for the next matching iteration. This feedback matching procedure continues until one of both sets is empty.

Termination: If one of sets(M or N) is empty, matching game processing is over.

5.5 Proposed Simulation Model(Algorithm)

*Enter two 2D arrays corresponding to the primary users and secondary users.

*Enter all the information of both the users correspondingly bandwidth acquired, bandwidth free, selling rate, bandwidth required, maximum buying rate, etc.

*Using bubble sort, sort all the primary users (players) according to their selling rate.

*Now extract out the players from primary users according to the maximum buying rate of the secondary users by comparing both the selling rate of all the PUs and maximum buying rate of all the SUs.

*Thereafter compare the bandwidth required by the SU and the bandwidth amount free with the extracted PU players.

*There can be three cases after this comparison

i. Bandwidth required=Bandwidth free

This is the best case. Bandwidth is straightforwardly allocated considering the cost options.

ii. Bandwidth required<Bandwidth free

Bandwidth is again allocated if cost factor gets accepted, and the PU again enters the game with the remaining bandwidth.

iii. Bandwidth required>Bandwidth free

Case rejected.

- The loop runs until unless the bandwidth free with the primary users goes zero or less than the bandwidth required by any of the compatible secondary user.

Flowchart

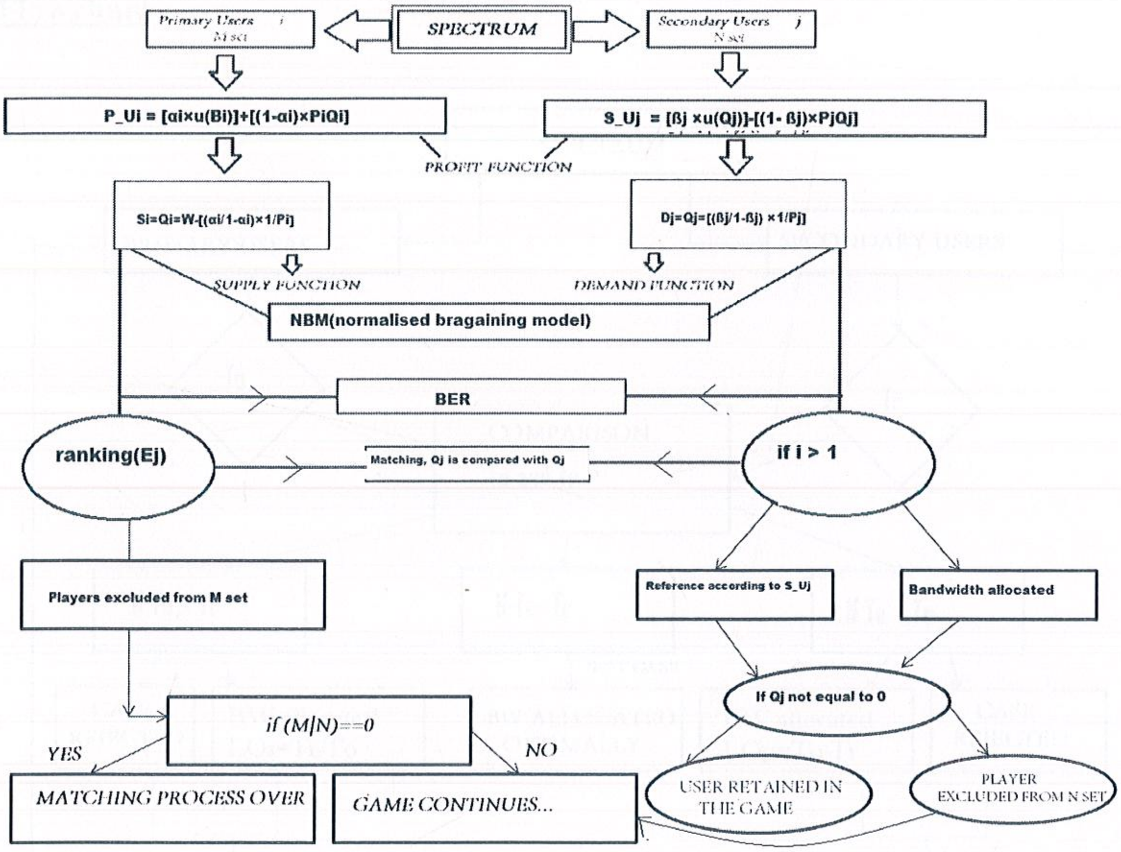

Fig 5.1 Flowchart showing how sharing takes place between primary users and secondary users

Flowchart

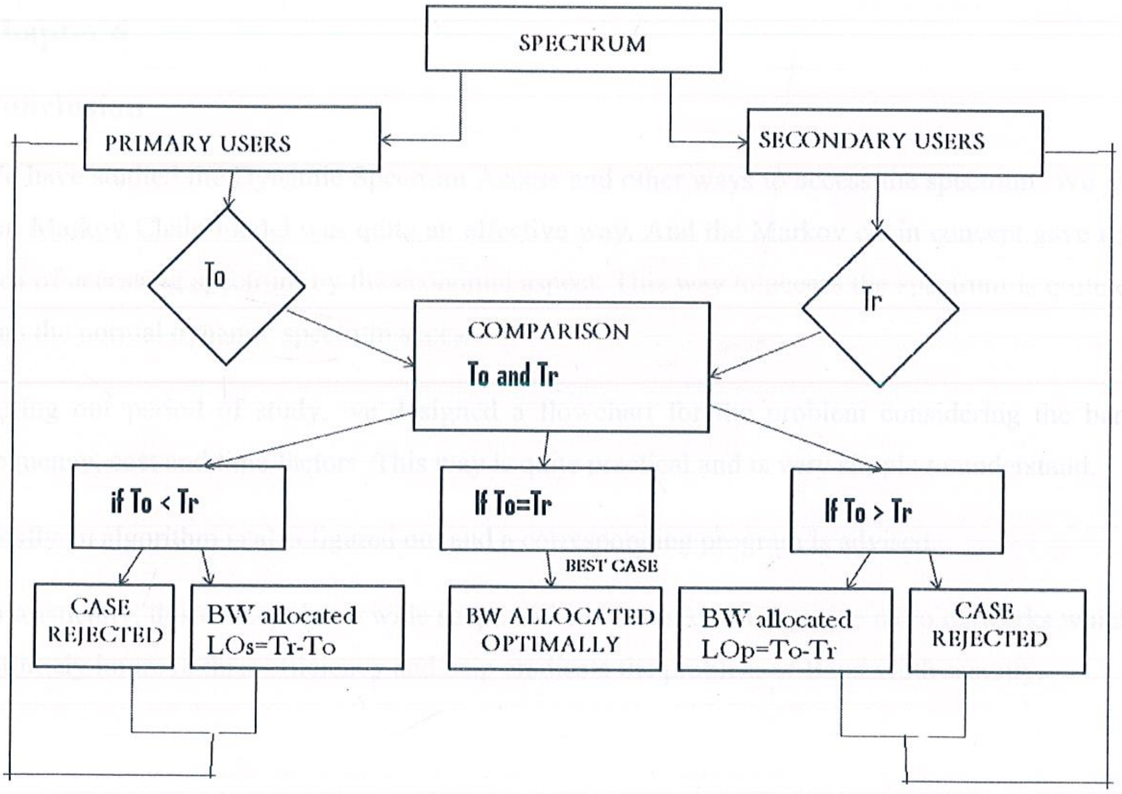

Fig 5.2 Flowchart showing how time is allocated to secondary users for using the bandwidth

T_o = time leftout

T_r = time required

Lo = leftover time

Chapter 6

Conclusion

We have studied the Dynamic Spectrum Access and other ways to access the spectrum. We found out that Markov Chain model was quite an effective way. And the Markov chain concept gave rise to the idea of accessing spectrum by the economic aspect. This way to access the spectrum is quite effective than the normal dynamic spectrum access.

During our period of study, we designed a flowchart for the problem considering the bandwidth, frequency, cost and time factors. This way is quite practical and is very simple to understand.

Finally an algorithm is also figured out and a corresponding program is advised.

Futuristically, this concept has a wide scope and can be used in Cognitive radio networks which would definitely improve their efficiency and help eradicate the problem of Bandwidth scarcity.

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APPENDIX A

Simulation

```
#include<iostream.h>
#include<conio.h>
#define MAX 100
int main()
{
        int bwf[MAX][4];
        int bwr[MAX][3];
        int cost[MAX];
        int a=0,b=0,i=0,j=0,temp=0,ch=0,k=0,fr=0;
        cout<<"Enter the primary user's information.\n";
        do{
                cout<<"\nEnter the bandwidth range now.\nEnter the starting value : ";
                cin>>bwf[a][1];
                cout<<"Enter the ending value : ";
                cin>>bwf[a][2];
           cout<<"Enter the bandwidth already used : ";
                cin>>bwf[a][0];
                cout<<"Enter the selling rate : ";
                cin>>bwf[a][3];
                cout<<"Do you wish to continue? 1.Yes 2.No";
                cin>>ch;
                a++;
        }while(ch==1);
        b=0;
```

```
cout<<"\n\nEnter the buyers information.\n";
do{
        cout<<"\nEnter the bandwidth needed : ";
        cin>>bwr[b][0];
        cout<<"\nEnter buying rate : ";
        cin>>bwr[b][1];
        bwr[b][2]=0;
        b++;
        cout<<"Do you wish to continue? 1.Yes 2.No";
        cin>>ch;
}while(ch==1);
for(i=0;i<a;i++)
{
        for(j=0;j<(a-1);j++)
        {
                if(bwf[j][3] > bwf[j+1][3])
                {
                        for(k=0;k<4;k++)
                        {
                                temp = bwf[j][k];
                                bwf[j][k] = bwf[j+1][k];
                                bwf[j+1][k] = temp;
                        }
                }
        }
}
for(i=0;i<b;i++)
{
        j=0;
        while(bwr[i][2]==0 && j<a && bwr[i][1]>=bwf[j][3])
        {
                fr = bwf[j][2]-bwf[j][1]-bwf[j][0];
```

```
            if(bwr[i][0]<fr)
            {
                bwf[j][0]-=bwr[i][0];
                cost[i] = bwf[j][3]*bwr[i][0];
                bwr[i][2]=1;
            }
            j++;
        }
        if(bwr[i][2]==1)
        {
            cout<<"\nBandwidth has been allocated at a total cost of "<<cost[i];
        }
        else
            cout<<"\nBandwidth is not allocated";
    }
    return 0;
}
```

Program 1

```
Enter the primary user's information.

Enter the bandwidth range now.
Enter the starting value : 0
Enter the ending value : 100
Enter the bandwidth already used : 40
Enter the selling rate : 10
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth range now.
Enter the starting value : 100
Enter the ending value : 200
Enter the bandwidth already used : 50
Enter the selling rate : 30
```

```
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth range now.
Enter the starting value : 400
Enter the ending value : 600
Enter the bandwidth already used : 70
Enter the selling rate : 40
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth range now.
Enter the starting value : 800
Enter the ending value : 900
Enter the bandwidth already used : 20
Enter the selling rate : 20
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth range now.
Enter the starting value : 900
Enter the ending value : 1000
Enter the bandwidth already used : 60
Enter the selling rate : 10
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth range now.
Enter the starting value : 0
Enter the ending value : 0
Enter the bandwidth already used : 0
Enter the selling rate : 0
Do you wish to continue? 1.Yes 2.No2
```

```
Enter the buyers information.

Enter the bandwidth needed : 30

Enter buying rate : 10
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth needed : 20

Enter buying rate : 15
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth needed : 25

Enter buying rate : 25
Do you wish to continue? 1.Yes 2.No1

Enter the bandwidth needed : 40

Enter buying rate : 10
Do you wish to continue? 1.Yes 2.No1
Enter the bandwidth needed : 35
Enter buying rate : 25
Do you wish to continue? 1.Yes 2.No2

Result we get is
Bandwidth has been allocated at a total cost of 300
Bandwidth has been allocated at a total cost of 200
Bandwidth has been allocated at a total cost of 250
Bandwidth has been allocated at a total cost of 400
Bandwidth has been allocated at a total cost of 350
```