Spectrum Sensing in Cognitive Radio: Use of Cyclo-Stationary Detector

by

Manish B Dave

Roll No. : 210EC4077

A Thesis submitted for partial fulfillment for the degree of

Master of Technology

in

Electronics and Communication Engineering

(Communication and Signal Processing)

Dept. Electronics and Communication Engineering

NATIONAL INSTITUTE OF TECHNOLOGY

Rourkela, Orissa-769008, India

May 2012

Spectrum Sensing in Cognitive Radio:

Use of Cyclo-Stationary Detector

by

Manish B Dave

Roll No. : 210EC4077

Under Guidance of

Prof. Sarat Kumar Patra

A Thesis submitted for partial fulfillment for the degree of

Master of Technology

in

Electronics and Communication Engineering

(Communication and Signal Processing)

Dept. Electronics and Communication Engineering

NATIONAL INSTITUTE OF TECHNOLOGY

Rourkela, Orissa-769008, India

May 2012

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

CERTIFICATE

This is to certify that the work in the thesis entitled, "***SPECTRUM SENSING IN COGNITIVE RADIO- USE OF CYCLO-STATIONARY DETECTOR***" submitted by ***MANISH B DAVE*** is a record of an original research work carried out by him during 2011-2012 under my supervision and guidance in partial fulfillment of the requirement for the award of Master of Technology Degree in Electronics & Communication Engineering (Communication and Signal processing), National Institute of Technology, Rourkela. Neither this thesis nor any part of it has been submitted for any degree or diploma elsewhere.

Place: NIT Rourkela

Date: June 04, 2012

Dr. SARAT KUMAR PATRA

Professor

ACKNOWLEDGEMENTS

I am deeply indebted to **Prof. SARAT KUMAR PATRA**, my supervisor on this project, for consistently providing me with the required guidance to help me in the timely and successful completion of this project. In spite of his extremely busy schedules in Department, he was always available to share with me his deep insights, wide knowledge and extensive experience.

I would like to express my humble respects **Prof. K. K. Mahapatra, Prof. S. Meher, Prof. S. K. Behera, Prof. S. Ari, Prof. P. Singh** and **Prof. A. K. Sahoo** for teaching me and also helping me how to learn.

I would like to thank my institution and all the faculty members of ECE department for their help and guidance. They have been great sources of inspiration to me and I thank them from the bottom of my heart.

I would like to thank all my friends and especially my classmates for all the thoughtful and mind stimulating discussions we had, which prompted us to think beyond the obvious. I've enjoyed their companionship so much during my stay at NIT, Rourkela.

I would like express my special thanks to all my research seniors and friends of mobile communication lab for their help during the research period.

Last but not least I would like to thank my parents and well-wishers.

MANISH B DAVE

ABSTRACT

Cognitive radio allows unlicensed users to access licensed frequency bands through dynamic spectrum access so as to reduce spectrum scarcity. This requires intelligent spectrum sensing techniques like co-operative sensing which makes use of information from number of users. This thesis investigates the use of cyclo-stationary detector and its simulation in MATLAB for licensed user detection. Cyclo-stationary detector enables operation under low SNR conditions and thus saves the need for consulting more number of users. Simulation results show that implementing co-operative spectrum sensing help in better performance in terms of detection.

The cyclo-stationary detector is used for performance evaluation for Digital Video Broadcast-Terrestrial (DVB-T) signals. Generally, DVB-T is specified in IEEE 802.22 standard (first standard based on cognitive radio) in VHF and UHF TV broadcasting spectrum.

The thesis is further extended to find the number of optimal users in a scenario to optimize the detection probability and reduce overhead leading to better utilization of resources. The gradient descent algorithm and the particle swarm optimization (PSO) technique are put to use to find an optimum value of threshold. The performance for both these schemes is evaluated to find out which fares better.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ADC	Analog to Digital Converter
AGC	Automatic Gain Control
CAF	Cyclic Auto-correlation Function
CSD	Cyclic Spectrum Density
DVB-T	Digital Video Broadcast - Terrestrial
FCC	Federal Communications Commission
LNA	Low Noise Amplifier
MAC	Medium Access Control
MIMO	Multi Input Multi Output
OFDMA	Orthogonal Frequency Division Multiple Access
PDF	Probability Density Function
PLL	Phase Locked Loop
PSD	Power Spectrum Density
PSO	Particle Swarm Optimization
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
ROC	Receiver Operating Characteristics
SNR	Signal to Noise Ratio
SU	Secondary User
TDD	Time Division Duplex
VCO	Voltage Controlled Oscillator
WRAN	Wireless Regional Area Network

Chapter 1. Introduction

1.1. History of Cognitive Radio

The need for a flexible and robust wireless communication is becoming more evident in recent times. The future of wireless networks is thought of as a union of mobile communication systems and internet technologies to offer a wide variety of services to the users.

Conventionally, the policy of spectrum licensing and its utilization lead to static and inefficient usage. The requirement of different technologies and market demand leads to spectrum scarcity and unbalanced utilization of frequencies. It has become essential to introduce new licensing policies and co-ordination infrastructure to enable dynamic and open way of utilizing the available spectrum efficiently.

One promising solution to such problems is the Cognitive Radio. It has an intelligent layer that performs the learning of environment parameters in order to achieve optimal performance under dynamic and unknown situations. It enables a smooth and interactive way of using the spectrum and communication resources between technologies, market and regulations.

The following steps highlights genesis of the cognitive radio to its evolution till the present [1] time:-

- In 1999, Joseph Mitola III coined the term 'Cognitive Radio' for the first time in his doctoral thesis [2].
- In 2002, the Defense Advanced Research Projects Agency (DARPA) funded the NeXt Generation (DARPA-XG) program whose purpose was to define a policy based spectrum

management framework so the radios can make use of the spectrum holes existing in time and space.

- This drew the attention of the Federal Communications Commission (FCC) which then confirmed the underutilization of the bands based on the research conducted by it. Later the commission issued a Notice for Proposed Rule Making (NPRM) [3] whose main aim was to explore the cognitive radio technology to imprefficiencyctrum utilization efficiently.
- In 2004, the Institute of Electrical and Electronic Engineers (IEEE) formed the IEEE 802.22 working group for defining the Wireless Regional Area Network (WRAN) Physical (PHY) and Medium Access Control (MAC) layer specifications.
- By end 2005, IEEE launched the Project 1900 standard task group for next generation radio and spectrum management. It was related to giving standard terms and formal definitions for spectrum management, interference and co-existence analysis and policy architecture, dynamic spectrum access radio systems.
- In 2006, IEEE organized the first conference on cognitive radio CROWNCOM so as to bring together new ideas regarding the cognitive radio from a diverse set of researchers around the world.
- It was followed by FCC's TV band unlicensed service project launch with cognitive radio technology.
- By 2008 end, the FCC established rules to allow cognitive devices to operate in TV White Spaces on a secondary basis.
- In 2010, FCC released a Memorandum Opinion and Order that determined the final rules for the use of white space by unlicensed wireless users [4].
- In July, 2011, the IEEE published IEEE 802.22 (WRAN) as an official standard [5].
- Currently, IEEE is working on the standard for recommended practice for installation and deployment of 802.22 systems.

1.2. Motivation

The cognitive radio presents a very lucrative area of the research field. Inefficient spectrum utilization is the driving force behind cognitive radio and adopting it can lead to a reduction of spectrum scarcity and better utilization of the spectrum resources. Spectrum Sensing i.e. checking the frequency spectrum for empty bands forms the foremost part of the cognitive radio. There are number of schemes for spectrum sensing like energy detector and matched filter. But the former functions properly for higher signal to noise ratio (SNR) value whereas the latter's complexity is very high. These constraints led to implementing a detector which performed well under low SNR conditions as well and with complexity not as high as the matched filter. Cyclo-stationary detector turned out to be the choice for such specifications.

In co-operative sensing (decision from number of users taken into consideration), number of users lead to more overhead and thus takes time for final decision. Hence better decision cost us time and efficiency. Lowering the detection threshold increases the detection as well as the chances of false detection. Thus one cannot lower the threshold value at will. The thesis presents an algorithm for finding an optimal number of users and a couple of threshold optimization schemes.

1.3. Thesis Layout

Chapter 1 – Introduction

The history of cognitive radio, right from the time when the term was coined to the present day is looked into and the motivation behind choosing this topic is discussed.

Chapter 2 – Cognitive Radio

Cognitive radio definitions, its physical architecture, different research areas, spectrum sensing and different fusion techniques for co-operative spectrum sensing are presented in this section. Different detectors and their advantages and disadvantages along with implementation of the cyclo-stationary detector and WRAN features are discussed thoroughly.

Chapter 3 – Optimal users and Threshold Adaptation

An algorithm for finding optimal number of users so as to reduce the overhead in case of sensing and adaptation of the threshold by gradient descent algorithm and particle optimization technique is discussed here. This section also presents simulation results for the algorithms on an arbitrary signal.

Chapter 4 – Application to DVB-T signals

The algorithms discussed in chapter 3 are applied to the DVB-T signals and the simulation results are discussed.

Chapter 5 – Conclusion and Future Work

The overall conclusion of the thesis and some of the future research areas which can be taken up in this field is outlined in this section.

Chapter 2. Cognitive Radio- A Review

2.1. Cognitive Radio

2.1.1 Features

Cognitive Radio is a paradigm that has been proposed so that the frequency spectrum can be better utilized. The formal definition for Cognitive Radio is given as [3] :-

"*Cognitive Radio is a radio for wireless communications in which either a network or a wireless node changes its transmission or reception parameters based on the interaction with the environment to communicate effectively without interfering with the licensed users*."

If the frequency range from 40 MHz to 1000 MHz is carefully observed in figure 2-1 then this range can be classified into 3 sub-categories (i) Empty bands most of the time, (ii) Partially occupied bands, and (iii) Congested Bands. The main category of interest for the cognitive radio users is the first category in which the hardly used or empty bands are classified. In layman terms cognitive radio is nothing but a methodology wherein the first category of the frequency range is brought to the use for unlicensed users in such a way that interference to the licensed users is minimized.

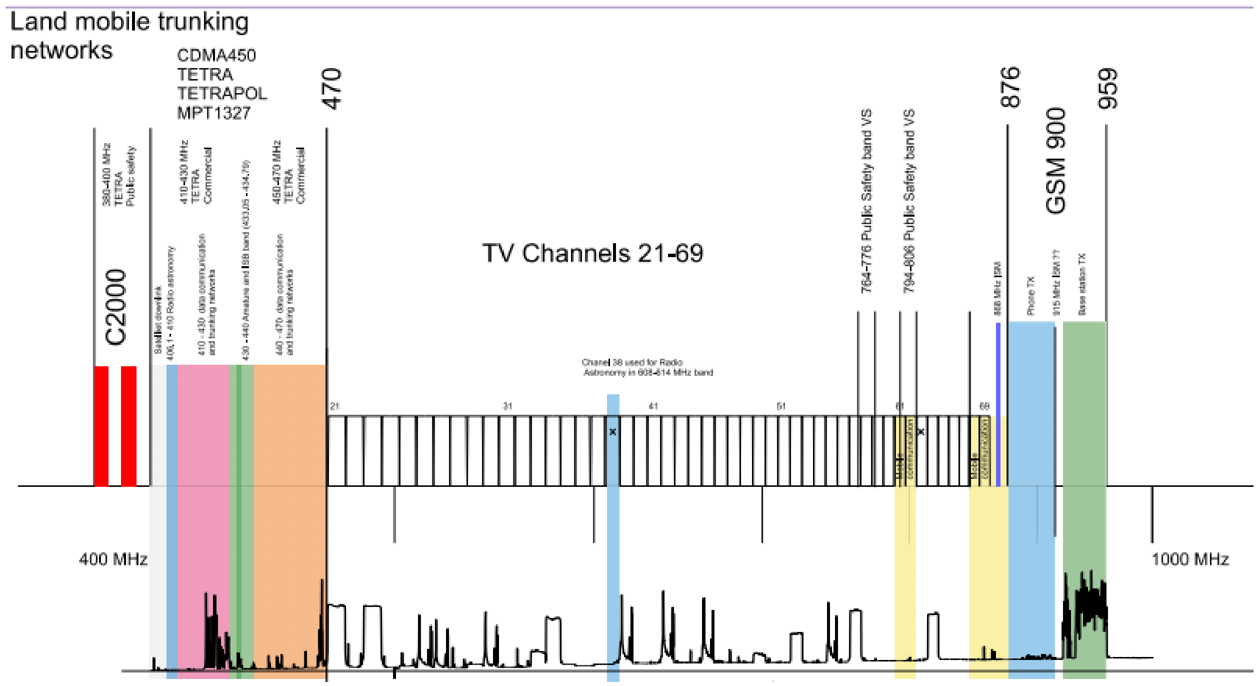

Figure 2-1: Spectrum Utilization [6]

In order for the unlicensed or secondary users to use the licensed spectrum there are many things that should be taken care of in advance like

- Scanning the frequency spectrum for the discovery of different empty bands.
- Selecting the best available band. The selection can be done on the basis of the secondary user's application frequency requirement.
- Before transmitting on the selected band the power level should be maintained such that it provides minimal interference to other users. Also the power level can be so adjusted as to have maximum number of secondary users in the frequency band of interest.
- Depending on the distance and the error performance requirement the modulation scheme used can be varied. Lower data rates can be achieved using low order modulation schemes like QPSK whereas 64-QAM enables one to achieve higher data rates.
- Spectrum sharing should be allowed so that other secondary users can also access the empty bands.
- Even after the beginning of the transmission the bands must be continuously checked for any primary user entering to transmit in this range. If so, then the secondary users should

vacate the bands as quickly as possible and go on to some other empty frequency spectrum.

Each of the above essential steps indicates a unique feature of the cognitive radio like Continuous Awareness, Dynamic Frequency Selection, Power Control, Adaptive Modulation, Frequency Negotiation and Frequency Agility. The steps are shown in the figure 2-2

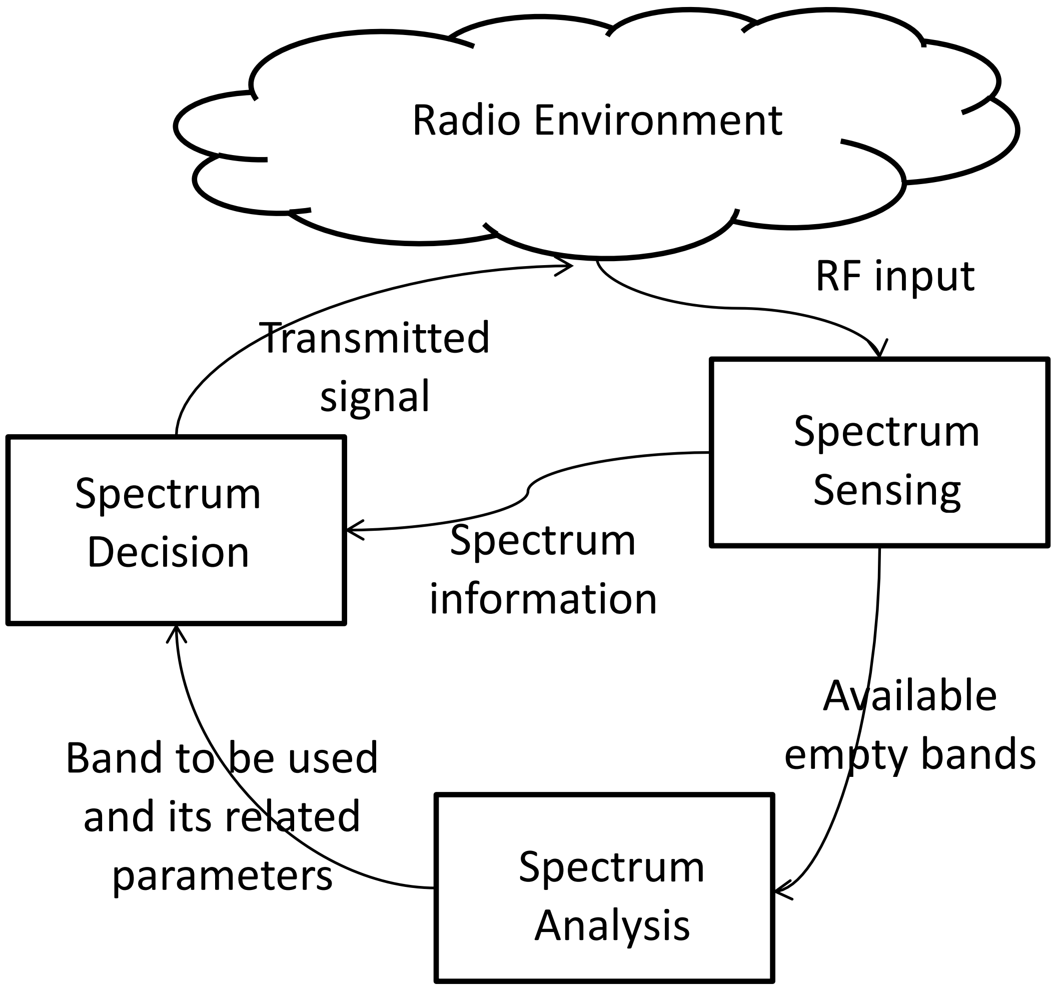

Figure 2-2: Cognitive Cycle

Thus two main characteristics of the cognitive radio come to the limelight from the information and they can be stated as:-

- Cognitive Capability- It refers to the ability of the cognitive radio to sense the environment or channels used for transmission and derive the information about the state of the channel. It encompasses all the basic functions of the cognitive radio like spectrum sensing, spectrum analysis and spectrum decision. Thus finding the vacant bands, selecting the most efficient of all available options and finalizing the transmission parameters come under this category.

- Reconfigurability- It refers to programming the radio dynamically without making any changes to its hardware section. Cognitive radio is a software based radio and not hardware based so it has the capability to switch between different wireless protocols and also supports a number of applications. This software based approach gives the reconfigurability characteristics to the cognitive radio. With this it can easily switch between frequencies, change modulation schemes and monitor power levels without affecting any of the hardware provided [7], [8].

2.1.2 Physical Architecture

Generally the cognitive radio employs a transceiver which consists of a RF front end and a baseband signal processing unit which performs modulation/demodulation and encoding/decoding functions [7]. The RF front (figure 2-3) end consists of:-

- RF filter- It is a band-pass filter which selects the frequency band of interest.
- Low noise amplifier (LNA) - Used for amplifying the desired signal and also for suppressing the noise part.
- Mixer- Used for translating the frequency to Intermediate Frequency (IF) in order to facilitate further processing.
- Phase locked loop (PLL) and Voltage Controlled Oscillator (VCO) - VCO generates the signal with specific frequency required for mixing. PLL ensures that the frequency is fixed and does not vary with time.
- Channel Selection Filter- It selects the required frequency bands and rejects the adjacent bands.
- Automatic Gain Control (AGC) – It keeps the output power level fairly constant over a wide range of input signal.
- A/D converter – It converts the signal in analog form to digital information so that it can be processed by the baseband processing unit.

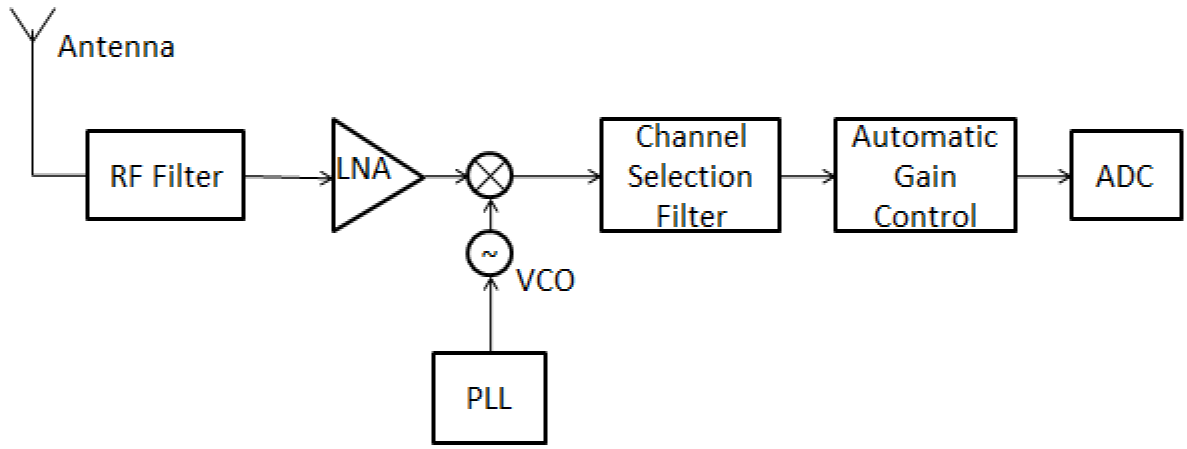

Figure 2-3: The RF Front End for a Cognitive Radio

2.1.3 *Research Areas*

All the functionalities call for a spectrum aware communication protocol. Since the cognitive radio is to adapt to the environment changes there must be a high degree of co-ordination among different protocol stack layers [7]. This happens to be in contrast to the conventional communication which occurs between layers in case of fixed frequency allocated applications. Thus networking in cognitive radio remains a burning topic in the field of research.

There has been constant scrutiny of the protocol stack as regards to its performance for wireless networks and with the advent of the cognitive radio paradigm there have been a number of research proposals wherein the protocols at different layers have been made dependent on the protocols of other layers. All such research work of enhancing the performance gain can be broadly classified under the term CROSS LAYER design [9]. In the cross layer design field there have been numerous interpretation of the concept as still it is not standardized and thus people are working independently to suggest different designs. Some of the notable designs that have come out as a result of the research work can be stated as:-

- ❑ Super Layer- Merging of two adjacent layers of the protocol stack.

- Additional Interface- Allowing two non-adjacent layers to communicate directly by creating an interface between them.
- Without Additional Interface- There is no direct communication between two layers but one is designed keeping in mind the functionalities of the other.
- Vertical calibration- Changing the top layer's parameters with respect to the bottom layers.
- Shared Database- A database which can be accessed by all layers or can be thought of as a layer to which all other layers have an access.

Figure 2-4 shows different forms of cross-layer that can be obtained.

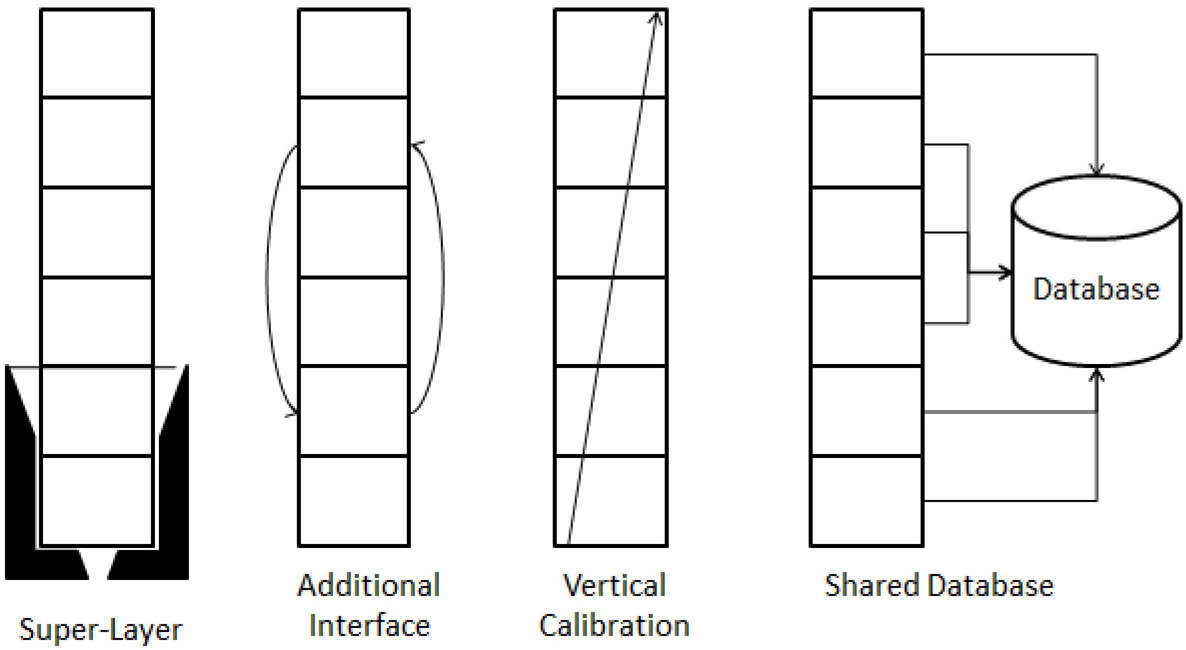

Figure 2-4: Different Cross-Layer Techniques

The main hurdle in this research field is that the cross layer designs aim to enhance the performance gains of the network but hardly a few look into the implementations issues of such design.

The prime motive behind the cognitive radio is that empty bands are utilized without causing interference to the primary users. Thus Quality of Service (QoS) requirements for the primary users should not be violated. The operation of a secondary user is limited by the maximum transmit power that it uses and this power puts an interference constraint on it. Work is going on this field to find out power adaptation strategies [10] so the secondary users SNR and capacity is maximized

Spectrum Sensing forms a very essential and foremost step in the setup of cognitive radio network. It helps one to determine the empty frequency bands in the spectrum and also finds out the state of the channel over which transmission is to occur. This is the main research area in the field of cognitive radio at the present time. There are a number of methods like energy detection, matched filter technique and so on which are discussed in the subsequent section.

2.2. Spectrum Sensing

2.2.1 Concept of two hypotheses (Analytical Model)

Spectrum Sensing is a key element in cognitive radio network. In fact it is the foremost step that needs to be performed for communication to take place. Spectrum sensing can be simply reduced to an identification problem, modeled as a hypothesis test [11]. The sensing equipment has to just decide between for one of the two hypotheses:-

$$H1: x(n) = s(n) + w(n) \tag{2.1}$$

$$H0: x(n) = w(n) \tag{2.2}$$

where '*s(n)*' is the signal transmitted by the primary users.
'*x(n)*' being the signal received by the secondary users.
'*w(n)*' is the additive white Gaussian noise with variances $\sigma^2{}_w$.
Hypothesis 'H0' indicates absence of primary user and that the frequency band of interest only has noise whereas 'H1' points towards presence of primary user.
Thus for the two state hypotheses numbers of important cases are:-

- H1 turns out to be TRUE in case of presence of primary user i.e. P(H1 / H1) is known as **Probability of Detection (P_d).**

- H0 turns out to be TRUE in case of presence of primary user i.e. P(H0 / H1) is known as **Probability of Miss-Detection (P_m).**
- H1 turns out to be TRUE in case of absence of primary user i.e. P(H1 / H0) is known as **Probability of False Alarm (P_f).**

The probability of detection is of main concern as it gives the probability of correctly sensing for the presence of primary users in the frequency band. Probability of miss-detection is just the complement of detection probability. The goal of the sensing schemes is to maximize the detection probability for a low probability of false alarm. But there is always a trade-off between these two probabilities. Receiver Operating Characteristics (ROC) presents very valuable information as regards the behavior of detection probability with changing false alarm probability (P_d v/s P_f) or miss-detection probability (P_d v/s P_m).

A number of schemes have been developed for detecting the presence of primary user in a particular frequency band. Some approaches use the signal energy or some particular characteristics of the signal to identify the signal and even its type [12].

Some of the most common methods employed for spectrum sensing in terms of their operation, pros and cons can be acknowledged as:-

2.2.2 Energy Detector

It is a simple detector which detects the total energy content of the received signal over specified time duration. It has the following components:-

- Band-pass filter -- Limits the bandwidth of the received signal to the frequency band of interest.
- Square Law Device – Squares each term of the received signal.
- Summation Device – Add all the squared values to compute the energy.

A threshold value is required for comparison of the energy found by the detector. Energy greater than the threshold values indicates the presence of the primary user. The principle of energy detection is shown in figure 2-5. The energy is calculated as

$$E = \sum_{n=0}^{N} |x(n)|^2 \qquad (2.3)$$

The Energy is now compared to a threshold for checking which hypothesis turns out to be true.

$$\begin{aligned} E > \lambda \Rightarrow H1 \\ E < \lambda \Rightarrow H0 \end{aligned} \qquad (2.4)$$

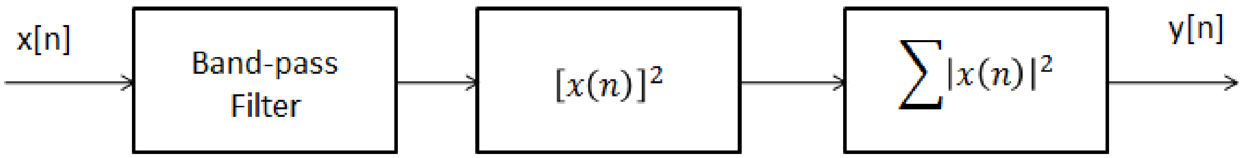

Figure 2-5: Principle of Energy Detection

Pros:-

- No prior knowledge of the primary user's signal required.
- Computational and implementation complexity low.

Cons:-

- Poor performance under low SNR conditions.
- No proper distinction between primary users and noise.
- Issues related to selecting a proper threshold for comparison purposes.

2.2.3 Matched Filter Technique

The Matched Filter Technique is very important in communication as it is an optimum filtering technique which maximizes the signal to noise ratio (SNR). It is a linear filter and prior knowledge of the primary user signal is very essential for its operation. The operation performed is equivalent to a correlation. The received signal is convolved with the filter response which is the mirrored and time shifted version of a reference signal. The figure 2-6 outlines the principle of its operation.

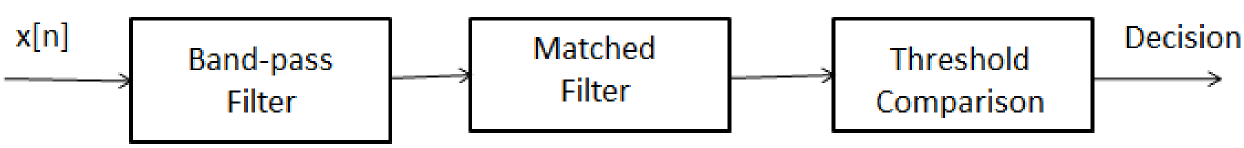

Figure 2-6: Principle of Matched Filter operation

The output of the matched filter, given that 'x[n]' is the received signal and 'h[n]' is the filter response, is given as

$$y[n]=\sum_{k=-\infty}^{\infty} x[k]h[n-k] \qquad (2.5)$$

Pros:-

- Optimal detector as it maximizes the SNR
- The sensing time is low as compared to other detectors but more than waveform based detector.

Cons:-

- Requires prior knowledge of the primary user signal.
- Computational complexity is high as compared to other detectors.
- Since the requirement is for large number of receivers so different algorithms need to be evaluated and thus power consumptions is large.

2.2.4 Waveform Based Sensing

This type of sensing makes use of Preambles, Mid-ambles, pilot carrier and spreading sequences. These are added to the signal intentionally as knowledge of such patterns help in detection and synchronization purposes. Preambles are set of patterns that are sent just before the start of the data sequence whereas mid-ambles are transmitted in the middle of the data. The more the length of these known patterns, more will be the accuracy of the detection.

The figure 2-7 highlights the main functional units of the detector. The received signal is correlated with the known patterns. The output of the correlator is compared with a threshold. In case the received signal is from the primary users then it must have the known patterns and thus the correlation will be more than the threshold or the case will be opposite in case of noise.

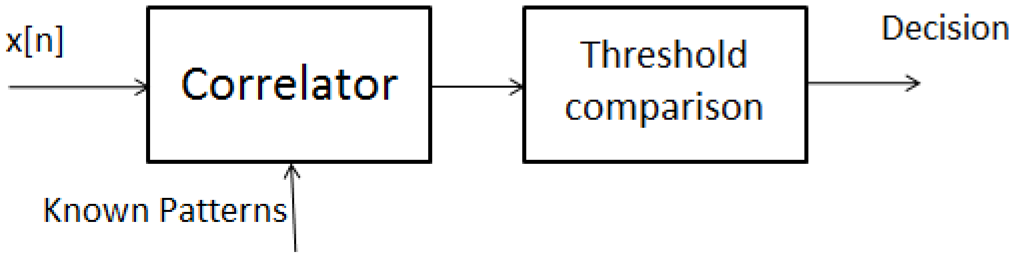

Figure 2-7: Waveform Based Sensing Method outline

Pros:-

- The sensing time required for the waveform based detector is low as compared to energy detector.
- It is more reliable than energy detector.

Cons:-

- Higher accuracy requires a longer length of the known sequences which results in lower efficiency of the spectrum.

2.2.5 Wavelet Based Sensing

A transition in frequency of a signal results in edges in the frequency spectrum. This property can be very helpful in detection algorithms. The frequency band is sub-divided into a number of sub-bands each characterized by its own changes in frequency. The wavelet transform is done on these sub-bands to gather the information about the irregularities or transitions. Wavelet transform is applied and not conventional Fourier transform as wavelet transform gives the information about the exact location of the different frequency location and spectral densities. On the other hand Fourier transform is only able to show the different frequency components but not the location.

The working principle [13] is illustrated in figure 2-8. The entire frequency range is divided into sub-bands. Wavelet transform is applied to each of these sub-bands. The spectral densities of all the sub-bands are searched for edges which represent transition from empty to occupied band. The presence of an edge indicates the presence of primary user in the band.

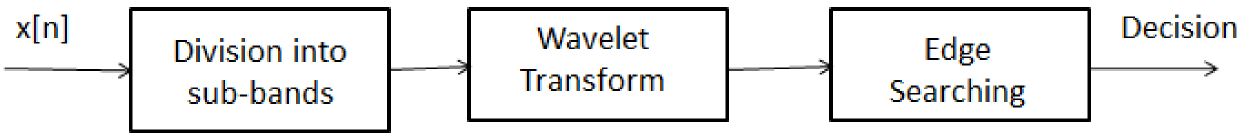

Figure 2-8: Principle of Wavelet Based Sensing

Pros:-

- Implementation cost is low as compared to multi-taper based sensing technique.
- It can easily adapt to dynamic PSD structures.

Cons:-

- In order to characterize the entire bandwidth higher sampling rates may be required.

2.2.6 Multiple Antenna Based Sensing

Wireless transmissions via multiple transmit and receive antennas, or the so called multi input multi output (MIMO) systems have gained considerable attention during recent times. MIMO systems generally employ sensing schemes based on the eigen values [14].

In order to perform sensing for MIMO systems two basic steps are followed:-

- Designing of the test statistics which is obtained using the eigen values of the co-variance matrix of the sample values. In this method two algorithms are generally used, one being the maximum eigen value detection and the other being condition number detection.
- Deriving of the probability density function (PDF) of the test statistics or eigen values so that sensing performance can be quantified.

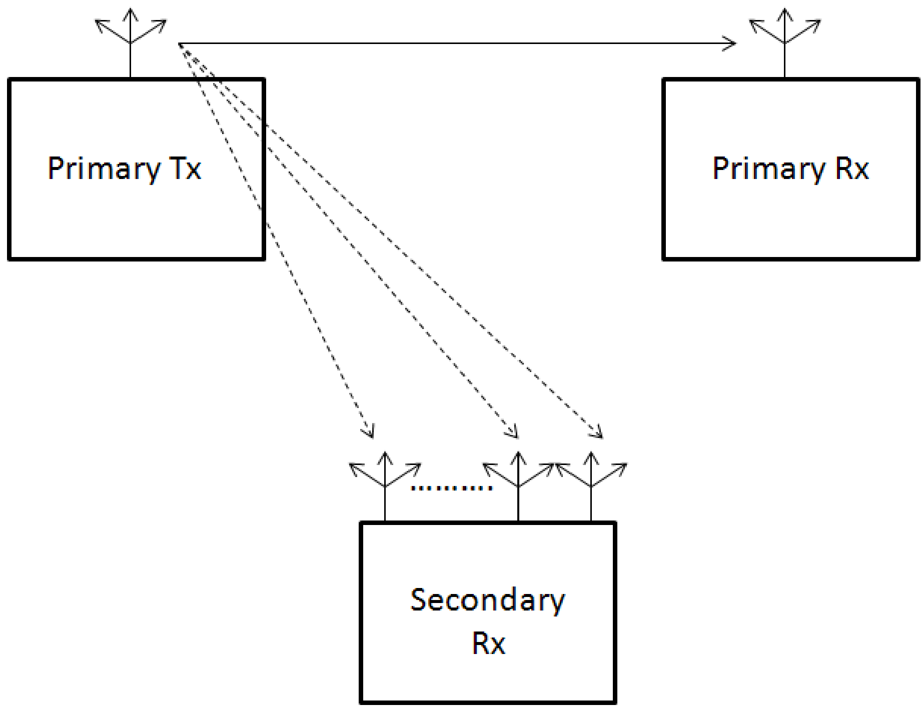

Figure 2-9: Detection using Multiple Antennas

Pros:-

- It does not require prior knowledge of the received signal characteristics.
- Since the same signal is received through multiple paths the noise power uncertainty is removed.

Cons:-

- Use of multiple antennas increases the cost of the detector.
- The complexity of detector is also increased.

2.2.7 Cyclo-stationary Detector

2.2.7.1 Cyclo-Stationarity- A Review

Nature has its way in such a manner that many of its processes arise due to periodic phenomenon. Examples include fields like radio astronomy wherein the periodicity is due to the rotation and revolution of the planets, weather of the earth due to periodic variation of seasons [15]. In telecommunication, radar and sonar fields it arises due to modulation, coding etc. It might be that all the processes are not periodic function of time but their statistical features indicate periodicities and such processes are called cyclo-stationary process.

For a process that is wide sense stationary and exhibits cyclo-stationarity has an auto-correlation function which is periodic in time domain. Now when the auto-correlation function is expanded in term of the Fourier series co-efficient it comes out that the function is only dependent on the lag parameter which is nothing but frequency. The spectral components of a wide sense cyclo-stationary process are completely uncorrelated from each other. The Fourier series expansion is known as cyclic auto-correlation function (CAF) and the lag parameter i.e. the frequencies is given the name of cyclic frequencies. The cyclic frequencies are multiples of the reciprocal of period of cyclo-stationarity. The cyclic spectrum density (CSD) which is obtained by taking the Fourier transform of the cyclic auto-correlation function (CAF) represents the density of the correlation between two spectral components that are separated by a quantity equal to the cyclic frequency.

The following conditions are essential to be filled by a process for it to be wide sense cyclo-stationary:-

$$E\{x(t+T_0) = E\{x(t)\} \tag{2.6}$$

$$\begin{gathered} R_x(t+T_0,\tau) = R_x(t,\tau) \\ where R_x = E\{x(t+\tau)x(t)\} \end{gathered} \tag{2.7}$$

Thus both the mean and auto-correlation function for such a process needs to be periodic with some period say T_0. The cyclic auto-correlation function (CAF) is represented in terms of Fourier co-efficient as:-

$$R_x^{n/T_0}(\tau) = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} R_x(t,\tau)e^{-j2\pi(n/T_0)t}dt \tag{2.8}$$

'n/T_0' represent the cyclic frequencies and can be written as 'α'. A wide sense stationary process is a special case of a wide sense cyclo-stationary process for '$n/T_0 = \alpha = 0$'.

The cyclic spectral density (CSD) representing the time averaged correlation between two spectral components of a process which are separated in frequencies by *'α'* is given as

$$S(f,\alpha) = \int_{\tau=-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi f\tau} d\tau \qquad (2.9)$$

The power spectral density (PSD) is a special case of cyclic spectral density (CSD) for 'α=0'. It is equivalent to taking the Fourier transform of special case of wide sense cyclo-stationary for 'n/T_0= α=0'.

2.2.7.2 Its usefulness in spectrum sensing

The signals which are used in several applications are generally coupled with sinusoid carriers, cyclic prefix, spreading codes, pulse trains etc. which result in periodicity of their statistics like mean and auto-correlation. Such periodicities can be easily highlighted when cyclic spectral density (CSD) for such signals is found out.

Primary user signals which have these periodicities can be easily detected by taking their correlation which tends to enhance their similarity. Fourier transform of the correlated signal results in peaks at frequencies which are specific to a signal and searching for these peaks helps in determining the presence of the primary user. Noise is random in nature and as such there are no such periodicities in it and thus it doesn't get highlighted on taking the correlation.

Pros:-

- ❑ Works well for low SNR conditions.
- ❑ It has the capability to distinguish between primary user and noise.
- ❑ It can differentiate between different types of signals

Cons:-

- ❑ Since all the cycle frequencies are calculated so the computational complexity is higher than energy detector.

2.2.7.3 Implementation of the detector

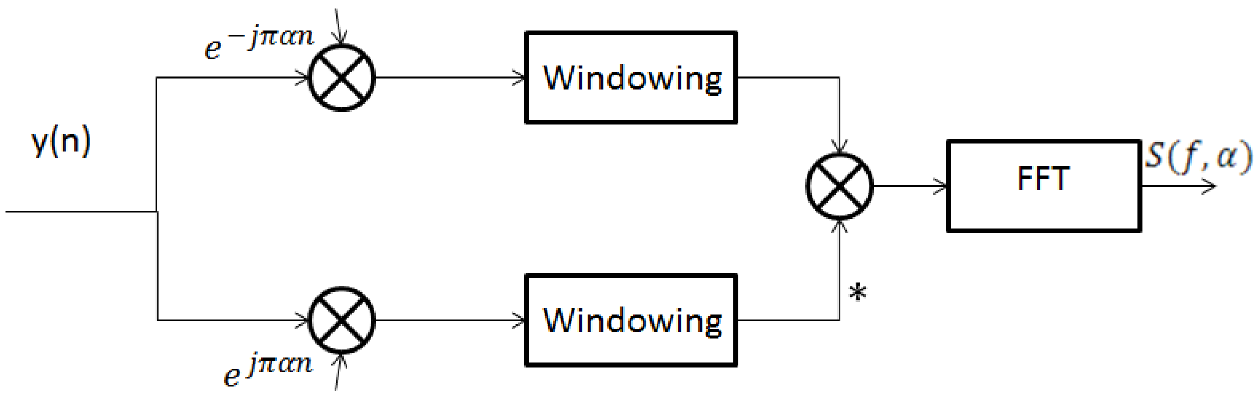

Figure 2-10: Principle of Cyclo-Stationary Detector

In order to implement the cyclo stationary detector [16] the following steps are followed:-

- Determine the cyclic frequencies for the signal, carrier frequency, window size, overlap number and fft size as

$$n = \text{message length}$$
$$nv = \text{overlap number}$$
$$nw = \text{window size}$$
$$nfft = \text{fft size}$$

$$nv = \frac{2}{5}n \qquad nw = \frac{3}{2}n \tag{2.10}$$

- The signal of interest say *'x(t)'* is shifted in time domain by *'-α/2'* and *'α/2'* as

$$x_1(t) = x(t).e^{-j2\pi(\alpha/2)t} \qquad x_2(t) = x(t).e^{j2\pi(\alpha/2)t} \tag{2.11}$$

- Now both the shifted signals are multiplied by a sliding window. The window used in this case is Hamming window. Figure 2-11 and Figure 2-12 shows the time domain and frequency domain representation of the Hamming window.

$$\begin{aligned} &window = hamming(nw) \\ &x_{i1}(t) = x_1(t).window \\ &x_{i2}(t) = x_2(t).window \end{aligned} \tag{2.12}$$

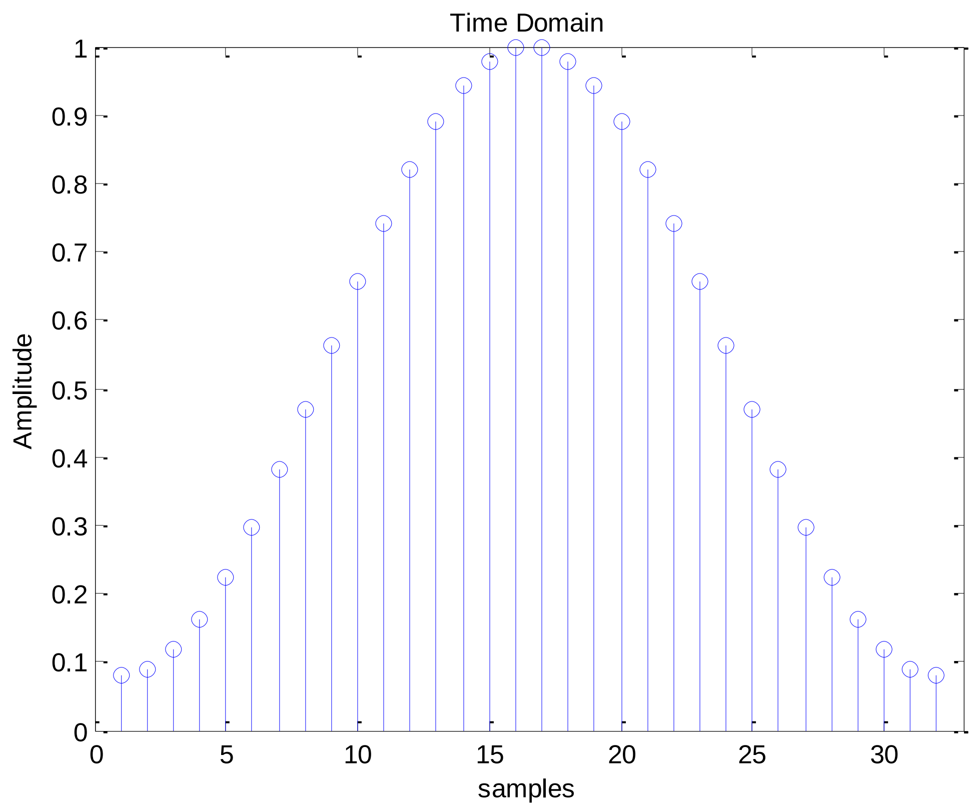

Figure 2-11: Time domain representation of Hamming Window

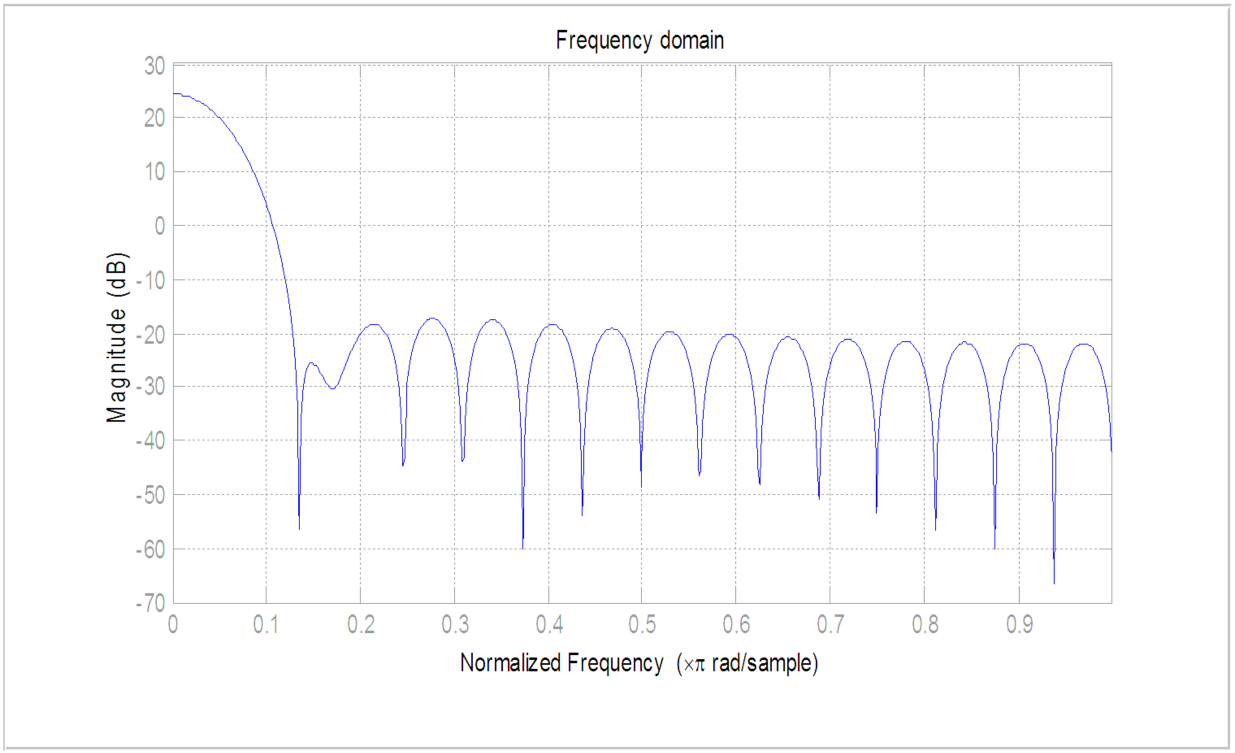

Figure 2-12: Frequency domain representation of the Hamming Window

- Now Fourier transform of these windowed signals is done as

$$X_{i1}(f) = fft(x_{i1}(t), nfft)$$
$$X_{i2}(f) = fft(x_{i2}(t), nfft) \tag{2.13}$$

- Spectral correlation function for each frame is found out and then it is normalized by its mean

$$S_{X_i}^{\alpha} = X_{i1}(f).conj(X_{i2}(f)) \tag{2.14}$$

$$S_X^{\alpha} = \frac{1}{K.W} \sum_{i=1}^{K} S_{X_i}^{\alpha} \tag{2.15}$$

where 'K' is the frame size and '$W = \|\ window\ \|^2$'.

- Now maximum of the spectral correlation function is found and compared to a threshold to find the presence of a primary user.

$$C = \max(S_X^{\alpha}) \quad (2.16)$$

Now 'C' is compared with a threshold 'λ'.

The probability of false alarm for the cyclo-stationary detector is given [17] as

$$P_f = \exp\left(-\frac{(2N+1)\lambda^2}{2\delta^4}\right) \quad (2.17)$$

From the above equation the threshold can be calculated as

$$\lambda = \sqrt{\frac{2\delta^4}{(2N+1)}\ln(P_f)} \quad (2.18)$$

This value of threshold can be used to calculate the probability of detection as

$$P_d = Q\left(\sqrt{\frac{2\gamma_{cp}}{\delta^2}}, \frac{\lambda}{\delta_B}\right)$$
$$where, \delta_B = \frac{(2\gamma_{cp}+1)\delta^4}{2N+1} \quad (2.19)$$

where 'δ' is the variance of the received signal, 'N' is the number of samples values of the signal and 'Υ_{cp}' is the SNR.

2.3. Co-operative Spectrum Sensing

2.3.1 Drawbacks of Single User Sensing

There are many hindering factors that compromise the detection performance of a secondary user like multipath fading, receiver uncertainty and shadowing. Figure 2-13 shows these scenarios, SU1 and SU2 (cognitive users) are located in the transmitting range of primary users PU [18] while SU3 is outside the range of PU. The signal from PU Tx has no direct path towards SU2 so it receives multiple copies of the signal after reflection from objects like buildings and also experiences shadow fading. This may result in incorrect detection of the PU Tx at SU2 site. Also SU3 is outside the range of PU Tx so it does not happen to know the presence of primary user and its communication with SU1 may lead to interference to primary user. The sensing equipment at the secondary user's site can be enhanced in terms of implementation complexity, leading to an increase in hardware cost, so that it can detect signals with low SNR values.

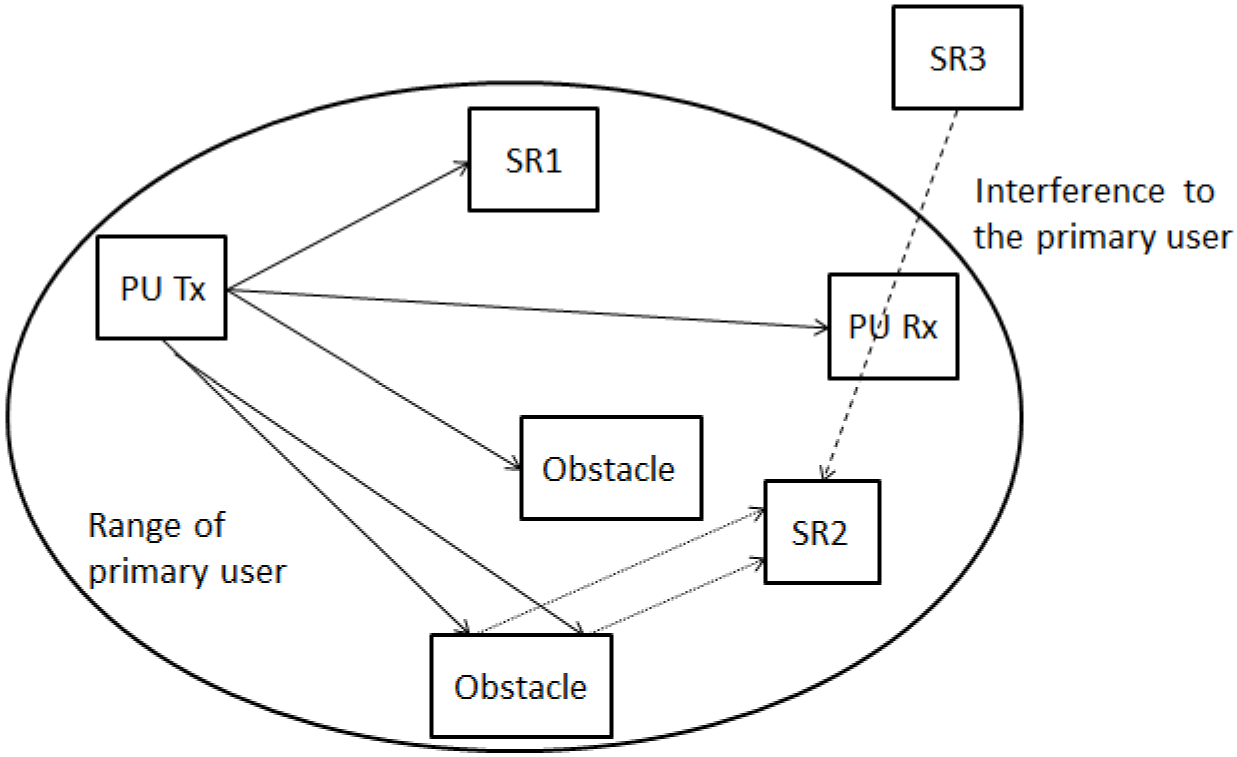

Figure 2-13: A Cognitive cell with primary and secondary users

2.3.2 *Idea of Co-operative Sensing*

However due to spatial diversity of each user it is very unlikely that each of them will face problems in detection simultaneously. Thus all the users can co-operate among themselves and share their information so that the chances of incorrect detection are minimized. The sharing of information among users leads to the concept of co-operative spectrum sensing without increasing the cost as little extra hardware is required. Figure 2-14 shows comparison of power level for non-cooperative and cooperative case [18], [19]. It can be easily concluded that due to cooperation the degradation in power level is much lower. The gain achieved due to cooperation defines the decrease in degradation which in turn is controlled by the amount of time spent on sensing the environment. With less sensing time more data can be transmitted during a given time interval and vice-versa. Thus there is always a trade-off between the sensing time and the cooperative gain achieved.

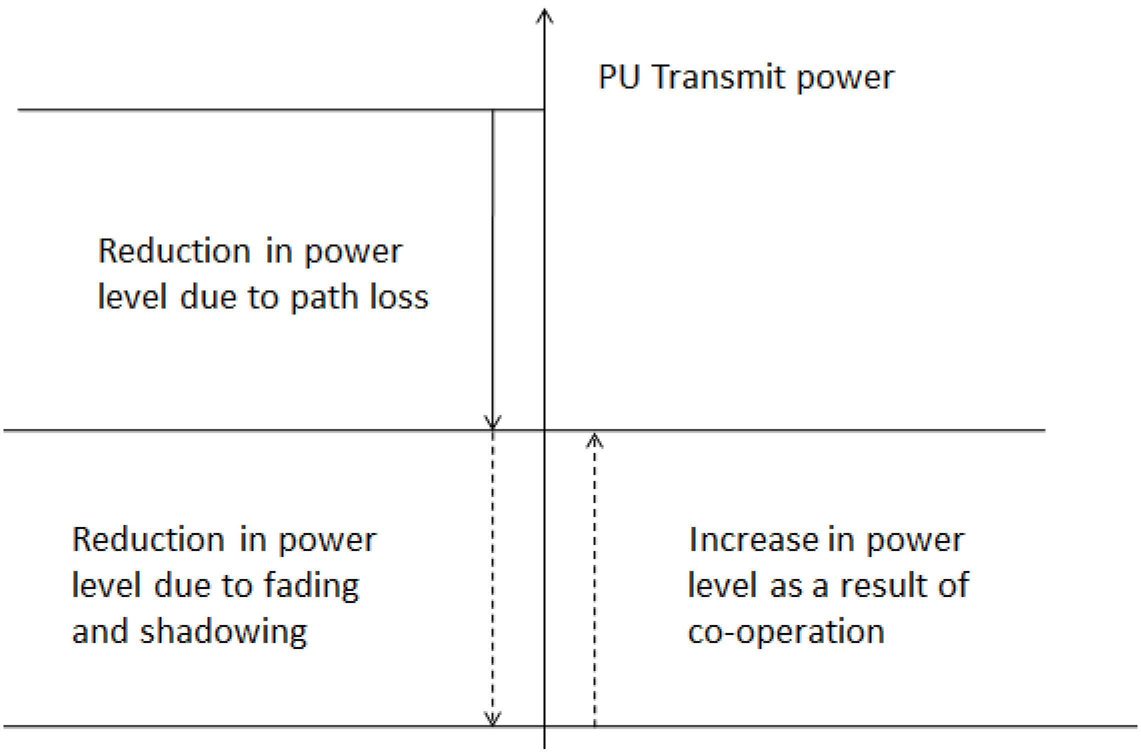

Figure 2-14: Power level comparison for co-operative and non-cooperative case

2.3.3 Different Techniques of Co-operative Sensing

FUSION RULES

The fusion center receives the information from all the secondary users. Depending on the type of information the fusion rules can be classified into two categories:-

- Data Fusion or Soft Combining- Each of the secondary users senses the channel and it amplifies its sensed data and sends this amplified information to the fusion center. At the fusion center Maximum ratio combining (MRC) or Square Law Combining (SLC) fusion techniques is applied. In MRC technique, the channel state information from both primary users to secondary users and from secondary users to the fusion center is required. On the other hand in SLC with fixed amplification factor, only the channel state information from the secondary users to the fusion center is required. However if variable amplification factor is used then channel state information from primary users to secondary users is also required [20].

- Decision Fusion- The problem with soft combining is that it requires large overhead as the entire sensed data is sent to the fusion center. Thus instead of all information only the decision made by the secondary user is sent to the fusion center. Depending on the decision threshold and the number of bits it can be further classified into

  - Bayesian and Neyman-Pearson Rule- Suppose the secondary user's decision be represented as 'u_i'. Bayesian rule requires a priori probabilities of the decision when it is '1' and '0' i.e. $P(u_i \mid H1)$ and $P(u_i \mid H0)$ and also priori probabilities $P(u=0)$ and $P(u=1)$. There are four possible cases and each is associated with its own cost. The Bayesian detection test can be given as

$$\begin{aligned} \prod_{i=0}^{m} \frac{P[u_i \mid H_1]}{P[u_i \mid H_0]} > \frac{P_0(C_{10}-C_{00})}{P_1(C_{01}-C_{11})} \Rightarrow H_1 \\ \prod_{i=0}^{m} \frac{P[u_i \mid H_1]}{P[u_i \mid H_0]} < \frac{P_0(C_{10}-C_{00})}{P_1(C_{01}-C_{11})} \Rightarrow H_0 \end{aligned} \quad (2.20)$$

    where 'C_{jk} $(j=0,1 \text{ and } k=0,1)$' is cost of declaring '$H_j$' true when '$H_k$' is present. On the other hand Neyman-Pearson rule makes no assumption regarding the probability of any hypothesis. It gives such a rule that by keeping the probability of false alarm within a certain limit say α, the probability of detection can be maximized. The test is given as

$$\begin{aligned} \prod_{i=0}^{m} \frac{P[u_i \mid H_1]}{P[u_i \mid H_0]} > \lambda \Rightarrow H_1 \\ \prod_{i=0}^{m} \frac{P[u_i \mid H_1]}{P[u_i \mid H_0]} < \lambda \Rightarrow H_0 \end{aligned} \quad (2.21)$$

    where λ is the threshold [21].

  - Quantized Fusion- This technique uses three decision thresholds and thus there are region is split into four regions. The decision sent to the fusion center is a two bit valued. The method is better than soft combining in terms of the complexity and overhead.

- Hard combining- Instead of sending two bits the overhead can be further decreased by sending just a single bit. This technique requires a single threshold. A binary ‘1’ indicates presence of primary user whereas binary ‘0’ indicates its absence. The decision made by the secondary user is sent to the fusion center. At the fusion center choice from a number of fusion rules is made and the rule is applied to the received decision. Some of the popular rules are OR, AND and MAJORITY. They are classified as k-out-of-n-rule. The rule can be expressed as

$$P_d = \sum_{i=k}^{n} \binom{n}{i} p_d^i (1 - p_d)^{n-i} \tag{2.22}$$

where k=n, AND operation

k=1, OR operation

k=ceil(n/2), MAJORITY operation

Here *‘P_d’* is the probability of detection and *‘p_d’* is the detection probability of single users.

Classification of spectrum sensing in the following categories (figure 2-15) leads to an easy analysis [18]:-

- Centralized cooperative sensing- A fusion center controls the entire process of spectrum sensing. It is responsible for selection of frequency band and instructs the secondary users to perform local sensing at their respective sites. The fusion center then collects the result of the local sensing through a control channel. Different fusion algorithms are available to decide on the presence of the primary users. The fusion center utilizes such algorithms and makes a final decision and conveys it to the secondary users.
- Distributed cooperative sensing- It does not require a fusion center. The secondary users perform local sensing at their site and send their results to other users that are in their vicinity. Based on its own result and the data from other secondary users it makes a decision regarding the presence of primary user using a local criterion. Now this decision is conveyed to other users and all the steps are again followed until all converge to a common decision.
- Relay assisted co-operative sensing- The decision reported on the fusion center travels on a control channel. It may so happen that a secondary user has a strong sensing channel

but a very weak reporting channel while another user in the vicinity might have the just opposite case. In such a scenario both can cooperate with each other such that one will sense the channel and sends its decision to the other user and then it conveys it to the fusion center. Thus the second user acts a relay and the scheme becomes a multi-hop one.

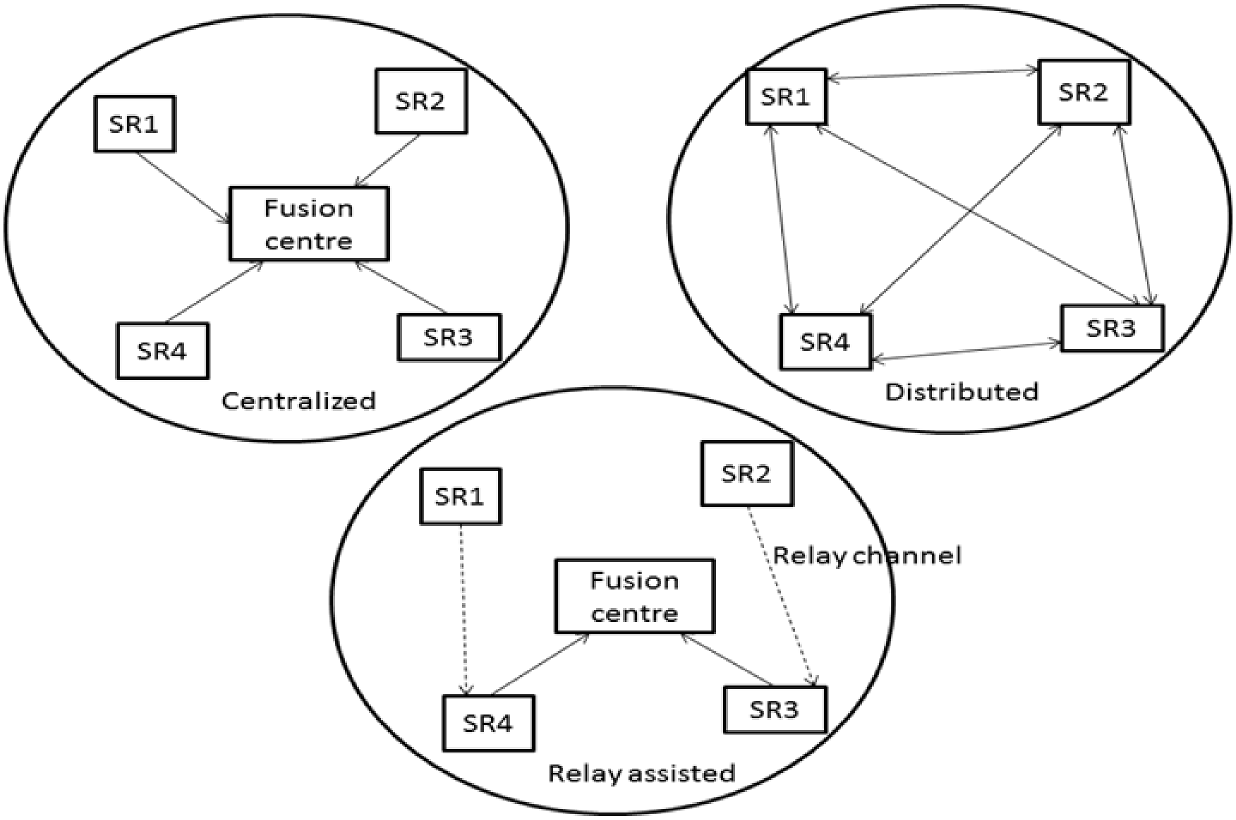

Figure 2-15: Different forms of Co-operative Spectrum Sensing

2.4. Wireless Regional Area Network (WRAN) – IEEE 802.22

2.4.1 Physical Layer Specifications

FCC has reported that 70% of the spectrum is underutilized [22] and thus it had given legal permission for unlicensed operation in VHF and UHF bands because of their good propagation characteristics. This led to the genesis IEEE 802.22 WRAN working group. The group came up with the first cognitive radio standard called the Wireless Regional Area Network (WRAN).

Physical and Medium Access Control (MAC) layer specifications are the main highlight of the standard.

The frequency range of operation is set to be 54 MHz to 862 MHz. Orthogonal Frequency Division Multiple Access (OFDMA) is used in the physical layer as it provides adaptability and flexibility and enables easy jumping from one frequency to another which is very essential for cognitive radio. The physical layer parameters for WRAN can be tabulated as in table 2-1 [5], [23]

Table 2-1: Physical Layer Parameters for IEEE 802.22

Parameters	**Specifications**
Frequency Range	54-862 MHz
Channel Bandwidth	6, 7 or 8 MHz
Data Rate	4.54 to 22.69 Mbps
Spectral Efficiency	0.76 to 3.78 bits/(s.Hz)
Payload Modulation	QPSK, 16-QAM, 64-QAM
Multiple Access	OFDMA
FFT Size	2048
Cyclic Prefix Mode	1/4, 1/8, 1/16, 1/32
Duplex	TDD
Coding	Block Convolutional Code

2.4.2 *Time domain description of symbols*

The OFDM signal is passed through inverse Fourier transform block to generate the time domain output T_{FFT}. The cyclic prefix is inserted in front of the time domain output for duration of T_{CP}. The combination of both gives the total symbol for WRAN which is shown in the figure 2-16.

The ratio of T_{CP} to T_{FFT} is conveyed to the customer premise equipment (CPE) through the control channel.

$$T_{CP} = \frac{T_{FFT}}{x} \tag{2.23}$$

where x=4,8,16 or 32 depending on the cyclic prefix. The total symbol time is given as

$$\begin{aligned} T_{SYM} &= T_{CP} + T_{FFT} = T_{FFT} + \frac{T_{FFT}}{x} \\ &= T_{FFT}\left(1 + \frac{1}{x}\right) \end{aligned} \tag{2.24}$$

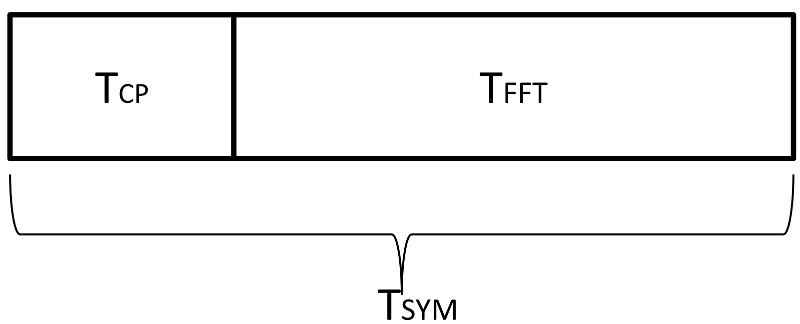

Figure 2-16: The Total symbol duration of an OFDM symbol

2.4.3 Frequency domain description of symbols

OFDM is represented in the frequency domain by its sub-carriers (2048 in number). They can be classified as:-

- Data sub-carriers – There 1440 sub-carriers which are used for data. They are grouped into 60 sub-channels each having 24 data sub-carriers.
- Pilot sub-carriers - The Pilot sub-carriers are distributed across the bandwidth and their location depends on the configuration used. Each of the 60 sub-channels has 4 pilot sub-carriers each giving rise to total of 240 pilot carriers.
- Guard sub-carriers – The remaining of the sub-carriers i.e. 384 in number are used for guard band with an amplitude of ‘0’ and phase of ‘0’.

The sub-carrier spacing and the sampling frequency can be tabulated as in table 2-2 [5]

Table 2-2: Different Carrier Spacing and Sampling frequency for WRAN

Bandwidth (MHz)	6	7	8
F_s **(MHz)**	6.856	8	9.136
$\Delta f = \frac{F_s}{2048}\ (Hz)$	3347.656	3906.25	9460.938
$T_{FFT} = \frac{1}{\Delta f}\ (\mu s)$	298.716	256	224.168
$TU = \frac{T_{FFT}}{2048}\ (ns)$	145.858	125	109.457

2.4.4 Transmitter and Receiver Description

The Transmitter section is shown in the figure 2-17

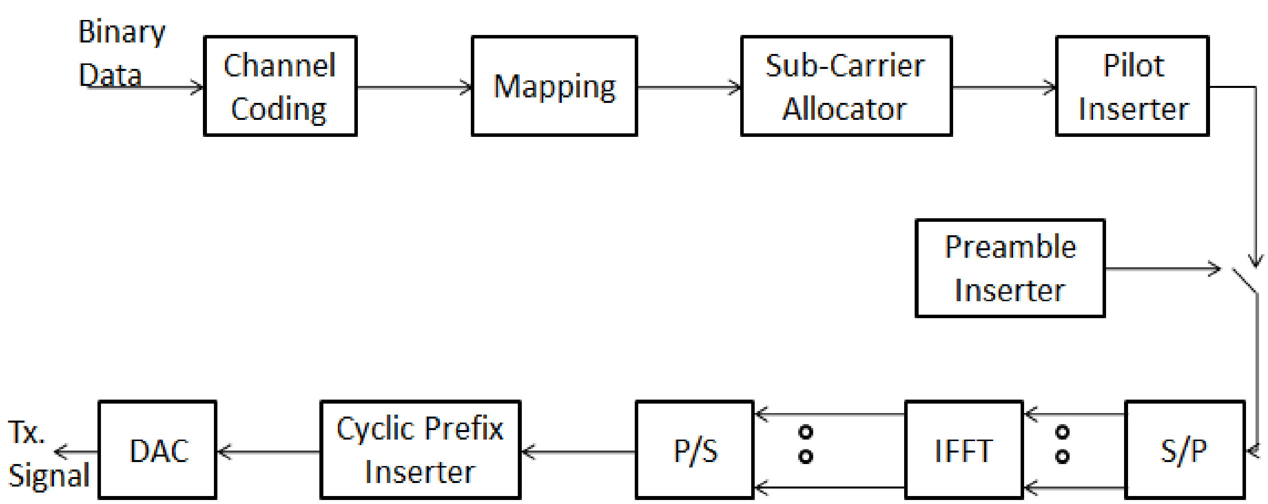

Figure 2-17: WRAN Transmitter Section

The important functional units can be described as:-

- The coding scheme consists of scrambler, Forward Error Correction (FEC), bit-interleaving and modulation or constellation mapping. Bit-interleaver arranges the data in a non-contiguous manner and thus helps in increasing the performance by reducing the error. There are 3 different modulation schemes :-

- Distance (D) < 15 km - 64 QAM
- D≥ 15 km and D<22 km – 16 QAM
- D ≥ 22 km – QPSK

Thus it can be seen that the modulation schemes are adaptive with respect to the distance of communication.

- Depending on the modulation scheme used the total bandwidth is sub-divided into carriers with each point of the constellation being mapped into a single sub-carrier.
- Pilot Inserter and Preamble Inserter are used for synchronization purposes. They further aid in channel estimation.
- The serial bits are converted to parallel so that Inverse Fast Fourier Transform (IFFT) can be performed on it.
- After performing IFFT the bits are gain converted to serial form and cyclic prefix is added to it. Cyclic prefix helps to prevent ISI caused by the channel delay spread. The OFDM symbol is extended by the cyclic prefix that contains the same waveform as the ending part of the symbol.
- The bits are then converted to analog domain to facilitate transmission.

The Receiver part (Figure 2-18) is just the reverse of the transmission part and each unit does the opposite function performed by it in the transmission part.

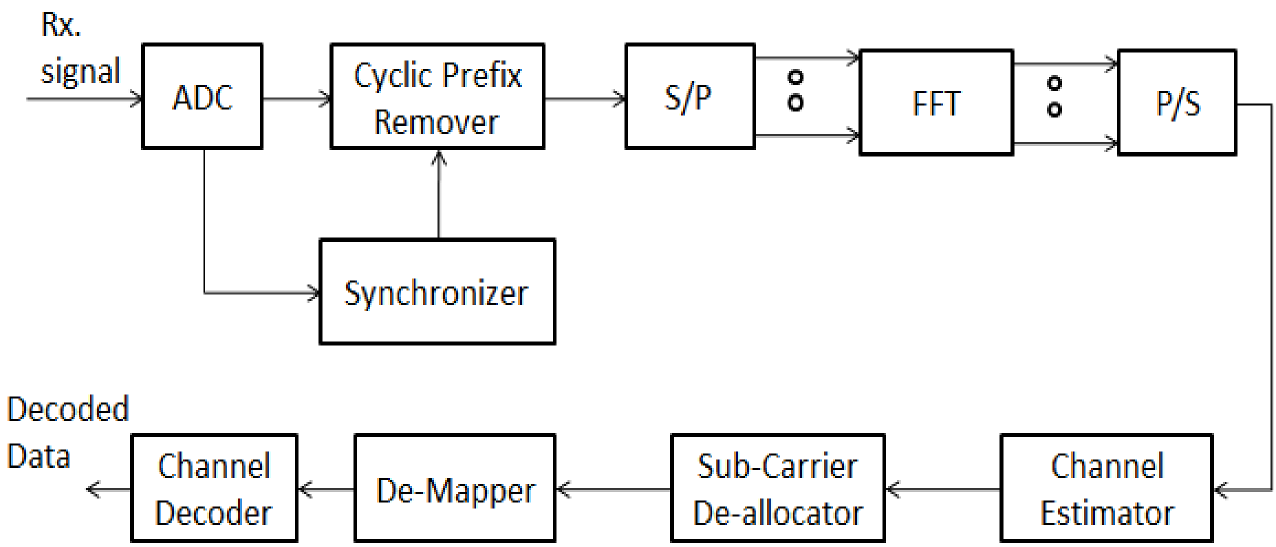

Figure 2-18: WRAN Receiver Section

2.4.5 DVB-T Signal and its mathematical description

Sensing is required for television (both analog and digital) and wireless microphones. Wireless microphones are being used by the industry in empty television bands. The format of the analog and digital television broadcasts depends on the area in which the system is being implemented. In North America, for example, analog television is based on NTSC and digital television is based on ATSC whereas Europe uses the Digital Video Broadcast-Terrestrial (DVB-T) standard. Wireless microphones standard is not yet specified but they generally tend to be analog frequency modulation (FM) transmitters. The bandwidth is typically limited to 200 kHz, though it can vary from region to region.

The sensing requirements are such that some of the licensed signals must be sensed at a very low SNR. This poses a primary challenge in spectrum sensing. The only way to fulfill these requirements is to ensure protection of licensed transmissions.

Spectrum sensing in WRAN [24] requires number of inputs to be given to the sensing equipment out of which the most important are Channel Number which is a 8 bit long number in the range 0 to 255. The other input being the channel bandwidth. Since there are 3 bandwidth specifications in

WRAN (6, 7 and 8 MHz) it is necessary to tell the equipment that for which bandwidth the sensing is being done.

As regards the output there are 3 different output values, TRUE indicating the presence of the primary user, FALSE indicating that the band is empty and NO DECISION which is the output when it is not directed to the sense the environment.

There are no specific spectrum sensing methods outlined in the WRAN standard. But the different spectrum sensing methods were evaluated by the IEEE 802.22 Working group. Based on this evaluation the schemes were classified as blind spectrum sensing in which the receiver has no idea about the characteristics of the signal (like energy detector and eigen value based detector) and other is signal specific sensing in which some characteristic of the received signal was known from beforehand (like waveform based, cyclo-stationary detector etc.) .

The symbol that is transmitted in DVB-T signals is OFDM symbol as it is the multiple access scheme that is used in WRAN. The symbol can be mathematically represented as:-

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{\substack{k=-N_T/2 \\ k\neq 0}}^{k=N_T/2} C_k e^{j2\pi k\Delta f(t-T_{CP})} \right\} \tag{2.25}$$

where t- Time elapsed since the beginning of the current symbol.

f_c- Carrier frequency

C_k- Data to be transmitted whose sub-carrier frequency is determined by the offset k.

Δf- Carrier spacing

T_{CP}- Duration of cyclic prefix

N_T- Number of used sub-carriers

Chapter 3. Optimal Users & Threshold Adaptation for Cognitive Radio

3.1. Challenges of Cognitive Radio for increased users

Co-operative spectrum sensing plays a major role in determining the Quality of Service (QoS) of the primary users and improving spectrum utilization efficiency. The more number of users are involved in sensing more will be the sensing accuracy. But with more number of users the overhead for sensing also increases and this result in decrease of the throughput that the network can achieve [25].

In IEEE 802.22 (WRAN) systems there is no separate control channel assigned to secondary users. Thus in order to report the sensing results the secondary users make use of a fraction of the data transmission duration to transmit the sensing report to the fusion center. Thus with more number of users a greater fraction of the data transmission time is used up and thus throughput is decreased. Figure 3-1 illustrates this scenario

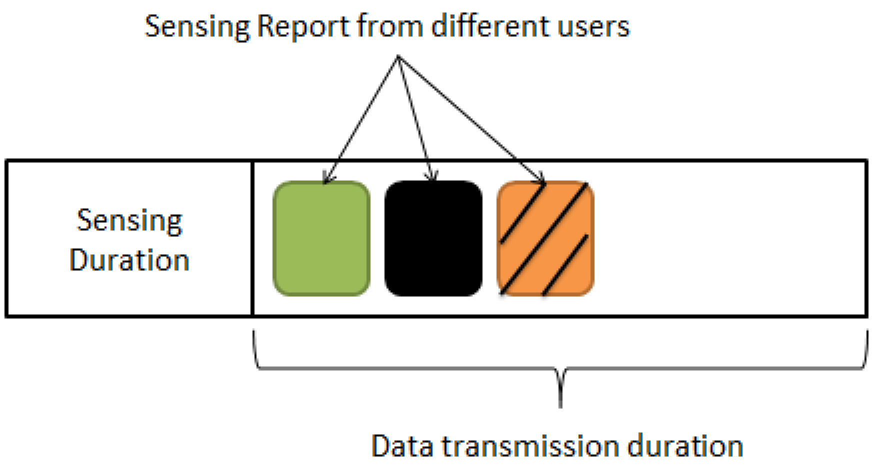

Figure 3-1: Sensing reports from different users occupying the data transmission part

3.2. Remedy of the increased overhead problem by finding the optimal number of users

In a co-operative spectrum sensing technique the important metric of sensing performance is either minimizing the miss-detection probability by keeping a cap on the false alarm probability or minimizing the false alarm probability by capping the miss-detection probability. In this part the total error $(P_f + P_m)$ is minimized in terms of numbers of users. Thus optimal numbers of users are found out such that detection performance is satisfactory without increasing the overhead to a large extent. Suppose that number of users and signal to noise ratio (SNR) is known from beforehand, then the algorithm mentioned in [26] is applied as:-

$$P_f = \sum_{l=n}^{k} \binom{k}{l} p_f^l (1-p_f)^{k-l}$$
$$P_m = 1 - \sum_{l=n}^{k} \binom{k}{l} p_d^l (1-p_d)^{k-l} \tag{3.1}$$

Now the total error probability is given as

$$P_f + P_m = \sum_{l=n}^{k} \binom{k}{l} p_f^l (1-p_f)^{k-l} + 1 - \sum_{l=n}^{k} \binom{k}{l} p_d^l (1-p_d)^{k-l} \tag{3.2}$$

In order to find the optimal number of users we minimize the error probability by differentiating with respect to *'n'* and equating it to zero for finding the value.

$$Let, G(n) = \sum_{l=n}^{k} \binom{k}{l} p_f^l (1-p_f)^{k-l} + 1 - \sum_{l=n}^{k} \binom{k}{l} (1-p_m)^l p_m^{k-l} \tag{3.3}$$

$$\frac{\delta G(n)}{\delta n} \approx G(n+1) - G(n) \tag{3.4}$$

$$\frac{\delta G(n)}{\delta n} = \binom{k}{n} \left[(1-p_m)^n p_m^{k-n} - p_f^n (1-p_f)^{k-n} \right] = 0$$

$$\Rightarrow \left(\frac{p_f}{1-p_m} \right)^n = \left(\frac{p_m}{1-p_f} \right)^{k-n} \tag{3.5}$$

$$\Rightarrow \frac{k-n}{n} = \frac{\ln\left(\frac{p_f}{1-p_m} \right)}{\ln\left(\frac{p_m}{1-p_f} \right)} = \alpha(say)$$

$$n \approx \left\lceil \frac{k}{1+\alpha} \right\rceil \tag{3.6}$$

Thus optimal value of user is given as

$$n_{opt} = \min\left(k, \left\lceil \frac{k}{1+\alpha} \right\rceil \right) \tag{3.7}$$

3.3. Adapting the threshold by using the gradient descent algorithm

The gradient descent algorithm can be used to adapt the threshold for detection. The algorithm is an iterative one and goes on till the difference between the required quantities is less than the tolerance value for the algorithm. The basic requirement of the algorithm is that the function on which it is applied must be differentiable. The gradient update equation [27] is given as

$$\lambda(n+1) = \lambda(n) - \mu \nabla \varepsilon(n) \tag{3.8}$$

where *'λ'* is the threshold, *'μ'* is the step size, *'ε'* is the sensing error.

$$\nabla \varepsilon(n) = \nabla (p_f + p_m)$$

$$\Rightarrow \nabla \varepsilon(n) = \nabla\left(\exp\left(-\frac{(2N+1)\lambda^2}{2\delta^4} \right) + 1 - Q\left(\sqrt{\frac{2\gamma_{cp}}{\delta^2}}, \frac{\lambda}{\delta_B} \right) \right)$$

$$\Rightarrow \nabla \varepsilon(n) = \left[-\frac{\lambda(2N+1)}{\delta^4} \exp\left(-\frac{(2N+1)\lambda^2}{2\delta^4} \right) \right] + \frac{\lambda}{\delta_B} \exp\left(-\frac{\frac{2\gamma_{cp}}{\delta^2} + \left(\frac{\lambda}{\delta_B}\right)^2}{2\delta^4} \right) I_0\left(\frac{\lambda\sqrt{2\gamma_{cp}}}{\delta_B . \delta} \right) \tag{3.9}$$

Here *'$I_0(.)$'* is the modified Bessel function of zeroth order and first kind. The series approximation for this function is given as

$$I_0(x) = 1 + \frac{x^2}{4} + \frac{x^4}{64} + \frac{x^6}{2304} + \frac{x^8}{147456} + ... \tag{3.10}$$

In case the value of 'x' is less than '1' then it can be approximated to

$$I_0(x) \approx 1 \tag{3.11}$$

Thus the gradient update equation becomes

$$\lambda(n+1) = \lambda(n) - \mu\left[-\frac{\lambda(2N+1)}{\delta^4} \exp\left(-\frac{(2N+1)\lambda^2}{2\delta^4} \right) \right] + \frac{\lambda}{\delta_B} \exp\left(-\frac{\frac{2\gamma_{cp}}{\delta^2} + \left(\frac{\lambda}{\delta_B}\right)^2}{2\delta^4} \right) \tag{3.12}$$

3.4. Particle Swarm Optimization (PSO) technique for adapting the threshold

The particle swarm optimization (PSO) is an algorithm which draws its inspiration from the nature. It is based on the social behavior of bird flocking and fish schooling which was originally introduced in [28]. It is in contrast to the optimization performed by the gradient descent algorithm as it does not require the gradient of the objective function. Thus it relaxes the requirement of the objective function to be differentiable. Hence, PSO is suitable for optimization problems that are relatively noisy, irregular, or dynamic [29].

In PSO the particles continually search for solutions that give rise to optimum condition. In each step the particles continuously change their position based on the knowledge of themselves and the other particles. Thus the positions of other particles have a great influence on the position of the particle under consideration. After several steps the particle moves towards an optimum value. Each particle updates its position on the basis of the following factors:-

- pbest- The particles best position from the previous iteration.
- gbest- The best position of the swarm or the group that all the particles found after agreeing to it.
- nbest- The best position of its neighboring particles from the previous step.

The update equation for position is given as

$$\begin{gathered} V = C_0 X + C_1 r_1 \times (pbest - X) + C_2 r_2 \times (gbest - X) + C_3 r_3 \times (nbest - X) \\ X = X + V \end{gathered} \tag{3.13}$$

where *‘c_0,c_1,c_2 and c_3’* are constants, *‘r_1,r_2 and r_3’* are random numbers between ‘0’ and ‘1’. Here ‘V’ is the velocity of the particle and ‘X’ is the position.

The procedure is continued iteratively until the stopping condition is satisfied. The stopping condition can be that the number of iterations reaches a maximum value or the change in the fitness function is less than a given tolerance value say *‘δ’*.

$$|\, gbest(n+1) - gbest(n) \,| < \delta \tag{3.14}$$

It is better to choose the first condition as the second one has the chance that it might get trapped in a local minimum.

The PSO technique can be applied to spectrum sensing part of the cognitive radio. Instead of position as the parameter in PSO algorithm, the threshold value as found out by the secondary users can be used as parameter. The threshold value is updated after every loop by taking into account the secondary users previous threshold value and the group's best threshold value from the previous step.

3.5. Results and Discussions

In order to find the receiver operating characteristics (ROC) suppose a signal at arbitrary frequency is taken and applied to the cyclo-stationary detector. This is considered as primary users signal and the detector is used to find the peaks at specific frequency points *'$\alpha=0, f=f_c$ and $\alpha=2f_c, f=0$'*. A particular secondary user is allowed to test for the signal for a number of times and the probability of correctly identifying the primary users gives the probability of detection whereas the threshold for detection is decided by the probability of false alarm. The threshold can be obtained from equation (2-18). Figure 3-2 shows the cyclic spectral density for a SSB signal with center frequency of 3 MHz and SNR of *'-5 dB'*. The peaks in the figure are searched for detection of primary user.

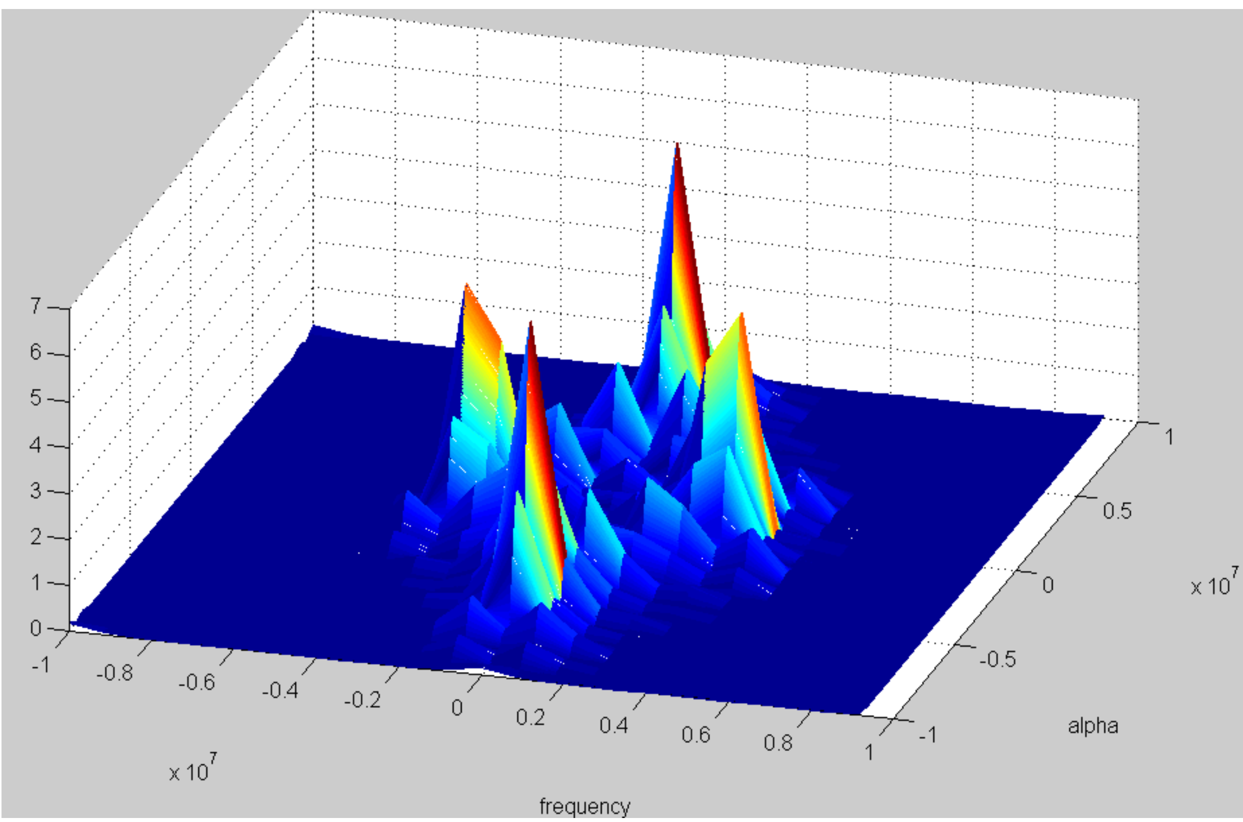

Figure 3-2: Cyclic Spectral Density for AM-SSB signal

Figure 3-3 shows the ROC curves for different fusion schemes for a total of 8 secondary users also for optimal number of users obtained from the equation (3-7). We see that probability of detection is higher for OR scheme as compared to others as it requires only 1 user to confirm that there is a primary user in the band whereas AND scheme requires that all the users must confirm that primary users is present. MAJORITY scheme performs better than single user but not as good as OR because it requires half or more than half to confirm the presence. It can be seen from the figure that the optimal curve does not follow a particular fusion scheme but varies along different schemes as number of user taken into consideration is varied. Thus it does not rely on any one of the scheme.

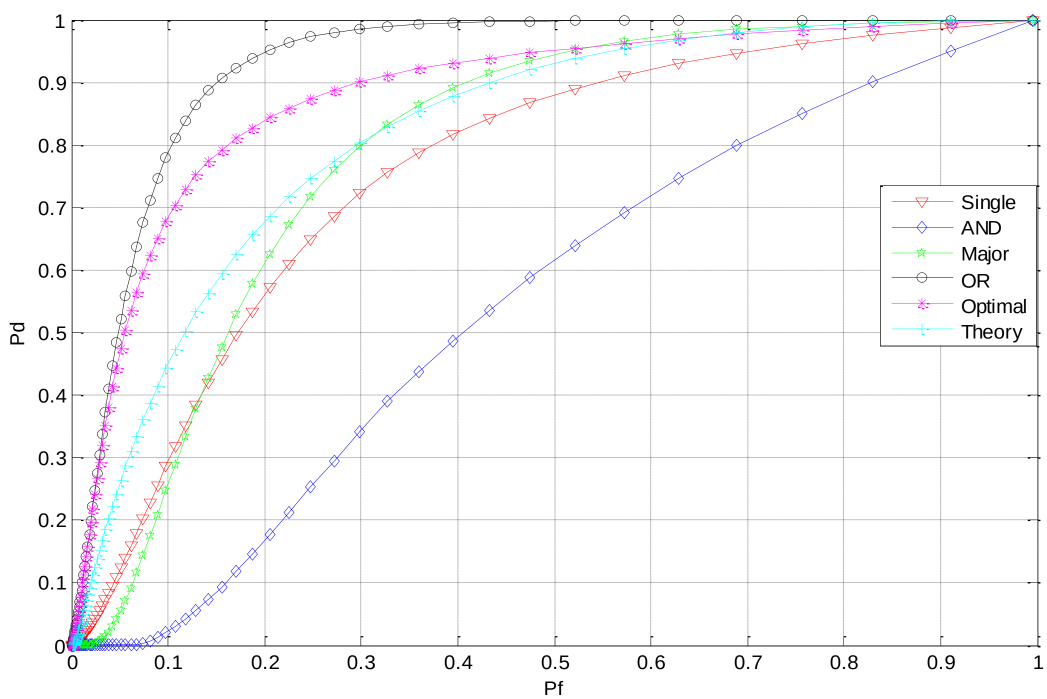

Figure 3-3: ROC curve for maximum 8 numbers of users

Figure 3-4 shows the detection probability versus the SNR curve for different number of users under OR co-operative sensing scheme. It can be easily concluded that the with more number of users the detection probability is higher for low values of SNR and for higher SNR values there is hardly a huge difference.

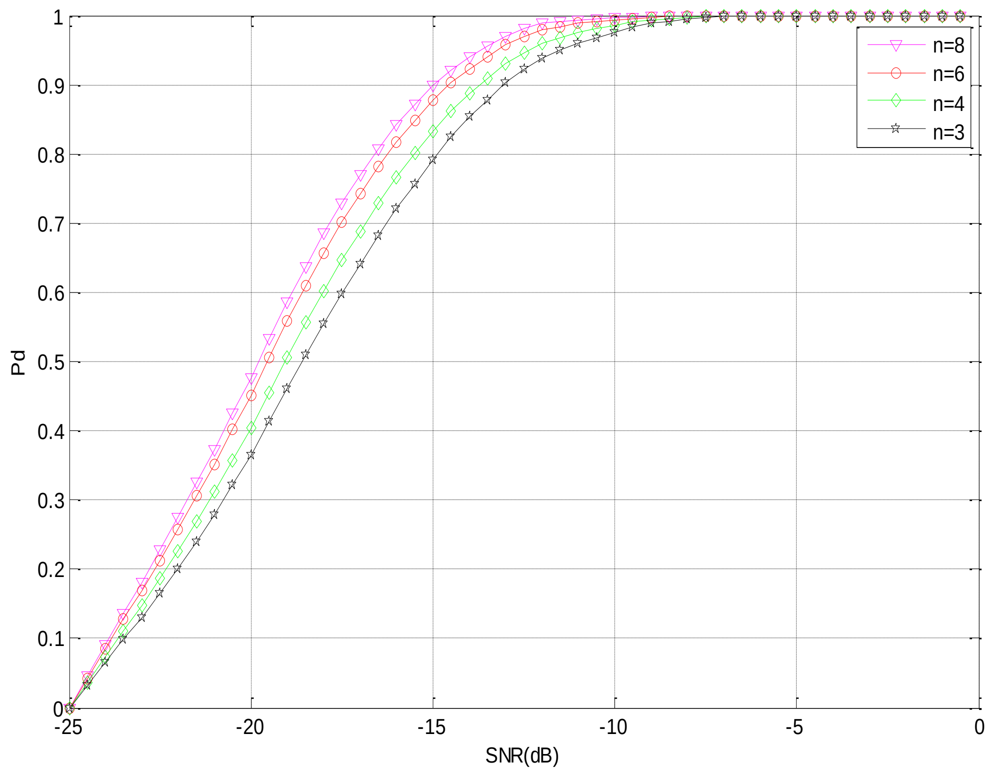

Figure 3-4: Detection probability versus SNR for different users

Figure 3-5 shows the number of users taken at a particular instant of probability of false alarm for finding the optimal ROC curve in figure 3-3. One finds that for low probability of false alarm the minimum number of users required is more as the threshold is less whereas for higher false alarm probability one requires less users as threshold is more and if a secondary user confirms a primary user presence than it is less doubtful.

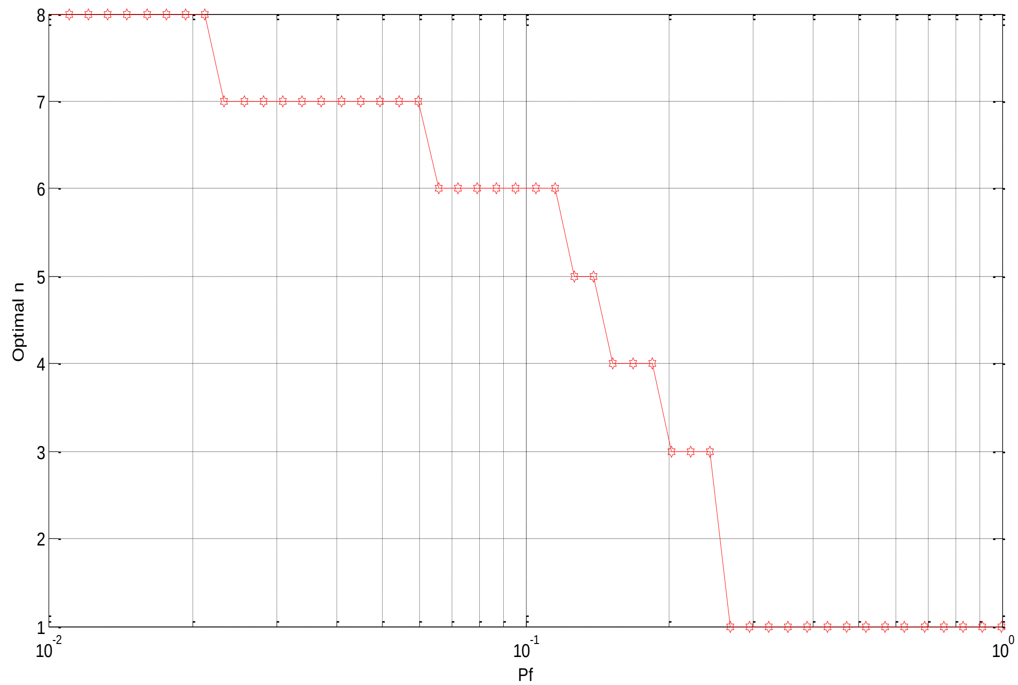

Figure 3-5: Optimal number of users versus false alarm probability

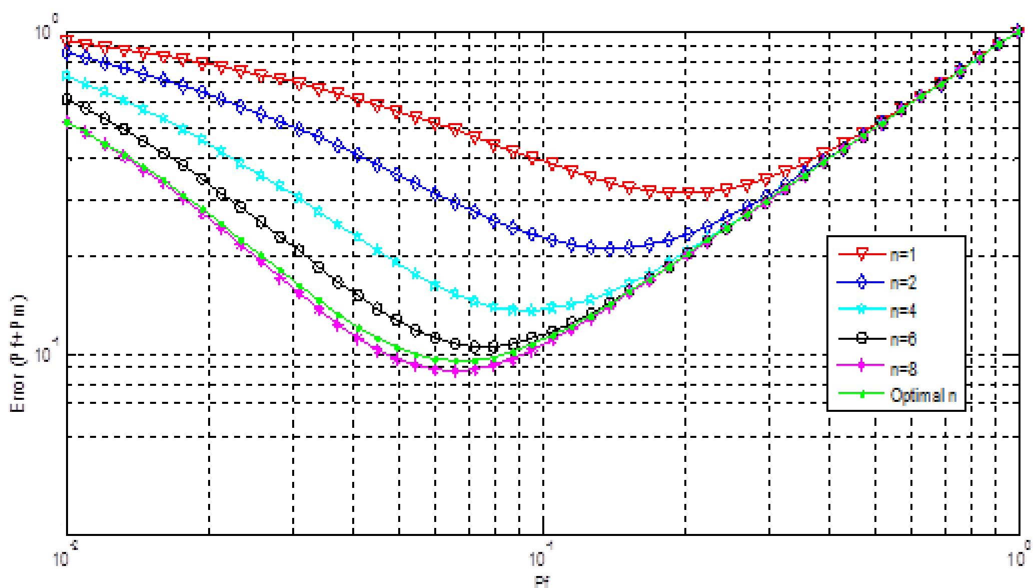

Figure 3-6: Error versus false alarm probability plot for different fusion schemes

Error versus false alarm probability curve is shown in figure 3-6 for different number of users. In this figure the green curve for the optimal case is seen to vary along the error curve of different number of users as the SU are varied depending on the algorithm.

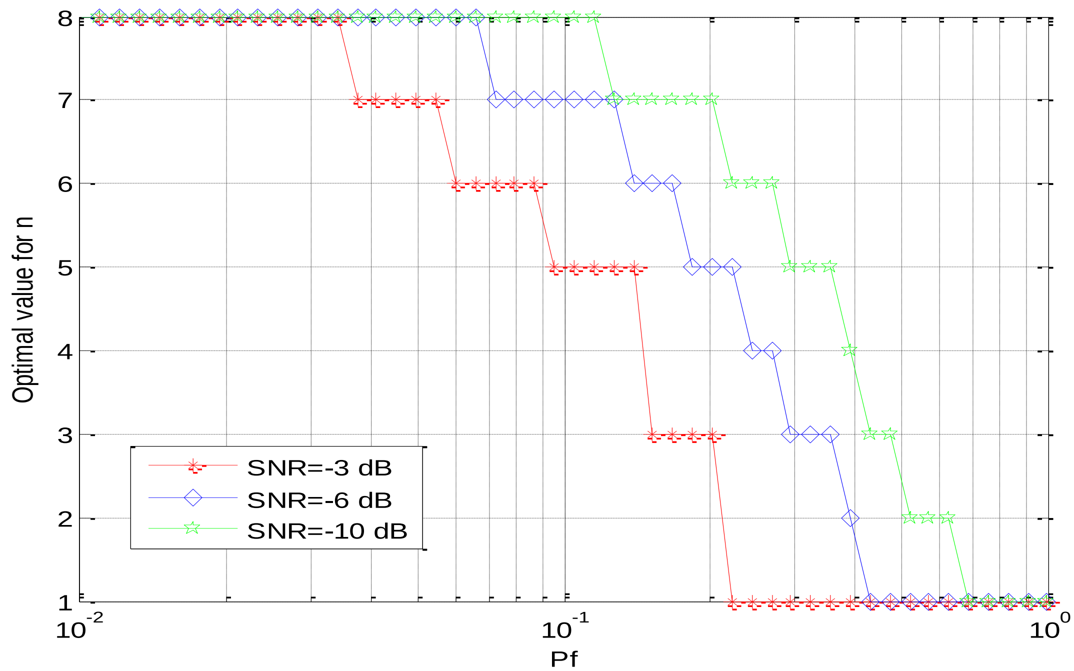

Figure 3-7: Optimal number of users vs. false alarm probability for different SNR

Optimal number of users for different values of false alarm probability is displayed in figure 3-7. It is evident from the figure that for higher values of SNR number of users required at a particular instant of false alarm probability is less for satisfactory performance as compared to low SNR values.

Figure 3-8 gives the ROC curve for different fusion schemes after application of threshold adaptation using the gradient descent algorithm. These curves when compared with figure 3-3 shows that the detection probability in the present case has shown some degree of improvement.

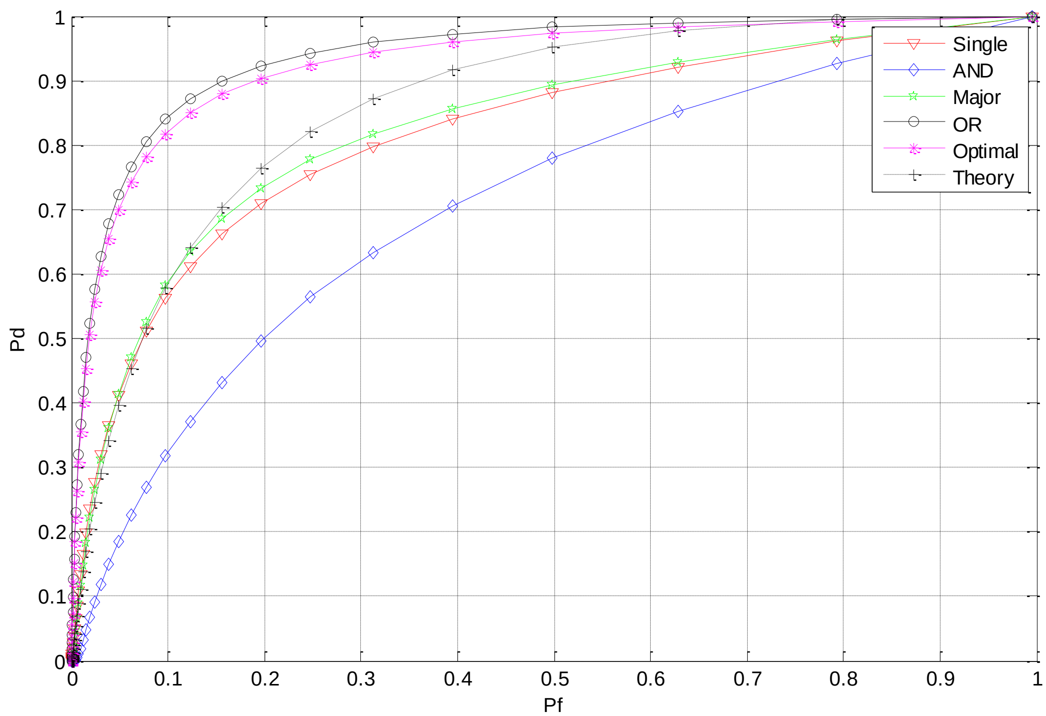

Figure 3-8: ROC curves after threshold adaptation using gradient descent algorithm

Chapter 4. Application to DVB-T signals

4.1. Cyclic Spectral Density and Contour diagram for DVB-T signal

The cyclic spectral density of DVB-T signal having center frequency of 91.44 MHz and SNR of '4 dB' is shown in figure 4-1. It has peaks at *'*$\alpha=0$*,* $f=f_c$ *and* $\alpha=2f_c$*,* $f=0$*'*. This peaks help in primary user detection as on searching if the peaks are present at the location then primary user is confirmed otherwise it the band is empty.

The contour diagram (2D) gives the top view of the cyclic spectral density (3D). Figures 4-2 and 4-3 are the contour diagram for the DVB-T whose CSD is shown above with SNR '-5 dB' and '-10 dB' respectively. In figure 4-2 the peaks are clearly visible as dark areas whereas in figure 4-3 the peaks are not as evident. It can be concluded that with the decrease in the SNR value the clutter in the background increases and thus it becomes more difficult to search for peaks.

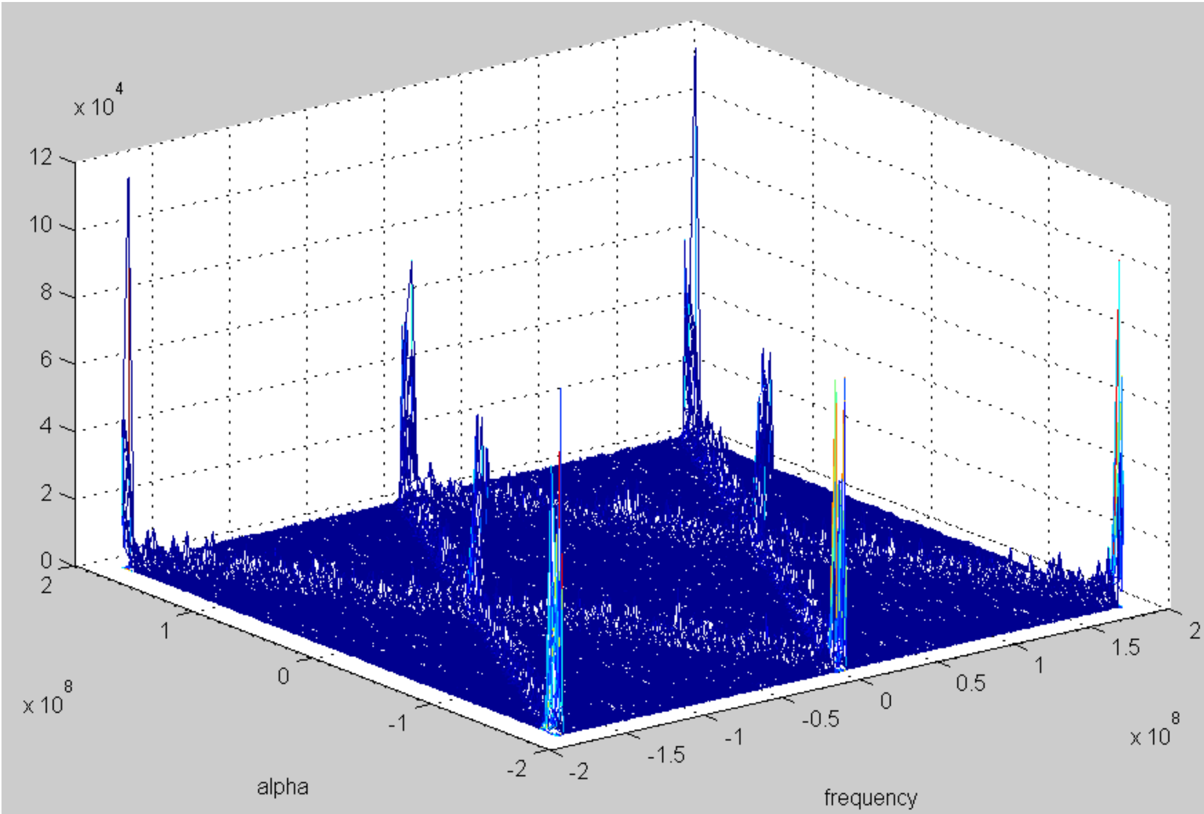

Figure 4-1: Cyclic Spectral Density for DVB-T signal at 91.44 MHz

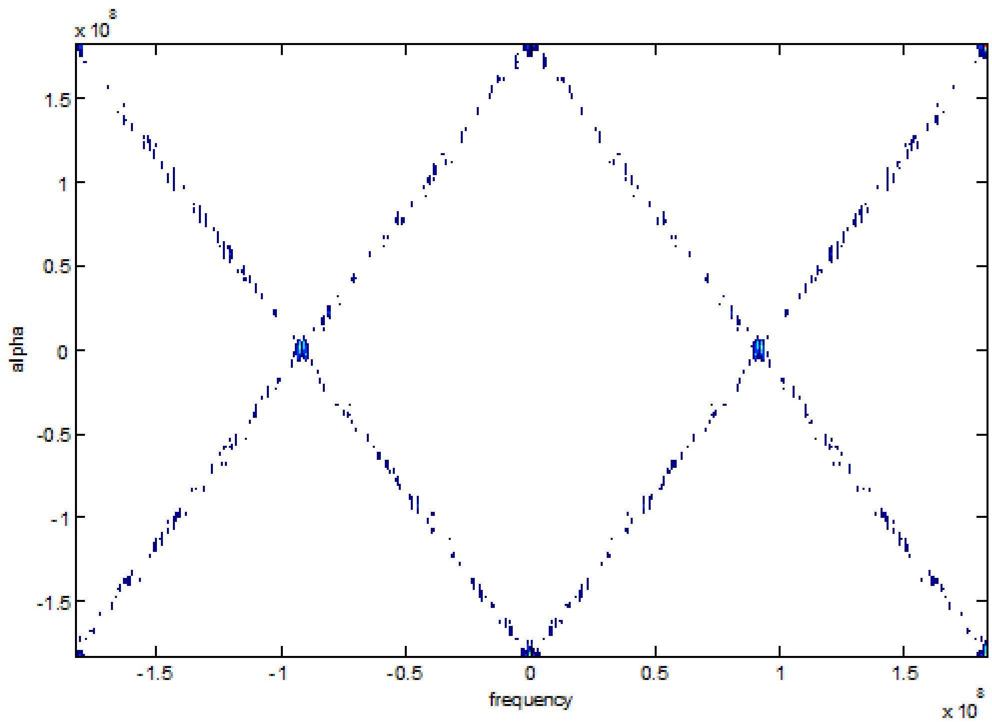

Figure 4-2: Contour diagram for CSD with SNR=-5 dB

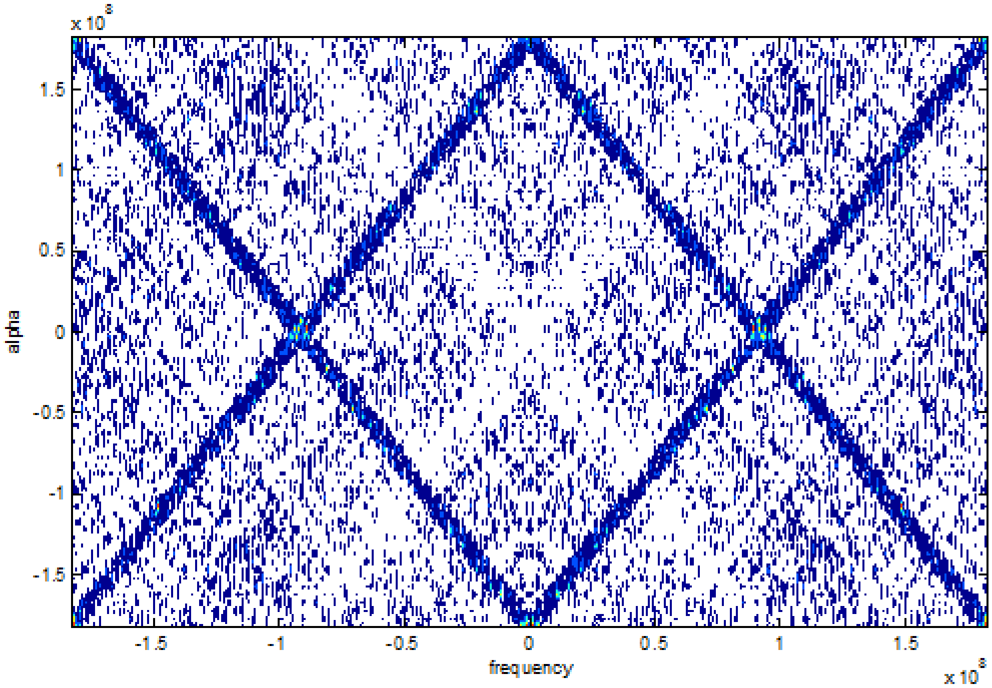

Figure 4-3: Contour diagram for CSD with SNR=-10 dB

4.2. ROC curves for various fusion techniques including the optimal user scheme

The peaks are searched for in the cyclic spectral density by different number of secondary users. Here the number of users taken into account is '8'. Depending on the decision of different users, various fusion schemes are applied to them and the detection probability is found out. The detection probabilities are plotted as ROC curve in figure 4-4. The optimal number of user fusion scheme performs better than most other schemes except the OR scheme as it requires only a single secondary user to confirm the presence and hence chances of detection increases.

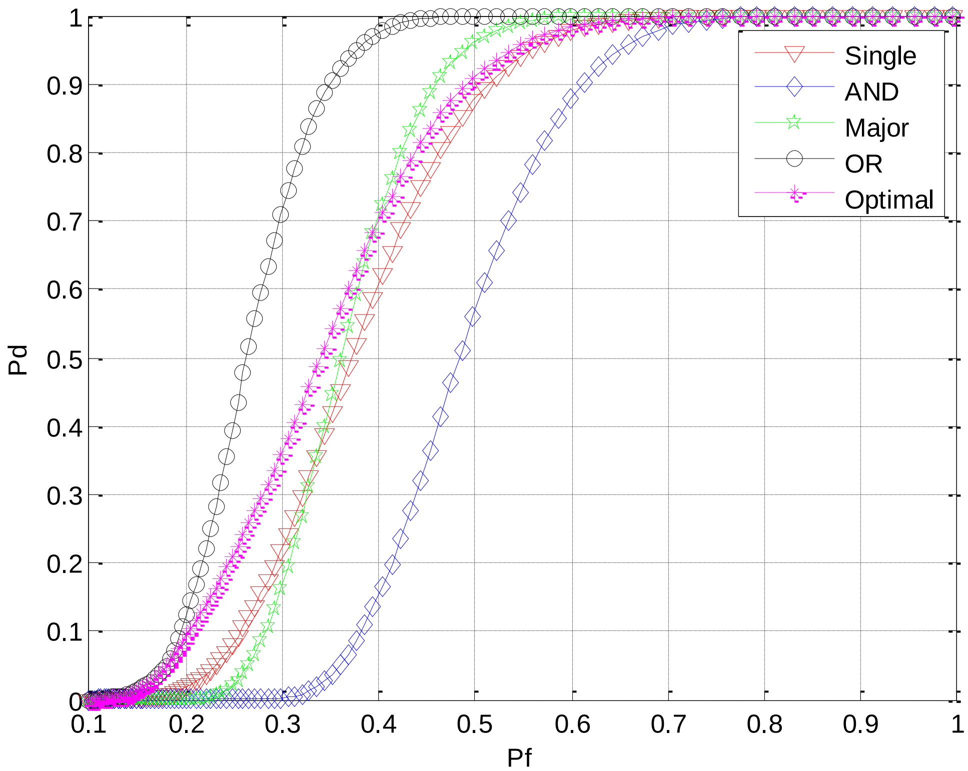

Figure 4-4: ROC curves for DVB-T signal with SNR=-5 dB

4.3. Error curve and optimal number of users for different SNR

Error versus the false alarm probability curve in figure 4-5 shows how the error for the optimal user case jumps from one curve to another as the number of users under consideration changes. For low false alarm probability the minimum users required is ‘8’, then as it increases the numbers of users shift to ‘7’, ‘6’ and so on till it comes down to single user as in such a scenario the error for a single user and ‘8’ user scheme is same.

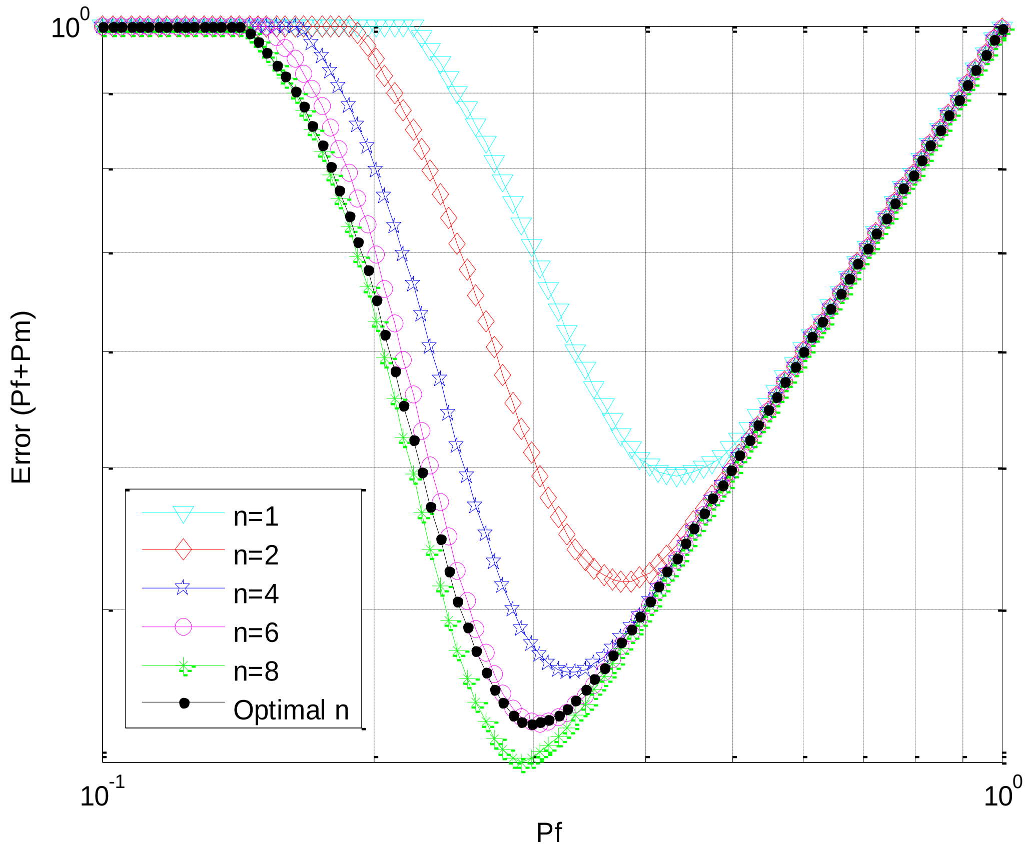

Figure 4-5: Error vs. false alarm probability for different number of users

Number of users versus the false alarm probability for different SNR is displayed in figure 4-6. Lower value of SNR requires more number of users as for lower values noise is more with peak searching becoming difficult. Thus more the users more will be the chances of correct detection.

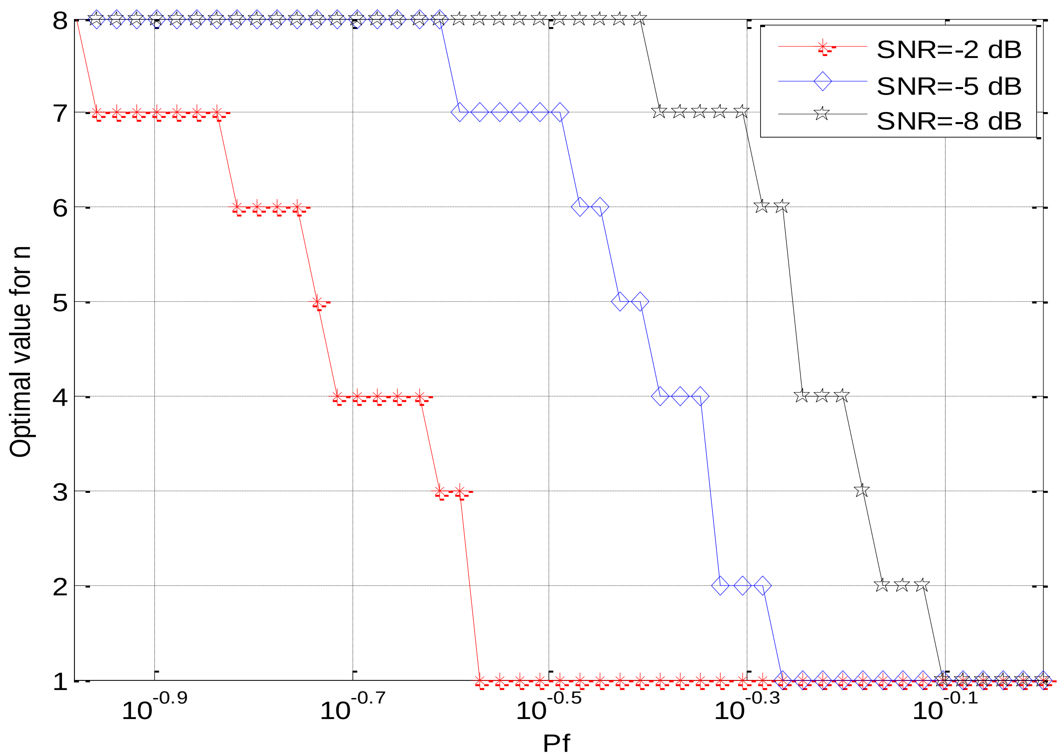

Figure 4-6: Optimal number of users vs. false alarm probability for different SNR

4.4. ROC with threshold adaptation using gradient descent algorithm

The threshold is adapted using the gradient descent algorithm signal with *'SNR=-5 dB'*. The ROC curve is then plotted for different fusion schemes as in figure 4-7. This curve can be compared to the figure 4-4 which is the ROC without threshold adaptation to find out that with adaptation the detection probability for all the fusion schemes show an improvement to a certain degree.

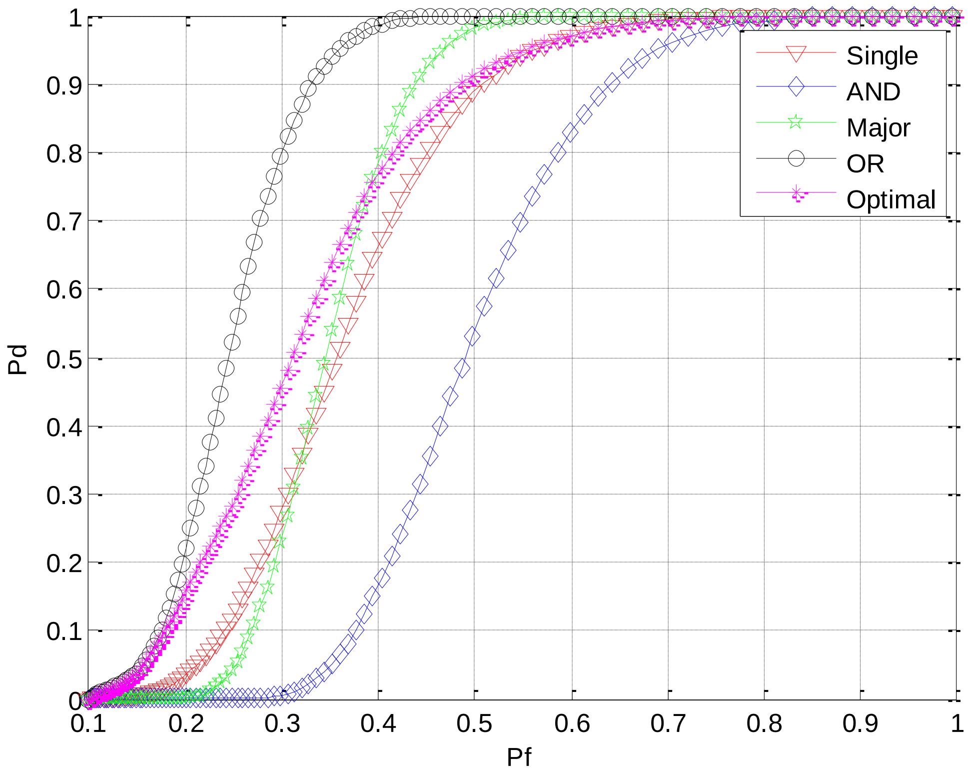

Figure 4-7: ROC curve after threshold adaptation using gradient descent algorithm

4.5. ROC with threshold adaptation using PSO technique and comparison with the gradient descent algorithm

Figure 4-8 displays the ROC curve after applying the particle swarm optimization technique. While applying the technique the constant were *'$C_0=0$, $C_1=1$, $C_2=1$, $C_3=1$'* where as the random values taken were *'r1=0.4211 and r2=0.3895'*. Instead of having a tolerance value the procedure was repeated for a fixed number of iterations. The red curve shows the detection probability of a single user after adapting threshold using particle swarm optimization. When compared to the un-optimized curve it shows a significant improvement in detection.

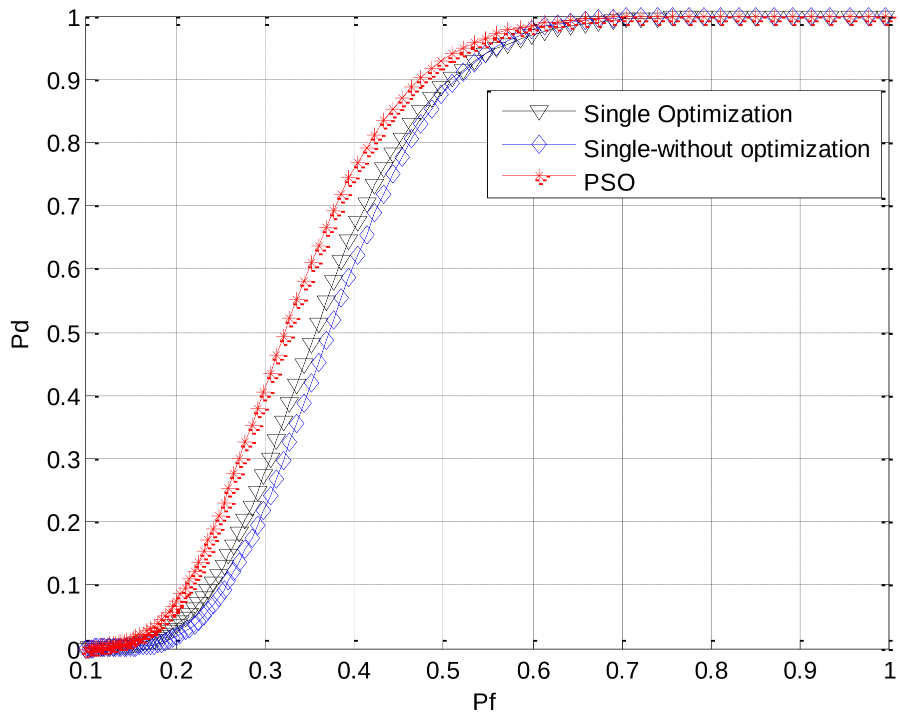

Figure 4-8: ROC for single user with particle swarm optimization and classical method

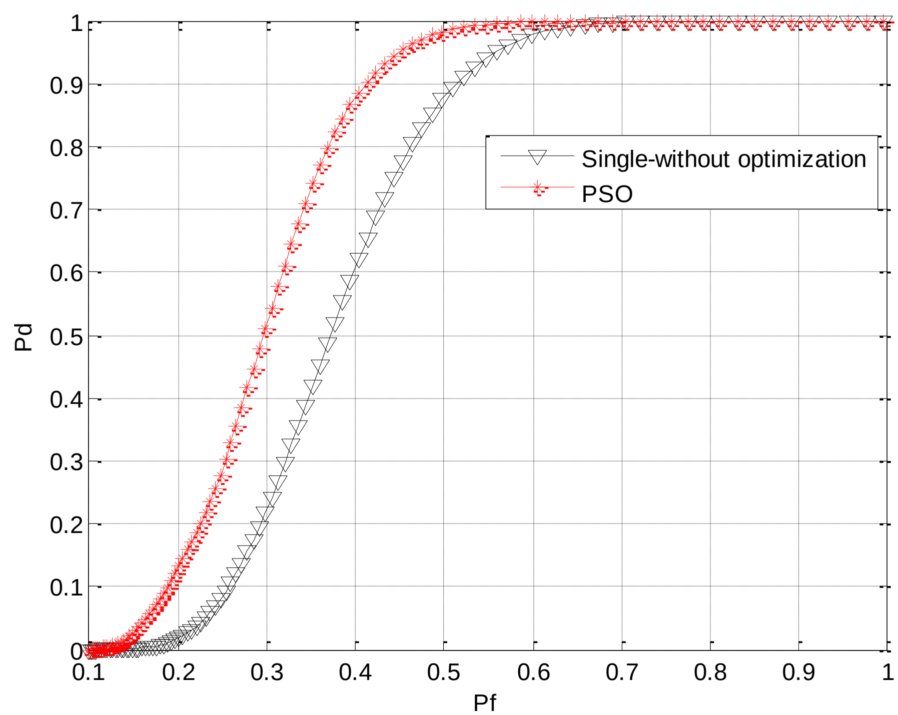

Figure 4-9: ROC with random values ‘r1=0.3811 and r2=0.1895’

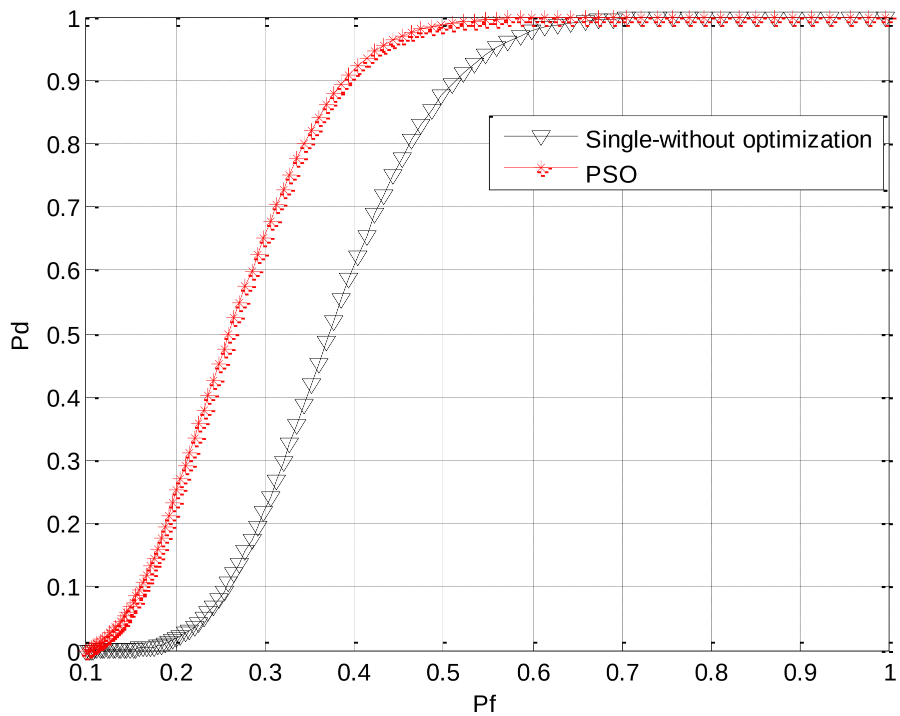

Figure 4-10: ROC with random values 'r1=0.4234 and r2=0.2695'

The detection probability can be changed by just varying the random numbers. Figure 4-9 shows the ROC with random values *'r1=0.3811 and r2=0.1895'* whereas figure 4-10 has values as *'r1=0.4234 and r2=0.2695'*. Thus unlike the gradient descent method this technique can easily change the threshold values by just varying few parameters.

Chapter 5. Conclusion and Future Work

5.1. Conclusion

In this thesis, focus was on exploration of cyclo-stationary spectrum sensing technique in the field of the cognitive radio. The features of the first cognitive radio standard IEEE 802.22 (WRAN) have also been discussed.

The major contribution to the thesis was to implement a cyclo-stationary detector which was then put to test for WRAN primary user signal for different SNR conditions. The performance evaluation was done for various numbers of users with ROC curves being the performance criteria. A scheme for optimal number of users in order to decrease the overhead and speed up performance along with techniques for adapting the threshold have also been examined.

Simulation results indicate that the optimal scheme varies the number of users so that error is kept as minimum as possible without compromising the detection probability. With the increase in false alarm probability the minimum number of users required for satisfactory performance decrease. Thus instead of keeping a fixed number of users for fusion schemes in co-operative spectrum sensing, the number can be varied in accordance with the false alarm probability.

Particle swarm optimization technique highlights a very good method which results in increased detection probability without putting many constraints on the objective function. It is applicable to functions even though they are not differentiable as it is different from classic methods in terms of operation. It also proves to be flexible as different weightage can be given to parameters and performance can be evaluated for different scenarios.

5.2. Scope for Future Work

- It is assumed that the signal from all users is sensed at a particular value of SNR only. However varying the SNR of different users gives a more practical scenario of the cognitive radio model. Thus making use of the optimization techniques remains a challenge to look into.
- The users can be given weightage and depending on correct decision it is increased or decreased in the event of miss-detection.
- A hardware implementation of the Cyclo-stationary detector can be done so that it can be put to real time sensing.
- It becomes difficult to go beyond the physical layer in MATLAB for optimization so use of Network Simulator (NS2) opens up more opportunities by allowing cross layer techniques.

References

[1] Bin Le, Building a Cognitive Radio: From Architecture Definition to Prototype Implementation, 2007, Doctor of Philosopy Dissertation, Virginia Polytechnic Institute and State University.

[2] Joseph Mitola III, Cognitive Radio- An Integrated Agent Architecture for Software Defined Radio, 2000, Dissertation, Doctor of Technology, Royal Institute of Technology, Sweden.

[3] FCC, "Spectrum Policy Task Force Report," vol. ET Docket No. 02-155, November 2002.

[4] FCC, Second Memorandum Opinion and Order, September 23, 2010, ET Docket No. 04-186, FCC 10-174.

[5] "IEEE Standard for Information Technology--Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)--Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands," *IEEE Std 802.22-2011*, pp. 1-680, Jan. 2011.

[6] Ir. Marnix Heskamp, AT Measurement Data, University of Twente.

[7] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, and Shantidev Mohanty, "NeXt generation/dynamic spectrum access/cognitive Radio Wireless Networks: A Survey," *COMPUTER NETWORKS JOURNAL (ELSEVIER*, vol. 50, pp. 2127-2159, 2006.

[8] Qing Zhao and B.M. Sadler, "A Survey of Dynamic Spectrum Access," *Signal Processing Magazine, IEEE*, vol. 24, no. 3, pp. 79-89, may 2007.

[9] V. Srivastava and M. Motani, "Cross-layer design: a survey and the road ahead," *Communications Magazine, IEEE*, vol. 43, no. 12, pp. 112-119, dec. 2005.

[10] S. Srinivasa and S.A. Jafar, "Soft Sensing and Optimal Power Control for Cognitive Radio," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 12, pp. 3638-3649, december 2010.

[11] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys Tutorials, IEEE*, vol. 11, no. 1, pp. 116-130, quarter

2009.

[12] D. Cabric, S.M. Mishra, and R.W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," *Signals, Systems and Computers, 2004. Conference Record of the Thirty-Eighth Asilomar Conference on* , vol. 1, nov. 2004, pp. 772 - 776 Vol.1.

[13] Zhi Tian and Georgios B. Giannakis, "A Wavelet Approach to Wideband Spectrum Sensing for Cognitive Radios," *Cognitive Radio Oriented Wireless Networks and Communications, 2006. 1st International Conference on* , june 2006, pp. 1-5.

[14] Ying-Chang Liang, Guangming Pan, and Yonghong Zeng, "On the Performance of Spectrum Sensing Algorithms Using Multiple Antennas," *GLOBECOM 2010, 2010 IEEE Global Telecommunications Conference*, dec. 2010, pp. 1-5.

[15] William A. Gardner, Antonio Napolitano, and Luigi Paura, "Cyclostationarity: Half a century of research," *Signal Processing*, vol. 86, no. 4, pp. 639-697, 2006. [Online]. http://www.sciencedirect.com/science/article/pii/S0165168405002409

[16] Refik Fatih USTOK, Spectrum Sensing Techniques For Cognitive Radio Systems With Multiple Antennas, 2010, MS Thesis, Izmir Institute of Technology.

[17] Wen-jing Yue, Bao-yu Zheng, and Qing-min Meng, "Cyclostationary property based spectrum sensing algorithms for primary detection in cognitive radio systems," *Journal of Shanghai Jiaotong University (Science)*, vol. 14, pp. 676-680, 2009, 10.1007/s12204-009-0676-0. [Online]. http://dx.doi.org/10.1007/s12204-009-0676-0

[18] Ian F. Akyildiz, Brandon F. Lo, and Ravikumar Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey," *Physical Communication*, vol. 4, no. 1, pp. 40-62,2011.[Online].http://www.sciencedirect.com/science/article/pii/S187449071000039X

[19] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio networks," *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, nov. 2005, pp. 137-143.

[20] S. Atapattu, C. Tellambura, and Hai Jiang, "Energy Detection Based Cooperative Spectrum Sensing in Cognitive Radio Networks," *Wireless Communications, IEEE Transactions on*, vol. 10, no. 4, pp. 1232-1241, april 2011.

[21] Ruiliang Chen, Jung-Min Park, and Kaigui Bian, "Robust Distributed Spectrum Sensing in Cognitive Radio Networks," *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, april 2008, pp. 1876-1884.

[22] FCC, Unlicensed Operation in TV Broadcast bands, 2004, Docket No. ET 04-186.

[23] C. Cordeiro, K. Challapali, D. Birru, and N. Sai Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, nov. 2005, pp. 328-337.

[24] Stephen J. Shellhammer, "SPECTRUM SENSING IN IEEE 802.22," *In Proceedings of 2008 IAPR Workshop on Cognitive Information Processing*, 2008.

[25] Young-June Choi, Yan Xin, and S. Rangarajan, "Overhead-Throughput Tradeoff in Cooperative Cognitive Radio Networks," *Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE*, april 2009, pp. 1-6.

[26] Wei Zhang, R. Mallik, and K. Letaief, "Optimization of cooperative spectrum sensing with energy detection in cognitive radio networks," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 12, pp. 5761-5766, december 2009.

[27] D.R. Joshi, D.C. Popescu, and O.A. Dobre, "Gradient-Based Threshold Adaptation for Energy Detector in Cognitive Radio Systems," *Communications Letters, IEEE*, vol. 15, no. 1, pp. 19-21, january 2011.

[28] J. Kennedy and R. Eberhart, "Particle swarm optimization," *Neural Networks, 1995. Proceedings., IEEE International Conference on*, vol. 4, nov/dec 1995, pp. 1942 -1948 vol.4.

[29] S. Motiian, M. Aghababaie, and H. Soltanian-Zadeh, "Particle Swarm Optimization (PSO) of power allocation in cognitive radio systems with interference constraints," *Broadband Network and Multimedia Technology (IC-BNMT), 2011 4th IEEE International Conference on*, oct. 2011, pp. 558-562.

Publication

- Sarat Kumar Patra and Manish B Dave, "Spectrum Sensing in Cognitive Radio", *Proceedings of the National Conference on Recent Trends in Information & Communication technology*, GITA Bhubaneswar, nov. 2011, pp31-40.