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AN EFFICACIOUS COGNITIVE RADIO NETWORK: PARAMETRIC MODELLING

Project Report submitted in partial fulfillment of the requirement
for the degree of

Bachelor of Technology

in

Electronics and Communication Engineering

By

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May 2010

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Waknaghat, Solan - 173 234, Himachal Pradesh

“The power of God is with you at all times; through the activities of mind, senses, breathing, and emotions; and is constantly doing all the work using you as a mere instrument.”

- Shrimad Bhagvat Geeta

Surrendered to the lotus feet of the Lord.

Certificate

This is to certify that the project report entitled "*An Efficacious Cognitive Radio Network: Parametric Modelling*", submitted by Jayant Rajpurohit, Mayank Agarwal and Pradeep Aluru 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.

Date : 19.05.2010

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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 Rajiv Kumar, Ms Neeru Sharma, Mr Bhasker Gupta 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.

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List of Abbreviations

AACR - Aware and Adaptive Cognitive Radio
ADC - Analog to Digital converter
AI – Artificial Intelligence
ASIC – Application Specific Integrated Circuit
BBU – Base band Unit
BER – Bit Error Rate
CCDF -- Complementary Cumulative Distribution Function
CDMA – Code Division Multiplex Access
CR – Cognitive radio
CSB -- Coarse Sensing Blocks
DAC – Digital to Analog Converter
DARPA – Defense Advanced Research Projects Agency
DC – Direct Current / Duty Cycle
DDC – Digital to Digital Converter
DSA -- Dynamic Spectrum Access
DSP -- Digital Signal Processor
DSPH – Digital Signal Processing Hardware
DSPS -- Digital Signal Processing Software
DSR -- Dedicated Sensing Receiver
DUC – Digital Up Converter
FCC -- Federal Commission on Communications
FER -- Frame Error Rate
FFT – Fast Fourier Transform
FPGA – Field Programmable Gate Array
FRS -- Fine Resolution Sensing
GSC -- Global Standards Collaboration
GSM – Global System for Mobiles
GUI -- Graphic User Interface
HDTV – High Definition Television

iCR – Ideal Cognitive radio

IF – Intermediate Frequency

IFU – Intermediate Frequency Unit

LO – Local Oscillator

LUT -- Look Up Table

MAC – Medium Access Control

MC-CDMA -- Multi- Code - Code Division Multiplex Access

NC – Non- Cooperative

OFDM – Orthogonal frequency Division Multiplexing

PA -- Power Amplifier

QoS -- Quality of Service

QoI -- Quality of Information

RBF -- Radial Basis Function

RF – Radio Frequency

RFU – Radio Frequency Unit

SDR – Software defined Radio

SINR -- Signal to Interference and Noise Ratio

SNR -- Signal to Noise Ratio

TC -- Totally Cooperative

VCO – Voltage Controlled Oscillator

WRC -- World Radio Communication Conferences

WSS -- Wide-Sense Stationary

Abstract

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 can also minimize spectral congestion

If a radio could use favourable frequencies and choose waveforms that would minimize and avoid interference with existing radio 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) interface with wide variety of networks and optimization of network resources (iii) interface with humans and providing electromagnetic resources (for example laptops and television) to aid the human in his or her activities. A complete three sixty degree adaptation to this model would result in an ideal cognitive radio (iCR).

In this project we have analysed various aspects of cognitive radio, particularly spectrum management issues in cognitive radio networks. The project deals in depth with the issues of dimensional validity of a cognitive radio. This aspect of dimensionality is unique and interesting. The project discussed and analysed this part in great detail.

The project validates the acceptance of a lower SINR value by a cognitive radio network. The report illustrates the successful logical methods devised during the course of the project, to optimize and reduce sensing time to a great extent. Also, the report mentions the limitations faced in reducing sensing time because of false alarm possibilities. This is followed by designing of the reasoning agent, through a geometric distribution fit. Finally the report solidifies the project my mentioning the various application possible through this cognitive radio network by using variable throughput.

Key words: Cognitive radio, Software defined radio, spectrum management, intelligence.

CHAPTER 1

Cognitive Radio: A Brief Overview

1.1 Familiarising with Cognitive Radio

The word cognitive means the process of acquiring knowledge by reasoning or by intuition or through the senses [1]. Therefore a CR is an intelligent radio with the ability to learn as it senses its surroundings [2].

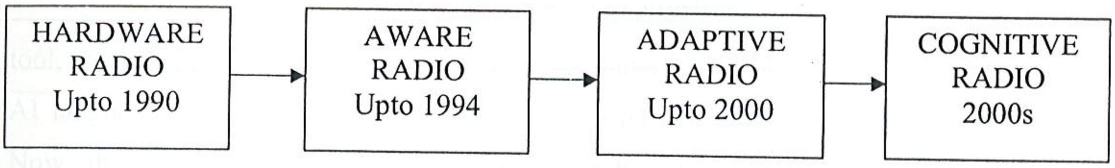

Figure 1.1 The journey towards cognitive radio.

Radios that sense all or part of their environment are considered aware systems [3]. It may drive only a simple protocol and provide information to maintain radios status as aware, e.g. CDMA [4]. To be adaptive is to modify ones operating parameters through programmed responses. If a radio is fully able to do the above through reasoning and also reprogram as it learns more about its environment with time and location, it is a cognitive radio [5].

Figure 1.1 and 1.2 illustrate the aforementioned concept with a conglomeration of new technologies and infrastructure. The cognitive radio is a complex model of various capabilities. The semiconductor processor, digital signal processor (DSP), analog to digital converter, digital to analog converter architecture have now turned into cognitive radio network infrastructure. Digital signal processing technologies transform into dynamic cognitive radio business model technologies that are capable of more relevant human interface and an advanced Graphic User Interface (GUI). Math, signal processing

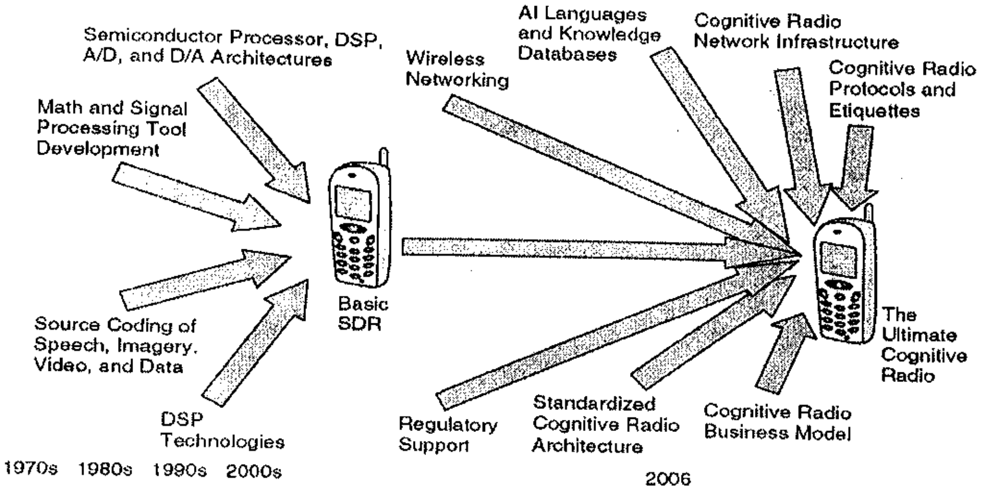

Figure 1.2 Technology timeline

tool, source coding techniques of speech, image, video and data are replaced by advanced AI languages and knowledge data base e.g. speech and emotion recognition software. Now, that the our foundation of the understanding of cognitive radio is strong, we proceed to understand the more deeper aspects of the cognitive radio [6, 7].

1.2 Spectrum Management Issues

With the rising demand of spectrum for various purposes, the current mechanism of fixed assignment of a frequency to one purpose across a huge geographic region (often an entire country) is quite inefficient [8, 9]. This results in underutilization of spectrum resources [10, 11]. This led to developing new methods to manage spectrum access in which the regulator is not required to micromanage. With cognitive radio, the regulator could define policies at a higher level [12] and expect the cognitive radio to resolve the details within the well defined boundary conditions such as available frequency [13], power, waveform [14], and geography and equipment capabilities [15].

Before we proceed further we must know what spectrum management constitutes of. It namely consists of three important tasks:

(i) Sensing

(ii) Reasoning

(iii)Accessing

Sensing and reasoning methodologies and their importance has been highlighted and discussed in depth in Chapter 4. The accessing is the real problem to be faced. Our project proposes a two tier model as a solution for this task. Once a suitable frequency is found the cognitive radio must be capable of vacating that frequency as soon as the primary user is identified [16].

An ideal approach would be to learn about current methodologies proposed for managing spectrum information. Co-operative sensing (or spectrum management) techniques have lately gained interest of researchers. It defines two protocols. First protocol is the non-cooperative (NC) protocol; in this protocol all users detect the presence of primary users and the first one to detect the primary users informs the other nodes through a central controller (distributed sensing). The second protocol defined is the Totally Cooperative (TC) protocol; here two or more cognitive radios patch up together and keep updating each other's table for new status of different bandwidths [17, 18].

1.3 Spectrum 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 [19].

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 [20]. 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.

1.3.1 How do We Create Awareness?

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.

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. This is discussed in detail in Chapter 4 and 5.

1.3.2 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 [21, 22]. 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

1.4 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. Geolocation 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). Geolocation 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 [23]. 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 [24], **LOng Range Navigation (LORAN)** used by ships at sea to calculate position, and the geopositional services of cellular telephone systems [25].

1.5 Cognitive Radio Architecture

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 [26].

For instance let us discuss the first and most important aspect of a Cognitive Radio Model (our proposed model).

1.5.1 Adaptive Receiver:

In wireless mobile communication (cognitive radio is a subset of it), info is transmitted through a radio channel. Unlike other channels, the radio channel is highly dynamic. The transmitted signal reaches the receiver by undergoing many effects corrupting the signal [27].

Hence, the receiver must be an adaptive receiver; a smart antenna is a perfect fit for it [28]. This is so because they are capable of the channel quality measurements such as;

- Received signal strength, this is done before demodulation.
- Signal to interference and noise ratio (SINR), measured during or after demodulation.
- Channel quality through BER and other metrics.

These aspects are discussed in detail in chapter 3. The other aspects of architecture are discussed in details such as the dedicated sensing receiver, reasoning agent and baseband design in Chapters 3, 4 and 5 respectively.

1.6 Regulatory 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.

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.

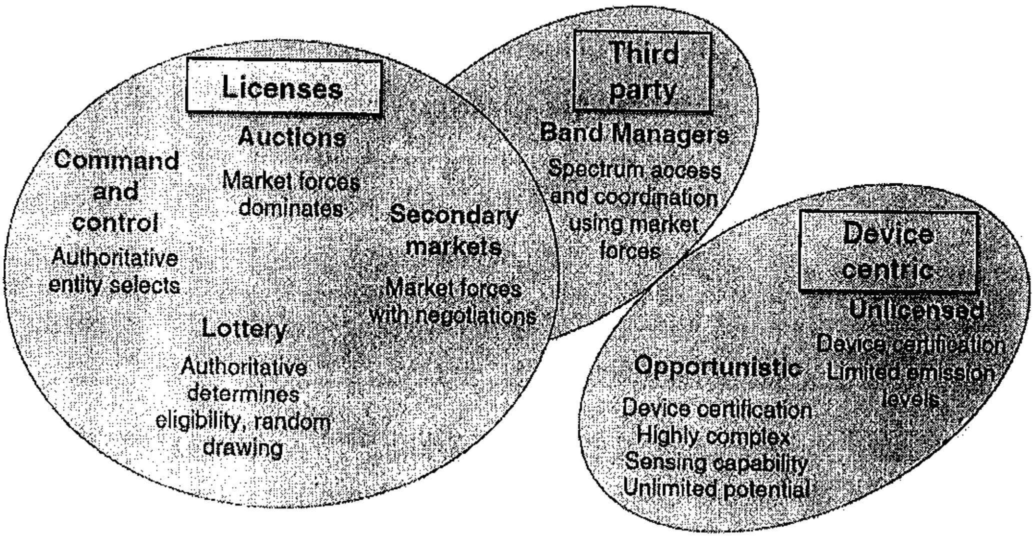

Figure 1.3 Spectrum access regimes.

- The government bodies periodically meet at World Radio Communication Conferences (WRCs)
- Global Standards Collaboration (GSC) group within the ITU

1.7 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; Geolocation 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. This knowledge, coupled with authentication goals, can prevent unauthorized users from using the CR. Most radios have sensors (e.g., microphones) that may be used in a biometric application.

CHAPTER 2

Cognitive Radio Model

2.1 Objective of the Project

The main objective of our project is to design an efficacious model for cognitive radio. To do so we must first present a broad frame of a Cognitive Radio. The diagram below shows the same.

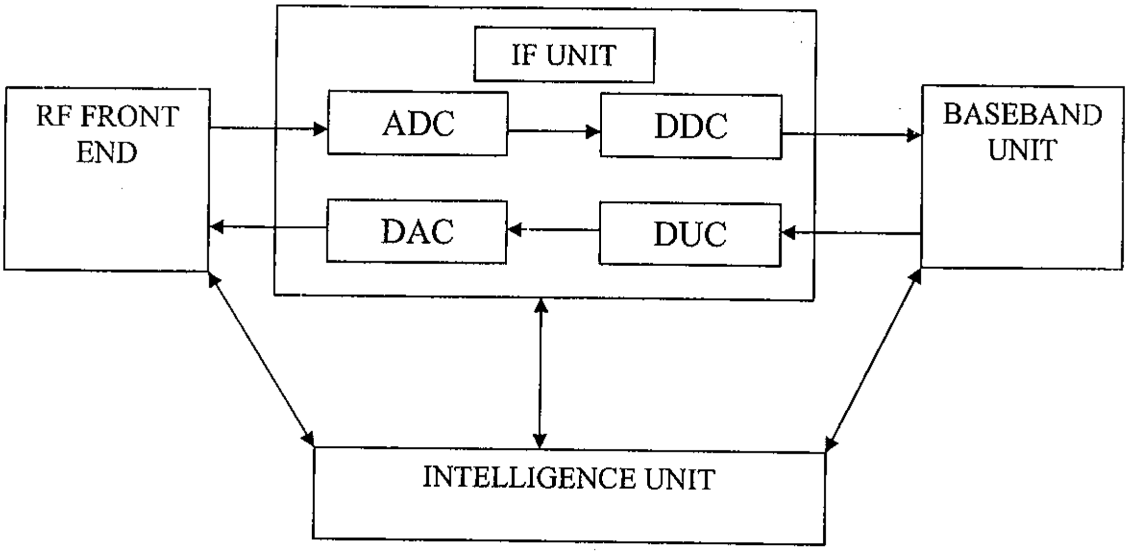

Figure 2.1 Framework of a Cognitive Radio.

The Radio frequency front end referred to as RF front end will be discussed in detail in Chapter 3. The Intelligent part comprising the dedicated sensing receiver will be discussed in Chapter 4 and finally the baseband configuration and metrics will be calculated in Chapter 5. Let us discuss these parts one by one.

2.2 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.

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.

2.3 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.

2.4 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 receiver.

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), demapping 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.

2.5 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 [31, 32]. Exploiting the statistics of spectrum use [14] or possibly the deterministic behavior of primary users [33, 34] have been proposed to make searching for spectrum holes more efficient in time and space domain.

2.6 What Parameters Are We Trying to Model?

The answer to this question lies in finding the answer to the following questions.

1. What is the Optimal SINR for a cognitive radio?
2. How does a Cognitive Radio behave in presence of variable number of other secondary and primary users?
3. Can we tradeoff SINR with some other parameters? If yes, then what are those parameters?
4. What is the optimal sensing time for a sensing technique?
5. Which is the most optimal sensing technique?

6. What methodology should be used to reduce sensing time?
7. Can sensing time be reduced indefinitely and why?
8. What are the constraints faced while trying to reduce the sensing time?
9. How should we design a reasoning agent?
10. On what basis should reasoning agent? How can we replace the work except the concept of look-up-table?
11. Which distribution fits the spectrum distribution best?
12. What is the throughput of the model?
13. Which operational frequencies provide the best throughput?
14. Can we alter our throughput? If yes, then on parameters this throughput depends?
15. What different applications can be supported by the model?
16. What are the future possible applications of this model?

All these questions are answered in the proceeding chapters. But before we proceed to find these answers we must understand what do we mean by an efficacious cognitive radio model.

2.7 Dimensional Validity of Cognitive Radio Model

An ideal CR model with the best fitted spectrum model in it should carefully check its validity in some dimensions before being confirmed as a good Cognitive Radio model with heuristic approach. We propose that the following parameters need to be considered while designing a Cognitive Radio model. Along with each dimension we also predict what features would be suitable for a model to be valid in that dimension.

1) *The Spectrum Model*: The model should be simple yet convey the relevant data through minimum number of false positive alarms. The distribution fit must be realistic and must convey the true data with least deviation from the actual spectrum scenario. A non binary spectrum model which shows the distribution of slot lengths over the time period will be a more feasible and better model. As it would result in fewer frequency jumps and a better model to support non-

contiguous spectrum usage. A Cognitive Radio model designed with this dimension in mind is proposed by [35]. But the drawback lies in the design is that it does not keep the sensing techniques and hardware implementation in mind. Hence this discussion of different dimensions is necessary.

2) *Reasoning Agent*: By definition the Cognitive Radio is always accompanied by a reasoning agent. Its responsibility lies to decide which spectrum to be accessed at what time and for what duration. These decisions are vital for a working of the Cognitive Radio. A reasoning agent must be able to comprehend the spectrum model efficiently for a better performance. As the Cognitive Radio will be able to detect the spectrum with the lowest duty cycle first at any instant and if found busy to access the next spectrum, ultimately moving towards the higher values of duty cycle and refresh this loop after every period of time defined.

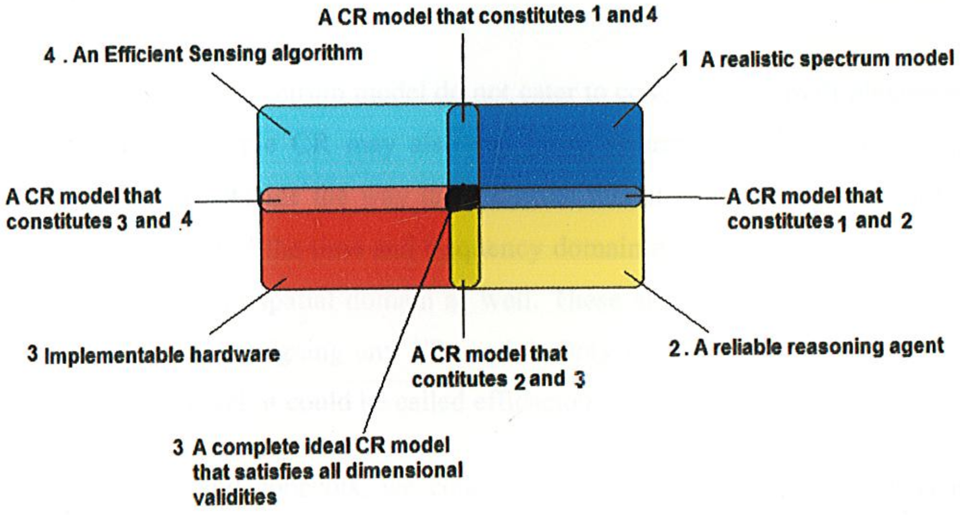

Figure 2.2 Dimensions of an ideal Cognitive Radio

3) *Spectrum Sensing Techniques*: There are various methods available in the research literature [36]. Our scope would be just to keep in mind that cooperative sensing using is the best method for sensing as it saves time and proves to be more efficient that other methodologies. For example, a cooperative sensing

methodology using GUESS (Gossip Utilization for Efficient Spectrum Sensing) methodology applied in the CR rather than complete dependence on the spectrum model. Each Cognitive Radio would be sensing only one particular spectrum at a time and share the data gathered after an interval [37]. The spectrum model will provide a base for when to sense which spectrum and result in less run time for the algorithms.

4) *Required Hardware*: The operations required for the above have a pre-requisite of MOPS (million operations per second) to run the thousands of floating operations per second. But since we propose a cooperative sensing this hardware would be required at only one place or in cooperative sensing would not be required. This dimension is at present of less concern because very efficient hardware is available in the market. Q. Zhang et al discuss such hardware aspects in [38].

2.8 Conclusion

The time series data of the spectrum model do not cater to code division multiplexing and spatial division. For example CR may also use beam steering as a way of avoiding interference as this may change the way the spectrum model is designed, because here apart from the knowledge of the time and frequency domain distribution the CR must be aware of the distribution in spatial domain as well. These are the main dimensions that must be validated before designing any CR model. Only when all four dimensions are taken care of in a CR model, it could be called efficacious.

With the above study and concepts, we conclude that only a spectrum model is not enough for heuristic approach towards a cognitive radio and a good model must be fit in all dimensions to be called an efficacious model this can be better understood with the help of Figure 2.2 .

Sood Book Binders

CHAPTER 3

Issues For RF Front End and IF Unit

3.1 The Front End

The RF front end of a cognitive radio consists of the parts as depicted in the figure below.

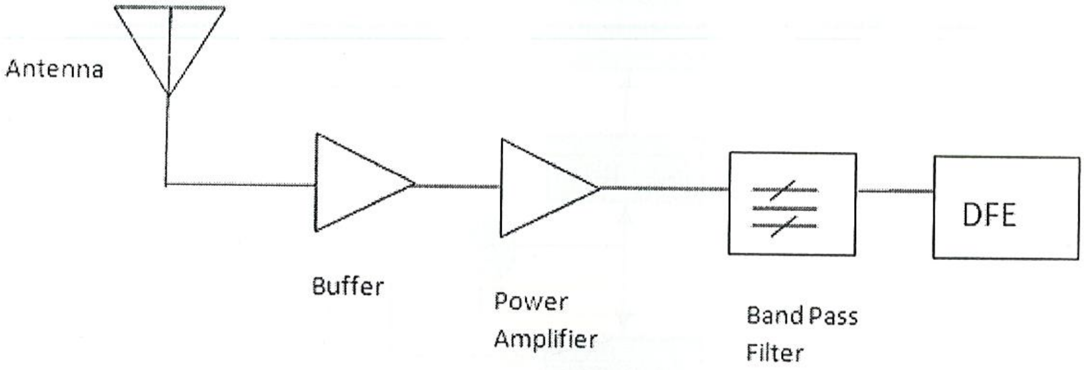

Figure 3.1 The RF Front End.

The antenna is a smart antenna as mentioned in Chapter 1, capable of various functions. Its sole purpose is to receive and transmit signals. The antenna for detection of spectrum vacancy is presented in the dedicated sensing receiver mentioned in Chapter 4.

3.1.1 Power Amplifier

The Power Amplifier (PA), is responsible for various distortions. Nonlinear distortions arise from the fact that a power efficient conversion of supplied DC power to RF signal power requires a nonlinear operation of the amplifier to a greater or lesser degree. Employing nonlinear amplification reduces the signal fidelity, so-called 'in-band' distortion occurs if seen in the frequency domain. Nonlinear amplification has a second major drawback. Due to the generated harmonics, out-of-band emissions occur, which can potentially cause interference to users in neighboring frequency bands. This interference must be kept low. Note also that, due to nonlinear effects, energy is transferred into undesired bands, thus lowering energy efficiency. Pre-distortion techniques thus have the potential to make power amplifiers more power efficient, which is an important factor for handheld terminals.

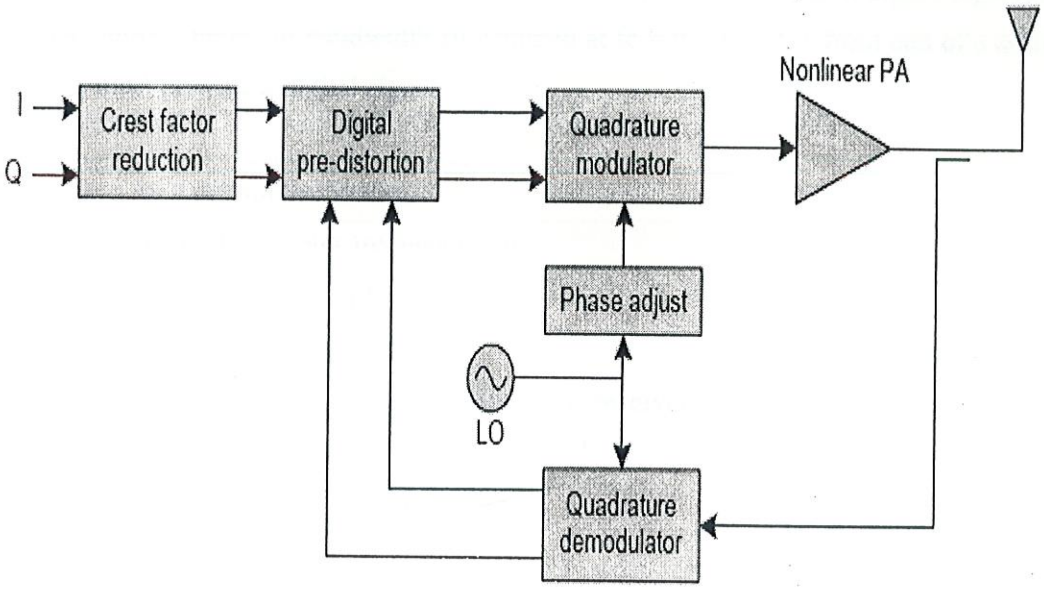

Figure 3.2 Block diagram for Digital pre-distortion with crest factor reduction.

To solve this a digital pre-distortion method is used to reduce the crest factor. Figure 3.2 shows a simplified block diagram of a digital pre-distortion scheme with crest factor reduction. Both the crest factor reduction and digital pre-distortion operate in the digital domain. The crest factor reduction aims to reduce the high 'crest factor' of modern communication systems like multi-code (MC) MC-CDMA and OFDM in order to ease the subsequent pre-distortion task. After the pre-distortion block, a DAC converts the information bearing signal into an analogue signal, which is then up-converted to RF.

3.1.2 Digital Front End

As the signal has to undergo some signal processing steps before the baseband processing is performed on a software programmable digital signal processor (DSP). These signal processing stages between antenna and DSP can be grouped and called the front end of the transceiver.

The output of the front end must deliver a digital signal (ready for baseband processing) with a sample rate determined by the current air interface. This digital signal represents the channel-of-interest of bandwidth Bi centered at fc = 0. Thus, the front end of a digital receiver must provide a digital signal:

1. of a certain bandwidth,
2. at a certain center frequency, and
3. with a certain sample rate.

Hence, the functionalities of the front end of a receiver can be derived from the four emphasized words as:

1. channelization,
2. down-conversion of the channel-of-interest from RF to baseband, and
3. filtering (removal of adjacent channel interferers and possibly matched filtering),
4. digitization,
5. sample-rate conversion
6. Synchronization

3.2 The IF Unit

Handsets impose restrictions on the size of devices as well as their power consumption in order to permit small casing and a long battery life. Further, the number of mobile handsets and competitiveness of the market favours low cost solutions. Therefore, factors such as size, power consumption, as well as the commercial cost of conversion devices are decisive in the handset.

At the base station it can be desirable to convert multi-carrier signals and hence replace multiple radios, each operating on one or a subset of carriers, by a single front-end device. Hence ADCs and DACs in the base station may require larger bandwidths, which can here be traded off against the size, power consumption and cost of the conversion devices.

While ADCs with 14 bit resolution have been utilised for most SDR test beds that permit a limited standard integration, future SDRs that can manage a whole host of standard implementations might require higher bit resolutions due to the potentially strong difference in power levels defined for the candidate schemes to be combined in a single device. For transmitters, the DAC is, in general, not as critical since commercially available devices are generally faster, cheaper and have higher resolution than their commercially available ADC counterparts. With respect to a required resolution, currently a word length of 12 bits is applied in most SDR prototypes and is often deemed sufficient. Some available hardware is mentioned below.

Table 3.1 Commercial ADCs aimed at SDR applications

Man.	**Component**	**Rate**	**Resolution**	**Power**	**Cost**	**Comment**
TI	ADS1605	5 MSps	16 bit	0.56 W	$33	Sigma-delta
AD	AD10678	80 MSps	16 bit	8 W	$580	
AD	AD6645105	105 MSps	14 bit	1.5W	$88	Bandpass,200MHz
TI	ADS5500	125 MSps	14 bit	0.78 W	$95	Pipeline
TI	ADS5541	105 MSps	14 bit	0.71 W		Pipeline
AD	AD12500	500 MSps	12 bit			Released 2005
AD	AD12400	400 MSps	12 bit	8.5 W	$540	Time-interleaved, Nyquist only
AD	AD9433125	125 MSps	12 bit	1.5 W	$76	Bandpass,150MHz
TI	ADS5273	70 MSps	12 bit	1.1 W		Pipeline
AD	AD6640	65 MSps	12 bit			Bandpass,300MHz
TI	ADS5521	65 MSps	12 bit	0.285 W	$14	
Maxim	MAX108	1.5GSps	8 bit			Flash

For transmitters, the DAC is, in general, not as critical since commercially available devices are generally faster, cheaper and have higher resolution than their commercially available ADC counterparts. With respect to a required resolution, currently a word length of 12 bits is applied in most SDR prototypes and is often deemed sufficient.

Table 3.2 Commercially available DACs

Man.	**Component**	**Rate**	**Resolution**	**Power**	**Cost**
AD	AD9726	600MSps	16 bit		
TI	DAC5686	500MSps	16 bit	0.44W	$38
AD	AD9777	400MSps	16 bit	0.41W	$40
AD	AD9736	1.2MSps	16 bit	0.38W	
TI	DAC5674	400MSps	16 bit		$25

We have discussed the front end and half described the induction of a Digital Front end which will directly supply digital data to the Baseband Unit. Hence there is not much to be discussed in the Intermediate Frequency Unit. It basically consists of Analog to digital converters, digital to analog converters, digital to digital converter and digital up converters.

3.3 SINR (Signal to Interference plus Noise Ratio)

In Cognitive Radio a major issue to be confronted is interference with primary users. Hence instead of Signal to Noise Ratio (SNR) we use Signal to Interference plus Noise Ratio (SINR) for measuring the signal strength of Cognitive Radio .It is necessary to study the SINR pattern of Cognitive Radio because-

1) SINR is an important metric of wireless communication link quality.
2) Interference with primary users should be within a acceptable range.
3) Evaluating the network performance.

In this chapter we will emphasize these aspects.

Before proceeding to analyze the implication of SINR on our Cognitive Radio model, we must understand what is SINR?

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Signal to Interference plus Noise Ratio (SINR) is the ratio of the received strength of the desired signal to the received strength of undesired signals (noise and interference). In simple words SINR can be defined as the ratio of signal power to the combined noise and interference power.

$$SINR = \frac{P_{signal}}{P_{noise} + P_{interference}} \tag{3.1}$$

Where, P is the averaged power. Values are commonly quoted in decibels.

The Signal-to-Interference-plus-Noise Ratio (SINR) is an important metric of wireless communication link quality. SINR estimates have several important applications. These include optimizing the transmit power level for a target quality of service, assisting with handoff decisions and dynamically adapting the data rate for wireless Internet applications. Accurate SINR estimation provides for both a more efficient system and a higher user-perceived quality of service.

The SINR provides a reliable signal quality parameter that is useful in a cellular communications system for procedures such as hand-off, adaptive channel allocation, dynamic power control, and cell tearing.

In mobile communication each mobile is assigned to the base station in the network where the mobile's SINR is maximized. So SINR is a very significant parameter for measuring the performance in a wireless network. Different users have different SINR requirement so it is very important that the SINR of a particular user is within a certain acceptable range. Consider a radio with a goal of achieving a target SINR. Presumably, an intelligent radio would prefer any SINR that is closer to its target over an SINR that is farther away. In Cognitive Radio our aim is to maximize their signals' SINR at the receiver. The aggregated transmit power of the secondary users must be constrained to keep the interference level low.

On the basis of environmental conditions, like estimated spectral occupancy and signal-to interference-noise ratio (SINR), devices should be able to make decisions that best suit their requirements but at the same time have minimum detrimental impact on other devices.

ADC conversion process, can inject noise into the signal through a variety of sources. Thus, the effective signal-to interference and noise ratio (SINR) of the received signal is lower than might otherwise be expected from the receiver front-end. To overcome this problem, software solutions will not suffice so Tunable RF components, such as tunable filters and amplifiers are used to overcome this problem [2].

3.4 Limitation in existing literature

Licenced Spectrum is the band for which the users have to pay to use it and these users are called primary users. CRs don't have pay to use the licensed as well as unlicensed band (or license exempt band like ISM 2.45 GHz band) and they are called secondary users. Primary users have a higher priority over the licensed spectrum than the secondary users so that the quality of communication of primary users is not affected

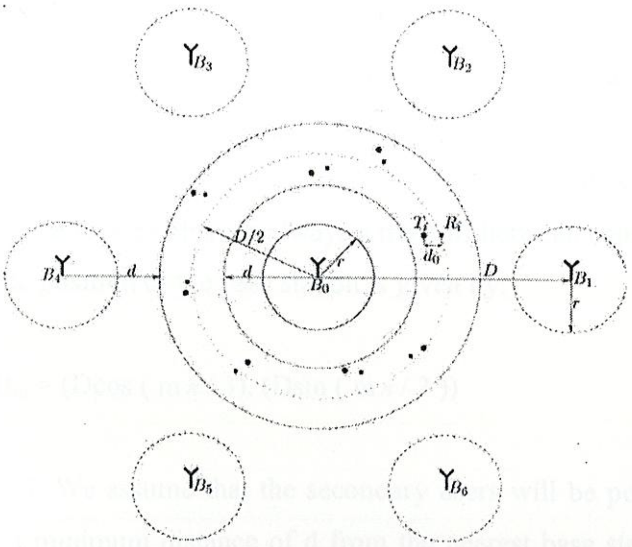

Figure 3.3 Cognitive Radio in primary spectrum

It is the responsibility of the secondary users to make sure that it's presence is not felt by the primary users because primary users have paid for using the licensed spectrum and moreover the primary users have a greater priority for using the licensed spectrum.

One of the most important responsibilities of CR is that the interference caused by the unlicensed users with the licensed users should be minimal. Interference limits the usable range of communication signals.

Downlink is the communication link for transmitting signals from base station to mobile station or cognitive transmitter to cognitive receiver. Uplink is the communication link for transmitting signals from mobile station to base station or cognitive receiver to cognitive transmitter. In the previous work [8] only calculates the Signal to Interference plus noise ratio (SINR) experienced by a cognitive receiver in the downlink.

We consider the downlink in hexagonal-type frequency reuse pattern [39]. We include the main primary base station and the first tier of co-channel interferers as shown in figure 3.3. The cell radius of the main primary base station (B_0) and other base stations (B_1 to B_6) is r. The distance from B_0 to all the other base stations is $D=(\sqrt{3n}).r$ [40], where n is the cluster size and 1/n is the frequency reuse factor of the primary system. The base stations (B_0 to B_6) are transmitting omni-directionally with a power P_B. For a hexagonal geometry the ratio $Q = D/r = \sqrt{3n}$ is called co-channel reuse ratio [40]. If n is small or Q is small then the capacity of the system is large but the inference will also be large. If n is large or Q is large then the capacity of the system will be less but the interference will also be less. So there is always a tradeoff between capacity of the system and interference. The position of the base station is given by:

$$B_0 = 0 \text{ and } B_m = (D\cos(m\pi/3), (D\sin(m\pi/3)) \qquad (3.2)$$

where m = 0,1,2... 5. We assume that the secondary users will be permitted to operate only if they are at a minimum distance of d from the nearest base station [39, 41]. We also assume that N cognitive transmitters are spread out randomly between the ring formed by the two circles, one centered at B_0 with radius d and another circle of radius (D-d) as shown in figure 3.3. For each Cognitive transmitter there is a corresponding cognitive receiver at a distance of d_0 and at an angle θ from the cognitive transmitter.

The range of θ is $[-\pi, \pi]$ but the cognitive receiver can be only inside the above mentioned ring. The position of the cognitive transmitters is:

$$T_j = (x_{Tj}, y_{Tj}), j = 1,2\ldots N. \quad (3.3)$$

The positions of the cognitive receiver are denoted by:

$$R_j = (x_{Tj} + d_0 \cos\theta, y_{Tj} + d_0 \sin\theta), j = 1,2\ldots N \quad (3.4)$$

Now we consider the path loss distance dependent model. We define the channel gain function at a distance x,

$$\rho(x) = x^{-\alpha} . 10^{\lambda/10}, \quad \lambda \sim N(0, \beta) \quad (3.5)$$

Where, α is the path loss exponent and β is the standard deviation of lognormal fading in decibels (dB). $\rho(x)$ is the function which measures he attenuation of a signal at a distance x from the base station. For example power received by a mobile station at a distance of x from the base station is $P_B \times \rho(x)$. So it means that if the mobile station changes its position then the power received by it from the base station also changes.
Area [8] of the cognitive operation is:

$$A = \frac{(D-d)^2 - d^2}{D^2} = 1 - 2\frac{d}{D} \quad (3.6)$$

This is the total permitted area where CR can operate.

We will limit the CR power according to the equation:

$$N P_C = \in P. \quad (3.7)$$

The operating point of primary system is [8]:

$$\Psi = \left[\frac{P\sum_{n=1}^{6}\rho(|((r\cos(\partial), r\sin(\partial)) - B_{n|}|)}{\sigma^2}\right] = \frac{P\mu}{\sigma^2} \tag{3.8}$$

Now we will calculate the interference power received by the j^{th} cognitive receiver. The cognitive receiver will receive two types of interference power [8].

First is the interference power from the base station and can be written as:

$$P_B \times \sum_{m=0}^{6}\rho(|R_j - B_m|) \tag{3.9}$$

Second is the interference power received from all the cognitive transmitters except the j^{th} cognitive transmitter and it can be written as:

$$P_C \times \sum_{i \neq j}\rho(|R_j - T_i|) \tag{3.10}$$

So the expression of the signal to interference plus noise ratio for the j^{th} cognitive receiver becomes:

$$\mathrm{SINR}_j = \frac{P_c \times \rho(d_0)}{[\sigma^2 + P_B\sum_{n=0}^{6}\rho(|R_j - B_m|) + P_C\sum_{i \neq j}\rho(|R_j - T_i|)]} \tag{3.11}$$

But this expression of SINR caters only to downlink and it does not consider the interference due to uplink. So in the next section we will calculate SINR by considering both the downlink as well as uplink.

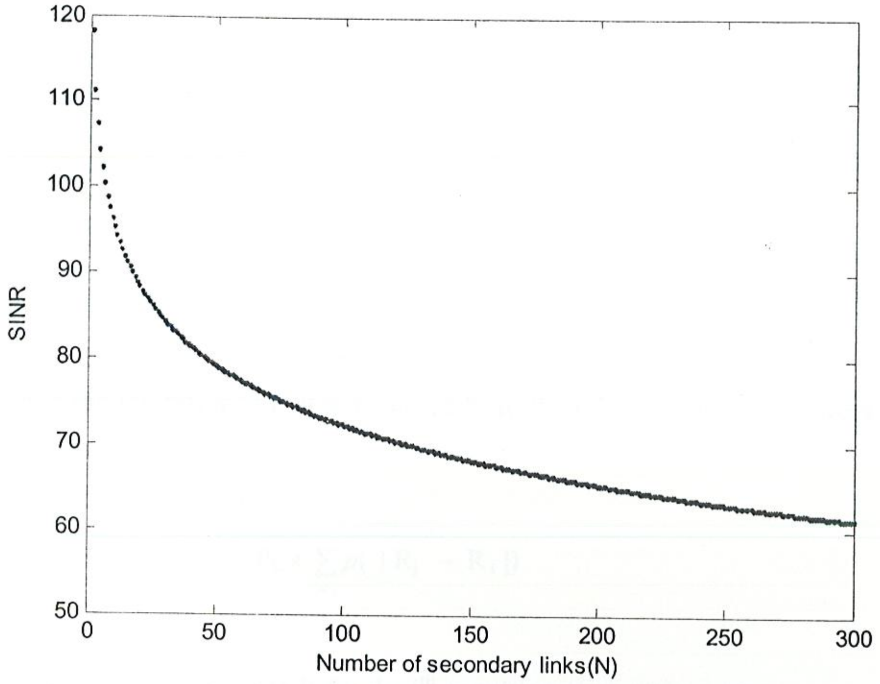

Figure 3.4 This graph shows the variation of SINR with increasing N

3.5 Our Approach in improving the limitation

In this section the previous work [8] which only calculates SINR experienced by a cognitive receiver in the downlink is extended. So in this section SINR experienced by a cognitive receiver in the downlink as well as uplink is calculated.

If we consider both uplink as well as downlink then the cognitive receiver will receive four types of interference power. First is the interference power from the base station and can be written as:

$$P_B \times \sum_{m=0}^{6} \rho(|R_j - B_m|) \tag{3.12}$$

Second is the interference power from the mobile stations which can be written as:

$$P_M \times \sum_{p=0}^{H} \rho(\,|R_j - M_p|\,) \tag{3.13}$$

Where, M_p represents the mobile stations and H are the number of mobile stations. Third is the interference power received from all the cognitive transmitters except the j^{th} cognitive transmitter and it can be written as:

$$P_C \times \sum_{i \neq j} \rho(\,|R_j - T_i|\,) \tag{3.14}$$

Fourth is the interference power received from the other cognitive receivers and it can be written as:

$$P_C \times \sum_{i \neq j} \rho(\,|R_j - R_i|) \tag{3.15}$$

So the expression of the SINR for the j^{th} cognitive receiver becomes:

$$\mathrm{SINR}_j = \frac{P_c \times \rho(d_0)}{[\sigma^2 + P_B \sum_{n=0}^{6} \rho(|R_j - B_m|) + P_M \sum_{p=0}^{H} \rho(|R_j - M_p|) + P_C \sum_{i \neq j} \rho(|R_j - T_i|) + P_C \sum_{i \neq j} \rho(|R_j - R_i|)\,]} \tag{3.16}$$

In this equation we have considered both uplink as well as downlink for calculating SINR and therefore the expression of SINR calculated here will be more accurate and realistic than the SINR calculated in [8].

Now we will plot the graph showing the variation of SINR with increasing Number of secondary links (N) according to equation 3.16. In figure 3.5, the red line represents the SINR value calculated from expression of SINR in [8] and the green line represents the SINR calculated from the above expression of SINR i.e. equation 3.16.

Our focus is to show the effect of both downlink and uplink on SINR which in turn characterizes a CR. Now in figure 3.5 we are able to see that our modified SINR has a trajectory equivalent to the SINR calculated without considering uplink. This result is completely valid and comes out to be as expected.

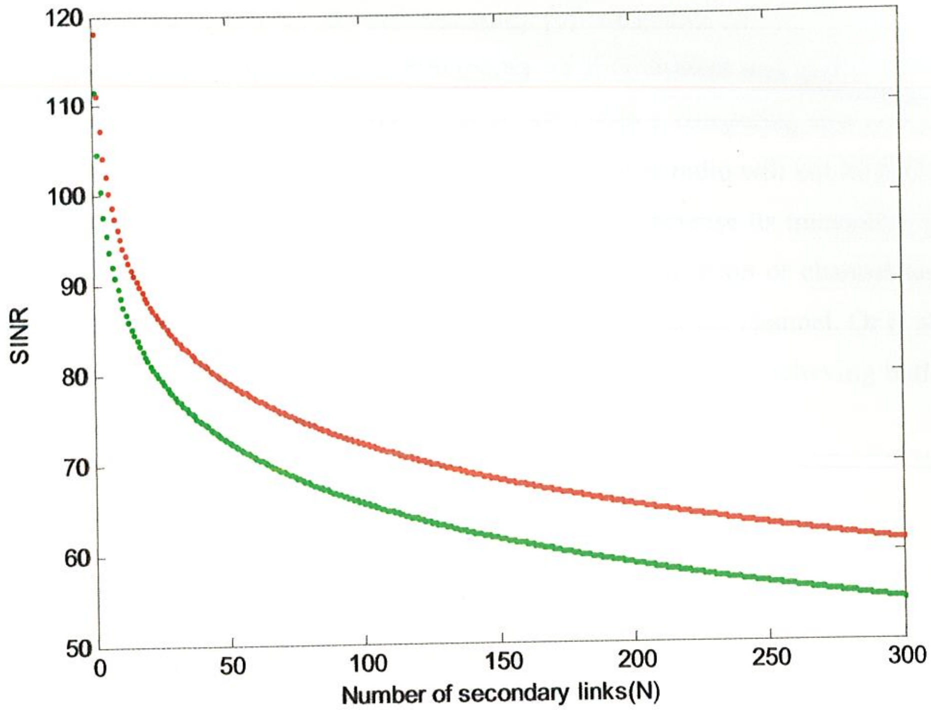

Figure 3.5 Comparison of the SINR for α =4, β =6db, n=7, A=25%, Ψ =5, ϵ = -15.

Although the SINR calculated in [8] is more than the SINR calculated from the equation (3.16) but SINR calculated in this section is more accurate, precise and apt then the SINR calculated in [8] as we have considered both the uplink and downlink for calculating the expression of SINR. As SINR is a very important parameter for calculating the performance in a wireless network, hence a more accurate and precise calculation of SINR will help us to calculate the exact performance of the system. Since the probability of a CR being affected by uplink is also there the existing literature supports the interference due to downlink but does not cater to the uplink factor. Our result brings this into consideration.

3.6 Conclusion

What we have tried to convey through our study (of acceptable SINR values by our CR model) is that; a radio capable of understanding its environment and making intelligent adaptations will recognize the problem it encounters with a competing link trying to use the same band. While observing the other link, the cognitive radio will not be limited by a simplistic understanding that "low SINR means it should increase its transmitter power." Instead, it will try other solutions, such as altering the modulation or channel coding in ways that will improve frame error rate (FER) performance in the channel. Or it will seek a channel free of interference and change its center frequency, thus relieving both radios of the burden of fighting for the spectrum.

CHAPTER 4

Optimization of Spectrum Management Issues

4.1 Sensing Time Issues

The second issue in concern with the RF front end along with the intelligence Unit (comprising the sensing and reasoning agents) is the issue of sensing time. It is necessary that the cognitive radio detect a free spectrum in a reasonable time, so that the spectrum can be utilized.

Spectrum sensing is the very task upon which the entire operation of cognitive radio rests. Cognitive radio, a new and novel way of thinking about wireless communications, has the potential to become the solution to the spectrum underutilization problem [42,43].

Spectrum sensing, defined as the task of finding spectrum holes by sensing the radio spectrum in the local neighborhood of the cognitive radio receiver in an unsupervised manner. The term spectrum holes stands for those sub bands of the radio spectrum that are underutilized (in part or in full) at a particular instant of time and specific geographic location. The task of spectrum sensing involves the following subtasks:

1) Detection of spectrum holes

2) Spectral resolution of each spectrum hole

3) Estimation of the spatial directions of incoming interferes

4) Signal classification

4.2 Spectrum Occupancy Detection Methods

The subtask of spectrum-hole detection is, at its simplest form, when the focus is on a white space (i.e., a sub band that is only occupied by white noise [44] Specifically, the detection of a white space may be performed by using a radiometer, which is well known for its energy- detection capability [45,46]. Alternatively, we may resort to the use of cyclostationarity, which s an inherent property of digital modulated signals that naturally occur in the transmission of communication signals over a wireless channel [47,48] .A number of different methods are proposed for identifying the presence of signal transmissions. In some approaches, characteristics of the identified transmission are detected for deciding the signal transmission as well as identifying the signal type.

4.2.1 Energy Detector Based Sensing

Energy detector based approach, also known as radiometry or periodogram, is the most common way of spectrum sensing because of its low computational and implementation complexities. [49]

In addition, it is more generic (as compared to methods given in this section) as receivers do not need any knowledge on the primary users' signal. The signal is detected by comparing the output of the energy detector with a threshold which depends on the noise floor [50]. Some of the challenges with energy detector based sensing include selection of the threshold for detecting primary users, inability to differentiate interference from primary users and noise, and poor performance under low signal-to-noise ratio (SNR) values [51]. The threshold used in energy detector based sensing algorithms depends on the noise variance. Consequently, a small noise power estimation error causes significant performance loss [52] .As a solution to this problem, noise level is estimated dynamically by separating the noise and signal subspaces using multiple signal classification (MUSIC) algorithms [53]. Noise variance is obtained as the smallest Eigen value of the incoming signal's autocorrelation. Then, the estimated value is used to choose the threshold for satisfying a constant false alarm rate. An iterative algorithm is proposed to find the decision threshold in [54].

The threshold is found iteratively to satisfy a given confidence level, i.e. probability of false alarm. Forward methods based on energy measurements are studied for unknown noise power scenarios in [55].

The proposed method adaptively estimates the noise level. Therefore, it is suitable for practical cases where noise variance is not known.

4.2.2 Cyclostationarity Based Sensing

Cyclostationarity feature detection is a method for detecting primary user transmissions by exploiting the cyclostationarity features of the received signals. Cyclostationary features are caused by the periodicity in the signal or in its statistics like mean and autocorrelation [56] or they can be intentionally induced to assist spectrum sensing. Instead of power spectral density (PSD), cyclic correlation function is used for detecting signals present in a given spectrum. The cyclostationarity based detection algorithms can differentiate noise from primary users' signals. This is a result of the fact that noise is wide-sense stationary (WSS) with no correlation while modulated signals are cyclostationary with spectral correlation due to the redundancy of signal periodicities. Furthermore, cyclostationarity can be used for distinguishing among different types of transmissions and primary users. The OFDM waveform is altered before transmission in [57-59] in order to generate system specific signatures or cycle-frequencies at certain frequencies. These signatures are then used to provide an effective signal classification mechanism. In [59], the number of features generated in the signal is increased in order to increase the robustness against multipath fading. However, this comes at the expense of increased overhead and bandwidth loss. Even though the methods given in [60, 61] are OFDM specific, similar techniques can be developed for any type of signal. Hardware implementation of a cyclostationary feature detector is presented in [62].

4.2.3 Waveform-Based Sensing

Known patterns are usually utilized in wireless systems to assist synchronization or for other purposes. Such patterns include preambles, midambles, regularly transmitted pilot patterns, spreading sequences etc. A preamble is a known sequence transmitted before each burst and a midamble is transmitted in the middle of a burst or slot. In the presence of a known pattern, sensing can be performed by correlating the received signal with a known copy of itself [51]. This method is only applicable to systems with known signal patterns, and it is termed as waveform-based sensing or coherent sensing. In [51], it is shown that waveform based sensing outperforms energy detector based sensing in reliability and convergence time. Furthermore, it is shown that the performance of the sensing algorithm increases as the length of the known signal pattern increases.

4.2.4 Radio Identification Based Sensing

In radio identification based sensing, several features are extracted from the received signal and they are used for selecting the most probable primary user technology by employing various classification methods. In [63] features obtained by energy detector based methods are used for classification. These features include amount of energy detected and its distribution across the spectrum. Channel bandwidth and its shape are used in [64] as reference features. Channel bandwidth is found to be the most discriminating parameter among others. For classification, radial basis function (RBF) neural network is employed. Operation bandwidth and center frequency of a received signal are extracted using energy detector based methods in [65]. These two features are fed to a Bayesian classifier for determining the active primary user and for identifying spectrum opportunities. The standard deviation of the instantaneous frequency and the maximum duration of a signal are extracted using time-frequency analysis in [66] and neural networks are used for identification of active transmissions using these features. Cycle frequencies of the incoming signal are used for detection and signal classification in [67].Signal identification is performed by processing the (cyclostationary) signal features using hidden Markov model (HMM).

4.2.5 Matched-Filtering

Matched-filtering is known as the optimum method for detection of primary users when the transmitted signal is known [68]. The main advantage of matched filtering is the short time to achieve a certain probability of false alarm or probability of miss detection [69] as compared to other methods that are discussed in this section. In fact, the required number of samples grows as O(1/SNR) for a target probability of false alarm at low SNRs for matched filtering [69]. However, matched-filtering requires cognitive radio to demodulate received signals. Hence, it requires perfect knowledge of the primary users signaling features such as bandwidth, operating frequency, modulation type and order, pulse shaping, and frame format. Moreover, since cognitive radio needs receivers for all signal types, the implementation complexity of sensing unit is impractically large [70]. Another disadvantage of match filtering is large power consumption as various receiver algorithms need to be executed for detection.

4.3 Dynamic 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 [71,72], 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 [73], 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 [74,75].

A two stage DSA approach comprises of preliminary coarse resolution sensing (CRS) [76] 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 [76], 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 [77] 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.

4.4 Dedicated Sensing Receiver

We propose a practical architecture for Cognitive Radio operation in time sensitive applications. We propose the use of a dedicated receiver that is solely focused on channel sensing and runs in parallel with a main receiver. The majority of the burden for accurate sensing and quick decision regarding channel conditions and spectrum availability is off-loaded to the Dedicated Sensing Receiver (DSR). The key to the DSR is an efficient algorithm that performs spectrum detection and continuously improves the quality of the collected data and decision process.

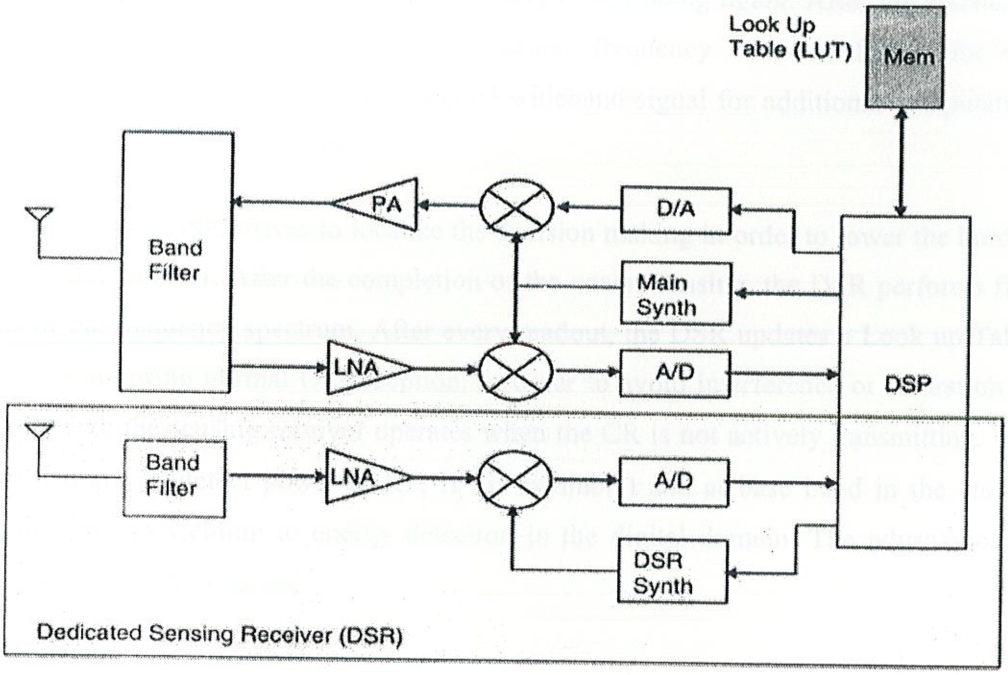

Figure 4.1 A dedicated Sensing Receiver Schematic.

The sensing receiver is equipped with detectors at RF, IF and base band for coarse and fine sensing. The main goal of the proposed DSR is to reduce sensing time and wait time and more importantly improve the quality of the decision made. The DSR main function is power detection and spectrum estimation. It must have the ability to detect the presence of another user in the band. It does not however need to perform demodulation. The addition of the DSR provides additional benefits to the overall system. The presence of two independent receive chains in the system provides channel diversity, as well as the ability to efficiently share the work load between the two receivers. However, the addition of a DSR must not add substantial cost or power consumption.

The proposed approach is to define an agile broadband radio dedicated to scan and record channel conditions in a look up table (LUT). More importantly, we propose the use of algorithms devoted to learning the channel conditions and to prioritizing the different channels for CR data transmission and reception, a method for this wil be discussed later in the chapter under the heading of *reasoning agent*. After the assistance of an initial setup, a coarse sensing generates frequency band candidates for CR operation; the DSR then stores the sampled wideband signal for additional computation and spectral detection techniques.

Specifically, the DSR strives to localize the decision making in order to lower the burden on the main receiver. After the completion of the coarse sensing, the DSR performs fine scans of the frequency spectrum. After every readout, the DSR updates a Look up Table (LUT) even during normal CR reception. In order to avoid interference or saturation of its front end, the sensing receiver operates when the CR is not actively transmitting. The DSR attempts to detect power at RF, IF (if available) and at base band in the analog domain prior to yielding to energy detection in the digital domain. The advantages of analog domain detection are

(1) Fast response

(2) Relatively low cost

(3) Relatively low power consumption.

However, analog domain detection does not work well at low SNR. It cannot differentiate among received signals and the frequency detection accuracy is mediocre at best. For the purposes of the sensing receiver and the DSR, the analog domain detection can be used to do a cursory search for the presence of energy in a band. In order to assist the initial scan time at power on, initial conditions are pre-loaded into the LUT.

The initial conditions direct the CR to avoid known frequencies where CR operation is either forbidden or unfavorable. Initial setup is dependent on geographic location, operation time and known channel conditions. For example, if the user is operating in the

US, then the CR may apply the 802.22 guidelines for CR operations in the TV bands. Additionally, the CR may be directed avoid the 0.8 GHz to 3 GHz band where the majority of wireless devices operates in the US. The initial setup reduces the scanning time and may improve the quality of decision making by avoiding false positives. The CR continuously refreshes the information in the LUT. The best time to scan and update the LUT is during off-peak hours (such as middle of night). Fast coarse scanning relies on the initial data and a priori information about the channel or user preferences that are saved in the LUT.

After completion of the fast coarse scan, the DSR prioritizes a list of candidate frequencies for use by the main receiver. The main receiver performs fine sensing on the smaller set of prioritized channels. The DSR continues on its wideband coarse scan of the remaining spectrum. Because of the need for fast scanning, the DSR uses non coherent energy detection to complete its coarse scanning before it reverts to fine sensing. The most common approach used in fine sensing is to perform Fast Fourier Transform (FFT). The FFT is performed on a captured segment of the frequency spectrum. The FFT resolution increases with the FFT size which also increases the observation time. In order to minimize power consumption, an adaptive FFT is used with the number of FFT points varying according to:

(1) Operating conditions

(2) The urgency to complete the scan.

After the fine tuning is completed and a candidate frequency band is identified, the sensing receiver continuously monitors and records activities in the band of interest.

4.5 Analysis of the Proposed DSR Design

We first describe the different notations required for the calculation of sensing time. The table below shows the practical values for certain parameters and describes the variables

Table 4.1 List of Parameters

B_{sys}	System frequency of operation
B_{crs}	Coarse sensing frequency bins
B_{fin}	Fine sensing frequency bins
F_{DSP}	DSP frequency
F_{res}	Sensing resolution
VCO control voltage	1V
PLL maximum phase jitter	1.0 deg rms
ρ	Percentage yield of candidate channels after Coarse sensing
Percentage of coarse bins known as bad channels	30%
Number of fine channel scanned between frames during normal cognitive radio operation	100
N_{crs}	FFT points for coarse mode
N_{fin}	FFT points for fine mode
M	Number of antennas
F_{res}	10KHz
N_{crs}	128 points
N_{fin}	1024 points
$T_{PLL\ crs}$	0.6 ms per channel
T_{PLL_fin}	0.35 ms for a single fine step of 10MHz

Now, the time taken by the system to perform one DFT (Discrete Fourier Transform) is given by:

$$T_{DFT} = \frac{1}{F_{DSP}}\left[4N\log_2(N) - 6N + 8\right] \tag{4.1}$$

Where, N is the number of FFT points, or points that take inputs.

If this is multiplied by the number of coarse bins and the number of FFT points in one coarse bin. We get the time for coarse sensing by:

$$T_{CRS} = \frac{B_{SYS}}{\alpha M N_{crs} F_{res} F_{DSP}}\left[4N_{crs}.\log_2(N_{crs}) - 6N_{crs} + 8\right] \tag{4.2}$$

Once this has been accounted for, we do the same for fine bins, and the expression stands out as:

$$T_{FIN}=\frac{\alpha.\beta.\rho}{F_{DSP}.M}\left[4N_{fin}.\log 2(N_{fin})-6N_{fin}+8\right] \tag{4.3}$$

Now, the processor needs some initializing time and that is taken to be 1.1 ms [78]. We also need to account for the *phase lock loop* time for both fine and coarse sensing.

$$\begin{aligned}T_{SYS}=&\frac{B_{SYS}}{\alpha M N_{crs} F_{res} F_{DSP}}\left[4N_{crs}.\log_2(N_{crs})-6N_{crs}+8\right]+\frac{\alpha.\beta.\rho}{F_{DSP}.M}\left[4N_{fin}.\log 2(N_{fin})-6N_{fin}+8\right]\\&+T_{init}+\frac{\alpha.\beta.\rho}{M}T_{PLL\_fin}+\frac{\beta}{M}T_{PLL\_crs}\end{aligned} \tag{4.4}$$

Now, in the expression for phase lock loop time, we find it to be inversely proportional to the number of antennas. But we must consider the fact that as the number of antennas increase, the synchronization problem comes into play. Therefore as proposed by [79], we should not discard the phase lock loop time even for large number of antennas. We shall assume in case of large antennas this expression would account for the time wasted in synchronization, i.e. it will then be like a penalty metric.

Now, we shall assign values to the above defined terms and run simulations accordingly to study patterns of how probability of false alarm affects the average detection time. Also we will see the trade off between number of antennas and the total system bandwidth. Equation (4.1) represents the total time to perform a DFT [79] where F_{DSP} is the Digital Signal Processor's operating frequency. Equation (4.4) represents the total sensing time of the receiver [80]. The following values have been assumed for our simulations. Further, we deduce the values of coarse and fine bins as follows:

$$\beta=\frac{B_{SYS}}{B_{cts}}=\frac{10GHz}{100MHz}=100 \tag{4.5}$$

$$\alpha = \frac{B_{crs}}{B_{fin}} = \frac{100\,MHz}{10\,MHz} = 10 \tag{4.6}$$

The number of coarse bins and fine bins are given by Equation (4.5) and (4.6) respectively [81]. A quick search which is done via the analog detector, considers only 70 good coarse bins. Considering that 40% of the measured channels are considered good, β is equal to 28. T_{init} which is the initial lock time is taken as 1.1 ms. Number of antenna is varied. F_{DSP} (Digital Signal Processor's operating frequency) is equal to 100MHz. Then the fine sensing effort is equally divided by the main receiver and the dedicated sensing receiver. The total sensing time given by Equation (4.4) is 93.9 ms for M=2. We can use an array of smart antennas say from 100 to 500. Substituting all the parameters in the equation (4.4) gives us a plot between the total sensing time and the number of antennas for a given frequency of operation.

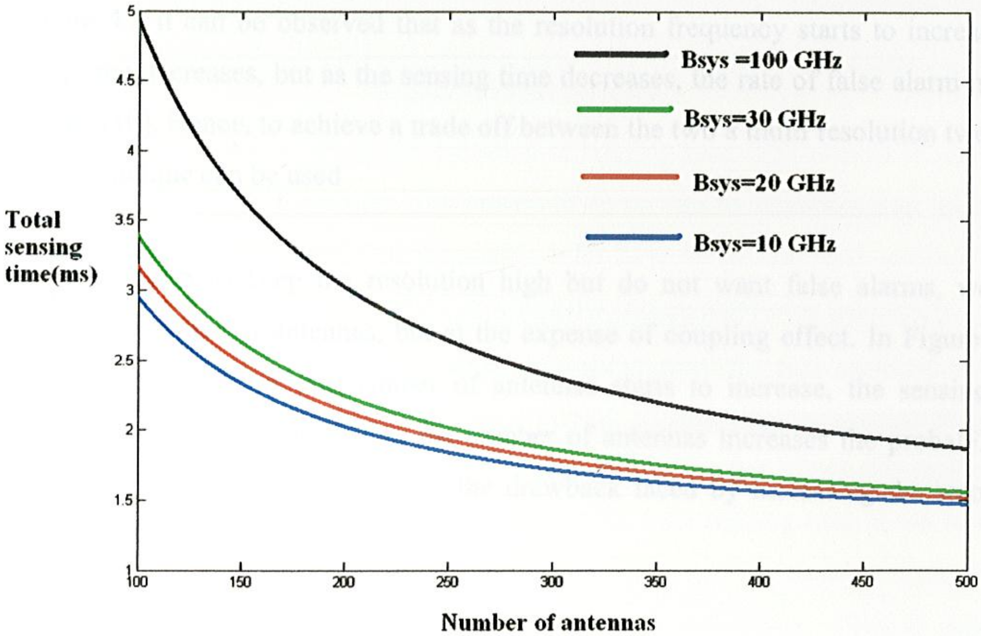

Figure 4.2. Total sensing time versus number of antennas.

We observe from the graph above that the total sensing time (t_{sys}) is reduced to a great extent as we keep on increasing the number of antennas. This graph proves the inverse relationship between the total sensing time and the number of antennas. We started with frequency of 10GHz and kept on increasing till 100 GHz. With the increase in frequency there is an increase in the total sensing time. But , as we keep on increasing the number of antennas along with the frequency ,we can reduce the total sensing time. Let us look at the plot by the values. If we fix the frequency as 10GHz and the number of antennas as 100 we get t_{sys} as 2.9562ms. Now at the same frequency if we increase the number of antennas to 200, we get t_{sys} as 2.0281ms.And finally at 500 antennas we get t_{sys} as 1.4712ms. Now if we increase the frequency of operation from 10 GHz to 20 GHz , we get tsys as 3.1768 ms for 100 antennas, 2.1384 ms for 200 antennas and 1.5154 ms for 500 antennas. Even though there is an increase in t_{sys} with an increase in frequency ,we can reduce t_{sys} with an increase in the number of antennas at such high frequencies. Let us consider the frequency of 100 GHz. We get t_{sys} to be 4.9418 ms for 100 antennas, 3.0209 ms for 200 antennas and 1.8684 ms for 500 antennas.

In figure 4.3 it can be observed that as the resolution frequency starts to increase, the sensing time decreases, but as the sensing time decreases, the rate of false alarm may go very high [16]. Hence, to achieve a trade off between the two a multi resolution two stage sensing technique can be used

Now, if we wish to keep the resolution high but do not want false alarms, we may increase the number of antennas, but at the expense of coupling effect. In Figure 4.2 it can be observed that as the number of antennas starts to increase, the sensing time decreases. It must be noted that as the number of antennas increases the probability of false alarms does not increase. Hence the drawback faced by increasing the resolution frequency is overcome.

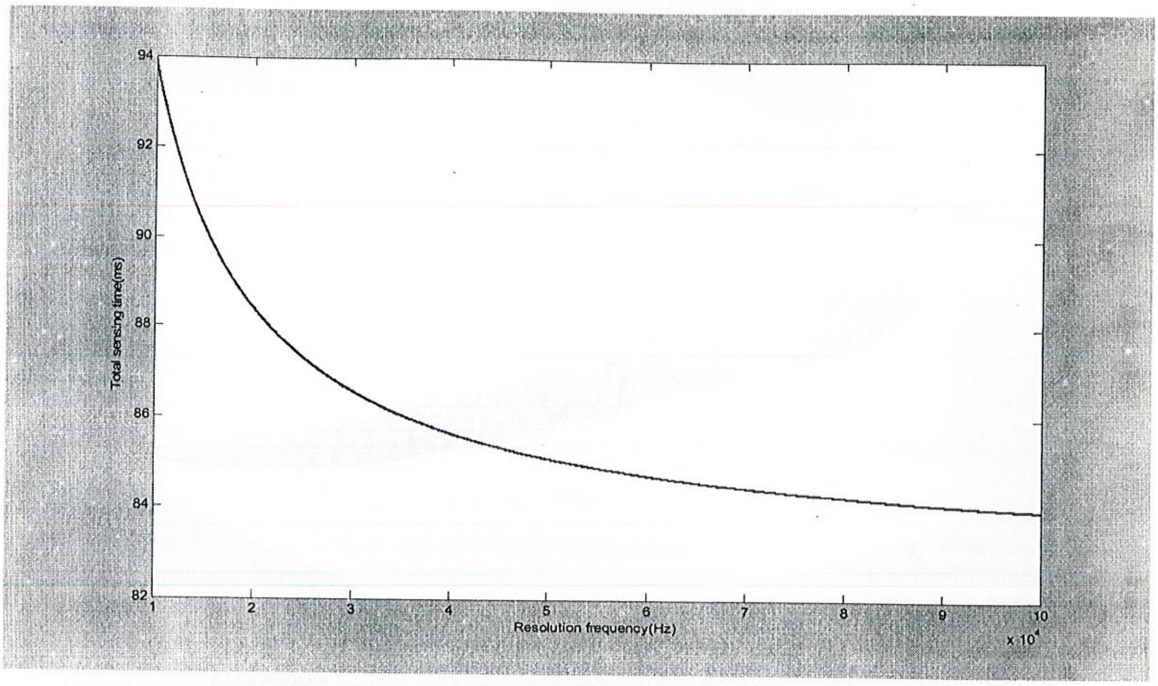

Figure 4.3 Variation of the total sensing time with the resolution frequency of the cognitive radio network.

Therefore in figure 4.4 we study the variation of sensing time with respect to number of antennas and resolution frequency. The reason to do so, can be understood as follows. In figure 4.3 with M=2 and resolution frequency at 10 KHz we get the total sensing time as 94 ms, the same can be verified in fig 1. We assume certain resolution frequency.

Figure 4.3 gives us a desired value of total sensing time for that assumed value of resolution frequency. Similarly, we assume a certain number of antennas and Figure 4.2 will give us the value of total sensing time for that assumed value of number of antennas. But, we cannot infer what would be the value of the total sensing time if we use these values of number of antennas and resolution frequency together. These two parameters, resolution frequency and number of antennas behave differently when it comes to working as a one factor i.e. as a combination. It could be a possibility that we may require the sensing time to be of 94 ms but do not want the resolution frequency to be 10 KHz

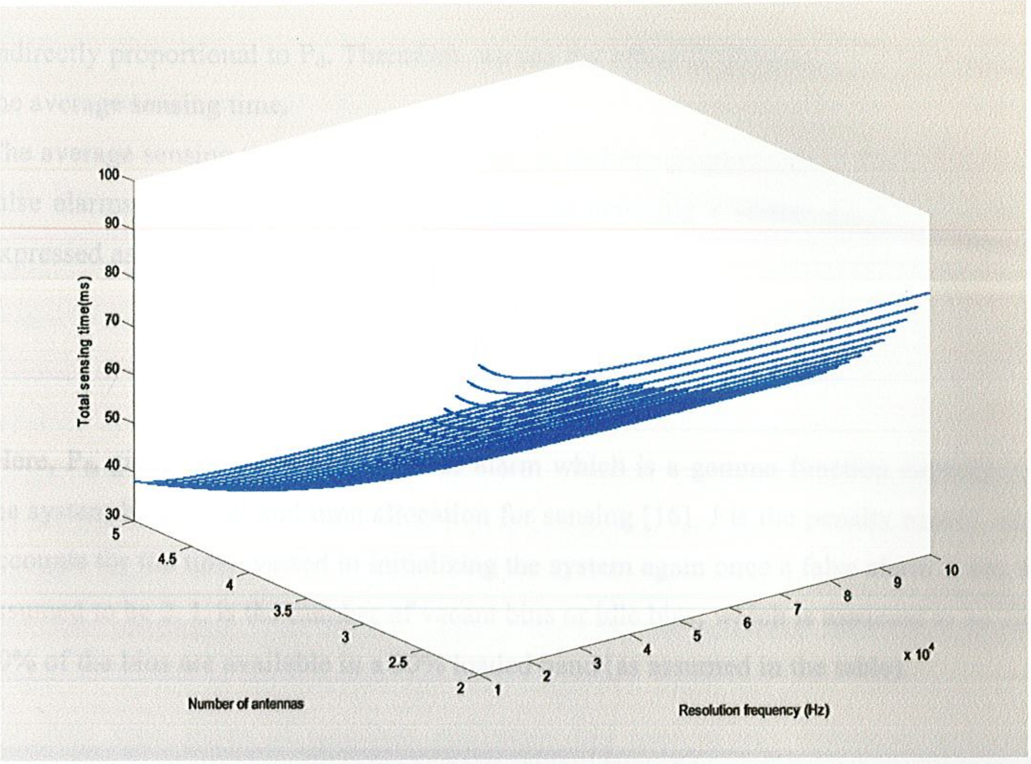

Figure 4.4 Variation of the total sensing time with the number of antennas and resolution frequency of the cognitive radio network.

. For this, we have plotted a graph in figure 4.4, from which optimal combination of number of antennas and resolution frequency can be deduced. We can observe that the total sensing time rises exponentially with the combination of antennas and resolution frequency. But with any one of the three axis values given, we can choose an optimal combination of the other two from figure 4.4. The combination of resolution frequency and number of antennas gives us a desired and practical combination of a total sensing time.

We must also keep in mind that playing with resolution frequency has a direct relation with the probability of false detection. The resolution frequency would change the P_d (probability of detection), it would become virtually very high, i.e. even if there is a primary user present the spectrum would be detected as vacant. We can logically deduce that resolution frequency is directly proportional to probability of false alarm and indirectly proportional to P_d. Therefore, we see the effect of probability of false alarm on the average sensing time.

The average sensing time (or detection time) is directly proportional to the probability of false alarms and inversely to the probability of detecting a vacant spectrum. It can be expressed as:

$$T_{\det} = \frac{(\beta - L)JP_{fa} + \beta}{P_d(L+1)} \tag{4.7}$$

Here, P_{fa} gives the probability of false alarm which is a gamma function dependant on the system bandwidth and time allocation for sensing [16]. J is the penalty matrix which accounts for the time wasted in initializing the system again once a false alarm is set, it is assumed to be 2. L is the number of vacant bins or idle bins, which is assumed to be 20 as 70% of the bins are available in a 30% loaded band (as assumed in the table).

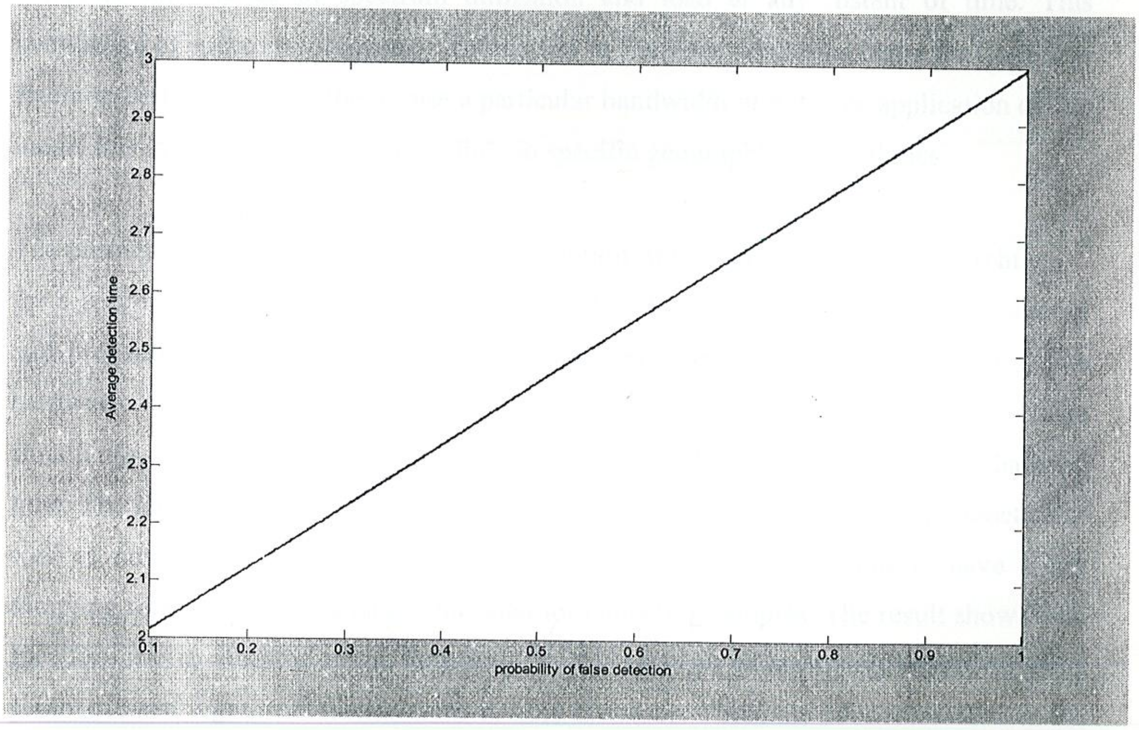

Figure 4.5 Variation of the average detection time with probability of false detection of the cognitive radio

Similarly P_d is calculated to be 0.7. Figure 4.5 reveals that average detection time has a liner relation with the probability of false alarm

4.6 Reasoning Agent

Exploiting the statistics of spectrum use [14] or possibly the deterministic behavior of primary users [33, 34] have been proposed to make searching for spectrum holes more efficient in time and space domain. Another example is the development of more flexible wireless systems that can also benefit from non-contiguous spectrum holes [82] and Cognitive Radio's must be aware of their environment. Various researches have focused on two basic fields of Cognitive Radio, first, sensing capabilities (for continuous updating for the Cognitive Radio's knowledge of the environment) and second, on models for spectrum utilization. The second field is the base for *heuristic* approach model of Cognitive Radio. In the heuristic approach Cognitive Radio has prior knowledge of the complete time series of spectrum utilization and load at any instant of time. This knowledge of spectrum occupancy in time and in frequency domains helps the Cognitive Radio to better judge whether to use a particular bandwidth or not. The application of this model lies in applying Cognitive Radio's in specific geographical boundaries.

The present methodology of deciding a distribution fit has anomalies. While searching for a solution for a new method of designing distribution fits that require less memory and processing time, we come across various other aspects of a cognitive radio, like hardware, software and sensing techniques. Models that describe the spectrum usage should not only be general to a particular area but must be able to comply with changing time. The model must provide statistical input or support for deciding QoS parameters as well as other Cognitive Radio operations. Matthias et al. [35] assume to have a low sampling rate spread over a large time span for collecting samples. The result shows that, spectrum use is clustered in the frequency domain and can be accurately described using geometric and lognormal distributions in time divisions. These are later referred to in the project as distribution fits but the heavy tailed behavior of lognormal is a drawback as it results in high probability of missed detections. Similarly in Geirhofer et al. [83] use a technology specific spectrum analyzer to study the spectrum model (utilization of spectrum in time domain) is fitted to a specific distribution, they propose that it follows a Hyper-Erlang distribution. The studies so conducted are based on assumptions that the data collected is similar even in the future and shall follow the same pattern. Thus, the results so achieved are misleading to certain extent as they do not answer some vital questions and assumes the data collected through the experiment is not prone to error and the setup is sturdy and robust. The basic loophole lies in the fact that the sampling rate decided for the experiments relies on the hardware specification rather than a calculated value through empirical or logical means.

The following questions arise and must be redressed when fitting a particular distribution fit. Firstly, the data collected through the above research is based on only the WLAN network and cannot be generalized, which brings the generality dimension into the picture. The WLAN use the exponential back-off algorithm for finding the medium access rate. Secondly, the WLAN is the dominant type of use in 2.4 GHz ISM–band, but the exponential back-off proves to be the destabilizing factor. This can be explained as the lower bandwidth (where the transmission is actually about to occur) is detected to be free and the higher frequency range where just a request is being transmitted (whose probability of being rejected is high) is detected to be vacant. This ambiguity cannot be spotted by mere distribution fit. Thirdly, the setup used for this study was technology specific with high sampling rates which gives details that may not be supported by a common Cognitive Radio of low sampling rates. Hence practicality of this distribution may not be feasible to be used in an ideal Cognitive Radio model. Ultimately, this brings the hardware dimension in the scenario. Also the empirical models explain and convey the free period that can be utilized by the Cognitive Radio but it gives no information about the QoS parameters like power. As suggested by Mittola [31] that Cognitive Radio must in the initial stages focus on low power transmission applications, the spectrum models are of little help here. Apart from the distribution fit the model must be able to convey the variance (in the detected signal power) and amount of power detected which can act as a parameter for deciding on the dynamic QoS parameter [15].

In this section we focus on finally converging towards a certain set of dimensions which must be fulfilled while deciding on a practical and efficacious distribution fit for a Cognitive Radio model.

4.7 Validation of the Reasoning Agent Model

The basic structure of a model is to present a time series of spectrum availability. It means that the Cognitive Radio should be aware of spectrum vacancies at all instances of time. There exist certain parameters that need to be elaborated before we understand how a model is prepared. Most models consider a binary availability (A) of the spectrum. The spectrum is either occupied or is vacant.

$$\mathbf{A(i)} = \begin{cases} 0 & \textbf{if the spectrum is used} \\ 1 & \textbf{if the spectrum is vacant} \end{cases}$$

To detect this availability various methods such as energy detection, matched filtering, cyclostationarity comparison may be applied [36]. But this is not within our area of interest. Such data is collected over a large span of time. This task takes a lot of time as large range of bandwidth is to be covered for the complete duration of the time taken into account. For each spectrum a separate cycle is to be run. A table is then prepared that shows the availability of a spectrum at any instant of time.

Another approach by [35] is that they calculated the number of times a one was detected and the number of times a zero. The probability of detection of a one was called a duty cycle. This was calculated as the ratio of number of samples (N) and the summation of A(i) over the span of I over 1 to N. A continuous chain of samples with no detection of interference with the primary user can be defined as a slot and a continuous chain of samples with no detection of availability can be termed as the block. A similar terminology for binary detection and availability is used in [84-87]. This could be interpreted as the probability of finding the spectrum under usage at any point of instant. Now, point is that, the Cognitive Radio is more concerned with the length of the free slot of time to use the spectrum than the probability.

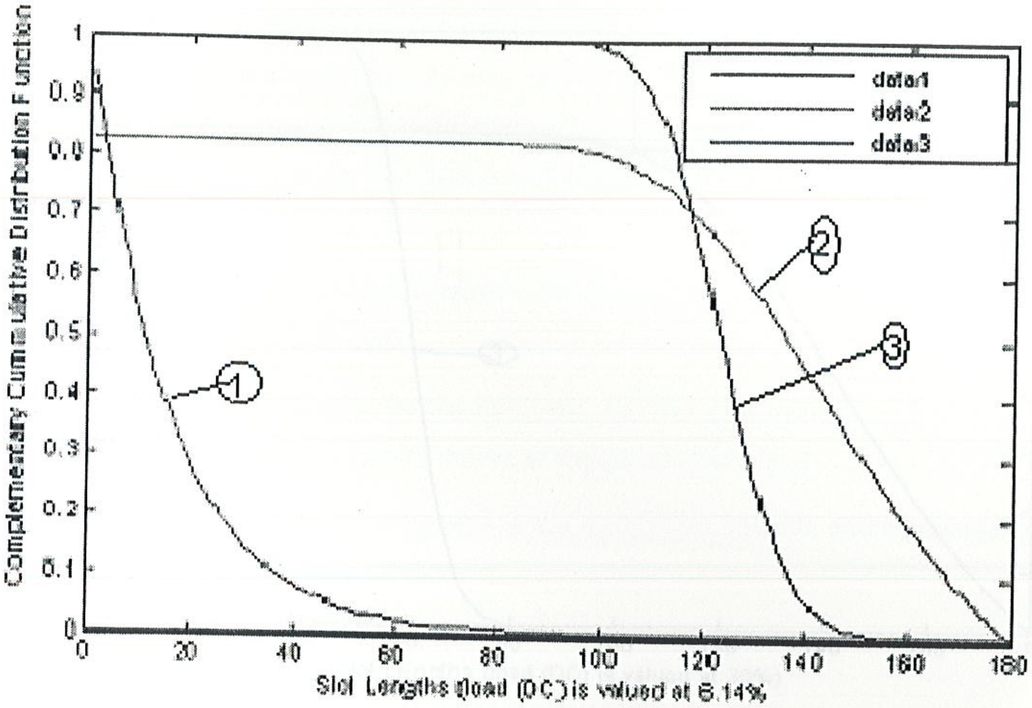

Figure 4.6 (a) Data 1, 2, and 3 are geometric, lognormal and Bernoulli, respectively.

The probability tells to whether check a spectrum for occupancy or hop to another, but it fails to specify the length or the period for which it is free. For this we need not plot a series of spectrum availability in time domain. To solve this problem we plot a graph between the probabilities of detection with respect to the slot length (i.e. we will be able to know that a specific frequency is available for how long). An ideal distribution can be visualized by Figure 4.6(a). We plot a graph which is ideal because it would be easy to simply let the Cognitive Radio calculate the Complementary Distribution Function by knowing the load value.

Now to understand our solution, we have use the slot and block distribution as shown in Fig. 4.6. We have plotted the complementary cumulative distribution function (or probability) of a slot length to occur at any given time. We have plotted three different complementary cumulative distribution function (complementary CDF), namely, geometric, lognormal and Bernoulli (in Bernoulli distribution we assume two thousand trials distribution to keep the graph restricted for our study).

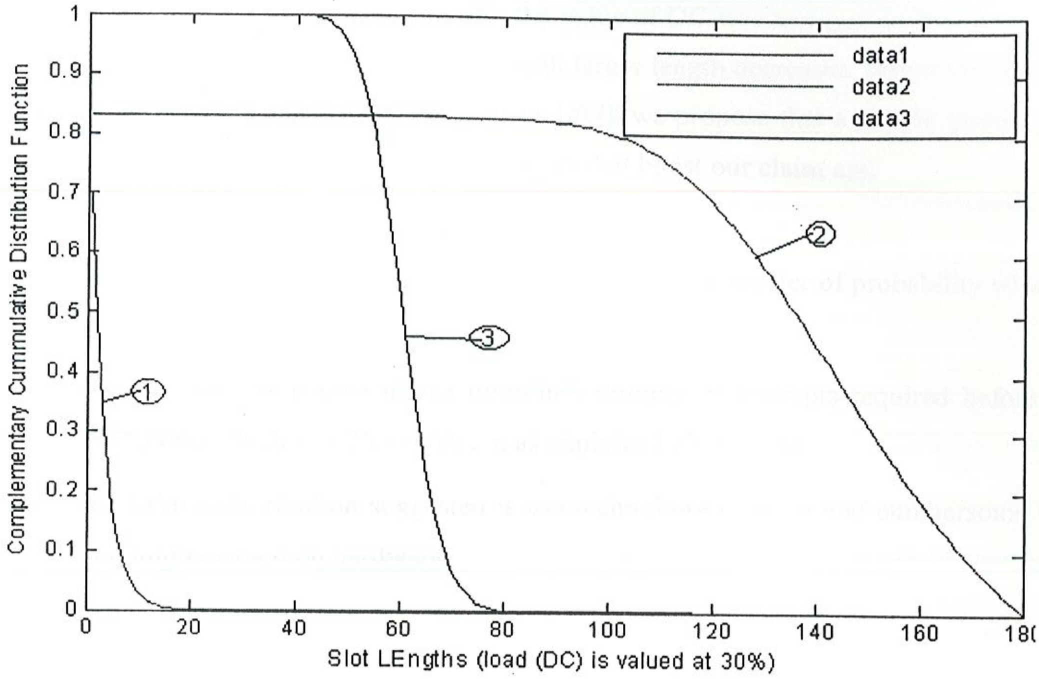

Figure 4.6 (b) Data 1, 2, and 3 are geometric, lognormal and bernoulli, repectively.

The need for complementary CDF rises because it presents a realistic and better graph for analysis. If a slot of length 80 (that is 80 consecutive samples) has a probability of occurrence 'x', then a slot of length less than 80 will have a probability greater than 'x'. The duty cycle (DC) here is considered to be of a very low load spectrum with DC as 6.14%. The graphs are the ideal reproduction of the distribution considered by [35]. The low load of 6.14% is a valid value as detected in the GSM 1800 band [35]. There are other proposed distributions as well such as exponential [88] and Markov chain model [89,90], but these distributions were found to be near optimal and gave specific results that could not support the need of generality. The geometric distribution referred to in [35] explains the occurrence of periodicities in the slots over a large span of time but it does not explain why the low load shows a lognormal behavior where as a high load shows a geometric. The given graphs on analysis show that lognormal distribution gives larger slots rather than geometric. Also if we increase the load as in Fig. 16(b), the lognormal distribution to an extent remains the same but the geometric shows a very realistic picture of slot lengths variation (i.e. to decrease with increase in length). We increased the load to 30% or to be specific the value of DC was assigned to be 0.3. With the increase in load the availability of slots with larger length decreases. Hence instead of lognormal or Erlang behavior as suggested by [*SG*], we propose that a simple geometric distribution be regarded as fit. The further factors that boost our claim are:

(i) The geometric distribution is based on the a single parameter of probability which is the practical duty cycle

(ii) The Bernoulli trial give us the minimum number of attempts required before a detection which us of less concern as explained above, and

(iii) The Erlang distribution suggested is too technology specific and cumbersome to be implemented on hardware.

4.8 Quality of Service and Reasoning Agent

The variance of power detected (or sensed) can be utilized as a parameter in deciding the dynamic QoS parameters. This can be done with the help of the Markowitz theory, where portfolio risk is often measured in terms of the variance of return, once the variance is known then a wealthy allocation strategy can be found [15]. In present case, we need not lookout for the variance in return values detected through spectrum sensing but rather through the spectrum model in consideration. The geometric distribution can give the variance according to the time as follows:

$$V(DC) = (1 - DC)/(DC^2) \tag{4.8}$$

We can restrict the values of DC from 5% to 91%, which is the actual practical range of load that has been verified through existing literature [91-93].

We have started with a distribution fit for slots and block length with their complementary CDF and also a time series with the slot lengths rather than a binary occupancy and are focusing on proving our predictions regarding an ideal CR model to stand true.

Now we proceed to the baseband design.

CHAPTER 5

Issues for Baseband Region

5.1 Importance of Throughput in Cognitive Radios

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 higher the achievable throughput for the secondary network. Thus there could exist a fundamental tradeoff between sensing capability and achievable throughput for the secondary network. We look at the problem of designing the sensing duration to maximize the achievable throughput for the secondary network under the constraint that the primary users are sufficiently protected. We formulate the sensing-throughput tradeoff problem mathematically, and use energy detection sensing scheme to prove that the formulated problem indeed has one optimal sensing time which yields the highest throughput for the secondary network.

Throughput or network throughput is the average rate of successful message delivery over a communication channel. This data may be delivered over a physical or logical link, or pass through a certain network node. The throughput is usually measured in bits per second (bit/s or bps), and sometimes in data packets per second or data packets per time slot. The system throughput or aggregate throughput is the sum of the data rates that are delivered to all terminals in a network. The frame structure is designed for a cognitive radio network with periodic spectrum sensing where each frame consists of one sensing slot and one data transmission slot. Suppose the sensing duration is τ and the frame duration is T. Denote C_0 as the throughput of the secondary network when it operates in the absence of primary users, and C_1 as the throughput when it operates in the presence of primary users. For example, if there is only one point-to-point transmission in the secondary network and the SNR for this secondary link is SNRs = Ps/N0, where P_s is the received power of the secondary user and N_0 is the noise power. Let P_p be the interference power of primary user measured at the secondary receiver, and assume that the primary user's signal and secondary user's signal are Gaussian, white and independent of each other. Then $C_0 = \log_2(1 + SNR_s)$ and where $SNR_p = P_p/N_0$. Obviously, we have $C_0 > C_1$. Note if the primary user's signal is non-Gaussian, the above formula for C_1 can be treated as the lower bound of achievable rate for secondary link when the primary user is active. For a given frequency band of interest, let us define $P(H_1)$ as the probability for which the primary user is active, and $P(H_0)$ as the probability for which the primary user is inactive. Then $P(H_0) + P(H_1) = 1$.

5.2 Analysing the throughput for our Model

Energy Detection is used for our consideration. The relation between achievable throughput and sensing time is as follows

$$R(t) = C_0 P(H_0)(1 - \frac{t}{T})(1 - Q(\alpha + \sqrt{\tau f_s \gamma})) \qquad (5.1)$$

Where α is given by,

$$\alpha = \sqrt{2\gamma + 1} Q^{-1}(P_d)$$

And the various parameters are given by the following table

Table 5.1 The parameters on which the throughput depends.

R(t)	Throughput of secondary network
C_0	Throughput of the secondary network when it operates in the absence of primary users.
$P(H_0)$	The probability for which the primary user is inactive
t	Sensing time
T	Duration for each frame

We can see that the achievable throughput of the secondary network is a function of the sensing time t .

$$P_d = 0.9$$

$$\gamma = \mathrm{SNRp} = -15\mathrm{dB}.$$

Next, suppose the SNR for secondary transmission is $\mathrm{SNR}_s = 20\mathrm{dB}$, thus,

$$C_0 = \log_2(1 + \mathrm{SNR}_s) = 6.6582 \tag{5.2}$$

We are interested in low SNR_p regime, and choose $P(H_1) = 0.2$. .As the sum of probabilities is equal to 1 $P(H_0) = 0.8$. T which is the frame duration is taken as 100ms. Substituting these values we first calculate the value of α. Then keeping this α in the main equation and taking the sampling frequency of 200 kHz we plot a graph in between R(t) and t which is shown below.

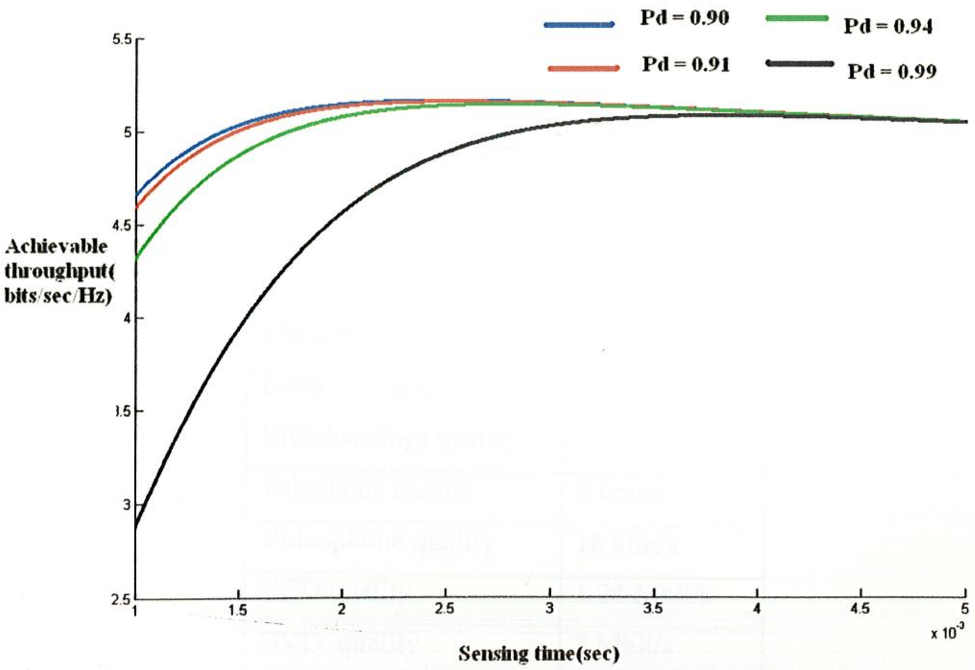

Figure 5.1 Achievable throughput versus sensing time for various probabilities of detection

Y axis represents the achievable throughput of the cognitive radio in bits/sec/Hz and X axis represents the sensing time. The blue line represents the relation for probability of detection of 0.9. As we increase the target probability of detection from 0.90 to 0.91 and finally to 0.99 we observe that the throughput is decreasing. We can say from the graph that we cannot increase the P_d to such a large extent but there must be a proper balance between P_d and P_f. We must look at the time at which throughput is maximum. At 0.9 probability of detection the initial throughput is higher and it achieves the maximum throughput at nearly 2.4 ms. As we keep on increasing the probability of detection the initial throughput reduces and also the maximum throughput is achieved at a larger sensing time than the previous case. So for a sampling frequency of 200 kHz the optimum probability of detection comes out to be 0.9.

5.3 Applications Achievable Through Our Model

The throughput at 2.4ms is 5 bits/sec/Hz. Multiplying this throughput with the sampling frequency of 200 kHz gives us bit rate to be equal to 5*200kHz which comes out to be 10^6 bits/sec or 1Mbits/sec.

Table 5.2 Bitrates for various multimedia applications.

MW (AM) quality	32 kbit/s
FM quality	96 kbit/s
DAB (Digital Audio Broadcasting) quality	192 kbit/s
Telephone quality	8 kbit/s
Videophone quality	16 kbit/s
VCD quality	1.25 Mbit/s
DVD quality	5 Mbit/s
HDTV quality	8 to 15 Mbit/s
HD DVD	29.4 Mbit/s
Blue-ray Disc	40 Mbit/s

We can look at the various bit rates of allocations used in day to day life. With a bit rate of 1Mbits/sec our model supports digital audio broadcasting, telephone quality audio and video phone quality audio. Our main concern is audio transmission which can be fulfilled by our model. We can also see that or model cannot support DVD quality, HDTV quality and VCD quality. So, video transmission cannot be fulfilled by our model.

For further analysis let us see the effect of sampling frequency on the achievable throughput.

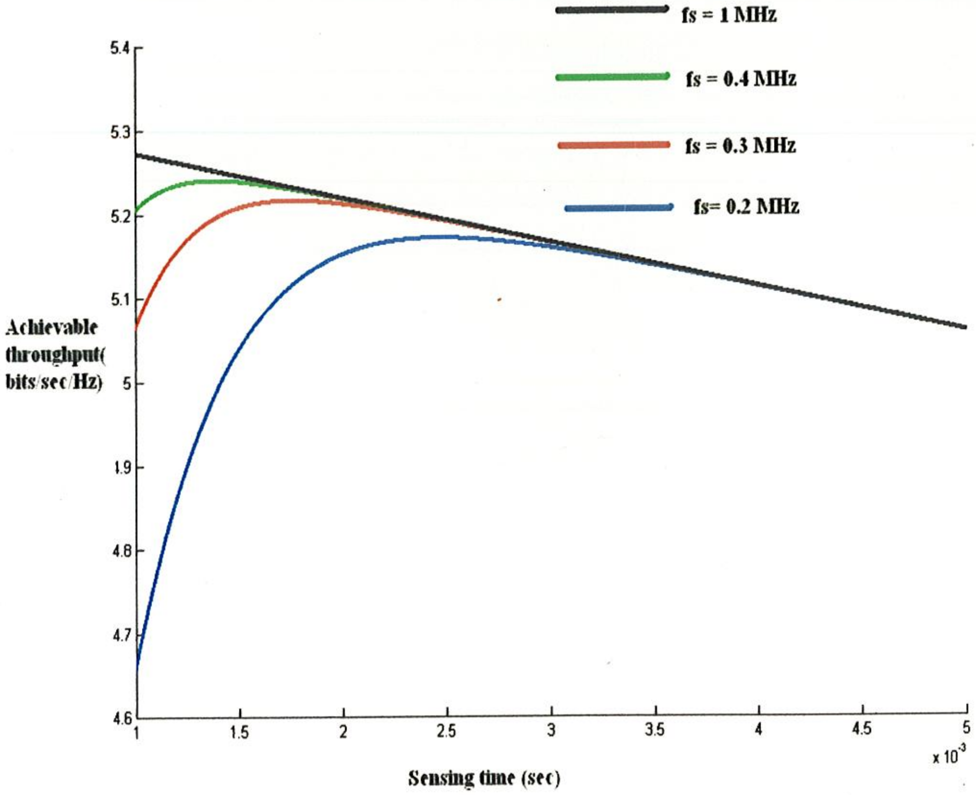

Figure 5.2 Throughput versus sensing time for a given sampling frequency

The graph above represents the relation between Throughput and sensing time for a given sampling frequency. We observe that as the sampling frequency is increased from 200 kHz to 300 kHz and finally to 1MHz the throughput is increasing.

5.4 Conclusion

Thus sampling frequency must be as high as possible in order to achieve a good throughput. If the throughput is higher the product of sampling frequency with the throughput comes out to be higher which the bit rate is. With higher bit rate a lot of applications can be utilised with the help of same model.

CHAPTER 6

Conclusion

The main objective of our project was to design an efficacious model for cognitive radio. We have validated that an ideal CR model with the best fitted spectrum model in it should carefully check its validity in some dimensions before being confirmed as a good Cognitive Radio model with heuristic approach. We propose that the following parameters need to be considered while designing a Cognitive Radio model, namely, required hardware, spectrum sensing techniques, reasoning agent and the spectrum model. Hence concluding that, only when all four dimensions are taken care of in a cognitive radio model, it could be called efficacious.

We have conveyed through our study of acceptable SINR values by our CR model; in Chapter 3 that the cognitive radio will not be limited by a simplistic understanding that "low SINR means it should increase its transmitter power." Instead, it will try other solutions, such as altering the modulation or channel coding in ways that will improve frame error rate (FER) performance in the channel.

We also observed that the total sensing time rises exponentially with the combination of antennas and resolution frequency. But with any one of the three axis values given, we can choose an optimal combination of the other two. The combination of resolution frequency and number of antennas gives us a desired and practical combination of a total sensing time. We also proved that playing with resolution frequency has a direct relation with the probability of false detection.

The project also described a new heuristic approach to detect available spectrum in a better and efficient manner using a geometric distribution based frequency selection method. These are referred to in the project as distribution fits. The model has an added advantage of also being able to decide on the QoS parameters through this distribution model itself. The heavy tailed behavior of lognormal was inferred to be a drawback as it results in high probability of missed detections.

Finally in the parametric modeling of the baseband unit we have concluded that sampling frequency must be as high as possible in order to achieve a good throughput. If the throughput is higher the product of sampling frequency with the throughput comes out to be higher which the bit rate is. With higher bit rate a lot of applications can be utilised with the help of same model.

6.1 Future Work

There are various applications of our model. Cognitive radio technology is already being used to some extent in 3G and in defense applications, but its potential – to intelligently react and adjust to optimise the available spectrum – has yet to be fully realized. Also there are many other aspects of Cognitive Radio which can be studied in detail. Some major works that need to be undertaken in the future are mentioned below:

1. Hardware implementation
2. Spectrum Analyzer
3. Orthogonal wavelet division multiplexing (OWDM)
4. Game theory
5. Genetic algorithm

Hardware implementation of the ideal CR model can be done . After doing the hardware implementation of Cognitive Radio it should be checked that whether the CR is fulfilling the conditions mentioned in Chapter 2. Also, if equipment is cheap, then it's not worth paying much for extra spectrum. Equipment and transmission are getting cheaper, and technology is becoming more sophisticated. So if in future the sophisticated Cognitive radio hardware is able to exploit the spectrum holes efficiently then operators will start investing in Cognitive radio and will not purchase the costly spectrum and thus will save money and their operating profits will increase. So in future the aim should be to make sophisticated Cognitive radio which should also be cheap.

Spectrum holes can be found during different times of the day using Agilent Spectrum analyzer. Load is different during different times of the day i.e. during day time the primary users are more and during night primary users are less. We can keep the hardware model of CR in Waknaghat and we can find out how efficiently the CR exploits the spectrum holes during different times of the day. Also we can develop the empirical model for Waknaghat. We can also observe that which distribution is best for a given place e.g. Waknaghat.

The main property of wavelets is their flexibility and ability to characterize signals accurately. Major applications of wavelets is in cognitive radio, wireless channel modeling, de-noising, OFDM modulation, Ultra Wideband communications and wireless networks. OWDM is a wavelet based multichannel modulation scheme. OWDM lowers interference to primary users. It is suitable to operate in TV band, GSM band, or other bands, where the available spectrum is composed of small and non-contiguous sub-bands. The main advantage of OWDM is its higher spectral containment. It means that the energy of each sub-channel is much more concentrated in main lobe. This property makes it possible to introduce lower interference to primary users. Moreover, it is more robust to narrowband interference due to this property. Only those sub-channels having main lobes overlapping with the narrowband interference are severely affected. Other sub-channels suffer much fewer interference than that in OFDM case. We know that, there are many narrowband interferers existing in the operating environment of a cognitive radio system.

Game theory is used to shape the design of dynamic spectrum access networks to yield powerful low complexity cognitive radio algorithms. Game theory provides the analysis tools needed to ensure your cognitive radio network behaves in a predictable, optimal manner instead of producing network chaos. Coalitional game theory is a branch of game theory that deals with cooperative behavior. In a coalitional game, the key idea is to study the formation of cooperative groups, i.e., coalitions among a number of players. By cooperating, the players can strengthen their position in a given game as well as improve their utilities. Coalitional game theory proves to be a powerful tool for modeling cooperative behavior in many wireless networking applications such as cognitive radio networks, wireless system.

Genetic algorithm (GA) to create a CR that can respond intelligently in changing and unanticipated circumstances and in the presence of hostile jammers and interferers. Genetic algorithms are problem solving techniques based on evolution and natural selection. GA models adapt Charles Darwin's evolutionary theory for analysis of data and interchanging design elements in hundreds of thousands of different combinations. Only the best-performing combinations are permitted to survive, and those combinations "reproduce" further, progressively yielding better and better results.

In future we can also do research in which other applications can we use Cognitive Radio and we can study and find out how cognitive radio can exploit the spectrum holes more efficiently.

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APPENDIX A

Program 1:

Plot between total sensing time and number of antennas

```
a=10;
b=28;
fres=10.^4;
bsys=10.^10;
ncrs=128;
nfin=1024;
tint=1.1;
tpllcrs=0.6;
tpllfin=0.35;
for m=100:1:500
d=a.*m*ncrs*fres;
mul2=(a*b*0.17412)./(m);
t4=(a*b*0.35)./m;
t5=(b*0.6)./m;
tsys=((bsys/d)*0.02824)+(mul2)+tint+t4+t5;
plot(m,tsys);
hold on;
end
```

Program 2:

Plot between total sensing time, number of antennas and system operated frequency.

```
a=10;
b=28;
fres=10.^4;
ncrs=128;
nfin=1024;
tint=1.1;
tpllcrs=0.6;
tpllfin=0.35;
for m=100:1:500
for bsys=10.^10:10.^10:5*(10.^11)
d=a.*m*ncrs*fres;
mul2=(a*b*0.17412)./(m);
t4=(a*b*0.35)./m;
t5=(b*0.6)./m;
tsys=(((1/d).*bsys)*0.02824)+(mul2)+tint+t4+t5;
plot3(bsys,m,tsys);
hold on;
end
end
```

Program 3:

Plot between system operated frequency and sensing time.

```
a=10;
b=28;
fres=10.^4;
ncrs=128;
nfin=1024;
tint=1.1;
tpllcrs=0.6;
tpllfin=0.35;
 m=200;
for bsys=10:0.1:500
d=a.*m*ncrs*fres;
mul2=(a*b*0.17412)./(m);
t4=(a*b*0.35)./m;
t5=(b*0.6)./m;
tsys=((((1/d).*bsys)*0.02824)*(10.^9)+(mul2)+tint+t4+t5);
plot(bsys,tsys,'y');
hold on;
legend('m=200');
end;
```

Program 4:

Plot between system operated frequency,number of antennas and total sensing time.

```
a=10;
fres=10.^4;
ncrs=128;
nfin=1024;
fdsp=10.^8;
 for m=100:1:500
for bsys=10.^10:10.^10:5*(10.^11)
d=a.*m*ncrs*fres*fdsp;
mul1=(4*(ncrs./m)*log2(ncrs./m))-(6*(ncrs./m))+8;
mul2=(a/fdsp)*((4*nfin*log2(nfin))-(6*nfin)+8);
tsys=(((1/d).*bsys)*0.02824)+(mul2)
plot3(bsys,m,tsys);
hold on;
end
```

Program 5:

Plot between throughput and sensing time.

```
c0 = 6.6582;
p=0.8;
T=0.1;
a=-1.3215;
for(t=1*10^-3:0.00001:5*10^-3)
s=sqrt(t*20*10^4*0.0316);
q=qfunc(a+s);
R=(c0)*(p)*(1-(t/T))*(1- q);
hold on;
plot(t,R);
end
```

Program 6:

Plot between normalized throughput and sensing time.

```
a=-1.3215;
g=0.0316;
T=0.1;
f=6*10^6;
for(t=1*10^-3:0.00001:5*10^-3)
 p=qfunc(a+(g*(sqrt(t*f))));
b=(1-(t/T))*(1-p);
plot(t,b);
hold on;
end
```

Program 7:

Plot between number of secondary links and SINR

```
for n=1:1:300
o=(0.28972.*n);
s=10*log(39800/o);
axis([0 300 50 120]);
plot(n,s,'r');
xlabel('Number of secondary links(N)');
ylabel('SINR');
hold on;
end
```

Program 8:

Comparison between existing acceptable SINR and modified SINR

```
for n=1:1:300
o=(0.28972.*n);
s=10*log(39800/o);
m=(0.55847.*n);
p=10*log(39800/m);
plot(n,s,'r'),hold on,plot(n,p,'g');
xlabel('Number of secondary links(N)');
ylabel('SINR');
hold on;
end
```