# NON-COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO USING COMBINED HYBRID MATCHED FILTER SINGLE CYCLE CYCLOSTATIONARY FEATURE DETECTOR

Thesis submitted in partial fulfilment for the award of the degree of

**MASTER OF TECHNOLOGY**

in

**Electronics and Communication Engineering**

By

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# DECLARATION

I, **DIVYA JOSHI**, hereby declare that thesis entitled "NON-COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO USING COMBINED HYBRID MATCHED FILTER SINGLE CYCLE CYCLOSTATIONARY FEATURE DETECTOR", has been carried out by me under the supervision of **Dr. NEERU SHARMA**, Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Waknaghat, Solan-173234, Himachal Pradesh, and has not been submitted for any degree or diploma to any other university. All assistance and help receive during the course of the investigation has been duly acknowledge.

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# CERTIFICATE

This is to certify that thesis entitled "**NON-COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO USING COMBINED HYBRID MATCHED FILTER SINGLE CYCLE CYCLOSTATIONARY FEATURE DETECTOR**", submitted by **DIVYA JOSHI** is a record of an original research work in partial fulfilment for the award of degree of Master of Technology in Electronics and Communication Engineering to Jaypee University of Information Technology, Waknaghat, Solan has been carried out under my supervision.

To the best of my knowledge, the matter embodied in thesis has not been submitted to any other university / institute for the award of any Degree or Diploma.

**Date:**

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# 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 minimize spectral congestion. This thesis exploits the NeXt generation communication system called cognitive radio. CR is a key to end an epoch of spectrum scarcity by utilizing spectrum band with licensed user to provide wireless communication services. CR foremost senses the spectrum band of licensed user to be utilized for wireless transmission. In this fashion CR contributes proficient employment of frequency spectrum. Main functions of CR are, namely, spectrum sensing, spectrum management, spectrum sharing and spectrum mobility. This thesis emphasize on spectrum sensing in cognitive radio. Spectrum sensing is a challenging task because determining the available spectrum holes and revealing the presence of licensed user is difficult.

In non-cooperative spectrum sensing, matched filter is a technique which faces the challenge of low frequency offset tolerance in very low SNR environments. Hybrid matched filter architecture is utilized to improve this frequency offset tolerance. But, in very low SNR region, where primary user is highly mobile, the multipath profile outcomes in unknown phase of signal. Such kind of signal cannot even be detected by HMF. So, combination of hybrid match filter and single cycle cyclostationary detector is proposed to enhance the detection of architecture. This technique enhanced the detection of such type of architecture. This results in both high frequency offset tolerance as well as fine detection of signal with unknown phase in very low SNR levels. Simulations results have shown that significant improvement in the probability of detection and false alarm of the proposed scheme.

# List of Tables

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# List of Abbreviations

| | | |
|---|---|---|
| 3G | : | Third Generation of cellular network |
| 4G | : | Fourth Generation of cellular network |
| AI | : | Artificial Intelligence |
| ADC | : | Analog to Digital Converter |
| BPSK | : | Binary Phase Shift Keying |
| BS | : | Base Station |
| CDF | : | Cumulative Distribution Function |
| CPE | : | Customer Premise Equipment |
| CR | : | Cognitive Radio |
| CSD | : | Cyclic Spectral Density |
| DARPA | : | Defense Advanced Research Projects Agency |
| DSA | : | Dynamic Spectrum Access |
| DSP | : | Digital Signal Processor |
| FCC | : | Federal Communication Commission |
| FDMA | : | Frequency division multiple access |
| FEC | : | Forward Error Control |
| FFT | : | Fast Fourier Transform |
| FIR | : | Finite Impulse Response |
| FPGA | : | Field Programmable Gate Array |
| GPP | : | General Purpose Processor |
| GPS | : | Global Positioning System |
| $H_0$ | : | Absence of primary signal |
| $H_1$ | : | Presence of primary signal |
| HMF | : | Hybrid Matched Filter |
| IF | : | Intermediate Frequency |
| IQ | : | In-phase / Quadrature |
| ISM | : | Industrial, Scientific and Medical |
| ITS | : | Intelligent Transportation System |
| LNA | : | Low Noise Amplifier |
| MAC | : | Medium Access Control |
| MFD | : | Matched Filter Detection |
| MSC | : | Magnitude Squared Autocoherence |
| NTSC | : | National Television System Committee |
| OSI | : | Open System Interconnection |
| OSA | : | Opportunistic Spectrum Access |
| PLL | : | Phase Locked Loop |
| PU | : | Primary User |
| $P_d$ | : | Probability of Detection |
| $P_{fa}$ | : | Probability of false alarm |
| PSD | : | Power Spectral Density |
| QAM | : | Quadrature Amplitude Modulation |
| QoS | : | Quality of Service |
| QPSK | : | Quadrature Phase Shift Keying |
| RF | : | Radio Frequency |
| Rx | : | Receiver |
| SDR | : | Software Defined Radio |

| | | |
|---|---|---|
| SNR | : | Signal to Noise Ratio |
| SU | : | Secondary User |
| SMF | : | Segmented Matched Filter |
| TDMA | : | Time Division Multiple Access |
| Tx | : | Transmitter |
| VCO | : | Voltage Control Oscillator |
| WLAN | : | Wireless Local Area Network |
| WMAN | : | Wireless Metropolitan Area Network |
| WRAN | : | Wireless Regional Area Network |
| XG | : | NeXt Generation |

# CHAPTER 1

# INTRODUCTION

## 1.1 History of Cognitive Radio (CR)

Radio refers to the wireless transmission of signals. Any wireless device needs radio frequency spectrum to operate. At present, the radio resources are very expensive and scarce. Federal Communication Commission (FCC) [1]-[3] report says that beyond 70% of radio spectrum is underutilized. To solve this problem, Cognitive Radio (CR) is introduced. Cognitive radio is prominent solution to end the era of spectrum scarcity. The word cognitive defines the way of learning, knowing and understanding things.

In 1999, the concept of Cognitive Radio [4] was first coined by Joseph Mitola and G.Q. Maguire. In 2001, J. Mitola again described as follows [5],

*"Cognitive radio is a goal-driven framework in which the radio autonomously observes the radio environment, infers context, assesses alternatives, generates plans, supervises multimedia services, and learns from its mistakes. This observe-think-act cycle is radically different from today's handsets that either blast out on the frequency set by the user, or blindly take instructions from the network. Cognitive radio technology thus empowers radios to observe more flexible radio etiquettes than was possible in the past".*

After six years of J. Mitola's first article of Cognitive Radio, Simon Haykin enumerates idea of cognitive radio as brain empowered wireless communications. In 2005, Simon Haykin defines [6] CR as,

"*An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind:*

- *Highly reliable communications whenever and wherever needed;*
- *Efficient utilization of the radio spectrum."*

The FCC uses precise definition for cognitive radio [2][3] as, *"A radio that can change its transmitter parameters based on interactions with the environment in which it operates".*

In general, from J. Mitola's description we can define the Cognitive Radio [7] as a radio or system which has the adequacy of sensing its operative electromagnetic surroundings to find spectrum fortuity, employing spectrum holes to disseminate anywhere and at any time needed and hence rising spectrum utilization. The amount of traffic carried by wireless networks in the radio frequency band is constantly rising, due to the rising number of users and new commercially emerging applications which often have higher data rate requirements. Cognitive Radio has been proposed as a potential solution for aforesaid problems and its scenarios describe primary users, who hold official licenses to use spectrum band, and secondary users that opportunistically access that spectrum when it is not used by primary users[8]-[11].

Cognitive Radio is a collaboration of Software Defined Radio (SDR) and artificial intelligence which pivot on the principle of more efficient use of spectrum, shown in figure 1.2. The Cognitive Radio is also known as Dynamic Spectrum Access network, unlicensed users or Secondary users because CR cannot be exert in desired band of spectrum.

## 1.2 Software Defined Radio

Cognitive Radio is based on the principle of efficient use of spectrum. Software Defined Radio (SDR) is the procreator of Cognitive Radio. SDR is a technology in which software curriculums run on hardware platform consisting of DSP and GPP microprocessors to implement radio functions [12]. The basic diagram shows in figure 1.1. Definition of SDR is given as [13]:

*"Software defined radio is a radio transmitter or receiver utilizing a technology which acknowledge the RF operating parameters along with modulation scheme, frequency ranges, and output power to be set or modified by software, eliminating difference to operating parameters which appear during the usual pre-installed and prearranged operation of a radio according to a setup requirement or standard."*

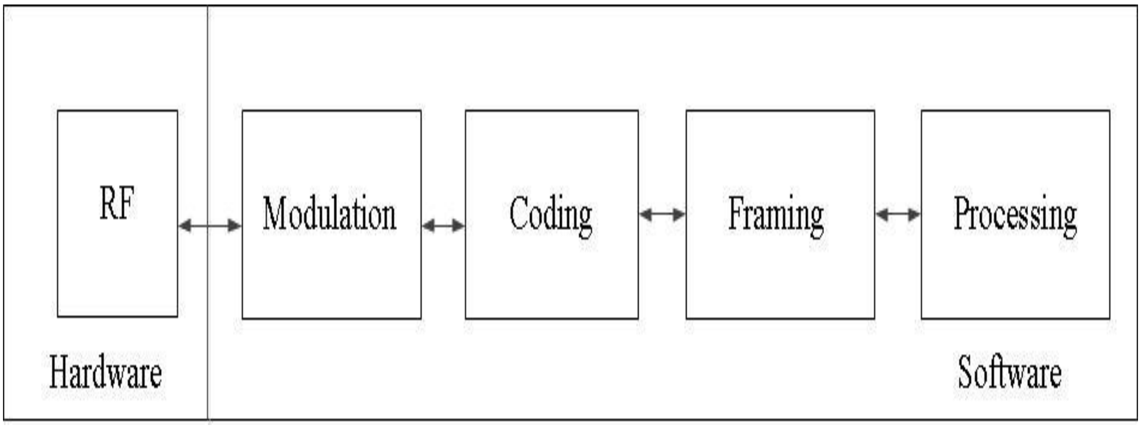



Figure 1.1 Block diagram of Software Defined Radio

### 1.2.1Artificial Intelligence (AI) Technology

The heart of a CR is artificial intelligence which has the capability to improve performance through sensing, learning and optimization. The process of learning is described as the process of acquiring information based on the recognized impact upon applying the action. Different AI techniques used in CR networks (e.g. based on Hidden Markov model, reinforcement learning, neural network, or genetic algorithm) [14][15].

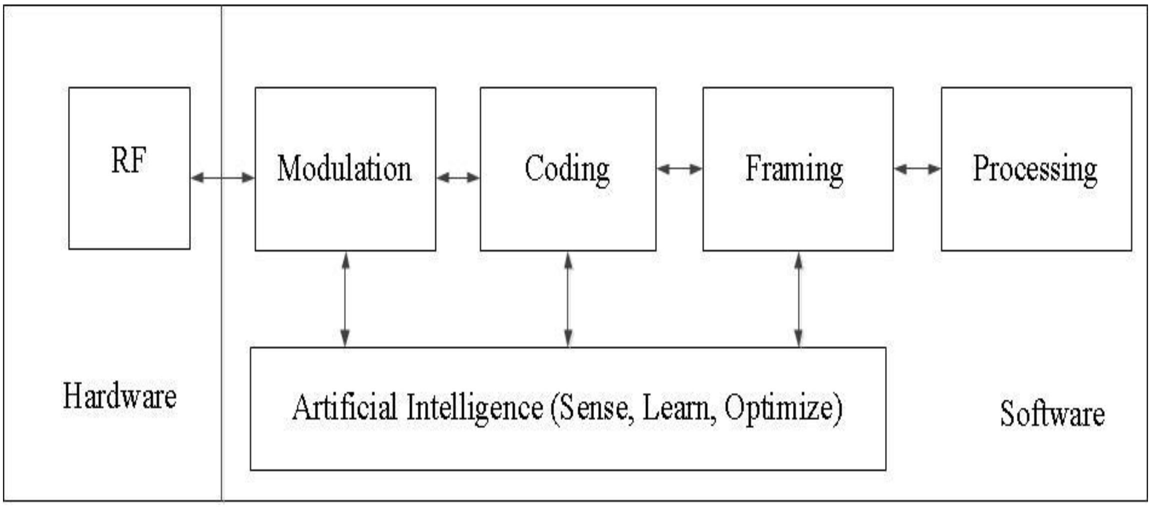



Figure 1.2 Block diagram of Cognitive Radio

### 1.2.2 Open System Interconnection Reference Model with SDR

Another and considerably different view of the Software Defined Radio [13]-[15] is in terms of usual Open System Interconnection (OSI) Reference model of a wireless communication system, the SDR mainly consist of the two lowest layers and parts of network layer as shown in figure 1.3 This figure shows that bottom two layers and the half of the network layer are implemented in SDR. It is very clear that SDR is a reconfigurable radio technology, not the applications that are implemented on the radio, which is based upon the OSI reference model [16]-[18]. SDR is key enabling technology for flexible radio systems like multi-band, multi-standard, multi-service, reconfigurable and reprogrammable by software. SDR is core technique for DSA which enables reconfigurations of radio characteristics. However, an SDR [13] can reconfigure itself only on demand, it is not capable of reconfiguring itself into the most effective from without its user even knowing it.

### 1.2.3 Pros

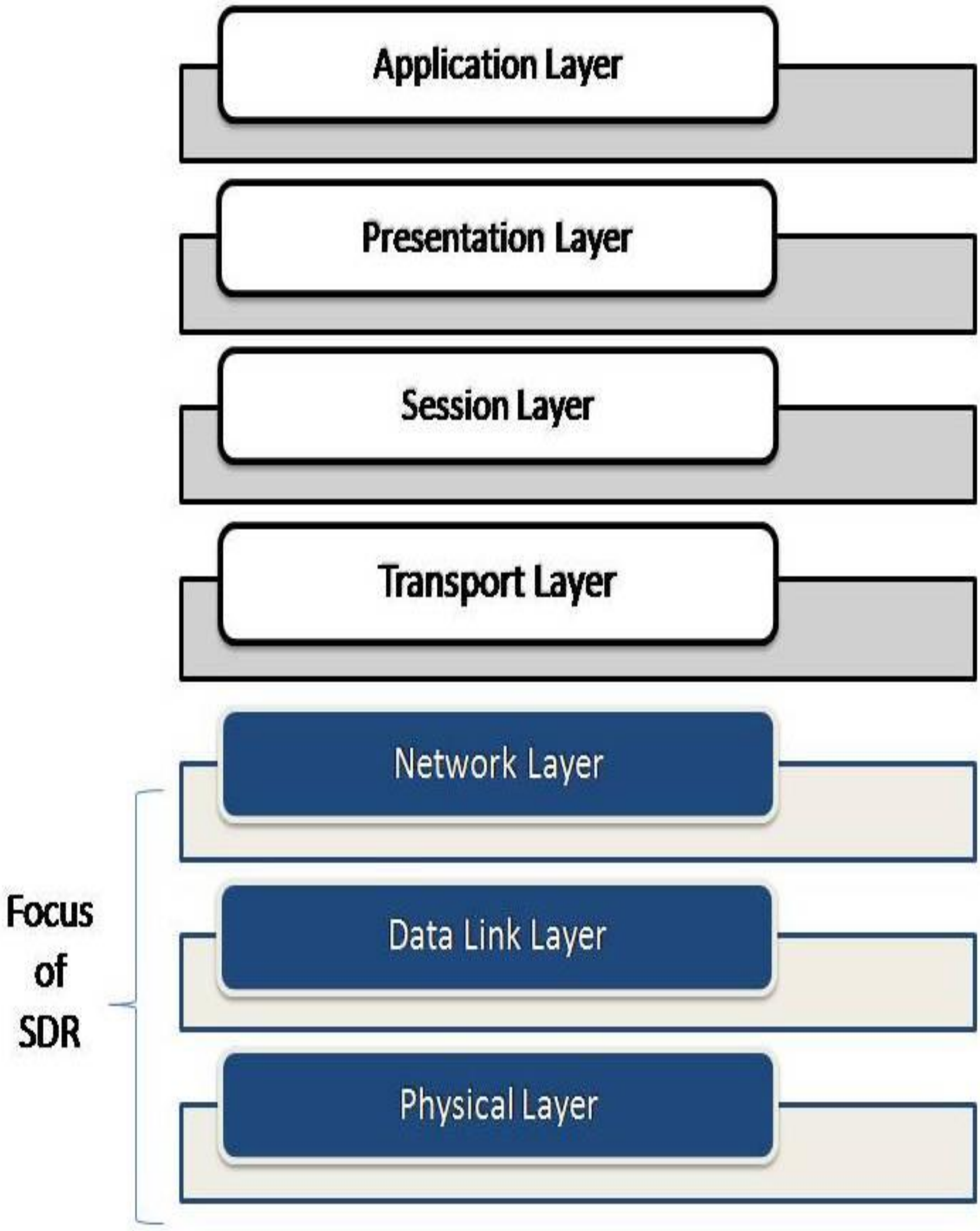



Figure 1.3 OSI Reference Model in regards with SDR

### 1.2.3 Pros

- Configure itself automatically

- Reduced component cost because hardware specific component replaced by DSP and FPGA.
- Allows for multiple types of radio modulation schemes internal to single systems.
- Flexibility
- Increases system efficiency
- Open architecture allows multiple vendors
- Condensed parts stock

### 1.2.4 Cons

- Security
- Overall cost
- Ideal SDR design employs non-existing technology
- Longer development time
- Power consumption
- Software reliability
- Technology implications

### 1.2.5 Applications

- Public safety
- Commercial
- Military
- Amateur and home use
- Better performance
- Full connectivity

**Table 1.1 Comparative Studies of Conventional Radio, Software Defined Radio, and Cognitive radio**

| Types of communication devices | Application | Design | Upgrade cycle |
|---|---|---|---|

| | | | |
|---|---|---|---|
| | | | |
| Conventional Radio | Supports fixed number of systems.<br>May hold multiple service, but chosen at the time of design.<br>Reconfigurability determined at the moment of design. | Traditional RF design.<br>Traditional Baseband design. | Cannot be made "future proof".<br>Typically radios are not upgradeable. |
| Software Defined Radio | Dynamically support multiple variable systems, protocols.<br>Interface with diverse systems<br>Provide a broad range of services with changeable QoS. | Conventional Radio + Software Architecture<br>Reconfigurability<br>Provisions for easy upgrades | Ideally software radios could be "future proof"<br>Many different external upgrade mechanisms<br>Over-the-Air(OTA) |
| Cognitive Radio | Can create new waveforms on its own<br>Can negotiate new interfaces | SDR + Intelligence Awareness Learning Observations | SDR upgrade mechanisms<br>Internal upgrades<br>Collaborative upgrades |

## 1.3 Cognitive Cycle

J. Mitola's Cognitive Radio [4][5] was an essential extension of SDR. A cognitive cycle may interact with the environment is illustrated in fig. 1.4. Joseph Mitola epitomized the dominant functions to readjust the transmission parameters in varying environment through a Cognitive Cycle. The six stages of cognition cycle explained as follows:

**Observe**

The radio receives information about its operating environment (outside world) through direct observation or through signaling.

**Orient**

Information which is observed, the radio considers determining its importance and relevance.

**Plan**

Based on this oriented information, the radio determines its alternatives (plan) for resource optimization

**Decide**

Chose an alternative in a way that presumably would improve the judgment including the contemporary action.

**Act**

Assuming waveform change was necessary, the radio then implements the substitute (act) by adapting its resources and performing the convenient signaling. These modifications are then communicated to the outside world in the interference profile represented by CR.

**Learn**

The cognitive radio then utilizes these observations and decisions to improve the operation of the radio (learn), possibly by creating new modeling states, generating new alternatives, or designing new judgments.

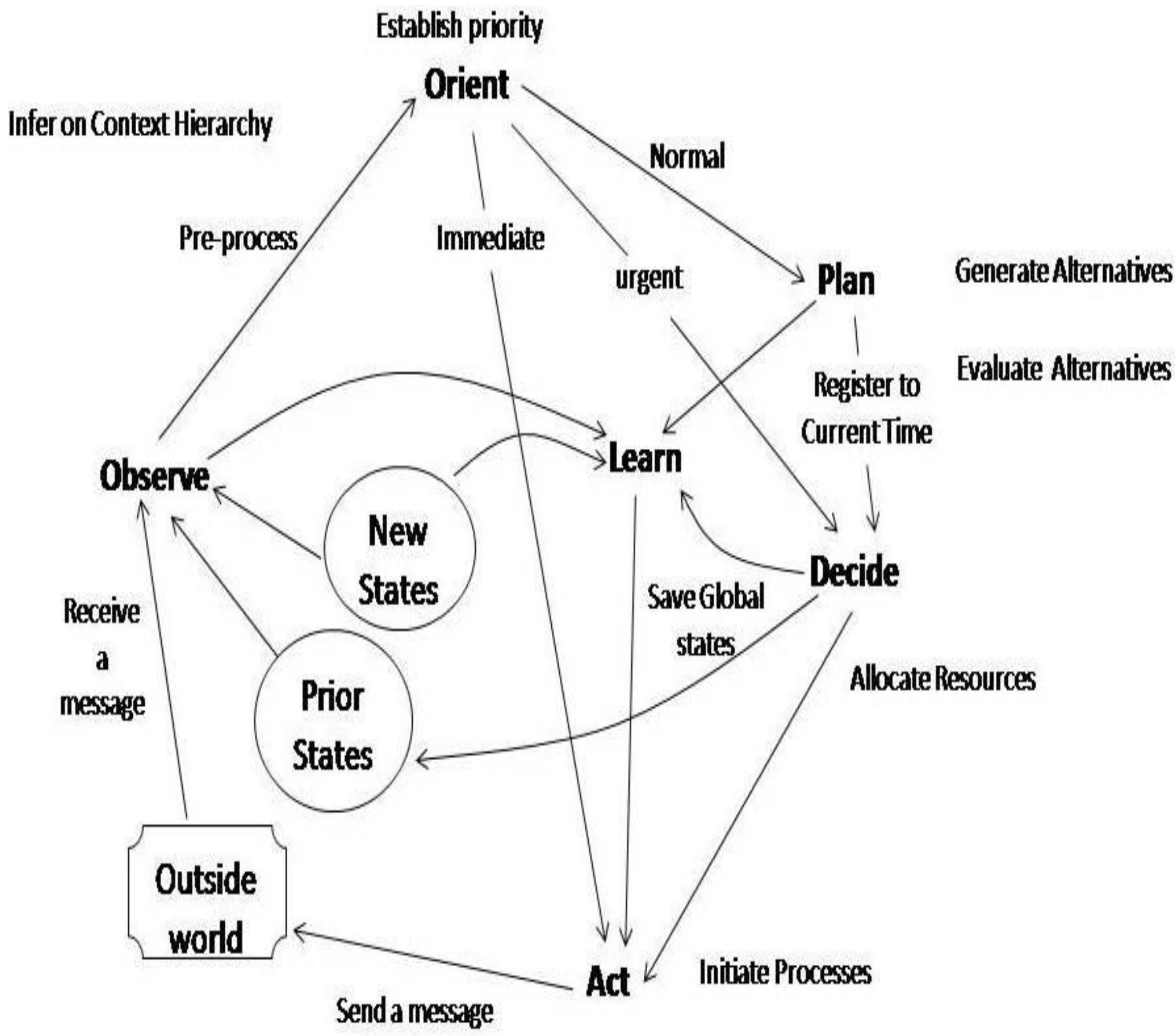



Figure 1.4 Joseph Mitola's cognitive cycle

Though Simon Haykin agreed with Joseph Mitola's description about CR and he determined his cognition cycle for Opportunistic Spectrum Access (OSA). OSA is an extensible approach to measure spectrum where users can actively search for unutilized spectrum (white spaces or holes or spectrum holes) in licensed band and conveying information utilizing these white spaces.

Opportunistic Spectrum Access is maintained by Federal Communication Commission (FCC) [1]-[3] and European Communication (EC) [8][9]. Cognitive Radio is unlicensed user, also called secondary user, coincide with licensed user (that is primary user) to operate over given frequency bands. The spectrum is perpetually sensed by the CR and detects its "spectrum holes" for opportunistic conversations termed *opportunistic communications.* The main disputes to expand an opportunistic cognitive radio network are how to construct an efficient ant adaptive channel access scheme which helps dynamic channel selection. Simon Haykin described [6] six important features of cognitive radio which is given as:

- Awareness
- Intelligence
- Learning
- Adaptability
- Reliability
- Efficiency

This combination of capabilities is achievable today with the help of machine learning, computer software and hardware, splendid achievements of digital signal processing and networking. Another capability of CR is reconfigurability which is contributed by SDR. In Haykin's cognition cycle [6], CR mainly subsist two components which is environment awareness (radio-scene analysis and channel estimation) and adaptability (transmit power control and dynamic spectrum management). The cognitive process begins with the static sensitivity of RF *stimuli* and terminates with the *action*. Haykin defined three cognitive tasks:

1) Radio-scene analysis, which contains the pursuing terms:
    - Detection of spectrum holes, and
    - Estimation of interference temperature of the radio environment.
2) Channel identification, which contains the pursuing terms:
    - Prediction of channel capacity for use by the secondary transmitter;
    - Estimation of channel-state information (CSI).
3) Transmit-power control and spectrum management.

In fig 1.5, task 1) and task 2) are formed in the receiver, and task 3) is formed in the transmitter. The interference temperature is a limit set at communication system's receiver that contributes an exact amount for the sufficient level of radio frequency interference in the frequency spectrum of interest; any transmission in that spectrum is deliberate to be "harmful" if it would raise the noise part above the interference-temperature limit.

Thus, secondary user can utilize the frequency spectrum of primary user until CR transmission does not pass over the interference-temperature limit set at primary receiver. The cognition also involves languages and communication. The CR languages include a set of signs and symbols that grants different internal components of the radio to communicate with each other. The task of learning language is discussed in Joseph Mitola's Ph.D dissertation [4][5].

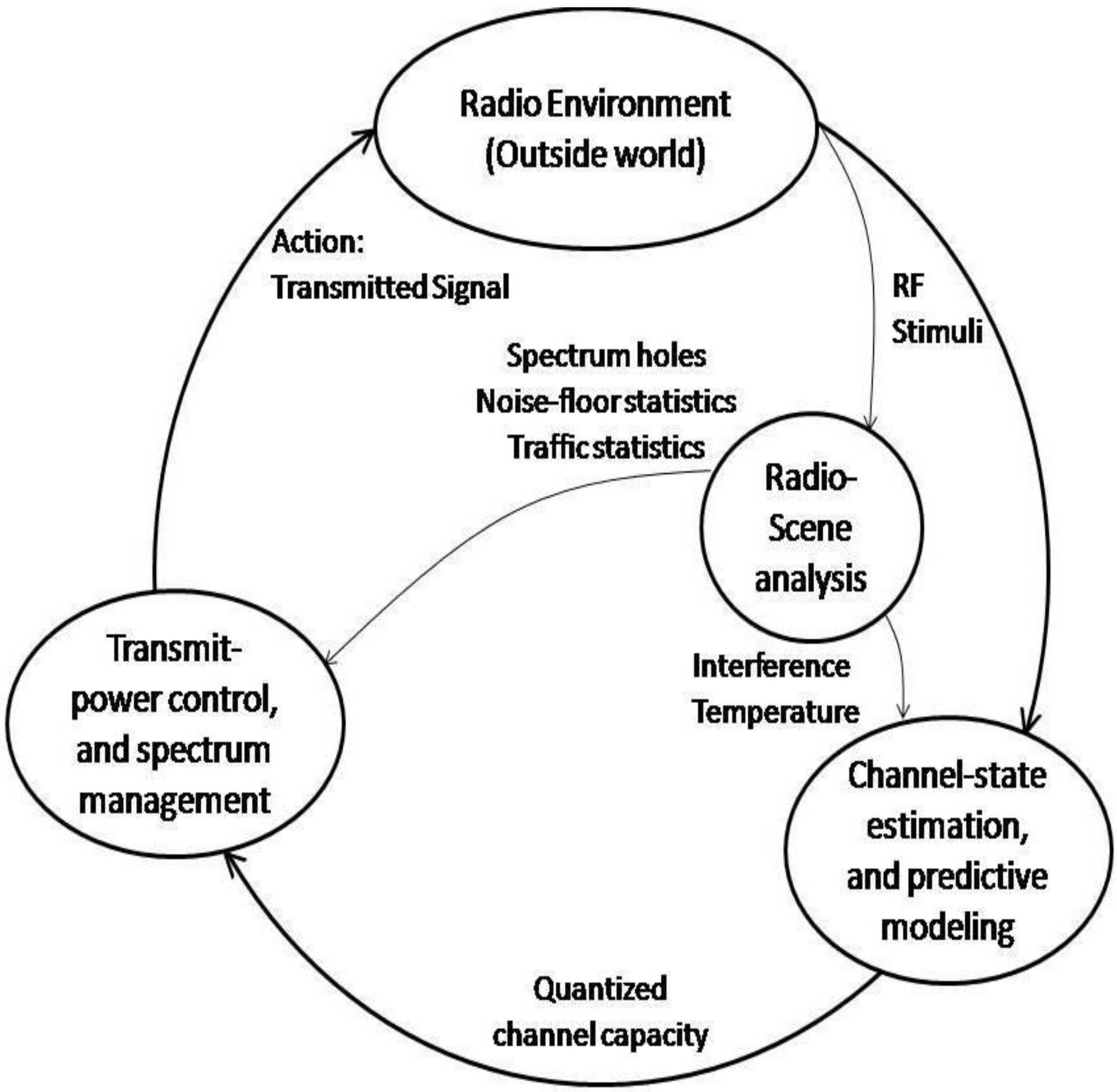



Figure 1.5 Simon Haykin's Cognition cycle

By this concise summary [6], it is perceptible that the cognitive part in the transmitter should work in synchronization with the cognitive part in the receiver. To prolong this synchronization between the CR transmitters and receiver at all times, we require a feedback channel which unite the receiver to the transmitter. During this feedback channel, the receiver is making possible to transfer the information on the presence of the channel to the transmitter [19][20].

The cognitive radio is, consequently, by requirement, a paradigm of a *feedback communication system* [16]-[18]. Spectrum can shared with primary user in two ways that is, if user may directly select a spectrum hole and make its cognitive cycle over that hole. Another way is that the secondary user may construct its cognitive cycle over a spectrum band which is presently utilized by primary user with such a transmit power that interference temperature limit at primary receiver does not exceed [7][19][20]. This spectrum management [21] and transmit-power control should be completed in most efficient and secure way as possible.

## 1.4 Cognitive Radio Capabilities

As a part of earlier analysis it is to be demonstrated that CR needs at least the subsequent capabilities [22]:

**Flexibility and agility:** It is the capability to modify the waveform and other radio operational parameters build upon environment circumstances. When CR is built on top of software defined radios then full flexibility becomes possible. One more essential requirement to accomplish flexibility [4] is the ability to reconfigure.

➢ **Sensing:** The capability to monitor and determine the environment circumstance, including spectral occupancy. Sensing is essential if the device have to modify its operation based on its existing information of RF environment.

➢ **Learning and adaptability:** The capability to evaluate sensing information, to distinguish patterns, and modify internal operational behavior based on the analysis of a latest condition, not only based on the precoded algorithms but also on a result of a learning mechanism.

**Reconfigurability:** This approach mentioned to program the radio dynamically without creating any alteration to its hardware section. CR is a software defined radio and not hardware based so it has the capability to toggle between distinct wireless protocols along with support to number of applications. This approach provides the reconfigurability [5][6] to the CR. Through this it can simply toggle between frequencies, modify modulation schemes and observe power levels without disturbing any of the hardware provided.

## 1.5 Cognitive Radio's Key Benefits

Cognitive Radio recommends optimal diversity in modulation scheme, frequency, power, coding, space, time, polarization etc. which show the way to [7][18][22]:

- **Improved Quality of Service (QoS):** Suitability, accessibility and consistency of wireless services will get better from the user's point of view.

- **Spectrum Efficiency:** It allows future requirement for spectrum to get together. It is the essential purpose of employing CR.

- **Graceful Degradation of Services:** When there is no idealistic scenario; a refined degradation of service is offered, as conflicting to the fewer desirable total and unexpected loss of service. This is very important feature of CR which provides services to the users particularly while they are highly mobile.

- **Higher Bandwidth Services:** Requirement of MBMS is continuously on the climb which will be assisted by the execution of CR.

- **Commercial Exploitation:** CR encourages spectrum liberalization. A business case may occur for flattering a spectrum broker, by which a third party handles the deal among provider and demander and collects a commission.

- **Future-Proofed Product:** A cognitive radio is capable to modify to services, protocols, modulation, spectrum etc. without required for a user and/or producer to promote a new device.

- **Benefits to the Service Provider:** Further clients in the market and/or raised information transfer rates to accessible customers. Additional players are able to arrive in the market.

- **Flexible Regulation:** Regulation may perhaps be changed relatively fast and when essential, easing the load on regulators by utilizing a form of policy database.

- **Benefits to the Licensee:** Cognitive Radio can cover the way for spectrum trading, where licenses would be permitted to lease a part of their spectrum rights to third parties on a temporal, spatial or further suitable basis to regain some of the expenditure of 24 hour per day license plus even build cash [23].

- **Emergency Service Communications:** Combined operations during key events would advantage greatly as coastguard, ambulance, fire and police force might be connected mutually in one radio with each radio user sensing the spectrum being utilized through the further parties and reconstructing itself.

- **Common Hardware Platform:** Manufacturers will benefit from it because they no longer require to built numerous hardware variants, instead utilizing a single general platform to lope a broad range of software. This feature also supports in fast service deployment.

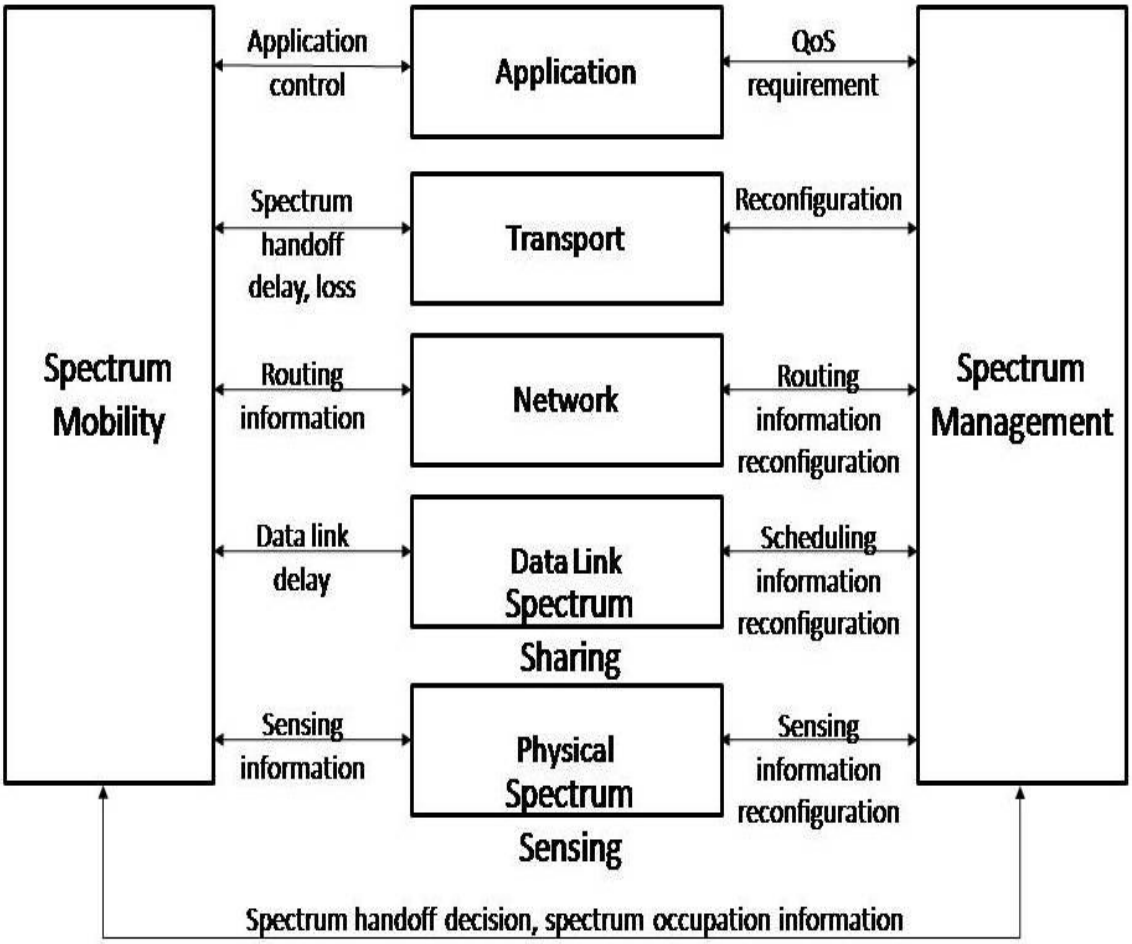



Figure 1.6 Protocol stack for XG networks

## 1.6 Cognitive Radio Architecture for Next Generation (XG) Communication System

Defense Advanced Research Projects Agency (DARPA) [8] commenced the NeXt Generation (XG) program for efficient utilization of the spectrum. Here, key idea is to utilize the dynamic spectrum access mechanism through CR for XG networks. In such a network, a CR user should be capable to sense spectrum availability and also detect the presence of licensed users in a target frequency band; so that it is able to use the frequency spectrum when the licensed users are not present [23][24].

These functions are referred to as spectrum sensing, spectrum management, spectrum sharing, and spectrum mobility [25]. The positions of these functionalities in the XG network protocol stack are shown in figure 1.6.

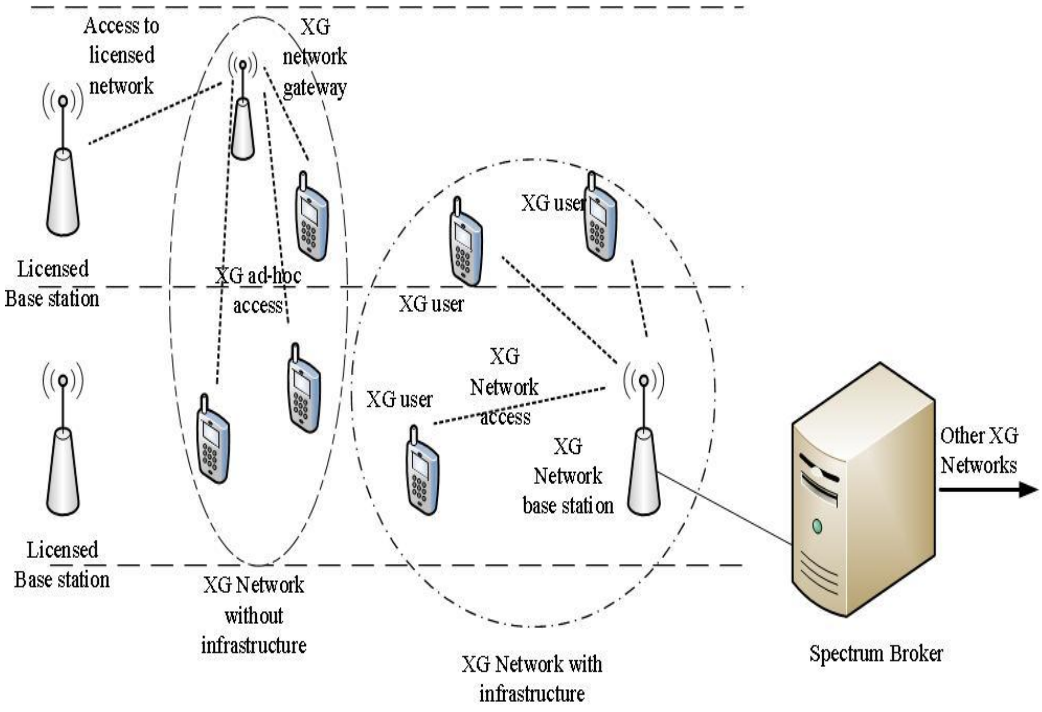



Figure 1.7 XG network architecture

The general architecture of an XG network is shown in fig 1.7. In this XG communication system architecture, there are two foremost groups of wireless systems, that is, licensed system and unlicensed system. In a licensed system, wireless connections for the licensed users are provided by the base station or access point. The unlicensed system may have infrastructure or ad-hoc [23]. For infrastructure based unlicensed system, a XG base station is used to manage the spectrum access by the XG users. Such a base station may connect to a spectrum broker for synchronization with other XG networks in order to support coexistence.

Spectrum broker owns a part of spectrum and distributes dynamic spectrum subleases to contending base stations in the area according to the demands. In case of ad-hoc XG communication mode, an XG network gateway can be used to connect the unlicensed system to the licensed system. Ian F. Akyildiz provides detailed survey on the related works in XG networks.

There are several cognitive radio systems which are based on the XG network architecture as follows:

- CORVUS
- DIMSUMnet
- DRiVE/OverDRiVE

- OCRA network

## 1.7 Potential Application of Cognitive Radio

The Cognitive Radio theory can be related to a variety of wireless system states, some of these briefly described as [22]-[25]:

**Emergency Network**

The concept of cognitive radio is utilized for public safety and emergency network to offer secure and flexible wireless communication. For e.g., the standard communication infrastructure may perhaps not be accessible in disaster situation, for that reason an emergency network may be required for disaster recovery. To enable wireless transmission and reception in excess of a wide range of the radio spectrum, CR network concept is used in such type of networks.

**Wireless eHealth Services**

There are many types of wireless technologies which are accepted in healthcare services to recover efficiency of the healthcare and patient care management. Though, utilizing wireless communication devices in healthcare application is restrained by Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) necessities. Since the medical equipment and bio signal sensors are sensitive to EMI, the transmit power of the wireless devices has to be carefully controlled. In addition, distinct biomedical devices (for e.g. monitoring devices, diagnostic and surgical equipment) are used for RF transmission. To avoid interference among each other, spectrum usage of these devices has chosen carefully. The CR concept is applied in this case. For e.g., various medical sensors are designed to manage in the ISM (industrial, scientific, and medical) band, which can utilize the CR concept to select the suitable transmission band to avoid interference.

**Military Networks**

The wireless communication parameters can be dynamically adapted based on the time and location as well as the mission of the soldiers with CR. For example, if some frequencies are jammed or noisy, the CR transceiver can search for and access alternative frequency bands for communication. In addition, location-aware CR can control the transmitted waveform in a particular region to avoid interference to the high priority military communication systems.

**Coexisting of Different Wireless Technologies**

IEEE 802.22 based WRAN [26] is developed to reuse the radio spectrum allocated to other wireless services for example T.V. services. To provide coexistence among these distinct technologies and wireless services, cognitive radio is a solution. For example, WRAN users can opportunistically utilize the TV band when there is no TV user nearby or when a TV station is not broadcasting. Spectrum management and Spectrum sensing will be essential components for IEEE 802.22 standard-based WRAN technology to avoid interference to TV users and to maximize throughput for WRAN users.

**Intelligent transportation system (ITS)**

ITS will increasingly use different wireless access technologies to enhance the efficiency and safety of transportation by vehicles. There are two types of communication scenarios which can arise in an ITS system: Vehicle-to-roadside (V2R) communication and Vehicle-to-vehicle (V2V) communication [23].

In V2R communication, information is exchanged between RSU (roadside unit) and OBU (onboard unit) in a vehicle.

In V2V communication, a special form of ad-hoc network, that is, a vehicular ad hoc network (VANET) is formed between vehicles to exchange safety-related information.

High mobility of the vehicles and rapid variations in network topologies pose significantly challenges to efficient V2R and V2V communications. CR concept can be utilized in both RSUs and OBUs so that they can adapt their transmission to cope with the rapid variations in the ambient radio frequency environment. With multi-radio capabilities at the OBUs, they should be able to adaptively choose the radio to communicate with the RSUs.

**Next Generation Wireless Networks**

CR is a key technology for next generation heterogeneous wireless networks. CR will make intelligence available to both the user-side and provider-side equipments to manage the air interface and network efficiently [24].

At the user-side, a mobile device with multiple air interfaces (e.g. Wifi, Wimax, cellular) can observe the status of the wireless access networks (e.g. transmission quality, throughput, delay, and congestion) and make a decision on selecting the access network to connect with.

At the provider-side, radio resource from multiple networks can be optimized for the given set of mobile users and their requirements. Based on the mobility and traffic pattern of the users, efficient load balancing mechanism can be implemented at the service provider's infrastructure to distribute the traffic load among multiple available networks to reduce network congestion.

## 1.8 Problem statement

There are four main aspects in cognitive radio: spectrum sensing, spectrum management, spectrum sharing and spectrum mobility in cognitive radio [25]. Most of the research is focused on the aspects of spectrum sensing, spectrum management and spectrum mobility.

This thesis emphasizes on the non-cooperative spectrum sensing in cognitive radio. The matched filter technique of non-cooperative spectrum sensing has the fastest sensing time but experiences low frequency offset tolerance in very low SNR environments. Zhang Zhang et. al. [27] used novel hybrid structure of matched filter for IEEE 802.22 to overcome the frequency offset and maintain the fast sensing time of matched filter. But hybrid matched filter results in coarse detection which renders it useless in multipath fading profile of wireless channel.

## 1.9 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 potential application of CR, thesis layout is discussed systematically.

**Chapter 2 – Cognitive Radio –A Review**

In this chapter, dynamic spectrum access and its models, physical architecture of cognitive radio and its protocol stack, spectrum hole concept are presented in this section. Functions of cognitive radio and WRAN features are discussed thoroughly.

**Chapter 3 – Spectrum Sensing in Cognitive Radio**

In this chapter, Spectrum sensing in CR is discussed. Concept of hypotheses model, non-cooperative sensing and its functions, cooperative spectrum sensing, and interference based sensing are explained. This section also presents advantages and disadvantages these techniques.

**Chapter 4 – Proposed Work and Simulation Results**

In this chapter, hybrid matched filter and single cycle cyclostationary detector are discussed. The proposed scheme of combined hybrid matched filter single cycle cyclostationary detector is also discussed in this chapter. The simulation results are also 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

Cognitive radio is emerging technique which is build up on the concept of Dynamic Spectrum Access by unlicensed users, conflicting to the existing spectrum allocation model of fixed spectrum access. With the conventional approach of assigning frequency spectrum to wireless transceivers, it is noticed that few frequency bands are highly occupied in some locations, while others are occupied for short period of time in other locations. Thus, spectrum opportunities are accomplished. With the help of software defined radio, a wireless transceiver can change its parameter according to requirement. Dynamic Spectrum Access is used to beget for distinct wireless systems with different capabilities and operating behavior.

## 2.1 Dynamic Spectrum Access (DSA)

DSA can be defined [28] as, "A mechanism to adjust the spectrum resource usage in a near-real-time manner in response to the changing environment and objective, changes of radio state and changes in environment and external constraints". Figure 2.1 [28] shows the DSA in cognitive radio.

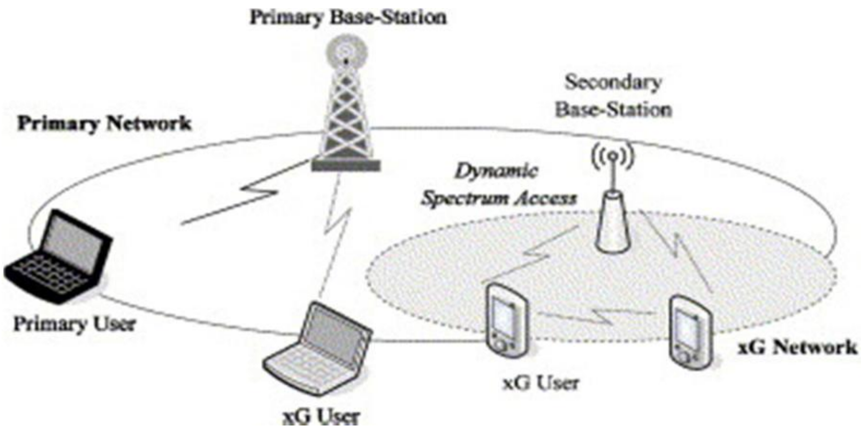



Figure 2.1 Dynamic Spectrum Access (DSA)

## 2.2 Dynamic Spectrum Access Models

DSA models can be categorized in three parts as Exclusive-use model, Shared-use model, and common models, [29] which is shown in figure 2.2.

### 2.2.1 Exclusive-Use Model

In exclusive-use model [23], a licensed user can grant permission to the unlicensed user for a definite amount of time, to access the specific frequency spectrum. The licensed user may not employ allocated spectrum every time and everywhere. Consequently, cognitive radio users get the permission to access the spectrum. In this case, cognitive radio user is defined as unlicensed user. To achieve better performance, cognitive radio user enhances the spectrum management. Exclusive-use model is further classified in Long-term exclusive-use model and dynamic exclusive-use model.

**Long-term and Dynamic Exclusive-use model**

In Long-term exclusive-use model [24], the spectrum is designated to specific amount of time. When spectrum is licensed, the different type of wireless services uses this spectrum according their requirement.

In flexible-type sub-model, the unlicensed user i.e. cognitive radio user can change the type of wireless service. In a fixed-type sub model, the licensed user describes the type of wireless service and the limitations for spectrum approaches by the CR user.

In Dynamic exclusive-use model, only single user can approach the spectrum at any instant of time.

### 2.2.2 Shared-Use Model

In this type of spectrum access model, licensed user and unlicensed user share the allocated spectrum. The licensed user is assigned to frequency spectrum which is tactfully accessed by the unlicensed users if it is not utilized by the licensed user [23]-[29].

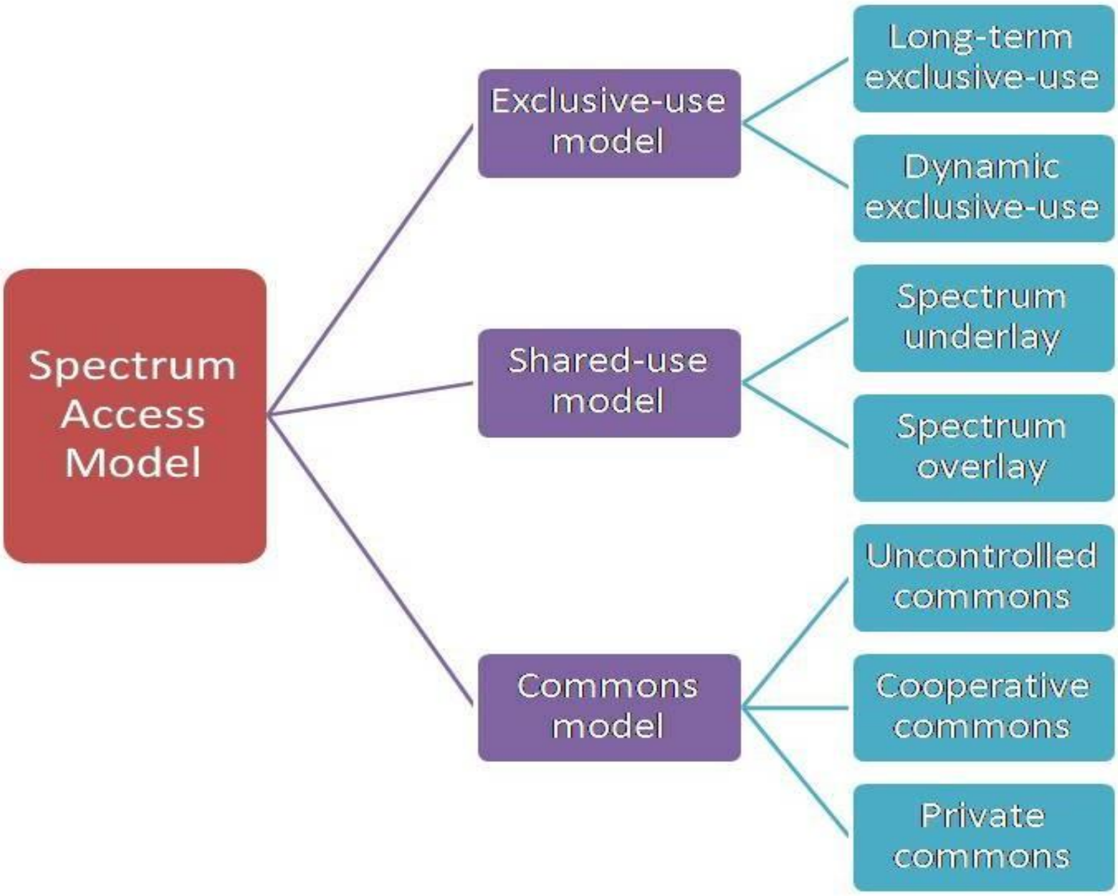



Figure 2.2 Dynamic Spectrum Access models

In Shared-use model, unlicensed user can access the spectrum in two ways i.e. spectrum overlay and spectrum underlay which is used for opportunistic access of spectrum, shown in figure 2.3.

**Spectrum Overlay**

This technique has exclusive permission to access the spectrum. If the primary user is not utilizing spectrum, the secondary user can access that spectrum opportunistically at specific time. Consequently, spectrum sensing is performing by secondary user to determine the existence of primary user in that particular band. If spectrum hole is accomplished, secondary user may access the frequency spectrum. This technique does not necessarily impose any strict restriction on the transmission power by secondary user. This technique is used for CR in various wireless technologies like FDMA, TDMA, or OFDM.

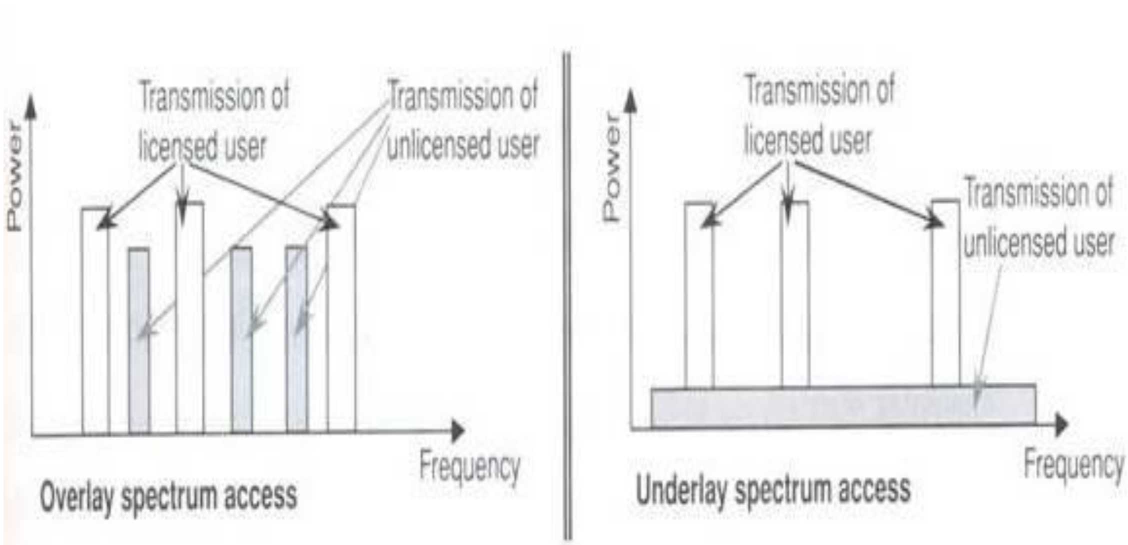



Figure 2.3 Spectrum overlay and Spectrum underlay[23]

**Spectrum Underlay**

In this technique, secondary user can transmit along with the primary user. The spectrum underlay approach restraints the transmission power of secondary user so that they operate below the interference limit of primary user. Spectrum underlay technique used for CR in distinct technology like CDMA and UWB.

## 2.2.3 Commons Model

In this type of model, spectrum is open for access all type of users. This model is categorized in three model, which is uncontrolled, cooperative, and private commons-use model. [30] These are described as follows:

**Uncontrolled- Commons Sub-Model**

In this type of sub-model, only maximal transmit power restraints apply to a secondary user. This technique is already used in ISM band (2.4 GHz) and U-NII (5GHz) unlicensed band. The secondary user suffers from uncontrolled interference or controlled interference because spectrum access is out of control. Uncontrolled interference occurs due to the outside network devices. Controlled interference occurred due to the neighboring devices in the network [30].

**Cooperative Commons Sub-Model**

This type of sub-model ignores the problems of uncontrolled commons sub-model. This sub-model technique concedes spectrum as resources which is required to be controlled by set of CR. In this case, CR must follow the rules and limitations to access the spectrum. To manage these rules and limitations, this management protocol is required. Some objectives of the management protocol are given as:

- Support advanced and efficient device design, services, and business model.
- Minimize communication and coordination overheads for spectrum access.
- Provide flexibility for protocol changes in the future to support new technology.
- Promote fair spectrum access among the cognitive radio users.

**Private - Commons Sub-Model**

In this type of model, a licensee (spectrum owner) can define a protocol and a technology for the CR users to access the spectrum. The spectrum owner may give a command to the CR user [23]-[31]. This command may possibly include the transmission parameter (that is frequency band, transmit power, and time) to be utilized by CR user. Instead, a CR user may opportunistically sense and connect the spectrum without disturbing the licensee.

## 2.3 Physical Architecture of Cognitive Radio

In general, the cognitive radio physical architecture utilizes a transceiver which contains a RF front end and a baseband signal processing entity which executes modulation/demodulation [7][23] and encoding/decoding tasks.

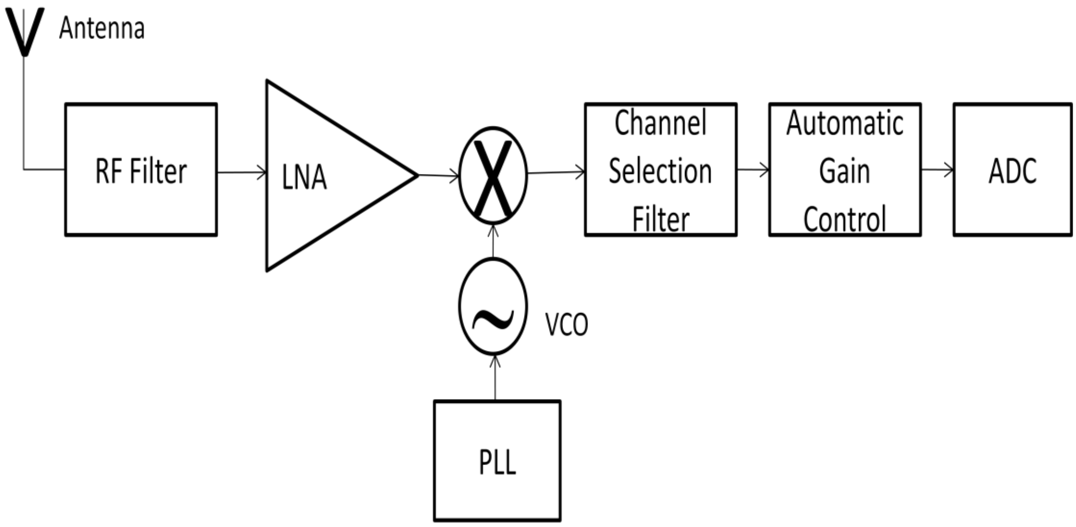



Figure 2.4 RF front end of Cognitive radio

In figure 2.4 the RF frontend is being shown which consists following parts:

- **RF Filter:** This is a band-pass filter which decides on the frequency band of interest.
- **Low Noise Amplifier (LNA):** This is employed for amplifying the preferred signal and more over for suppressing the noise part.
- **Mixer:** This is employed for converting the frequency to Intermediate Frequency (IF) in order to make possible further processing.
- **Voltage Controlled Oscillator (VCO):** It develops the signal through specific frequency essential for mixing.
- **Phase Locked Loop (PLL):** Assure that frequency is fixed and does not change with time.
- **Channel Selection Filter:** Works as channel selector and rejecter filter. It chooses the desired frequency bands and dismisses the adjacent bands.
- **Automatic Gain Control (AGC):** It maintains the output power level literally constant above a large range of input signal.

- **A/D Converter:** Signal is converted in analog form to digital information. Hence, signal can be measured by the baseband processing unit.

## 2.4 Cognitive Radio Protocol Stack

Figure 2.5 shows the architecture of cognitive radio protocol stack. The RF front-end of CR is situated on the SDR transceiver in the physical layer. The adaptive protocols in Medium Access Control (MAC) layer, network layer, transport layer, and application layer must be alert to the distinctions in the CR environment [23].

The traffic actions of the primary user, secondary users transmission requirement, and differences in channel quality, etc. are considered by the adaptive protocols. To connect all modules, a CR control is utilized to establish interfaces along with the adaptive protocols, SDR and wireless applications and services.

This CR module employs intelligent algorithm for the progression of the deliberate signal from the physical layer, and obtain information on transmission necessities from the applications to manage the protocol parameters in the distinct layers [32].

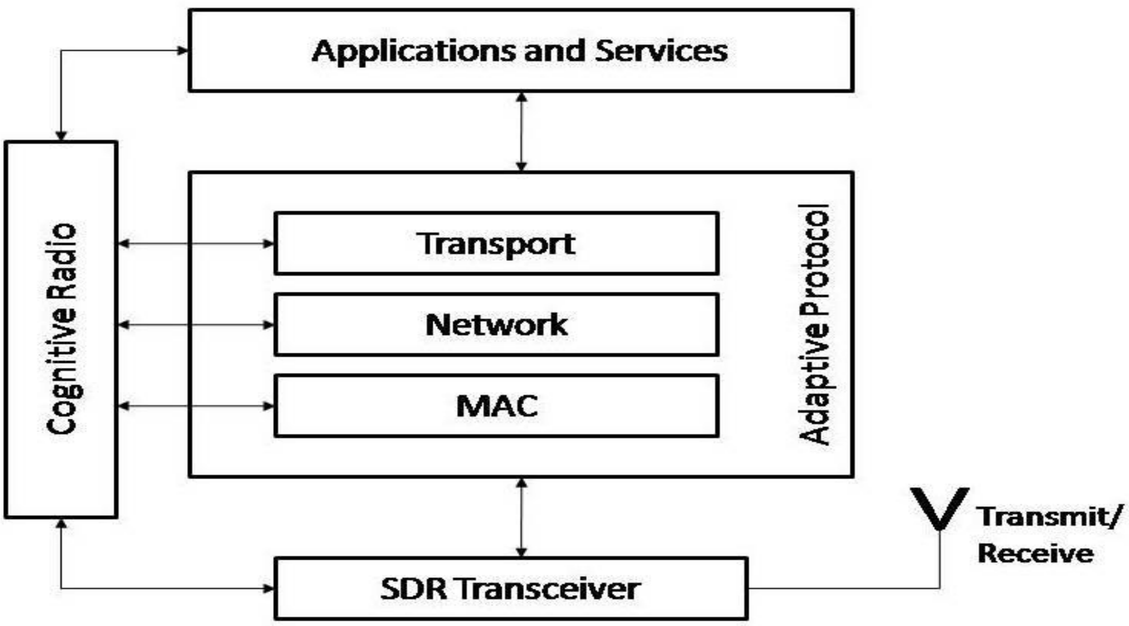


Figure 2.5 Cognitive Radio Protocol Stack

## 2.5 Spectrum Hole Concept

Cognitive radio is a new paradigm wireless communication systems which aims to enhance the utilization of the radio frequency (RF) spectrum. The motivation behind cognitive radio is the scarcity of the available frequency spectrum, increasing demand, caused by the emerging wireless applications for mobile users [33]. Most of the available spectrum has already been allocated to existing wireless applications. Some frequency bands are heavily used by licensed user in particular locations and at particular time, but that there are also many frequency bands which are only partly occupied or scarcely occupied.

The right to access the spectrum (or license) is generally defined by frequency, space, transmit power, spectrum owner (or licensee), type of use, and the duration of license. Normally, a license is assigned to one licensee, and the use of spectrum by this licensee must conform to the specification in the license (e.g. maximum transmit power, location of base station) [23][31]-[33]. In the current spectrum licensing scheme, the license cannot change the type of use or transfer the right to other licensee. This limits the use of the frequency spectrum and results in low utilization of the frequency spectrum. Essentially, due to the current static spectrum licensing scheme, *spectrum holes* [34] or spectrum opportunities arise which is shown in figure 2.6 [31]. Spectrum holes are defined as frequency bands which are allocated to, but in some locations and at sometimes not employed by, primary users, and, hence, might be accessed by secondary users.

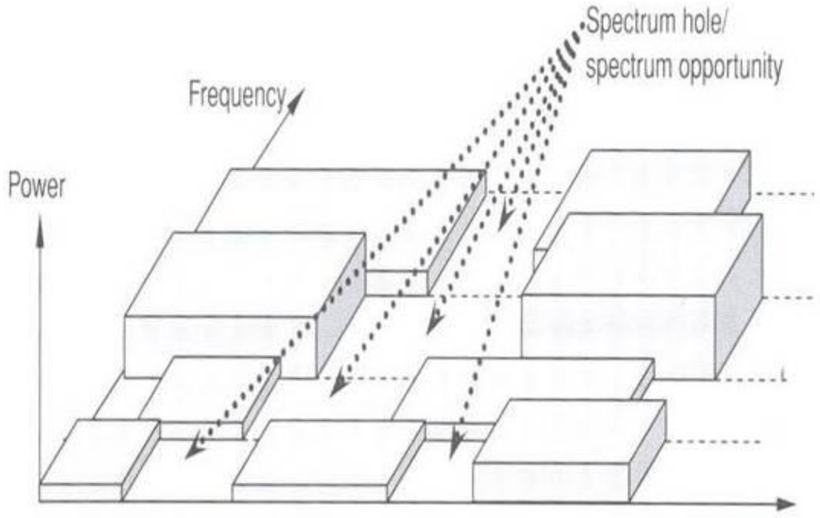



Figure 2.6 Spectrum Hole (White spaces)

In provisions of occupancy, sub bands of the radio spectrum could be classified as follows:

- *White spaces:* These are open for RF interferers, excluding for noise due to natural and/or artificial sources.
- *Gray spaces:* These types of spaces are partially engaged by interferers as well as noise.
- *Black spaces:* These types of spaces are fully occupied by the RF interferers due to the mutual occurrence of communication and probably interfering signals plus noise.

## 2.5.1 Limitations in Spectrum Access

The limitations in spectrum access due to the static spectrum licensing scheme can summarized [23][24][35] as follows:

- *Fixed type of spectrum usage:* In the current spectrum licensing scheme, the type of spectrum cannot be changed. For example, a TV band which is allocated to National Television System Committee (NTSC) - based analog TV cannot be used by digital TV broadcast or broadband wireless access technologies. However, this TV band could remain largely unused in many locations due to cable TV systems.

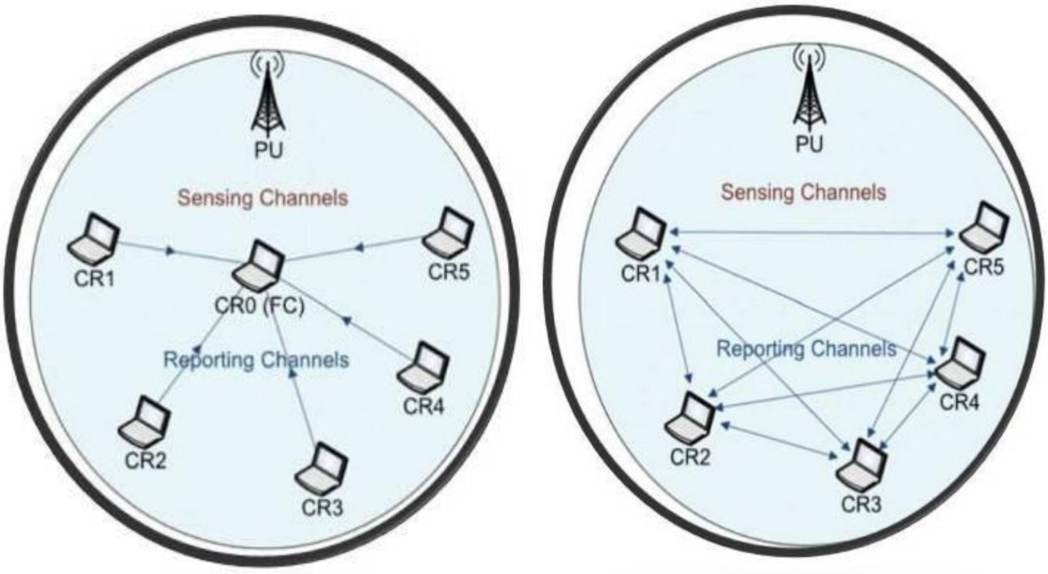
- *Large chunk of licensed spectrum:* A wireless service provider is generally licensed with a large chunk of radio spectrum (e.g. 50MHz). For a service provider, it may not be possible to obtain license for a small spectrum band to use in certain area for a short period of time to meet a temporary peak traffic load. For example, a CDMA2000 cellular service provider may require a spectrum with bandwidth of 1.25 MHz or 3.75 MHz to provide temporary wireless access service in a hotspot area.

- *Licensed for a large region:* When a spectrum is licensed, it is usually allocated to a particular user or wireless service provider in a large region. However, the wireless service provider may use the spectrum only in areas with a good number of subscribers, to gain the highest return on investment. Consequently, the allocated frequency spectrum remains unused in other areas, and other users or service providers are prohibited from accessing this spectrum.

- *Prohibit spectrum access by unlicensed users:* In the current spectrum licensing scheme, only a licensed user can access the corresponding radio spectrum and unlicensed users are prohibited from accessing the spectrum even though it is unoccupied by the licensed users. For example, in a cellular system, there could be areas in a cell without any users. In such a case, unlicensed users with short-range wireless communications would not be able to access the spectrum, even though their transmission would not be able to access the spectrum, their transmission would not interfere with cellular users.

## 2.6 Functions of Cognitive Radio

The architecture of CR network varies tremendously depending on the preferred applications [36]. CR network can be centralized wherever a central node synchronizes spectrum sensing, allocation and management of every serviced node, shows in figure 2.7(a) [37]. Moreover, nodes in a distributed CR network correspond to each other in an ad-hoc manner to synchronize CR tasks which is show in figure 2.7(b) [37]. In general, a centralized CR network simplifies the communication and computation load of every end node, although necessitates more infrastructure and costs. However, distributed network is more structurally flexible and requires little infrastructure at the expense of increased complexity [37].




(a) Centralized (b) Distributed

Figure 2.7 Centralized and Distributed cognitive radio network

Centralized: CR users communicate through the central node.

Distributed: CR users communicate directly with each other and converge to a unified decision on the presence or absence of primary users.

Apart from architecture, CR must be flexible in detecting variations in primary user (PU) activities; hence the cognitive tasks must be performed periodically. Communally, cognition cycle ensures the integrity of CR network and protection of primary user actions. The cognition cycle is already discussed in chapter 1 which focused on the spectrum sensing and cognitive intelligence feature of CR. Although cognitive tasks may fluctuate between application and implementations, the main functions which consist of cognitive cycle: spectrum sensing, spectrum analysis, spectrum decision, and spectrum mobility.

### 2.6.1 Spectrum Sensing

The main object of spectrum sensing is to establish the status of the spectrum and the commotion of the licensed users by infrequently sensing the objective frequency band.

The CR transceiver identifies an unutilized spectrum or white space [28] and as well determines the transmit power and access duration without interfering with the transmission of licensed user. Sensing can be performed in-band or out-of-band. In-band sensing is used to detect primary user on the spectral channel currently used by the secondary user. Out-of-band sensing is used to recognize additional probable spectrum spaces besides the channel currently in use. Out-of-band sensing is advantageous in locating possible back-up channels in case in-band sensing failed, or assisting alternative secondary user in detecting a usable channel. Parallel search senses multiple channels unitedly while sequential search senses single channels iteratively. Spectrum sensing is the main focus of this research; therefore an in-depth review will be presented in the following chapter. Once white spaces are detected, the secondary users go into next task of spectrum analysis [35]-[38].

### 2.6.2 Spectrum Analysis

The information acquired from the spectrum sensing task is utilized to schedule and plan spectrum access by the SU. It depends on the transmission, spectrum frequency, and propagation characteristics of certain channels may be unable to support the desired operation, like unsatisfactory QoS, insufficient coverage, etc. In spectrum analysis [23]-[25], information from spectrum sensing is analyzed to gain knowledge about the spectrum holes. Afterward, a decision to access the spectrum is made by optimizing the system performance given the desired constraints and objectives.

### 2.6.3 Spectrum Access

This function decides on which spectrum space to continue communication and will influence all nodes within the secondary user network. The decision may initiate the nodes to stay behind the current channel if primary user is not detected, or immediately shuffle to the subsequently backup channel if primary user is present. If the secondary user network is changing to a distinct channel, then each secondary user nodes must distinguish which channel to modify [37]. Spectrum access is performed based on cognitive medium access control (MAC) protocol, which intends to avoid collision with primary users and moreover with other secondary users. The CR transmitter is also required to perform negotiation with the CR receiver to synchronize the transmission so that transmitted data can be received successfully. A cognitive MAC protocol could be based on a fixed allocation MAC (e.g. FDMA, TDMA, CDMA) or a random access MAC (e.g. ALOHA, CSMA/CA).

### 2.6.4 Spectrum Mobility

This is a function which is related to the change of operating frequency band of secondary users. When PU initiates the accessing of a radio channel which is currently being utilized by SU, the SU can change to a spectrum band which is idle. This operating frequency change is referred to as spectrum handoff.

These protocol constraints at the distinct layers in protocol stacks have to be familiar to equivalent the latest functioning frequency band throughout spectrum handoff. These conditions have to try to make sure that the data transmission by the secondary user can continue in the new spectrum band. While CR is moderately new conception, there are already various applications proposed to implement DSA. The subsequent sections will briefly evaluate some applications of CR, in particular the draft standard IEEE 802.22 WRAN, and applications for a cellular network scenario.

## 2.7 IEEE 802.22 Wireless Regional Area Network (WRAN)

WRAN is a standard in development by IEEE working group 802.22. The objective of the WRAN is to deliver wireless broadband to rural area utilizing a DSA model on spectrum allocated for TV broadcast [26][31]. WRAN implements a centralized infrastructure, where multiple customer premise equipment (CPE) is serviced by a single base station (BS), and BS communicate with each other through infrastructure [39]. The proposed network architecture of WRAN is illustrated in figure 2.8 [39].

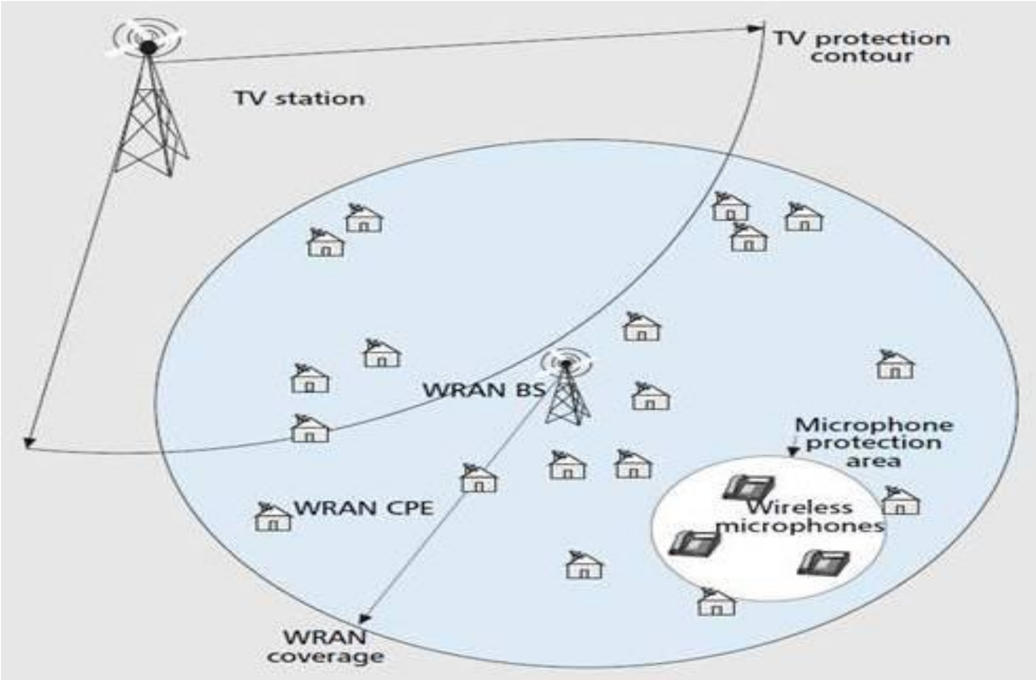



Figure 2.8 Network Architecture of WRAN

Various cognitive functions are included in WRAN to protect primary user and ensure efficient spectrum utilization. Both CPE and BS have geolocation capabilities and BS maintains the locations of all associated CPE. The incumbent user database is dynamically updated and contains information of protected PU operation in surrounding areas, like protection contour, transmission power limit etc. This information is utilized to supplement spectrum sensing capabilities. The BS schedules quiet periods for synchronized sensing to ensure sensing results are not corrupted by other secondary user transmission. Both CPE and BS perform spectrum sensing, while CPE return sensing information back to BS for central decision. The sensing detector is not specified by the standard, but spectrum sensing must be performed in the current operating spectrum as well as identifying possible backup spectra. A newly projected IEEE802.22 WRAN is typically targeted at remote and rural areas, its coverage range is almost <100 km. A comparison among different IEEE802.11 standards is given in figure 2.9 [40].

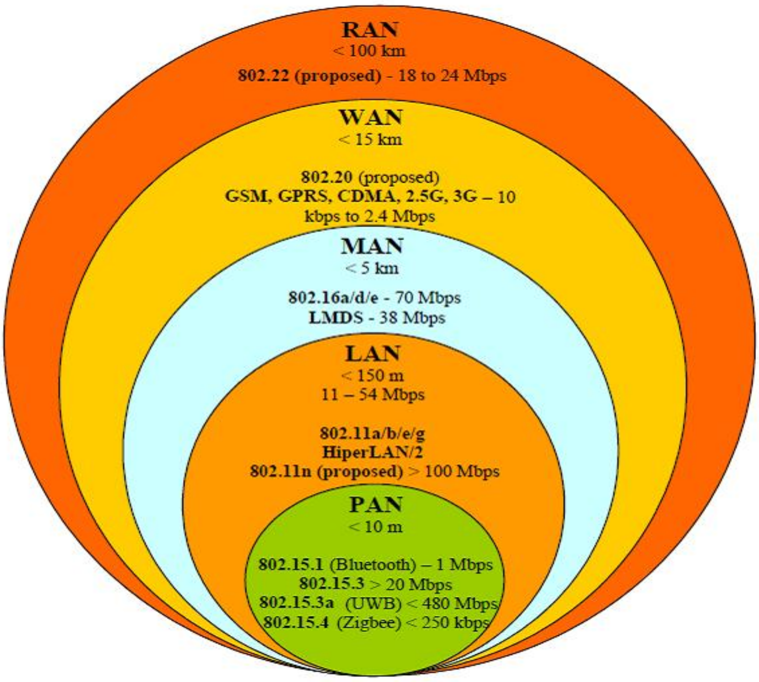



Figure 2.9 IEEE 802.22 WRAN classifications as compared to other popular wireless standards

## Table 2.1 Physical Layer Parameters for IEEE 802.22 (WRAN)

| **Parameters** | **Specifications** |
|---|---|
| Data Rate | 4.54 – 22.69 Mbps |
| Frequency Range | 54-862 MHz |
| Spectral Efficiency | 0.76- 3.78 bits/s |
| Channel Bandwidth | 6-8 MHz |
| Multiple Access | OFDMA |
| Payload Modulation | 16-QAM, 64 QAM, QPSK |
| Coding | Block Conventional Code |

| | |
|---|---|
| FFT size | 2048 |
| Duplex | TDD |
| Cyclic Prefix Mode | 1/4, 1/8,1/16,1/32 |

### 2.7.1 Transmitter and Receiver Description

The significant functional components of transmitter section of WRAN can be explained. 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 [2][26][40].

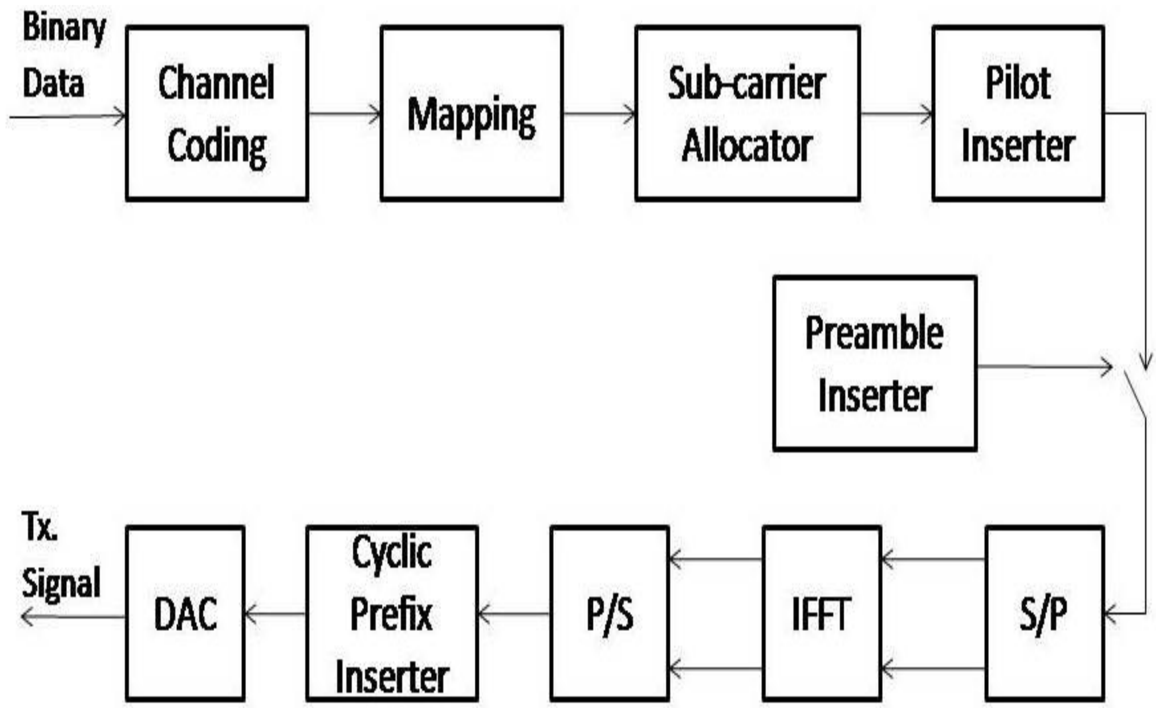



Figure 2.10 Transmitter section of WRAN

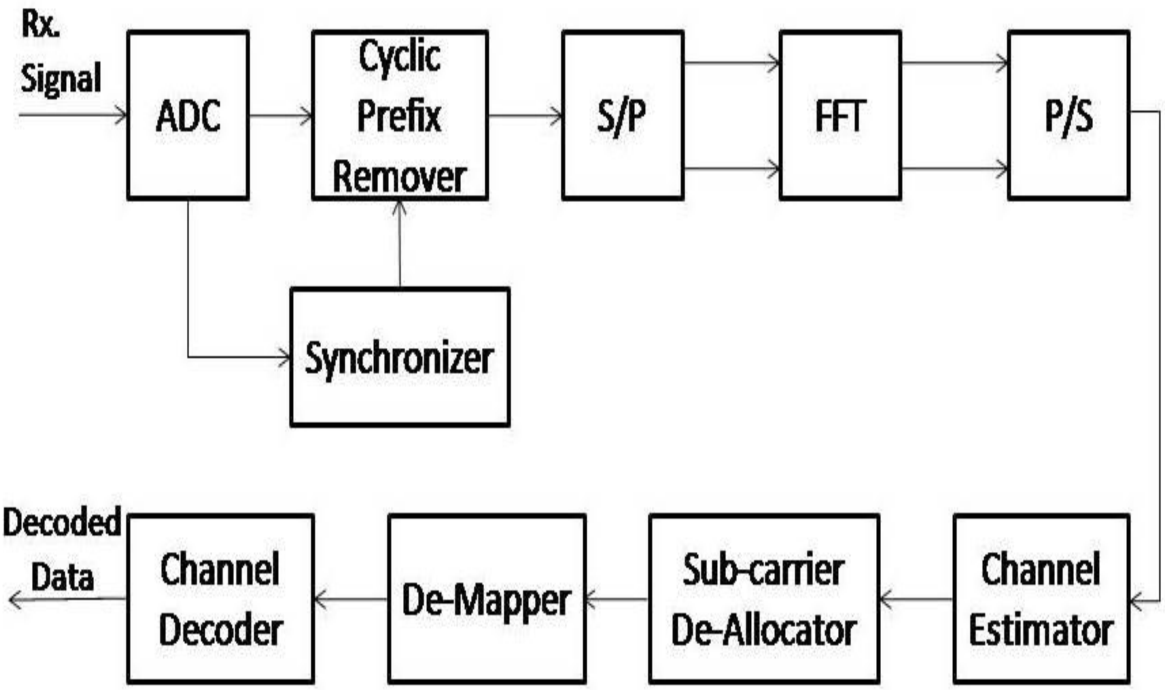



Figure 2.11 Receiver section of WRAN

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 Transmitter and receiver section is shown in the figure 2.10 and figure 2.11, respectively [40]. The Receiver part is just the reverse of the transmission part and each unit does the opposite function performed by it in the transmission part.

# CHAPTER 3

# Spectrum Sensing in Cognitive Radio

While spectrum sensing technique is barely a single module of CR, it is already a broad field to explore with much intricacy and countless research problems. This chapter appraises aspects of spectrum sensing technique to offer greater knowledge in the operation, applications, difficulties and challenges related to this issue to support the argument of the remaining thesis. The review includes topics such spectrum sensing, types of spectrum sensing, and brief review of non-cooperative spectrum sensing. In Cognitive Radio networks, the major task of signal processing is spectrum sensing for detecting the unemployed spectrum as well as sharing it with no damaging interference to further users. One important requirement in cognitive radio network is sensing spectrum holes reliably and efficiently.

Spectrum sensing technique [35][36] can be classified into three categories. First, cognitive radios must be capable of determining the condition of a signal from a primary transmitter which is nearby there in a fixed spectrum. Some approaches are utilized for transmitter detection, like energy detection, match filter detection, Cyclostationary feature detection, and wavelet detection. Second, collaborative detection indicates the methods of spectrum sensing where information from various CR users is subjugated for primary user detection. Third, the sensing devices can be separated from the secondary users and can be deployed into the cognitive network by the cognitive radio service provider.

By doing this, the cost of the secondary user devices can be reduced and hidden terminal problem/exposed terminal problem can be moderated. Figure 3.1 shows the spectrums sensing techniques and their parts.

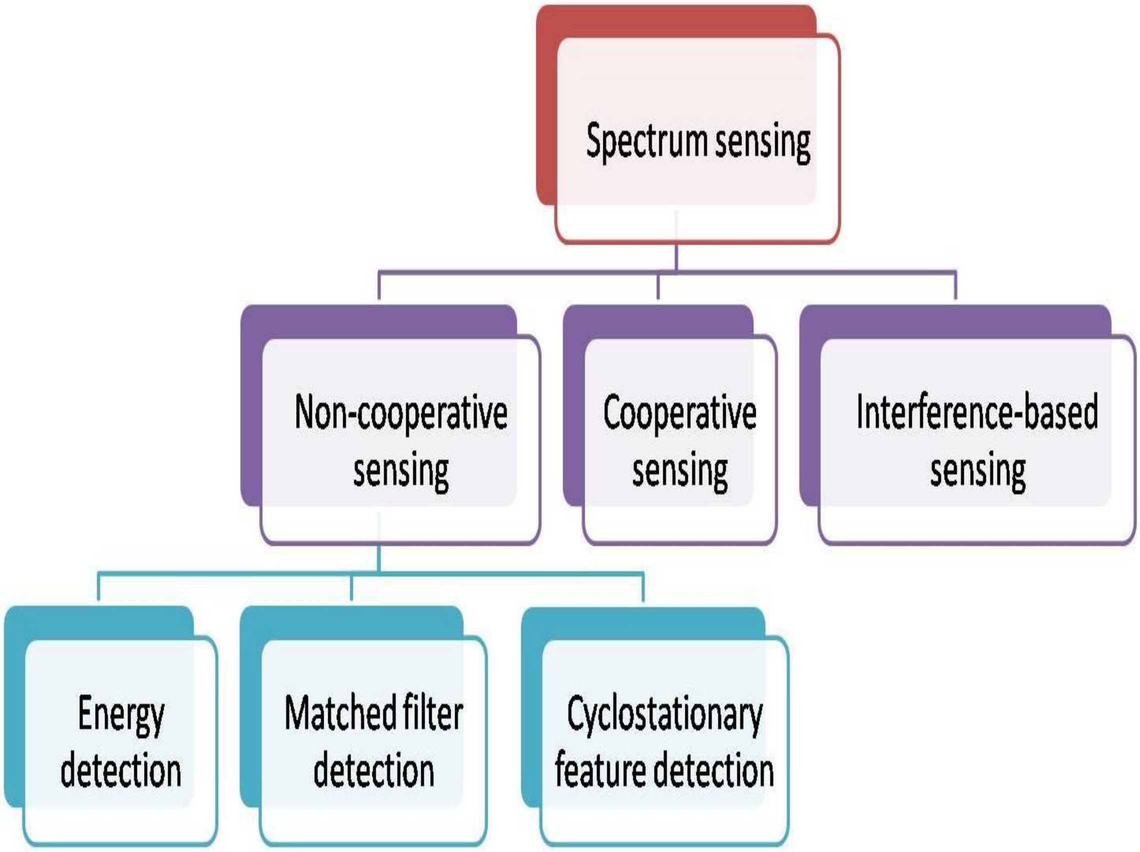



Figure 3.1 Different types of spectrum sensing in the physical layer

## 3.1 Concept of Two Hypotheses (Analytical Model)

Non-cooperative spectrum sensing (transmitter detection) is utilized by secondary (unlicensed) user to distinguish the transmitted signal from a primary (licensed) user by employing local assessments and local scrutiny. Spectrum sensing can be reduced to an identification problem, designed as Hypothesis test [37]. The model for signal detection at time $t$ can be illustrated as:

$$x(t) = n(t) \quad , \qquad H_0 \qquad (3.1)$$

$$x(t) = h \times s(t) + n(t) \quad , \qquad H_1 \qquad (3.2)$$

Where, $x(t)$ is received signal of secondary user.

$s(t)$ is the transmitted signal of the primary users.

$n(t)$ is the additive white Gaussian noise (AWGN).

$h$ is the channel gain.

Here, $H_0$ and $H_1$ is defined as Hypothesis. $H_0$ Hypotheses indicate absence of the primary user and that the frequency band of interest simply has noise while $H_1$ Hypothesis points towards presence of primary user with noise. Therefore, the two state hypotheses of important cases are:

- $H_1$ Hypotheses brings out to be TRUE in case of presence of primary user, namely, $P(H_1|H_1)$ is identified as **Probability of Detection ($P_d$)**.

- $H_0$ Hypotheses brings out to be TRUE in case of presence of primary user, namely, $P(H_0|H_1)$ is identified as **Probability of Miss-Detection ($P_m$)**.

- $H_1$ Hypotheses brings out to be TRUE in case of absence of primary user, namely, $P(H_1|H_0)$ is identified as **Probability of False Alarm ($P_f$).**

The probability of detection ($P_d$) is major concern because it provides the probability of properly sensing for the presence of primary users in the desired frequency band [37][39]. Probability of miss-detection ($P_m$) is just the complement of the detection probability. The aim of the sensing techniques is to maximize the detection probability and minimize probability of false alarm ($P_f$).

## 3.2 Non-cooperative Spectrum Sensing Detectors

A number of methods have been developed for detecting the presence of primary user in a particular frequency band [41]. Several approaches utilized the signal energy or various exacting characteristics of the signal to recognize the signal and even its type. Some of the most common methods occupied for the spectrum sensing in terms of their operation, pros and cons can be acknowledge as [42]:

### 3.2.1 Transmitter Energy Detector

The energy detector, also known as radiometry or periodogram based detector is the optimal method for spectrum sensing technique when the information from a primary user is unavailable [43]. The output signal from a bandpass filter is squared and integrated over the observation interval, in energy detection. This detector has elementary analytical model, therefore low computational complexity and can be simply employed in either software or hardware.

Further, this is comprehensive as the detector does not necessitate any information regarding primary user that's why the implementation is not very much dependent on primary user. There are two prior requirements which are required for energy detection operation [44] that is noise should be statistically stationary and noise power (variance) known to the detector. Whereas there are circumstances that may nullify these assumptions, many authors believe them as a reasonable approach. The energy detector has inferior detection performance as compared to other signal detectors and faces complexities in detection of spread spectrum signals. When noise is non-stationary or noise-power not identified ideally then energy detector performs very poorly. An energy detector is a non-coherent detector. The basic block diagram of energy detector shown in figure 3.2 which is as follows:

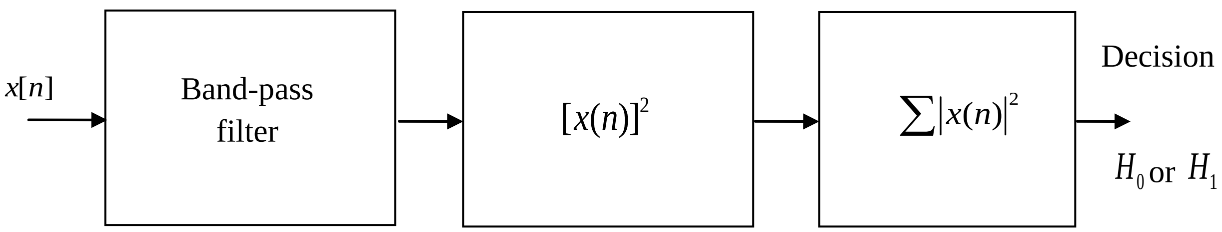



Figure 3.2 Principle of Energy Detection

In figure 3.2, the energy detector has following components:

- Band-pass filter – It limits the bandwidth of the received signal to the frequency band of interest.

- Square Law Device – It is used to square every term of the received signal.
- Summation Device – Add all the squared values to compute the energy.

Here, a threshold value [45] is required for comparison of the energy initiate by the detector. If energy is greater than threshold value then it points out the presence of primary user. The energy is calculate as

$$E = \sum_{n=0}^{N} |x(n)|^2 \tag{3.3}$$

Now, the energy is compared to a threshold for checking which hypotheses turn out to be true.

$$E > \lambda \Rightarrow H_1 \tag{3.4}$$

$$E < \lambda \Rightarrow H_0 \tag{3.5}$$

An energy detection algorithm was proposed in [46] for a non-fading environment and the expressions for probability of false alarm ($P_f$) and probability of detection ($P_d$) were obtained. The output of energy detector is given as test statistic and computed as the total energy (or total power) of the received signal which can be performed in either frequency domain or time domain in hardware or software. The energy detector performance is influenced by signal power, time of detection, and noise power wherever high signal power, extended detection time, and small noise power outcomes in enhanced performance. The energy detector can get better performance but the cost is increasing detection time. The detector output is measured up to a decision threshold to accomplish different detection performance reflecting design approaches. Threshold can be chosen to minimize decision error (ME) [47]; however such approach needs the accurate noise and primary user signal power. There are many techniques to estimate signal and noise power, but noise power is more static and can be more exactly estimated, but primary user signal strength can change relaying upon distance and transmission characteristics.

The threshold utilized in the energy detector relies on the noise variance; therefore noise variance errors known as noise uncertainty will result significant performance degradation [45][47]. In face of a constant noise uncertainty, energy detector shows an affect which is known as ‘SNR wall’, by which energy detector cannot detect a primary user signal beyond a minimum SNR indifferent on the detection time duration [48]-[50]. To solve this issue exact noise estimation algorithm is used that are capable to separate primary user signal and noise from the observe signal.

**Pros**

- Very simple to implement.
- No prior knowledge of PU signal’s required.

**Cons**

- Spectrum sensing speed is relatively slow.
- Threshold for detection is very susceptible to the noise level and in-band interference.
- Energy detector cannot differentiate modulated signal, noise, and interference.
- PU and SU cannot be distinguished, while only the primary user’s transmission should be protected.
- Energy detection cannot work for spread spectrum signals.

### 3.2.2 Matched Filter Detector

The Matched Filter technique is very important in communication as it is an optimum filtering technique which maximizes the received signal to noise ratio (SNR) for measured signal [51]-[55]. Matched filter is generally utilized to detect a signal by comparing a known signal, namely, a template with the input signal. Thus, if the information of the signal from a primary user like packet format and modulation scheme or order, pulse shaping etc. is known, a matched filter is an optimal detector in stationary Gaussian noise. While a template is utilized for signal detection, a matched filter necessitates merely a little amount of time. Though, if this template is not accessible or is incorrect, the spectrum sensing performance degrades drastically.

Matched filter detection is appropriate when the transmission of a primary user has preambles, pilot, synchronization words or spreading codes, which can be utilized to create the template for spectrum sensing. Due to the coherent nature of matched filter, detection can be very fast. But if there are multiple primary users, the secondary users have to be equipped with multiple dedicated receivers. The secondary sensing node must be synchronized to the primary system and it must be able to demodulate the primary signal. 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 matched filter operation shows in figure 3.3 as follows:

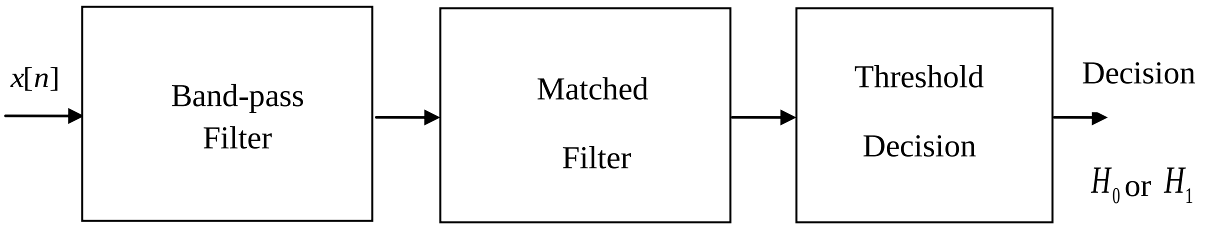



Figure 3.3 Block Diagram of Matched Filter Detection

The operation of matched filter detection is given as:

$$y[n] = \sum_{k=-\infty}^{\infty} x[k]h[n-k] \qquad (3.6)$$

Where, $x[n]$ is the received signal, and

$h[n]$ is the filter response.

After this decision is made by hypotheses test, here $H_0$ shows absence of user and $H_1$ shows presence of primary user.

**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.

### 3.2.3 Cyclostationary Feature Detector

Cyclostationary feature detection [56]-[59] is used to detect the cyclostationary signatures and features which is exclusive to the primary user. The transmitted signal normally has periodic pattern. Basically, this periodic pattern is referred as cyclostationarity. In the wide sense, a signal is cyclostationary if the signal statistics such as mean and autocorrelation is a periodic pattern. Communication system signals usually have provoked cyclostationary features because information data is over and over again modulated onto periodic carriers. The basic approach is based on the autocorrelation function and the power spectral density. The spectral correlation function has a cyclic spectrum with cyclic frequency.  It can work in low SNR.

Since, cyclostationary detection is based on cyclic spectral density (CSD), it is capable to separate primary user signal from noise due to the fact that white noise has little correlation hence its cyclic spectral density is weak. A pattern recognition scheme is based on a neural network can be utilized to implement cyclostationary feature detection for spectrum sensing. The basic block diagram is shown is figure 3.4 as follows:

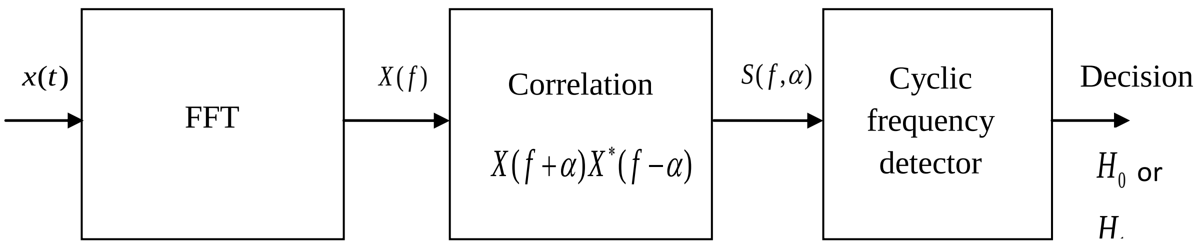


Figure 3.4 Block diagram of Cyclostationary Feature Detection

**Pros**

- Robust the noise uncertainties.
- Performs better than energy detector.

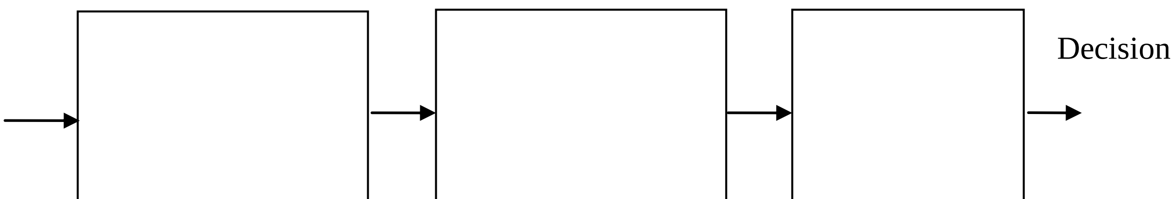
**Cons**

- Requires prior knowledge of primary user.
- High computational complexity.
- Long sensing time.

## 3.2.4 Wavelet based Detector

The wavelet detection [60] determines benefits for wideband spectrum sensing above the conventional utilization of multiple narrow band filter banks in stipulations of implementation cost and flexibility. A change in frequency of a signal results in limits in the frequency spectrum. These assets can be extremely useful in detection algorithms. The frequency band is sub-divided into a number of sub-bands which is characterizing by its own variations in frequency. On these sub-bands, wavelet transform is made to assemble the information regarding 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 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 3.2 shows the wavelet based sensing.



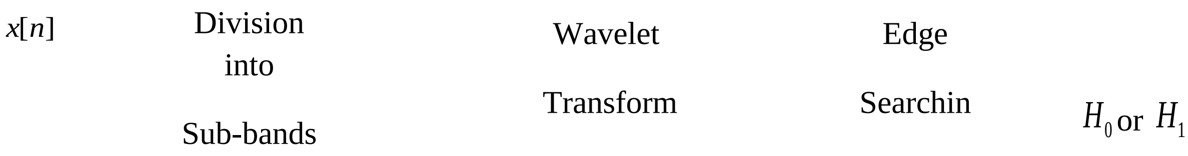



Figure 3.5 Principle of Wavelet based sensing

**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.

## 3.2.5 Waveform based Detector

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 [60][61]. The more the length of these known patterns, more will be the accuracy of the detection. The figure 3.6 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.

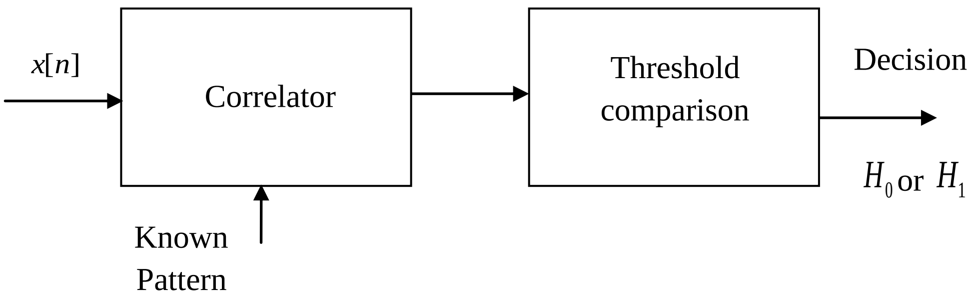


Figure 3.6 Waveform Based Sensing

**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.

## Table 3.1 Comparison among Spectrum Sensing Techniques

| **Spectrum Approach** | **Advantage** | **Disadvantage** |
| --- | --- | --- |

| | | |
|---|---|---|
| **Energy detection** | ➢ No prior information required.<br>➢ Low cost. | ➢ Cannot work in low SNR.<br>➢ Cannot distinguish primary and other secondary users. |
| **Matched filter Detection** | ➢ Optimal performance.<br>➢ Low cost. | ➢ Prior knowledge of primary user signal is required. |
| **Cyclostationary Feature detection** | ➢ Robust in low SNR and interference. | ➢ Partial information of primary user.<br>➢ High computational cost. |
| **Wavelet detection** | ➢ Effective for wideband signal. | ➢ Not usable for spread Spectrum signals.<br>➢ High computational cost. |

## 3.3 Cooperative Spectrum Sensing

Transmitter detection (non-cooperative detection) techniques depend on the fragile signals from the primary transmitters because of inadequacy between primary users and secondary users. The unlicensed transmitter cannot always be capable to sense the signal from a primary user due to its geological severance and channel fading. In figure 3.7, transmitter and receiver of the secondary user cannot reveal the signal from the transmitter of primary user because they are out of range. So, this problem is introduced as hidden node problem [62].

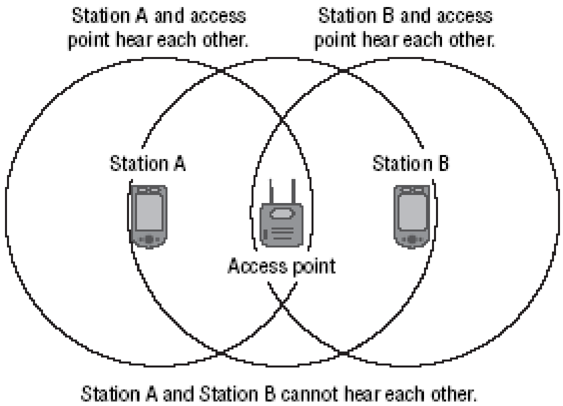



Figure 3.7 Hidden Node Problem

In this scenario, when the transmitter of unlicensed user transmits, it will interfere with the receiver of the licensed user.

Solution of this hidden node problem in non-cooperative spectrum sensing is cooperative sensing. In this type of sensing, information from several secondary users are interchanged along with each other to detect the presence of primary user. By utilizing cooperative spectrum sensing information the hidden node problem can be resolved and the detection probability can be considerably enhanced in a heavily shadowing atmosphere. Though, this acquires a larger communication and computation overhead compared with non-cooperative sensing. In cooperative sensing, there are two distinct networks, namely, a sensor network and an operational network can be organized to perform spectrum sensing and spectrum access, respectively [63].

**Pros**

- Plummeting sensitivity requirements
- Agility improvement

**Cons**

- Limited bandwidth
- Short timescales
- Large sensory data

**Table 3.2 Non-cooperative versus Cooperative Spectrum Sensing**

| Sensing Method | Advantages | Disadvantages |
|---|---|---|
| **Non-cooperative Sensing** | ➢ Computational and implementation Simplicity. | ➢ Hidden node problem.<br>➢ Multipath and shadowing. |
| **Cooperative Sensing** | ➢ Higher accuracy.<br>➢ Reduced sensing time.<br>➢ Shadowing effect and hidden node Problems can be prevented. | ➢ Complexity.<br>➢ Traffic overload.<br>➢ The need for a control channel. |

## 3.4 Interference based Sensing

In this type of sensing, algorithm will determine the interference level from all sources of signals at the receiver side of the primary user. This information is utilized by secondary user to control spectrum access without violating the interference temperature limit. On the other hand, secondary user transmitter may monitor the feedback signal from the primary user receiver to achieve knowledge on the interference level.

# CHAPTER 4

# PROPOSED WORK AND SIMULATION RESULTS

Now a days, wireless services have arrive a long way since the roll out of the voice-centric cellular systems. The requirement for wireless access in voice and high rate data multi-media applications has been rising. New generation wireless communication systems are aimed at accommodating this demand through better resource management and improved transmission technologies.

## 4.1 Hybrid Matched Filter

The hybrid model for matched filter [27] for non cooperative detection for IEEE 802.22 standard is the combination of orthogonal, parallel, and segmented matched filter. The traditional matched filter has benefit of short sensing time over other methods [64]-[66]. The only flaw of this method is low frequency offset tolerance in IEEE 802.22 standard. To solve this problem, a combination of orthogonal, parallel and segmented matched filter, namely, hybrid matched filter was proposed [27][67]-[69]. The important parameter of MFD (Matched Filter Detection) performance is sampling frequency $f_s$. The sensing time of MFD is $N / f_s$, where $N$ is total number of samples. The sensing time is reduced by over sampling and frequency offset tolerance can be improved.

The segmented matched filter [69] is used to reduce frequency offset sensitivity. In GPS receiver [70][71], Matched Filters in FIR (Finite Impulse Response) structure are transformed to FFT-IFFTs pairs to perform the synchronization function. Each matched filter matches an assured residual demodulate offset in parallel matched filter structure. This parallel MF structure [66] endures the large frequency offset without rising the sensing time but it increases the hardware complexity. To solve this problem segmented matched filter (SMF) [67][69] is proposed which is extensively used in GPS system. It can tolerate large frequency offset and reduces the hardware structure. The only drawback of this method is its sensing time. SMF increases the sensing time very greatly. In 802.22 standard, spectrum holes utilization decreases with this increasing sensing time. To overcome these problems HMF (Hybrid Matched Filter) is proposed [27].

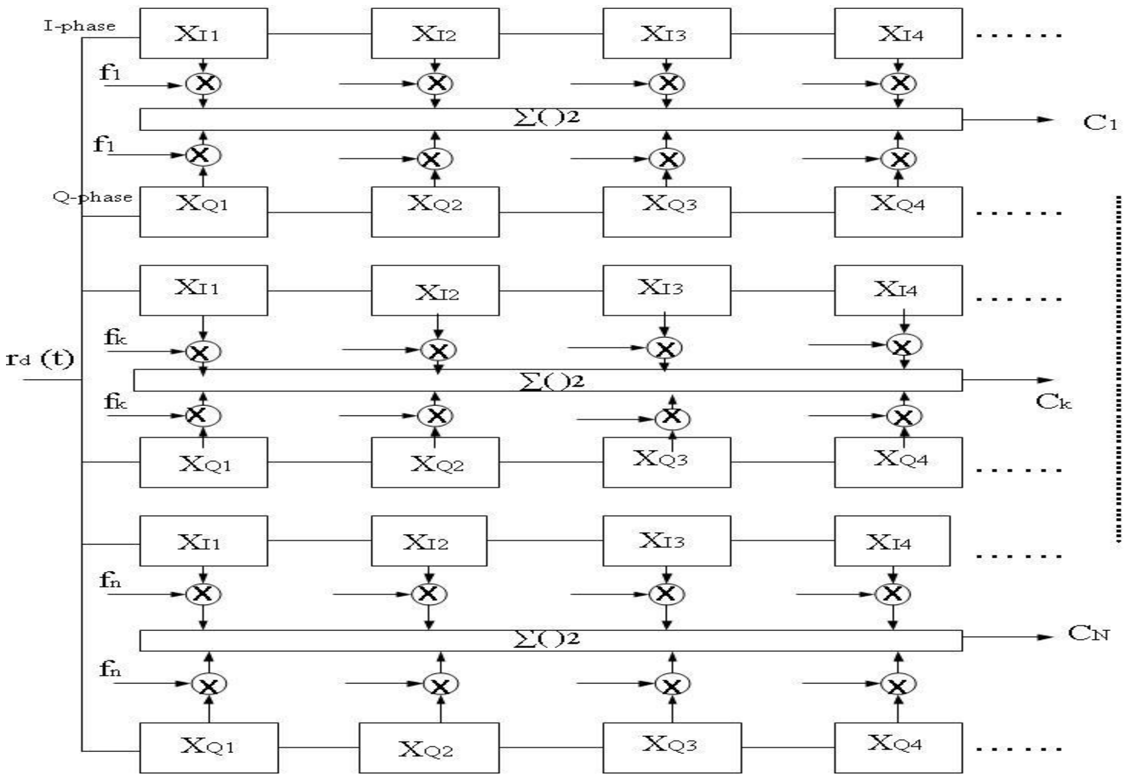



Figure 4.1 Structure of Hybrid Matched Filter detection

HMF is the combination of orthogonal, parallel and segmented matched filter where each parallel branch is demodulating the received signal at different residual offset frequency and consists of several segments. Furthermore, each segment is orthogonal matched filter. Therefore instead of performing sequential checks on different residual frequencies to identify the correct offset, each parallel branch performs parallel check at the same time which enhances the sensing time. If $f_{\min}$ is the minimum frequency offset tolerance of a matched filter then the desired frequency offset tolerance $f_{TO}$ is given by:

$$f_{To} = N_{seg} \times f_{\min} \tag{4.1}$$

Where $N_{seg}$ is the number of segments in one parallel branch of HMF.

Let $N$ be the number of samples of a transmitted waveform taken over one period during sampling. When the received signal is demodulated to baseband frequency and sampled at a certain frequency $f_s$, then the sensing time is given by $N / f_s$. The sampling frequency is given by:

$$f_s = N_{seg} \times N_s \qquad (4.2)$$

Where $N_s$ is the number of samples per segment.

Thus, increasing the sampling frequency has a twofold benefit. It increases the frequency offset tolerance because increasing the sampling frequency leads to increase in $N_{seg}$ which will increase $f_{TO}$ as can be seen from (4.1). The sensing time can also be improved by over sampling at the receiver by increasing the number of samples. Once the number of segments is fixed in order to acquire a desired frequency offset tolerance, then number of samples can be further increased by increasing the number of samples per segment. Thus, as a result of over sampling each segment further consists of certain number of samples. Therefore, HMF also results in reduced sensing time in low SNR scenarios along with high frequency offset tolerance by deploying different parallel branches each working on certain residual offset frequency.

## 4.2 Single Cycle Cyclostationary Detector

Cyclostationary feature detector determines the difference between noise and primary user signal by using its periodicity [72]-[74]. The periodicity is ingrained in pulse trains, transmitted signals are conjoined with sine wave carriers, spread codes, hopping sequences or cyclic prefixes. Autocorrelation function of the transmitted signal shows periodicity so these signals are distinguished as Cyclostationary. All of these features are identified by considering spectral correlation function. Noise energy can be differentiated from transmitted signal energy by using spectral correlation function. Cyclostationary feature detector performs better than energy detector in low SNR regions. The mathematical preliminary of Single Cycle Cyclostationary detection is based on the Gardner's work, of which full description is given in [75]. Gardner defines single-cycle cyclostationary detector in which magnitude-squared autocoherence (MSC) estimation is utilized as a metric to differentiate whether the signal is present or not. Thus, probability of detection and probability of false alarm is determined in noise-only (absence of primary user) scenario. The figure 4.2 shows the single cycle cyclostationary detector.

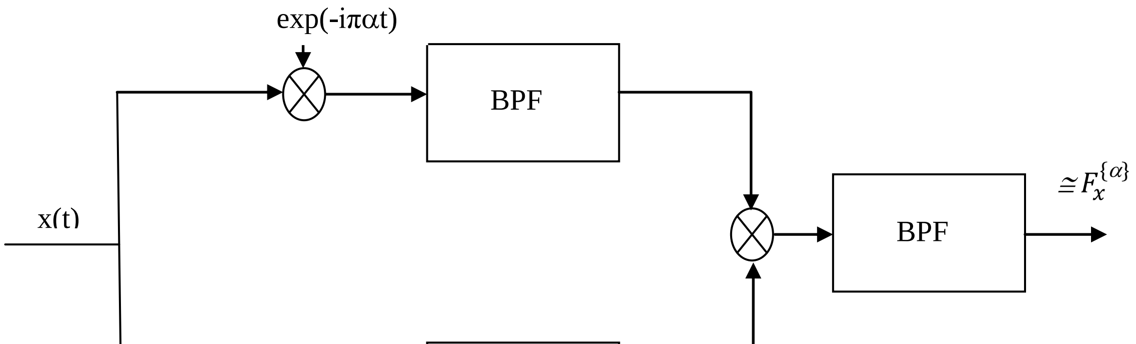


Figure 4.2 Single cycle Cyclostationary Feature Detector

Gardner's definition of cyclostationarity says that a signal is said to have cyclostationarity if the mean value of its second order delay product exhibits periodicity. The mean value of second order delay product is also called autocorrelation function. There are two approaches towards the cyclostationary analysis of a signal: Stochastic as well as non-stochastic approach. In this paper, our focus is on stochastic approach where the received signal is modeled as a stochastic process having several sample functions [76]-[80]. Therefore, the autocorrelation function is given by:

$$R_X(\tau) = \mathrm{E}[X(t)X(t+\tau)] \qquad (4.3)$$

Where, $\mathrm{E}[\cdot]$ is the expected value operator which is the mean value equivalent in probability space theory. Furthermore, $X(t)$ and $X(t+\tau)$ are the two random variables at time instants, $t$ and $(t+\tau)$.

Now, if the received signal exhibits cyclostationarity then the probability space autocorrelation function will be periodic in behavior. Since, it is known that any periodic function can be represented using Fourier series, therefore, the probability space autocorrelation function is given as:

$$R_X^{\{\alpha\}} = \sum_{n=-\infty}^{\infty} R_X^{\alpha} e^{jn\alpha t} = R_X(\tau) \qquad (4.4)$$

Where, $R_X^{\alpha}$ are the Fourier coefficients of individual components at different cyclic frequencies, $\alpha$.

Furthermore, these Fourier coefficients are equal to the CDFs (Cumulative Distribution Functions) evaluated at different sampling instants and hence we can re-write the above equation as:

$$F_X^{\{\alpha\}} = \sum_{n=-\infty}^{\infty} F_X^{\alpha} e^{jn\alpha t} = R_X^{\{\alpha\}} \qquad (4.5)$$

Where, $F_X^{\alpha}$ is a Cumulative Distribution Function which is defined as:

$$F_X^{\alpha} = Prob[X(t+\tau) < x] \qquad (4.6)$$

Therefore, probability space autocorrelation function can also be found out by evaluating Cumulative Distribution Function at every sample of a sampled signal. If this autocorrelation function is periodic or polyperiodic then it is called cyclic autocorrelation function and shows the presence of a signal.

## 4.3 Proposed Methodology

### 4.3.1 Combined Hybrid Matched Filter Single Cycle Cyclostationary Detector

Matched filter technique is a technique of spectrum sensing in Cognitive Radio (CR) which faces the challenge of very low frequency offset tolerance in very low SNR environments. HMF is used to improve the frequency offset tolerance. Primary user is eminently adaptable in low SNR than the multipath profile results in unknown phase of signal in low SNR region. This kind of signal is tough to recognize by Hybrid Matched Filter. To detect these weak signals we are proposing Combined Hybrid Matched Filter Single cycle Cyclostationary Detector.

This architecture increases the probability of detection as compared to the Hybrid Matched filter alone. By this architecture we have the advantage of high frequency offset tolerance and fine detection of signal in low SNR region. Simulation results show significant improvement in the probability of detection and false alarm of the proposed scheme over Hybrid Matched Filter.

The desired frequency offset tolerance of HMF (Hybrid matched filter) is given by equation (4.1). Therefore, total number of samples per parallel branch of HMF is given by:

$$f_s = N_{total} = N_s \times N_{seg} \tag{4.7}$$

Where, $N_{total}$ is the total number of samples per parallel branch of HMF.

$N_s$ is the number of samples per segment.

Now, assume that the transmitted signal is given by:

$$m(t) = c(t)\sqrt{2S}\cos(2\pi f_b t + \phi_M) \tag{4.8}$$

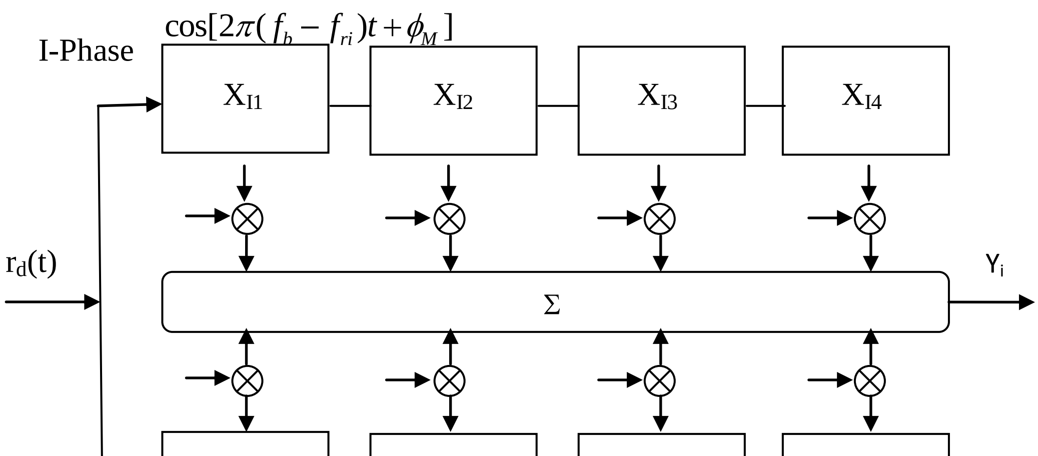
Where, $c(t)$ is the code word waveform which is modulated over one of the M-ary PSK waveform, $S$ is the signal power, $f_b$ is the baseband frequency, $\phi_m$ one of the values of M-ary phase. But because of channel impairments such as Doppler shift and Additive White Gaussian Noise (AWGN), the receiver will receive $m(t)$ in the form given below:

$$r(t) = c(t)\sqrt{2S}\cos(2\pi f_b t + \phi_M + \theta(t)) + n(t) \tag{4.9}$$

Where, $\theta(t)$ is a dynamic phase due to Doppler shift which is the function of time. $n(t)$ is the AWGN process. Therefore, the received signal can be represented as:

$$r(t) = c(t)\sqrt{2S}\cos(2\pi f_b t + \varphi(t)) + n(t) \tag{4.10}$$

Where, $\varphi(t) = \phi_M + \theta(t)$ and is the total dynamic phase shift. The received signal, $r(t)$ is then demodulated at different residual offset frequencies whose number is equal to the number of parallel branches in HMF structure, where each branch samples $r(t)$ into $N_{total}$ samples. The following demodulation process explained for a single branch will get replicated for all the branches-



$\sin[2\pi(f_b - f_{ri})t + \phi_M]$

Figure 4.3 Diagram of demodulation process of signal

Therefore, the demodulated received signal in branch $i$, $r_d^i(t)$ is given by:

$$r_d^i(t) = r(t)[\cos(2\pi(f_b - f_{ri})t + \phi_M) + j\sin(2\pi(f_b - f_{ri})t + \phi_M)] \quad (4.11)$$

Where, $f_{ri}$ is the residual offset frequency of branch $i$. Furthermore,

$$r_d^i(t) = [r_I^i(t) + n_I^i(t)] + j[r_Q^i(t) + n_Q^i(t)] \quad (4.12)$$

Where,

$r_I^i(t)$ is the I-phase component of the received demodulated signal,

$n_I^i(t)$ is I-phase component of the AWGN process,

$r_Q^i(t)$ is the Q-phase component of the received demodulated signal, and

$n_Q^i(t)$ is the Q-phase component of AWGN process.

The equation of $r_I^i(t)$ and $r_Q^i(t)$ can be elaborated as:

$$r_I^i(t) = c(t)\sqrt{2S}\cos[2\pi f_b t + \varphi(t)] \cdot \cos[2\pi(f_b - f_r)t + \phi_M] \quad (4.13)$$

$$r_Q^i(t) = c(t)\sqrt{2S}\cos[2\pi f_b t + \varphi(t)] \cdot \sin[2\pi(f_b - f_r)t + \phi_M] \quad (4.14)$$

Similarly, the I-phase and Q-phase components, $n_I^i(t)$ and $n_Q^i(t)$ respectively of AWGN process are given as:

$$n_I^i(t) = n(t)\cos[2\pi(f_b - f_r)t + \phi_m] \quad (4.15)$$

$$n_Q^i(t) = n(t)\sin[2\pi(f_b - f_r)t + \phi_m] \tag{4.16}$$

The received demodulated signal $r_d^i(t)$ is sampled at sampling instants of $T_s = 1/N_{total}$ which results in column vectors. Therefore,

$$r_d^i(T_s) = [r_I^i(T_s) + n_I^i(T_s)] + j[r_Q^i(T_s) + n_Q^i(T_s)] \tag{4.17}$$

Where, every element is a column vector. Furthermore,

$$r_d^i(T_s) = [X_I^i(t + nT_s)] + j[X_Q^i(t + nT_s)] \tag{4.18}$$

Where,

$X_I^i(t + nT_s)$ and $X_Q^i(t + nT_s)$ are the column vectors of Gaussian distributed random variables with mean as the corresponding elements of the column vectors $r_I^i(T_s)$ and $r_Q^i(T_s)$ respectively and the variance set according to specific SNR.

Then the magnitude squared values of the statistic to be observed is calculated for every branch $i$ as:

$$M_i = \sum_{n=1}^{N_{total}} [X_I^i(t + nT_s)]^2 + \sum_{n=1}^{N_{total}} [X_Q^i(t + nT_s)]^2 \tag{4.19}$$

This statistic results in a column vector as for every single cyclic shift of codeword by one sample, one element of $M_i$ will be produced. Therefore, $V$ will be two dimensional vector such that $V = [M_1 M_2 .............. M_B]$ where $B$ is the total number of parallel branches and $M_i$ is a column vector.

Therefore, after a complete cyclic shift at every branch, the output will be a row vector of normalized correlation coefficients, $C = [c_1 c_2 c_3 ......... c_B]$ calculated from individual columns of two dimensional vector $V$. Every element of $C$ is the correlation coefficient of the corresponding branch. Hence, the received demodulated signal of branch $j$ is selected for further processing if $c_j = \max\{c_i\}$ where $i \neq j$. Furthermore, the autocorrelation function, $R_j^{\{\alpha\}}(\tau)$ of received demodulated signal of branch $j$ is given by:

$$R_j^{\{\alpha\}}(\tau) = F_{jI}^{\{\alpha\}}[N(\mu_{jI,}\sigma_{jI}^2)] + iF_{jQ}^{\{\alpha\}}[N(\mu_{jQ,}\sigma_{jQ}^2)] \tag{4.20}$$

Where, $F_{jI}^{\{\alpha\}}$ is the Cumulative Distribution Function evaluated for the Normal Distribution $N(\mu_{jI,}\sigma_{jI}^2)$ and $F_{jQ}^{\{\alpha\}}$ is the Cumulative Distribution Function evaluated for the Normal Distribution $N(\mu_{jQ,}\sigma_{jQ}^2)$. The $\{\alpha\}$ in the suffix shows that it is a set which can consist of one cyclic frequency or multiple cyclic frequencies. If it consists of only one cyclic frequency as zero then primary user signal is not present. If it consists of only one cyclic frequency then primary user signal is present and cyclostationary otherwise polycyclostationary.

The degree of similarity between transmitted signal and received signal is further determined by computing magnitude squared autocoherence value, $MSAC_j$ which is given by:

$$MSAC_j = \frac{|M(f)|^2}{\left|R_j^{\{\alpha\}}(f - \frac{\alpha}{2})\right|\left|R_j^{\{\alpha\}}(f + \frac{\alpha}{2})\right|} \tag{4.21}$$

Where, $M(f)$ is the power spectral density of the transmitted signal. In order to perform hypothesis test on $MSAC_j$, the probability distribution followed by these values is to be determined by performing Monte Carlo simulation for large number of times. Hypothesis test is further performed on that distribution with null hypothesis stating that only noise is present, whereas alternative hypothesis stating that primary user signal is present with a specific level of significance.

## 4.4 Simulation Results for Hybrid Matched Filter Detection

**Table 4.1 Simulation results for Hybrid Matched Filter Detector**

| Signal to Noise Ratio (SNR) | -25 db | -20 db | -15 db | -10 db | - 5 db |
|---|---|---|---|---|---|
| **Probability of Detection ( $P_d$ )** | 0.4747 | 0.5111 | 0.5652 | 0.50 | 0.6452 |
| **Probability of false alarm ( $P_{fa}$ )** | 0.5253 | 0.4889 | 0.4348 | 0.50 | 0.3548 |

Two sets of simulations have been performed for the case of HMF. For the first scenario, the frequency offset is set to 500 Hz and for the second one the value of offset has been set to 449 Hz which is the value selected in [27]. The results shown in Table 4.1 are for the case when frequency offset is set to 500 Hz.

As the frequency offset in the received signal will increase, for a fixed number of parallel branches, the local oscillator at the receiver will find it more difficult to synchronize its residual offset frequency with the introduced frequency offset in the received signal. Therefore, the increasing frequency offset has a negative impact on the probability of detection and hence probability of false alarm.

**Probability of detection**

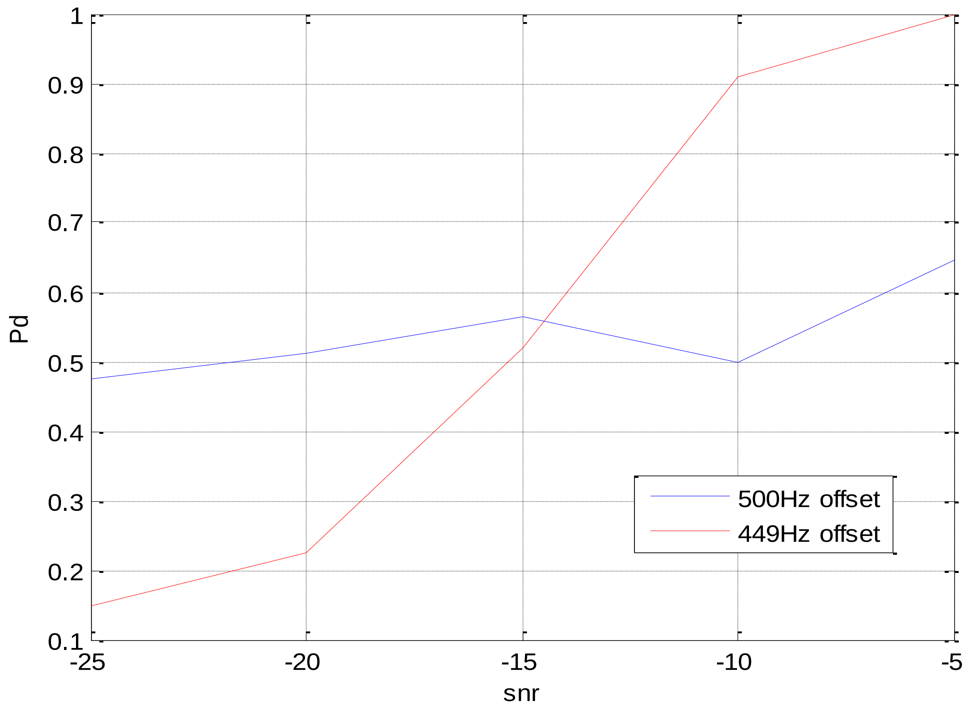



Figure 4.4 Probability of detection for Hybrid Matched Filter

This trend in the degradation of performance in terms of probability of detection as well as false alarm can be observed from Figure 4.4 as well as Figure 4.5. It can be observed from figure 4.4 that the probability of detection shows heavy degradation when the frequency offset is 500 Hz relative to the frequency offset of 449 Hz. Figure 4.5 shows the probability of false alarm when frequency offset was set to 500 Hz.

**Probability of false alarm**

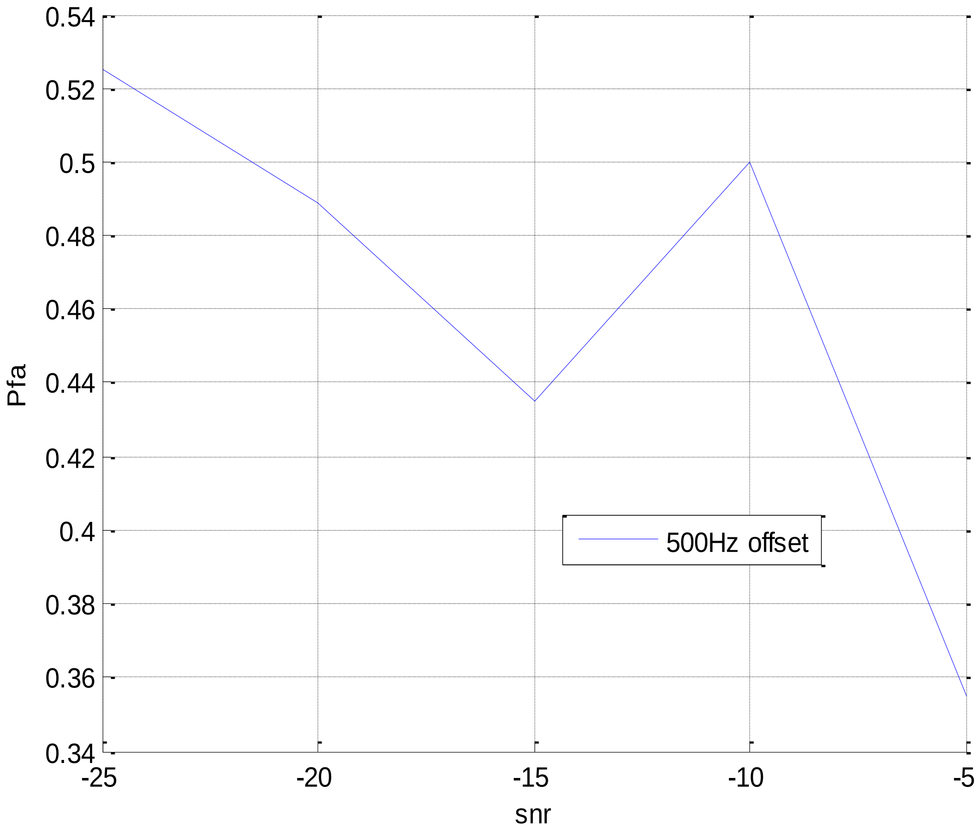



Figure 4.5 Probability of false alarm for Hybrid Matched Filter

## 4.5 Simulation Results for Combined Hybrid Matched Filter Detection Single Cycle Cyclostationary Feature Detector

A set of extensive simulations have been performed for both HMF (Hybrid Matched Filter) and the proposed scheme on Matlab. The performance is evaluated in terms of probability of detection and probability of false alarm. The prominence is to evaluate the comparative performance of HMF and the proposed scheme. In the performed simulations, the number of samples per segment has been set to four.

To determine the distribution followed by magnitude squared autocoherence value, an extensive set of Monte Carlo simulations for different values of SNR have been performed for 1000 iterations and it came out to be log-normal distribution for the case when primary user signal is present.

During the actual simulations, each computed value of magnitude squared autocoherence have been put through hypothesis test on the log-normal distribution of generated magnitude squared autocoherence values at a significance level of 0.15. The null hypothesis in the test is the absence of signal whereas the alternative hypothesis is the presence of the signal. Table 4.2 shows the results for probability of detection and probability of false alarm through Matlab simulations at different SNR

**Table 4.2 Simulation Results for Combined Hybrid Matched Filter Detector Single Cycle Cyclostationary Detector**

| **Signal to Noise Ratio (SNR)** | -25 db | -20 db | -15 db | -10 db | - 5 db |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **Probability of Detection (** $P_d$ **)** | 0.6078 | 0.7413 | 0.8032 | 0.8000 | 0.8679 |
| **Probability of false alarm (** $P_{fa}$ **)** | 0.2000 | 0.1500 | 0.1200 | 0.1100 | 0.0700 |

The figure 4.6 demonstrates higher probability of detection of the proposed scheme in comparison to the HMF. This is because the algorithm selects the highest value of correlation coefficient from all the corresponding correlation values of individual branch. This highest value is the indicator that the residual offset frequency of the corresponding branch used in demodulating the signal finds perfect correlation with the Doppler phase shifted received signal due to multipath profile. This provides the coarse detection that some signal has been detected whose phase shift actually correlates well with one of the residual offset frequencies.

**Probability of detection**

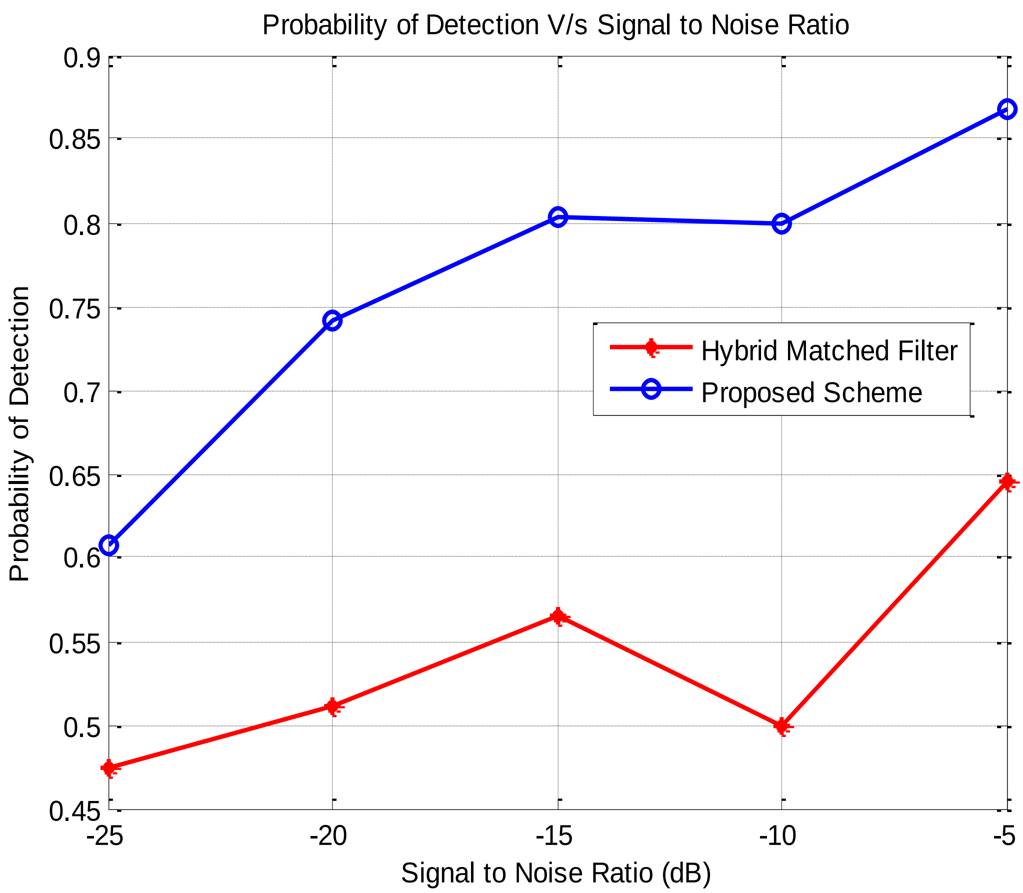



Figure 4.6 Probability of detection for Combined Hybrid Matched Filter Single cycle Cyclostationary Detection

Then the demodulated signal using that residual offset frequency is sent to the cascaded stage of processing where it becomes further processed using single cycle Cyclostationary Feature Detector. Therefore, due to this cascaded stage of Cyclostationary Feature Detector, the course detection becomes finer; hence there is little chance of being a miss detection.

**Probability of false alarm**

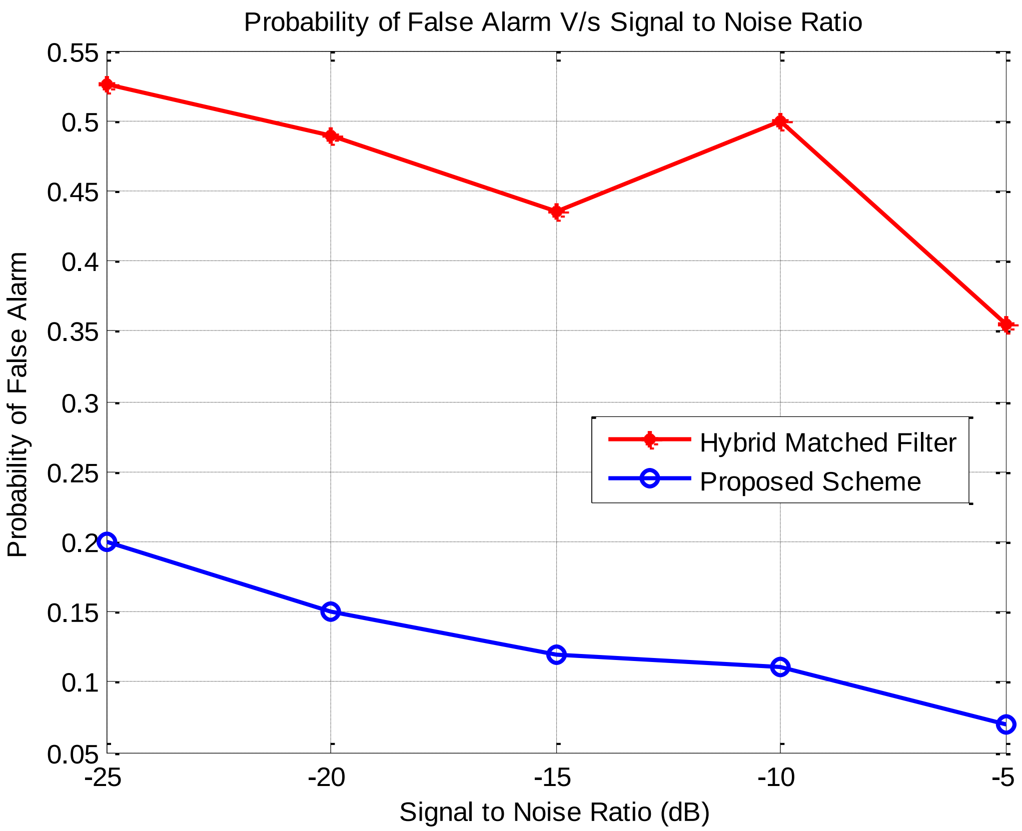



Figure 4.7 Probability of false alarm for Combined Hybrid Matched Filter single cycle Cyclostationary Detection

Since, the probability of detection increases therefore, the probability of false alarm reduces. Figure 4.7 depicts the same trend in the probability of false alarm for the proposed scheme as well as HMF. The probability of false alarm for proposed scheme is much less than that of HMF.

# CHAPTER 5

# CONCLUSION AND FUTURE SCOPE

## 5.1 Conclusion

In this thesis, center of attention was on exploration of matched filter detection technique in the form of hybrid match filter and single cycle cyclostationary detector in cognitive radios. The characteristics of the first cognitive radio standard IEEE 802.22 (WRAN) has also been deliberated.

The foremost contribution of the thesis was to first implement hybrid matched filter and second combining this hybrid matched filter with single cycle cyclostationary detector which was then put to test for the detection of WRAN primary user signal in different conditions.

Simulation results indicate that combined hybrid matched filter single cycle cyclostationary detector performs better than the hybrid matched filter to overcome the flaw of low frequency offset tolerance in low SNR region. The primary users are highly mobile in low SNR region, so the multipath profile results in unknown phase of signal. Such kind of signal is even harder to detect for hybrid matched filter. By combining Hybrid Matched Filter Single Cycle Cyclostationary detector, the probability of detection of such kind of architecture gets enhanced. This results in both high frequency offset tolerance as well as fine detection of signal with unknown phase in very low SNR environments.

The Matlab simulation outcomes show significant improvement in the probability of detection and false alarm of the proposed scheme over Hybrid Matched Filter. The results verify the effectiveness of proposed scheme. This is because the algorithm selects the highest value of correlation coefficient from all the corresponding correlation values of individual branch. This highest value is the indicator that the residual offset frequency of the corresponding branch used in demodulating the signal finds perfect correlation with the Doppler phase shifted received signal due to multipath profile. This provides the coarse detection that some signal has been detected whose phase shift actually correlates well with one of the residual offset frequencies. Then the demodulated signal using that residual offset frequency is sent to the cascaded stage of processing where it becomes further processed using single cycle Cyclostationary Feature Detector. Therefore, due to this cascaded stage of Cyclostationary Feature Detector, the course detection becomes more fine, hence there is little chance of being a miss detection.

## 5.2 Future Scope

Simulation results depict significant improvement in the probability of detection and probability of false alarm in case of proposed scheme over HMF. Hence, the proposed scheme clearly outperforms HMF in terms of both metrics. Some recommendations for future work proposals can be:

- The proposed scheme incurs significant overhead in terms of execution time involved in the signal processing related to cascaded stages. Therefore, it would be interesting to reduce the execution time of the proposed scheme.

- Since, in the proposed work only two hypotheses are applied but it would be interesting to see the effect of using multiple hypotheses for numerous different random phase shifts in the received signal due to multipath fading. Therefore, multiple hypotheses test can be used.

- It would be interesting to design a pipelined application specific processor with its own instruction set architecture. The instruction set architecture should be designed in such a way that it achieves drastic speed up of arithmetic operations involved in the signal processing operations of such kind of complex algorithms.

- Since, all the processing in the proposed work is happening in the baseband domain so it would be interesting to see the effectiveness of this work to different domains of speech processing such speech recognition etc.

# REFERENCES


1. Federal Communication Commission, "Spectrum Policy Task force report", ET Docket No. 02-135, Nov. 2002.

2. Federal Communications Commission (FCC), "FCC 03-322," 2003.

3. Federal Communications Commission, "Notice of proposed rulemaking and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies," ET Docket No. 03-108, Feb. 2005.

4. Mitola, J. and J. Maguire, G. Q., "Cognitive radio: making software radios more personal." IEEE Personal Commun. Mag., vol. 6, no. 4, Aug. 1999, pp. 13–18.

5. J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in Proc. IEEE Int. Workshop Mobile Multimedia Communications, 1999, pp. 3–10.

6. S. Haykin, "Cognitive radio: brain-empowered wireless communications," "IEEE J. Select. Areas Commun." vol. 23, no. 2, 2005, pp. 201–220.

7. Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, "NeXt generation/dynamic spectrum access/ cognitive radio wireless networks: A survey", Computer Networks 50(2006), p2127-2159(2006).

8. DARPA ATO, Next Generation Program, http: // www .darpa.mil/ sto/ small unit ops/ xg.html.

9. International Telecommunication Union Recommendations, http://www.itu.int.

10. Wireless World Research Forum, "Cognitive Wireless Networks and Systems: Charter," http://www.wirelessworldresearch.Org.

11. Wireless World Research Forum, "Cognitive radio and management of spectrum and radio resources in reconfigurable networks," WWRF Working Group 6 White Paper, 2005.

12. J. Mitola III, "Software radio architecture: A mathematical perspective", IEEE J. Sel. Areas Commun., 1999.

13. H. Harada, "Software Defined Radio Prototype toward Cognitive Radio Communication Systems," IEEE Dyspan 2005, vol. 1, pp.539-547, Nov. 2005.

14. Tabassam, A.A.; Ali, F.A.; Kalsait, S.; Suleman, M.U. "Building Software-Defined Radios in MATLAB Simulink - A Step Towards Cognitive Radios", Computer Modeling and Simulation (UKSim), 2011 UkSim 13th International Conference on, On page(s): 492 – 497.

15. S. Kapoor, S. Rao, and G. Singh, "Opportunistic spectrum sensing by employing matched filter in cognitive radio network," in Communication Systems and Network Technologies (CSNT), 2011 International Conference on, june 2011, pp. 580 -583.

16. B. Skalar, "Digital Communications: Fundamentals and Applications" (2nd Edition) (Prentice Hall Communications Engineering and Emerging Technologies Series).

17. Proakis, J.G., 2001 Digital Communications, United States: McGraw Hill.

18. P. Pawelczak, K. Nolan, L. Doyle, S.W. Oh, and D. Cabric, "Cognitive radio: Ten years of experimentation and development," Communications Magazine, IEEE, vol. 49, no. 3, pp. 90-100, Mar 2011.

19. M. Gandetto and C. Regazzoni, "Spectrum sensing: A distributed approach for cognitive terminals," IEEE J. Select. Areas Commun. vol. 25, no. 3, pp. 546–557, Apr. 2007.

20. Hoyhtya, M., A. Hekkala, M. Katz, and A. Mammela, "Spectrum Awareness: Techniques and Challenges for Active Spectrum Sensing Cognitive Radio" Wireless Networks: 353-372, 2007.

21. I. F. Akyildiz et al., "A Survey on Spectrum Management in Cognitive Radio Networks," IEEE Commun. Mag., vol. 46, no. 4, Apr. 2008, pp. 40–48.

22. Prabhjot Kaur, Moin Uddin, and Arun Khosla, "Cognitive Radios: Need, Capabilities, Standards, Applications and Research Challenges", International Journal of Computer Applications (0975-8887), Vol 30, September 2011.

23. Ekram Hossain, D Niyato, and Zhu Han, "Dynamic spectrum access and management in cognitive radio networks", Cambridge University Press, New York, USA, 2009.

24. Ekram Hossain and Vijay Bhargava, "Cognitive Wireless Communication Networks", New York: Springer, 2007.

25. Nolan, K. E., Rondeau T.W., Sutton, P.D., Bostian, C. W., Doyle, L.E., "A Framework For Implementing Cognitive Functionality", in Proceedings of the 51st SDR Forum General Meeting and 2006 Technical Conference, Nov. 13- 17, 2006, Orlando, Florida

26. 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.

27. Zhang Z, Yang Q, Wang L, Zhou X (2010), "A novel hybrid matched filter structure for IEEE 802.22 standard". Circuit Syst (APCCAS), IEEE Asia Pacific conference, 2010, pp 652–655.

28. 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.

29. Doyle, L.E., Nolan, K.E., Forde T.K. et al., " A Platform for Dynamic Spectrum Experimentation", in Proceedings of the 1st International workshop on Technology and Policy for Accessing Spectrum (TAPAS), Boston, August 1-5 2006.

30. S. Geirhofer, L. Tong, and B. Sadler, "Dynamic spectrum access in the time domain: Modeling and exploiting white space," IEEE Commun.Mag., vol. 45, no. 5, pp. 66–72, May 2007.

31. Cordeiro, C., Ghosh, M., "Spectrum Sensing for Dynamic Spectrum Access of TV Bands", CROWNCOM 2007, p225-233, Aug, 2007.

32. D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in Proc. Asilomar Conference on Signal, Systems and Computers, Nov. 2004.

33. S. Kapoor and G Singh, "Non cooperative spectrum sensing: a hybrid model approach", Proc. Int. Conf. on Devices and Communications (ICDeCom-11), 24-25 Feb. 2011, India, pp. 1-5.

34. Parikshit Karnik and Sagar Dumbre, 2004. “Transmitter Detection Techniques for Spectrum Sensing in CR Networks", Department of Electrical and Computer Engineering Georgia Institute of Technology.

35. Bodepudi Mounika, Kolli Ravi Chandra, Rayala Ravi Kumar, “Spectrum Sensing Techniques and Issues in Cognitive Radio” (IJETT) - Volume4Issue4- April 2013.

36. Sajjad Ahmad Ghauri “Spectrum Sensing For Cognitive Radio Networks Over Fading Channels” International Journal of Computer and Electronics Research [Volume 2, Issue 1, February 2013.

37. 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.

38. Ashutosh Singh and Varsha Saxena,"Different Spectrum sensing Techniques used in non cooperative sensing" International Journal of Engineering and Innovative Technology (IJEIT), Vol 1, Issue 2, February 2012.

39. Stephen J. Shell hammer, "SPECTRUM SENSING IN IEEE 802.22," In Proceedings of 2008 IAPR Workshop on Cognitive Information Processing, 2008.

40. "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.

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

42. Mr. Pradeep Kumar Verma1, Mr. Sachin Taluja2, Prof. RajeshwarLal Dua3 “Performance analysis of Energy Detection, Matched filter detection & Cyclostationary feature detection Spectrum Sensing Techniques” jceronline.com) Vol. 2 Issue. 5,2012.

43. Zhai Xuping, Pan Jianguo, “Energy-detection based spectrum sensing for cognitive radio,” IET Conference on Wireless, Mobile and Sensor Networks, 2007, pp. 944-947, 2007.

44. Steven M. Kay, “Fundamentals of statistical signal processing: Detection theory”, Prentice Hall PTR, 1998, vol. 2, Publishing House of Electronics Industry, Beijing, 2003, translated edition.

45. Gerald C., Danijela C., “Sensing Threshold”, doc.: IEEE 802.22-06/0051r8, July 2006.

46. F.F. Digham, M.S. Alouini and M.K. Simon, “Energy Detection of unknown signals over fading channels”, IEEE Transactions on Communications, Vol. 5, No.1, pp. 21-24, 2007

47. A. Papoulis, Probability, Random Variables and Stochastic Processes, New York: McGraw-Hill 1991.

48. R. Tandra and A. Sahai, (2005), “Fundamental limits on detection in low SNR under noise uncertainty,” in Proc. IEEE Int. Conf. Wireless Networks, Commun And Mobile Computing, vol. 1, Maui, HI, June , pp: 464–469.

49. H. Liu, D. Yu, and X. Kong, “A new approach to improve signal classification in low snr environment in spectrum sensing,” Cognitive Radio Oriented Wireless Networks and Communications, Crown Com, pp. 1–5, May. 2008.

50. D. Cabric, “Addressing feasibility of cognitive radios,” IEEE Signal Process. Mag., vol. 25, no. 6, pp. 85–93, Nov. 2008.

51. Fano, R. M., “On Matched-Filter Detection in the Presence of Multipath Propagation,” unpublished paper, M. I. T.,Cambridge, Mass.; 1956.

52. Lvtle, D. W., “On the Properties of Matched Filters,” Stanford Electronics Labs. Stanord Univ., Stanford, Calif., Tech. Rept.17 June 10, 1957.

53. Lerner, R. M., “A matched filter detection system for Doppler shifted signals,” this issue, p. 373.

54. G.L. Turin, “An introduction to matched filters,” IRE Trans. Inform. Theory, vol. IT-6, no. 3, pp. 311–329, Jun. 1960.

55. J.C Bancroft, ‘Introduction to matched filters’, CREWES Research report, vol. 14, 2002.

56. Kim, K., I.A. Akbar, K.K. Bae, J. Um, C.M. Spooner, and H.J. Reed, “Cyclostationary Approaches to Signal Detection and Classification in Cognitive Radio”, 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks: 7: 212-215, 2007.

57. Ye,Z., J. Grosspietsch and G. Memik, “Spectrum Sensing using Cyclostationary Spectrum Density for Cognitive Radios”, IEEE Workshop on Signal Processing Systems: 1-6, 2007.

58. Chen, J., A. Gibson, and J. Zafar, "Cyclostationary Spectrum Detection in Cognitive Radios". IET Seminar on Cognitive Radio and Software Defined Radios: Technologies and Techniques 8: 1-5, 2008.

59. Tengyiz, Y. and G. Chi., “Performance of Cyclostationary Feature Based Spectrum Sensing Method in a Multiple Antenna Cognitive Radio System”, Wireless Communications and Networking Conference WCNC 200 9, pp. 1 – 5, 2009.

60. 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.

61. Ning Han, SungHwan Shon, Jae Hak Chung, Jae Moung Kim, “Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems”, ICACT 2006, p1770-p1776, Feb. 2006.

62. Ian F. Akyildiz, Brandon F. Lo, and Ravi kumar Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey," Physical Communication, vol.4,no.1,pp.4062,2011.[Online].http://www.sciencedirect.com/science/article/pii/S187449071000039X.

63. S. Mishra, A. Sahai, and R. Brodersen, “Cooperative sensing among cognitive radios,” in Proc. IEEE Int. Conf. Commun., vol. 2, Istanbul,Turkey, May 2006, pp. 1658–1663.

64. D.L. Noneaker, “The performance of serial, matched-filter acquisition in direct sequence packet radio communications,” in Proc. IEEE Military Commun. Conf., McLean, VA, Oct. 2001, pp. 1045–1049.

65. A. Swaminathan, D. L. Noneaker, “A technique to improve the performance of serial, matched-filter acquisition in direct-sequence spread-spectrum packet radio communications,” IEEE J. on Selected Areas in Commun., Volume 23, Issue 5, May 2005 pp. 909 – 919.

66. Tsugawara T.and Miyanaga Y. "A design of parallel matched filter with low calculation cost" Advanced System Integrated Circuits 2004. Proceedings of 2004 IEEE Asia-Pacific Conference on 4-5 Aug. 2004 Page(s):410-411.

67. D.Dodds, R.Mason, R.Schmitz, A.Dinh, and R.Bolton, “A Segmented Matched Filter for CDMA Codephase Acquisition,” inCanadian Conference on Electrical and Computer Engineering, May 1998, pp. 253–256.

68. Rahaman, M.S., Dodds, D.E., “Throughput and PN Code phase Acquisition for Packet CDMA without Preamble”, Electrical and Computer Engineering, 2008, p1179-1182, May. 2008.

69. B. Persson, D.E. Dodds, and R.J. Bolton, “A Segmented Matched Filter for CDMA Code Synchronization in Systems with Doppler Frequency Offset” Proceedings IEEE Globecom, San Antonio, Texas, Nov 2001, Session BWS07-1.

70. Sagiraju, P.K., Agaian, S., Akopian, D., “Reduced complexity acquisition of GPS signals for software embedded applications”, Radar, Sonar and Navigation, vol. 153, p69-78, Feb. 2006.

71. M.S.Braasch and A.J.van Dierendonck,"GPS receiver architectures and measurements", Proceedings of IEEE, vol.87, no. 1, 1999, pp.48-64.

72. S. Enserink and D. Cochran, “A cyclostationary feature detector,” in Proc. 28th Asilomar Conf. Signals, Systems, Computers, pp. 806-810, October, 1994. Article (Cross Ref Link).

73. 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.

74. H.-S. Chen, W. Gao, and D. G. Daut, "Spectrum sensing using cyclostationary properties and application to IEEE 802.22 WRAN," Proc. Of Global Telecommunications Conference, pp. 3133–3138, Nov. 2007.

75. W.A. Gardner, "Exploitation of spectral redundancy in cyclostationary signals," IEEE Signal Processing Magazine, vol. 8, no. 2, pp. 14-36, April 1991.

76. Gardner, W.A., A. Napolitanob, and L. Paurac, "Cyclostationarity: Half a century of research Elsevier Signal", Processing 86: 639-697, 2006.

77. Y. Lin and C. He, "Subsection-average cyclostationary feature detection in cognitive radio," Neural Networks and Signal Processing, pp. 604– 608, Jun. 2008.

78. K. W. Choi, W. S. Jeon, and D. G. Jeong, "Sequential detection of cyclostationary signal for cognitive radio systems," IEEE Trans. Wireless Commun., vol. 8, no. 9, pp. 4480–4485, Sep. 2009.

79. G. C. Carter, C. H. Knapp, and A. H. Nutall, "Estimation of the magnitude-squared coherence function via overlapped fast fourier transform processing," IEEE Trans. on Audio and Electroacoustics, vol. AU-21, no. 4, pp. 337–344, Aug. 1973.

80. H. Gish and D. Cochran, "Invariance of the magnitude-squared coherence estimate with respect to second-channel statistics," IEEE Trans. On Acoustics, Speech and Sig. Proc., vol. ASSP-35, no. 12, pp. 1774–1776,Dec. 1987.

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