EAST WEST UNIVERSITY

APE 598

RESEARCH PROJECT

ON

SPECTRUM SENSING OF COGNITIVE RADIO NETWORK UNDER LINEAR COMBINATION OF GAUSSIAN RANDOM VARIABLES

Submitted to the Department of Electronics and Communications Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Applied Physics and Electronics

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Declaration

We hereby declare that we have completed project on the topic entitled *"Spectrum Sensing of Cognitive Radio Network Under Linear Combination of Gaussian Random Variables"* as well as prepared a research report to the department of Electronics and Communications Engineering in partial fulfillment of the requirement for the degree of Masters in Applied Physics and Electronics, under the course 'APE 598'.

We further assert that the work presented in this report is our own except where due reference or acknowledgment is presented as to the work of others.

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The research project report “*Spectrum Sensing of Cognitive Radio Network Under Linear Combination of Gaussian Random Variables*” submitted by John D’ Costa (SID# 2013-3-89-001) and Muhammad Nazimuzzaman (SID# 2014-2-89-003) to the Department of Electronics and Communications Engineering, East West University, has been accepted as satisfactory for the partial fulfillment of the requirements for the degree of Masters in Applied Physics and Electronics as approved as to its style and contents.

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Abstract

In this project work we studied the Spectrum Sensing techniques for Cognitive Radio (CR) and derived Probability of Detection (P_D) and Probability of False Alarm (P_F) of a Cognitive Radio Network (CRN). Here we considered the test statistics as the weighted sum of the Gaussian random variables where the weighting factor depends on the eigenvalues of covariance matrix of Multiple-Input-Multiple-Output (MIMO) channel with Additive White Gaussian Noise (AWGN). We calculated P_D and P_F by changing channel parameters like number of sample values to find the threshold Signal-to-Noise Ratio (SNR) within condition P_D above 80% and P_F less than 8%.

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Chapter-1

Introduction

Today’s wireless networks are characterized by fixed spectrum assignment policy. The wide expansion of wireless communications unavoidably leads to the scarcity of frequency spectra. On one hand, it has become increasingly difficult to find available frequency bands for wireless users. On the other hand, many pre-allocated frequency bands are ironically under-utilized and thus the valuable resources are being wasted.

Regulatory bodies in the world such as the Federal Communications Commission (FCC) in the United States and ‘Ofcom’ in the United Kingdom as well as different independent measurement campaigns found that most radio frequency spectrum was inefficiently utilized [2]. Cellular network bands are overloaded in most parts of the world, but other frequency bands such as military, amateur radio and paging frequencies are insufficiently utilized. Independent studies performed in some countries confirmed that observation, and concluded that spectrum utilization depends on time and place. Moreover, fixed spectrum allocation prevents rarely used frequencies (those assigned to specific services) from being used, even when any unlicensed users would not cause noticeable interference to the assigned service. Regulatory bodies in the world have been considering whether to allow unlicensed users in licensed bands if they would not cause any interference to licensed users. These initiatives have focused Cognitive Radio (CR) research on dynamic spectrum access.

Based on a report in 2002, FCC decided to make a paradigm shift by allowing more and more number of unlicensed users to transmit their signals in licensed bands so as to efficiently utilize the available spectrum. The motivating factor behind this decision was the findings in a report by Spectrum Policy Task Force, in which vast temporal and geographic variations in spectrum usage were found ranging from 15% to 85% [2]. FCC was now open to new approaches for efficient spectrum sharing techniques with unlicensed users. One of the solutions is the introduction of cognitive radio, which was proposed in the last decade to address this dilemma. By using the technologies that are available today, it is possible to develop a radio that is able to analyze the spectrum, detect which frequencies are clear and then implement the best form of communication for the required conditions.

Cognitive radio is a concept derived from the need of higher data rate and efficient utilization of licensed spectrum [3]. It is widely defined as *an* adaptive, intelligent radio and network technology that can automatically detect available channels in a wireless spectrum and change transmission parameters enabling more communications to run concurrently and also improve radio operating behavior [4]. Its objective is to enrich the efficient utilization of electromagnetic radio spectrum by empowering Dynamic Spectrum Access (DSA) for the current and next-generation wireless communication technology [5]. The technique is simply to sense the inactive licensed bands and temporarily use them for data transmission. To achieve this goal different detection methods are used to detect the presence of Primary User (PU) signal in the channel or sub channel such as matched filtering [6, 7], energy detection [8], cyclostationary feature detection [9], stochastic process technique etc.

Of these, matched filter detection (also referred to as coherent detector) is better than energy detection as it starts working at lower SNR [10]. Additionally, a complete system is described to determine the threshold of the matched filter to obtain stricter requirements of the probability of detection and probability of false alarm. The matched filter detector that can be used for CRNs has been first proposed in [11]. It is known as the optimum method for detection of PUs when the transmitted signal is known. It is very accurate since it maximizes the received SNR. Matched filter correlates the signal with time shifted version and compares between the final output of matched filter and predetermined threshold to decide the PU presence or absence. However, matched-filtering requires CR to demodulate received signals. Hence, it requires perfect knowledge of the PU’s signaling features such as bandwidth, operating frequency, modulation type and order, pulse shaping, and frame format [11, 12].

Wireless communication using MIMO systems enables increased spectral efficiency for a given total transmit power [13]. Increased capacity is achieved by introducing additional spatial channels that are exploited by using space-time coding. MIMO systems provide a number of advantages over single-antenna-to-single-antenna communication. Sensitivity to fading is reduced by the spatial diversity provided by multiple spatial paths. Under certain environmental conditions, the power requirements associated with high spectral-efficiency communication can be significantly reduced by avoiding the compressive region of the information-theoretic capacity bound.

In our work we explored the spectrum sensing capabilities of cognitive radio network using matched filter technique for Gaussian MIMO channel by calculating Probability of Detection and Probability of False Alarm.

The project report is organized as follows:

- **Chapter 2** provides the concept of Cognitive Radio Network and introduces basic traffic parameters of the network
- **Chapter 3** discusses about the concept of Spectrum Sensing and different techniques as well as their characteristics
- **Chapter 4** describes the system model for the analysis of Gaussian channel and provides analytical condition for the optimal detector.
- **Chapter 5** provides the mathematical analysis of spectrum sensing of secondary user under linear combination of Gaussian random variables provides the results based on previous analytical modes.
- Finally we conclude our project report with a brief discussion about future work.

Chapter-2

Basic Concepts of Cognitive Radio Network

2.1 Cognitive Radio

The idea for cognitive radio has come out of the need to utilize the radio spectrum more efficiently and to be able to maintain the most efficient form of communication for the prevailing conditions. The concept was first proposed by Joseph Mitola III in a seminar at the Royal Institute of Technology in Stockholm in 1998 and published in an article by Mitola and Gerald Q. Maguire, Jr. in 1999 [14]. There are a variety of different views of what exactly what a cognitive radio may be. Few widely acclaimed definitions are mentioned below:

The standard FCC definition defines cognitive radio as: [15]

“A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.”

Another standard definition of cognitive radio is provided by renowned scientist Simon Haykin in his 2005 IEEE publication [16]. It explained:

Cognitive radio is 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*

We can define CR in a simplified way as an intelligent wireless communication technology which can utilize wireless spectrum resource efficiently and improve communication system performance notably. It’s a wireless communication in which the transmission and reception parameters are changed to communicate efficiently without interfering the licensed users. Parameters changes are based on the active monitoring of several factors in the radio environment.

From above definitions we can stand out some key characteristics for CR such as: *awareness, intelligence, learning, adaptivity, reliability,* and *efficiency*. Current advancement of wireless technologies such as digital signal processing, networking, machine learning, computer software, and computer hardware provides capability to implement these combinations of key features of cognitive radio.

2.2 Basic Cognitive Cycle

Basically cognitive radio looks to signal-processing and machine-learning procedures for their implementation. The cognitive process starts with the passive *sensing of RF stimuli* and culminates with *action*.

The cognitive task can be categorized as follows:

1) Radio-scene analysis:
    - Estimation of interference temperature of the radio environment
    - Detection of spectrum holes
2) Channel identification:
    - Estimation of Channel-State Information (CSI)
    - Prediction of channel capacity for use by the transmitter
3) Transmit-power control and dynamic spectrum management

Tasks 1 and 2 are carried out in the receiver end and task 3 is carried out in the transmitter end. These three tasks form a cognitive cycle through interaction with the RF environment which is graphically represented in Figure 2-1.

It’s obvious that the cognitive module in the transmitter must work in a harmonious manner with the cognitive modules in the receiver [16]. In order to maintain this harmony between the cognitive radio’s transmitter and receiver at all times, we need a *feedback channel* connecting the receiver to the transmitter. Through the feedback channel, the receiver is enabled to convey information on the performance of the forward link to the transmitter. The cognitive radio is, therefore, by necessity, an example of a *feedback communication system*.

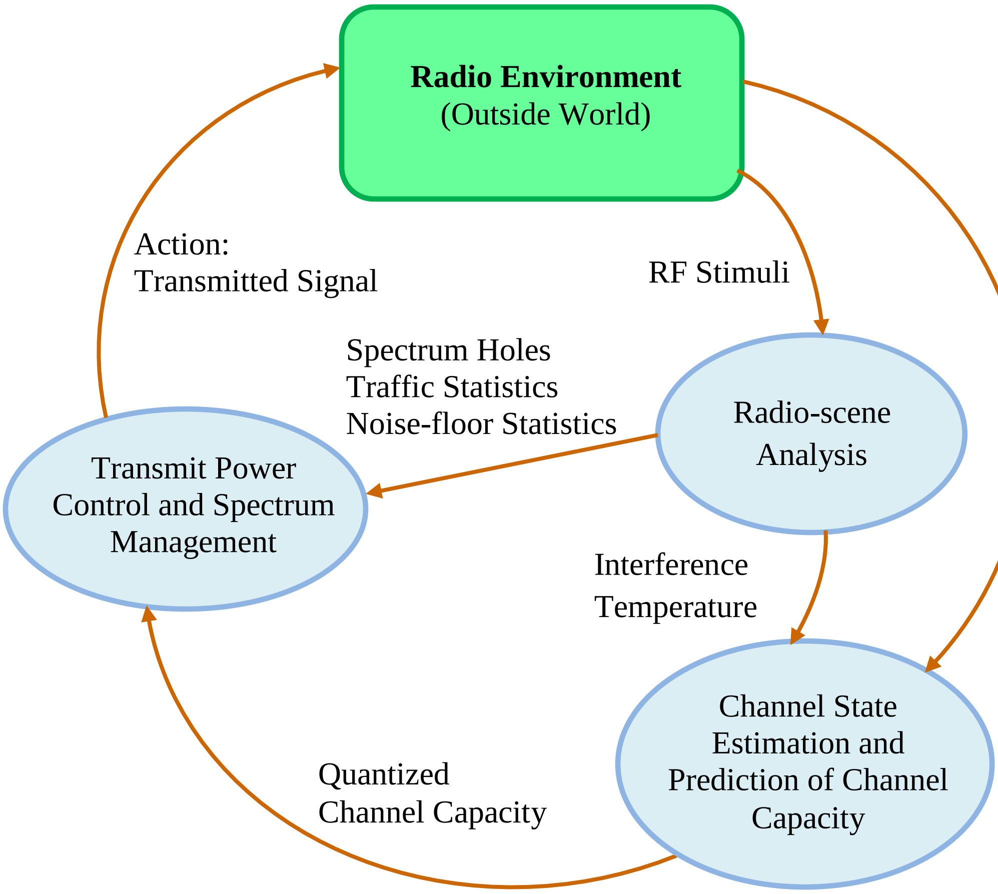

Figure 2-1: Basic Cognitive Cycle

2.3 Cognitive Radio Network

From the viewpoint of well-established wireless communication manufacturers, the development of cognitive radio is *‘Evolutionary’*, building on the world-wide wireless telephone network already in place. [17]

On the other hand, from the viewpoint of computer manufacturers eager to move into the wireless market, the development of cognitive radio is *‘Revolutionary’*.

The cognitive radio network is an intelligent multiuser wireless communication system that embodies the following list of primary tasks:

(a) To perceive the radio environment by empowering each user’s receiver to sense the environment on a continuous-time basis.

(b) To learn from the environment and adapt the performance of each transceiver to statistical variations in the incoming RF stimuli.

(c) To facilitate communication between multiple users through cooperation in a self-organized manner.

(d) To control the communication processes among competing users through the proper allocation of available resources.

(e) To create the experience of intention and self-awareness.

(f) To accomplish all of these tasks in a reliable and robust manner.

2.4 Cognitive Radio Network Architecture

The components of the infrastructure-based (or centralized) CR network architecture, as shown in Figure 2-2, can be classified in two groups as the *Primary Network* and the *CR Network* [18]. The *Primary Network* is referred to as the legacy network that has an exclusive right to a certain spectrum band. Examples include the common cellular and TV broadcast networks. In contrast the *CR Network* does not have a license to operate in the desired band. Hence, the spectrum access is allowed only in an opportunistic manner.

The following are the basic components of primary networks: [19]

2.4.1 Primary User

A primary user (PU) has a license to operate in a certain spectrum band. This access can only be controlled by the primary base station and should not be affected by the operations of any other CR users. Primary users do not need any modification or additional functions for coexistence with CR base stations and CR users.

2.4.2 Primary Base Station

A primary base station is a fixed infrastructure network component that has a spectrum license, such as a base station transceiver system (BTS) in a cellular system. In principle, the primary base station does not have any CR capability for sharing spectrum with CR users.

2.4.3 CR User

A CR user (also known as *Secondary User*) has no spectrum license. Hence, additional functionalities are required to share the licensed spectrum band. In infrastructure-based networks, the CR users may be able to only sense a certain portion of the spectrum band through local observations. They do not make a decision on spectrum availability and just report their sensing results to the CR base station.

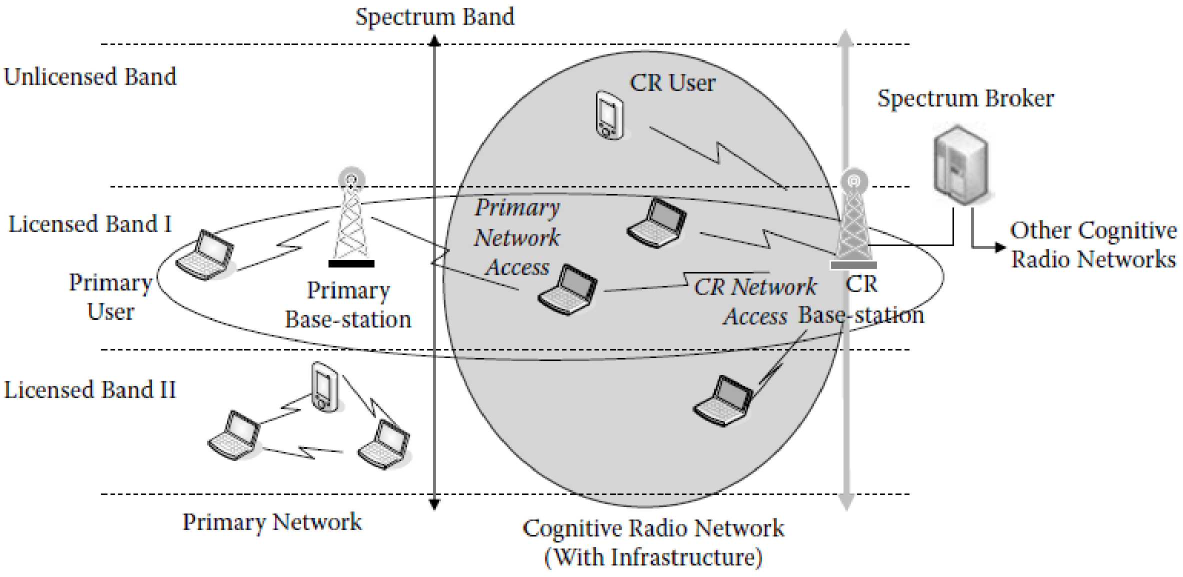

Figure 2-2: Infrastructure-based Cognitive Radio Architecture

2.4.4 CR Base Station

A CR base station is a fixed infrastructure component with CR capabilities. It provides single-hop connection without spectrum access licenses to CR users within its transmission range and exerts control over them. Through this connection, a CR user can access other networks. It also helps in synchronizing the sensing operations performed by the different CR users. The observations and analysis performed by the latter are fed to the central CR base station so that the decision on the spectrum availability can be made.

2.4.5 Spectrum Broker

A spectrum broker (or scheduling server) is a central network entity that plays a role in sharing the spectrum resources among different CR networks. It is not directly engaged in spectrum sensing. It just manages the spectrum allocation among different networks according to the sensing information collected by each network.

2.5 Wireless Mesh-Based Cognitive Radio Network Architecture

While wireless mesh networks (WMNs) can be broadly categorized as *distributed* networks, they exhibit various levels of node-level independence. There are three major classifications of WMNs based on how the Mesh Clients (MCs) are linked to the Mesh Routers (MRs): [20]

(i) Backbone
(ii) Mesh-Client
(iii) Hybrid

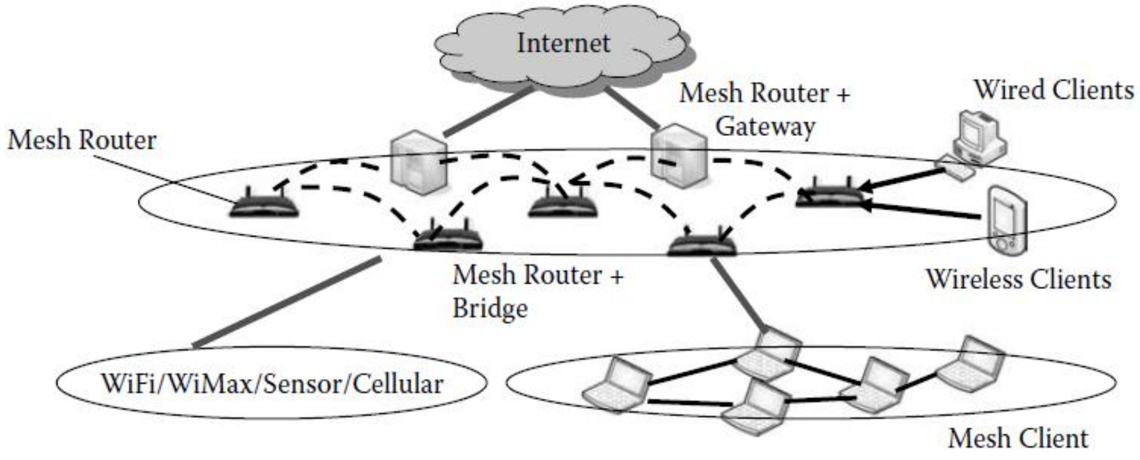

Figure 2-3: Wireless Mesh-Based Network Architecture

2.5.1 Backbone Mesh

These are the most commonly used type of mesh networks, with the MRs serving as the *Access Point* supporting several users in a residential setting or along a road. The MCs can only connect to the MRs, and thus each MR along with its associated nodes forms a *Cluster-like* arrangement. The MR serve as the routing backbone, forwarding packets till the *gateway* that provides the final link to the Internet is reached. These MRs may serve other networks with independent communication standards, such as a WiMAX network in Figure 2-3.

2.5.2 Client Mesh

The client mesh consists of several MCs connected to each other without MR support. They form ad hoc networks for peer-to-peer connection and are not connected to the Internet. In the absence of total central control, the sensing task is particularly complicated. Network-wide messaging and pairwise network sensing during transmission are the best suited mechanisms to sense the channel and then disseminate this information in the network. This architecture is seldom explored in the literature and constitutes the hardest scenario for implementing a CR network.

2.5.3 Hybrid Mesh

This architecture strikes a balance between the cluster-like and totally centralized approaches. Here, MCs are free to either associate themselves with an MR in a cluster, or form their own ad hoc network. The ad hoc network is connected to the backbone via any closest peer and this poses some interesting research issues:

- ✓ A symbiotic relationship can be envisaged between the backbone and the ad hoc components of the mesh network. As the individual peer nodes can be spread widely around the network, they can perform channel sensing on the network edge. This information is then conveyed back to the backbone MR, and in return, the node is allowed to forward packets towards the gateway through that MR. This raises issues of devising feasible economic models, and also this supply-reward structure allows a check on nodes submitting malicious or intentionally misleading sensed information.
- ✓ Assigning of the sensing task by the MR to these fringe ad hoc networks needs a suitable handshaking mechanism calling for an interaction between application and lower-level sensing layers.

2.6 Regulations

The major regulatory agencies are developing rules for the unlicensed use of TVWS such as the FCC in the United States, ‘Ofcom’ in the UK, and the Electronic Communications Committee (ECC) of CEPT in Europe.

The FCC provided the final rules for TVWS in 2010 [21]. There is ongoing proceeding for secondary use of the 2.36 GHz to 2.4 GHz band for medical area networks. Other opportunistic spectrum access beyond the already completed TVWS proceedings and cognitive techniques to better utilize the radio spectrum are currently under investigation.

Ofcom has also made significant progress in developing regulations for the TVWS with a first public consultation in 2009 [22]. The statement on white spaces devices and implementation of

Geo-location databases was released on September 1st, 2011 [23]. The detailed rules will be released in the future.

The ECC studied the technical and operational requirements for the operation of CRS in the WS of the UHF broadcasting band (470–790 MHz) [24]. This work is used as the starting point for regulatory activities within the ECC.

2.7 Standardizations

Currently international standardization of CRS is performed at all levels (ITU, IEEE, ETSI, and ECMA) [21, 25]. They are considering multiple deployment scenarios and business directions.

In ITU, Working Party (WP) 1B has worked on the definition of SDR and CRS and their relationship and summarized the technical and operational studies, and relevant recommendations. It has considered the SDR and CRS usage scenarios in different radio services and regulation implications. The WP 5A is currently addressing the definition, description, and application of CRS in the land mobile service.

IEEE is very active in CRS. In 802 WGs (LAN/MAN), the activity to define CRSs is currently performed in the 802.11 and 802.22, while the activity to specify components of a CRS is currently performed in 802.19, 802.21, and 802.22. 802.11y is an amendment for 3650–3700 MHz operation in USA defining new regulatory classes, transmit power control, and dynamic frequency selection for 802.11 to share frequency bands with other users. Draft standard P802.11af is an amendment for TVWS operation defining standardized modifications to both the 802.11 physical (PHY) layers and medium access control (MAC) sub-layer to meet the legal requirements for channel access and coexistence in the TVWS. Draft standard P802.19.1 concerns TVWS coexistence methods. IEEE 802.21 focuses on media independent handover services enabling the optimization of handover between heterogeneous IEEE 802 networks, and facilitating handover between IEEE 802 networks and cellular networks. The draft standard P802.22 is on policies and procedures for operation in the TV bands. It specifies the air interface, including the cognitive MAC and PHY, of point-to-multipoint wireless regional area networks, operating in the unlicensed TV bands between 54 MHz and 862 MHz. Draft standard P802.22.1 is to enhance harmful interference protection for PUs operating in TV bands.

The ETSI Reconfigurable Radio Systems (RRS) Technical Committee (TC) is also active in standardizing SDR and CRS [26]. TC RRS main responsibility is to carry out standardization activities related to reconfigurable radio systems (RRS) encompassing both SDR and CR with a focus on specific needs of the European Regulatory Framework, and CR/SDR TV white space standards adapted to the digital TV signal characteristics in Europe. Two out of the four working groups within ETSI RRS have activities resulting in standardization of potential regulatory aspects of CRS and SDR. Working group 3 has proposed and investigated the feasibility of standardizing a functional architecture for management and control of reconfigurable radio systems and cognitive pilot channel. SDR-related standardization is considered for both base station and mobile device. Working group 2 relies mainly on mobile device SDR related interface standardization. ETSI RRS is also working on operation in WS frequency bands and coexistence architecture for cognitive radio and investigating security and threats issues.

ECMA-392 released in 2009, specifies MAC and PHY for personal/portable cognitive wireless networks operating in TVWS, a MUX sub-layer for higher layer protocols and a number of incumbent protection mechanisms.

3GPP is also interested in standardizing CR-like features in its future releases. For example, the idea of a cognitive reference signal is proposed through which each RAN can broadcast the interference level, frequency bands, and RATs of other networks, and other information that can help newly joined user equipment to choose the best RAN.

Chapter-3

Overview
of
Spectrum Sensing

A cognitive radio is designed to be aware of and sensitive to the changes in its surroundings, which makes *Spectrum Sensing* (SS) an important requirement for the realization of CR networks. Spectrum sensing enables CR users to adapt to the radio environment by determining currently unused spectrum portions, so-called *spectrum holes*, without causing interference to the primary network represented in Figure 3-1.

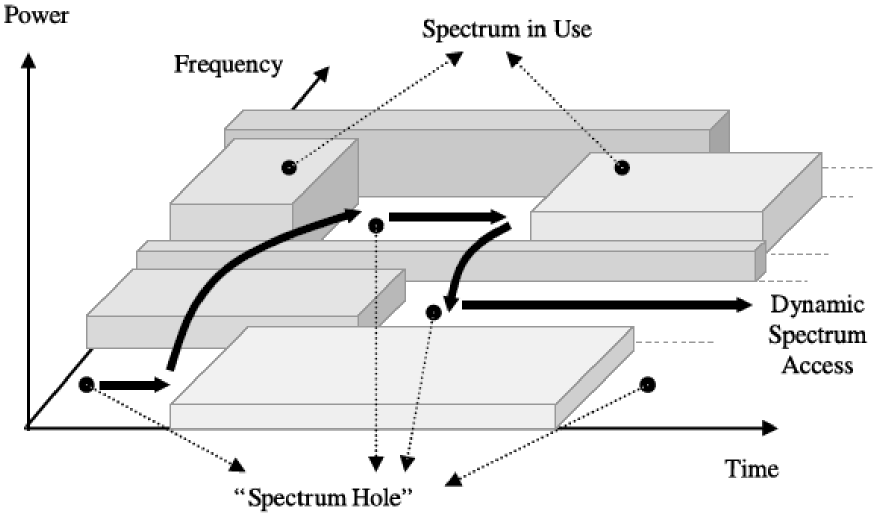

Figure 3-1: Spectrum Sensing in Cognitive Radio

3.1 Frequency Band Categorization

Licensed portion of the spectrum consists of frequency bands that belong to one of the following categories:

- **(a)** *White Spaces:* Primary users are absent. These bands can be utilized without any restriction.
- **(b)** *Gray Spaces:* Primary users are present. Interference power at primary receivers should not exceed a certain threshold called interference temperature limit.
- **(c)** *Black Spaces:* Primary user's power is very high. Secondary users should use an interference cancellation technique in order to communicate.

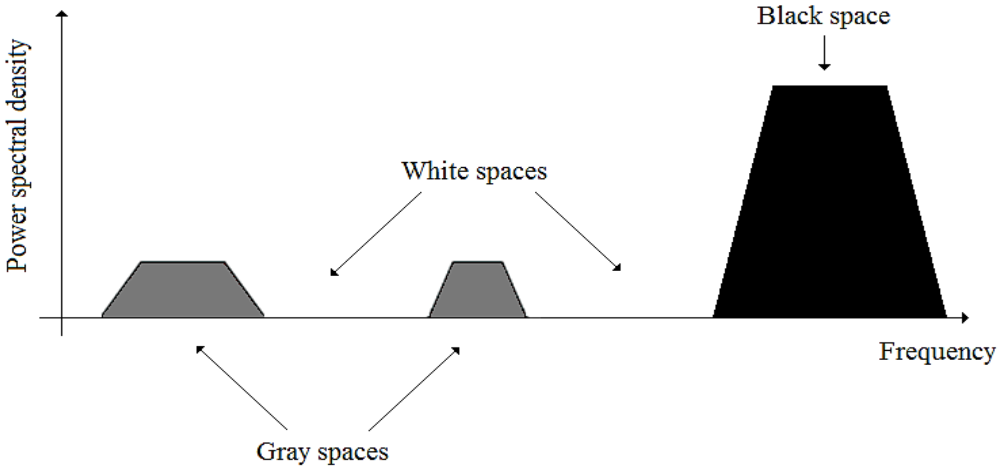

Figure 3-2: Licensed Spectrum Band Categorization

With Cognitive Radio being used in a number of applications, the area of spectrum sensing has become increasingly important. As Cognitive Radio technology is being used to provide a method of using the spectrum more efficiently, spectrum sensing is the key to this application.

The ability of Cognitive Radio systems to access spare sections of the radio spectrum and to keep monitoring the spectrum to ensure that the Cognitive Radio system does not cause any undue interference relies totally on the spectrum sensing elements of the system.

For the overall system to operate effectively and to provide the required improvement in spectrum efficiency, the Cognitive Radio spectrum sensing system must be able to effectively detect any other transmissions, identify what they are and inform the central processing unit within the Cognitive Radio so that the required action can be taken.

3.2 Considerations for Spectrum Sensing

In many areas cognitive radio systems coexist with other radio systems, using the same spectrum but without causing undue interference. When sensing the spectrum occupancy, the cognitive radio system must accommodate a variety of considerations: [27]

- ***Continuous Spectrum Sensing:*** It is necessary for the cognitive radio system to continuously sense the spectrum occupancy. Typically a cognitive radio system will utilize the spectrum on a non-interference basis to the primary user. Accordingly it is necessary for the Cognitive radio system to continuously sense the spectrum in case the primary user returns.

- ***Monitor for Alternative Empty Spectrum:*** In case the primary user returns to the spectrum being used, the cognitive radio system must have alternative spectrum available to which it can switch should the need arise.
- ***Monitor Type of Transmission:*** It is necessary for the cognitive radio to sense the type of transmission being received. The cognitive radio system should be able to determine the type of transmission used by the primary user so that spurious transmissions and interference are ignored as well as transmissions made by the cognitive radio system itself.

3.3 Types of Cognitive Radio Spectrum Sensing

There are a number of ways in which cognitive radios are able to perform spectrum sensing. The ways in which cognitive radio spectrum sensing can be performed falls into one of two categories: [27]

- ***Non-cooperative Spectrum Sensing:*** This form of spectrum sensing occurs when a cognitive radio acts on its own. The cognitive radio will configure itself according to the signals it can detect and the information with which it is pre-loaded.
- ***Cooperative Spectrum Sensing:*** Within a cooperative cognitive radio spectrum sensing system, sensing will be undertaken by a number of different radios within a cognitive radio network. Typically a central station will receive reports of signals from a variety of radios in the network and adjust the overall cognitive radio network to suit.

  Cognitive radio cooperation reduces problems of interference where a single cognitive radio cannot hear a primary user because of issues such as shading from the primary user, but a second primary user acting as a receiver may be able to hear both the primary user and the signal from the cognitive radio system.

3.4 Cognitive Radio Spectrum Sensing Methodologies

There are a number of attributes that must be incorporated into any cognitive radio spectrum sensing scheme. These ensure that the spectrum sensing is undertaken to meet the requirements for the particular applications. The methodology and attributes assigned to the spectrum sensing ensure that the cognitive radio system is able to avoid interference to other users while maintaining its own performance. [27]

- ***Spectrum Sensing Bandwidth:*** There are a number of issues associated with the spectrum sensing bandwidth. The first is effectively the number of channels on which the system will sense whether they are occupied. By sensing channels apart from the one currently in use, the system will be able to build up a picture of alternative channels that can be used should the current one become occupied. Secondly the actual reception bandwidth needs to be determined. A narrow bandwidth will reduce the system noise floor and thereby improve the sensitivity, but it must also have a sufficiently wide bandwidth to detect the likely transmissions on the channel.
- ***Transmission Type Sensing:*** The system must be capable of identifying the transmission of the primary user for the channel. It must also identify transmissions of other units in the same system as itself. It should also be able to identify other types of transmission that may be spurious signals, etc.
- ***Spectrum Sensing Accuracy:*** The cognitive radio spectrum sensing mechanism must be able to detect any other signal levels accurately so that the number of false alarms is minimized.
- ***Spectrum Sensing Timing Windows:*** It is necessary that the cognitive radio spectrum sensing methodology allows time slots when it does not transmit to enable the system to detect other signals.

3.5 Spectrum Sensing Instabilities

When developing a methodology it is necessary to ensure that the overall system remains stable. There are instances where levels of occupancy increase where cognitive radio systems will continually move from one channel to another. This considerably reduces the efficiency and at the worst case could almost render the system inoperable. [27]

To illustrate the types of scenario that could be encountered, consider the case where channel occupancy is high and a limited number of channels are allocated or are available. The first cognitive radio system may have settled on a channel, but then detects another user so it moves to the next channel. This second channel may have been in use by another user which detects the new channel occupancy and moves. This could continue until the final user then moves into the first channel and the whole procedure repeats.

While it is possible that events may not occur in exactly this fashion, these types of scenario will occur and the cognitive radio spectrum sensing algorithms must be designed to take account of these forms of scenario, and ensure the optimum usage of the available spectrum.

Also with cognitive radio usage increasing, there will be an increase in signal frequency agility and signals will often appear on new frequencies. Accordingly this must be built into the decision algorithms to ensure that CR systems only move when it is necessary.

Cognitive radio spectrum sensing is one of the key algorithms associated with the whole field of cognitive radio. As experience grows, the cognitive radio spectrum sensing techniques will be refined and they will be designed to accommodate the increasing use of the spectrum as well as any malicious attacks that could be presented to CR systems.

3.6 Spectrum Sensing Techniques

Generally, spectrum sensing techniques can be classified into four groups: [18]

(1) Primary transmitter detection
(2) Cooperative transmitter detection
(3) Primary receiver detection
(4) Interference temperature management

3.7 Primary Transmitter Detection

Since CR users are usually assumed not to have any real-time interaction with the primary transmitters and receivers, they cannot know the exact information on current transmissions within the primary networks. Thus, in transmitter detection, in order to distinguish between used and unused spectrum bands, CR users detect the signal from a primary transmitter through only the local observations of CR users, as shown in Figure 3-3.

Thus, CR users should have the capability to determine if a signal from the primary transmitter is locally present in a certain spectrum. A basic hypothesis model for transmitter detection can be defined as follows:

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

Where $x(t)$ is the signal received by the CR user, $s(t)$ is the transmitted signal of the primary user, $n(t)$ is a zero-mean Additive White Gaussian Noise (AWGN), and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some primary user signal.

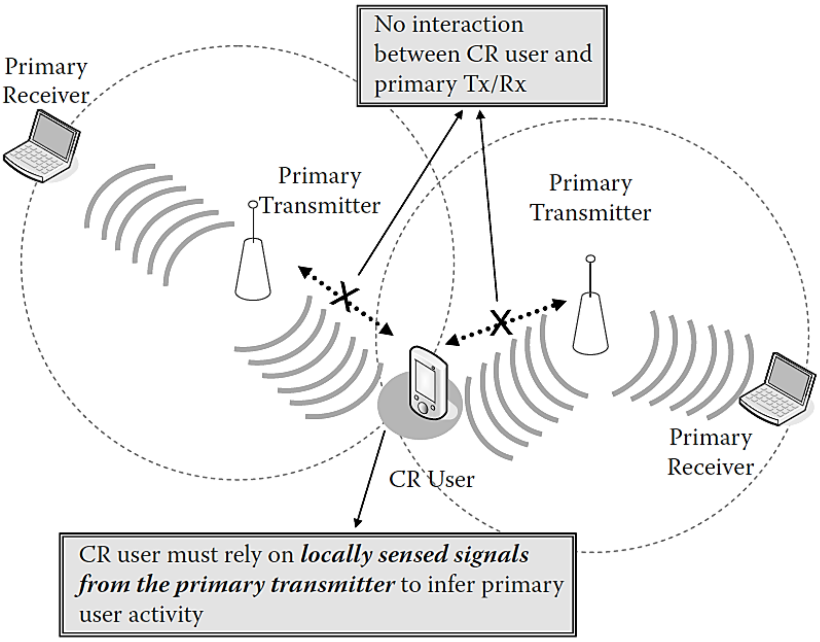

Figure 3-3: Primary Transmitter Detection

Three schemes are generally used for the transmitter detection: *matched filter detection*, *energy detection* and *feature detection*. [28]

3.7.1 Matched Filter Detection

When the information of the primary user signal is known to the CR user, the optimal detector in stationary Gaussian noise is the matched filter for maximizing the signal-to-noise ratio (SNR) in the presence of additive stochastic noise. This detection method requires only O (1/SNR) samples to achieve a detection error probability constraint. However, the matched filter requires not only *a priori* knowledge of the characteristics of the primary user signal, but also synchronization between the primary transmitter and the CR user. If this information is not accurate, then the matched filter performs poorly.

3.7.2 Energy Detection

If the receiver cannot gather sufficient information about the primary user signal, for example, if only the power of the random Gaussian noise is known to the receiver, the optimal detector is an energy detector. In the energy detection scheme, CR users sense the presence/absence of the primary users through the energy of the received primary signal. In order to measure the energy of the received primary signal, the received signal is squared and integrated over the observation interval. Finally, the output of the integrator is compared with a threshold to decide if a primary user is present. The energy detector requires *O* (1/SNR2) samples for a given detection error probability. Thus, if CR users need to detect weak signals (SNR: −10dB to −40 dB), energy detection suffers from longer detection time compared to matched filter detection.

While the energy detector is easy to implement, it can only determine the presence of the signal but cannot differentiate signal types. Thus, the energy detector often generates false detection triggered by unintended signals. Another shortcoming is that since energy detection depends only on the SNR of the received signal, its performance is susceptible to uncertainty in noise power. If the noise power is uncertain and can take any value in the range of x dB, the energy detector will not be able to detect the signal reliably when the SNR is less than the threshold $10\log_{10}10^{x/10}$ -1, called an *SNR wall*. [29]

3.7.3 Cyclostationary Feature Detection

Modulated signals are, in general, coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. Thus, these modulated signals are characterized by *Cyclostationarity*, since their mean and autocorrelation exhibit periodicity. The feature detector exploits this inherent periodicity in the primary user’s signal by analyzing a spectral correlation function [30]. The main advantage of the feature detection scheme is its robustness to the uncertainty in noise power. The feature detector distinguishes between the noise energy and the modulated signal energy, which is the result of the fact that the noise is a wide-sense stationary signal with no correlation, while the modulated signals are cyclostationary with spectral correlation due to the built-in periodicity. Furthermore, since the feature detector is also capable of differentiating different types of signals, it can tolerate false alarms caused by external signals, such as those from other CR users or interference. Therefore, a cyclostationary feature detector can perform better than an energy detector in differentiating different signal types. However, it is computationally complex and requires significantly longer observation time.

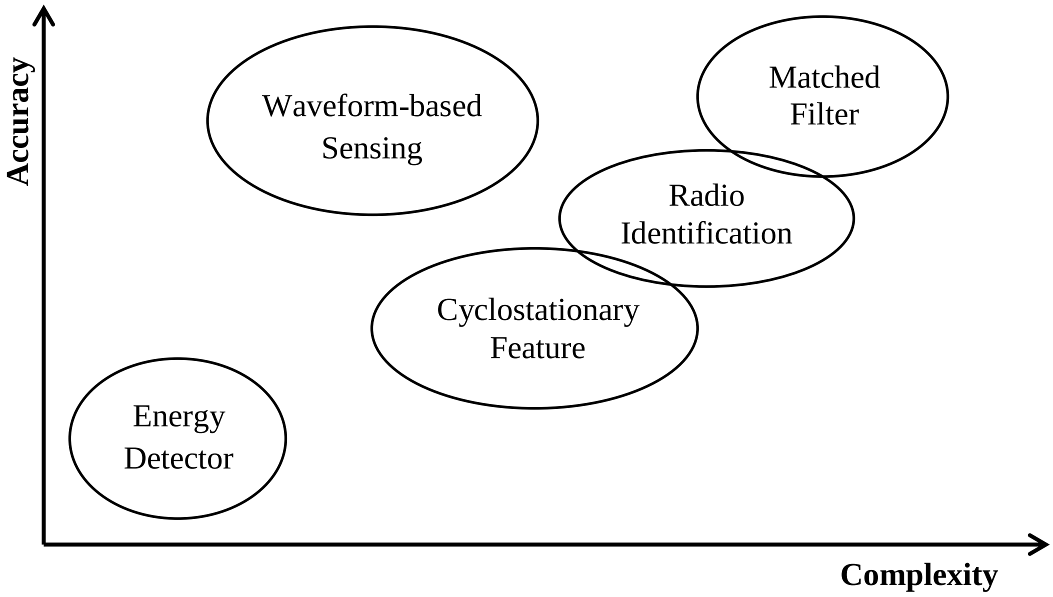

Figure 3-4: Graphical Comparison between Different Spectrum Sensing Methods

3.8 Cooperative Transmitter Detection

Because of the lack of interaction between the primary users and the CR users, transmitter detection techniques rely on the weak signals from only the primary transmitters. Hence, transmitter detection techniques alone cannot avoid causing interference to primary receivers because of the lack of primary receiver information as depicted in Figure 3-5. Moreover, transmitter detection models cannot prevent the hidden terminal problem. A CR user (transmitter) can have a good line-of-sight to a CR receiver, but may not be able to detect the primary transmitter due to shadowing as shown in Figure 3-6. Therefore, sensing information from other users is required for more accurate primary transmitter detection; this is referred to as *cooperative detection*. Cooperative detection is theoretically more accurate, since the uncertainty in a single user's detection can be minimized through collaboration [31]. Moreover, multipath fading and shadowing effects can be mitigated so that the detection probability is improved in a heavily shadowed environment.

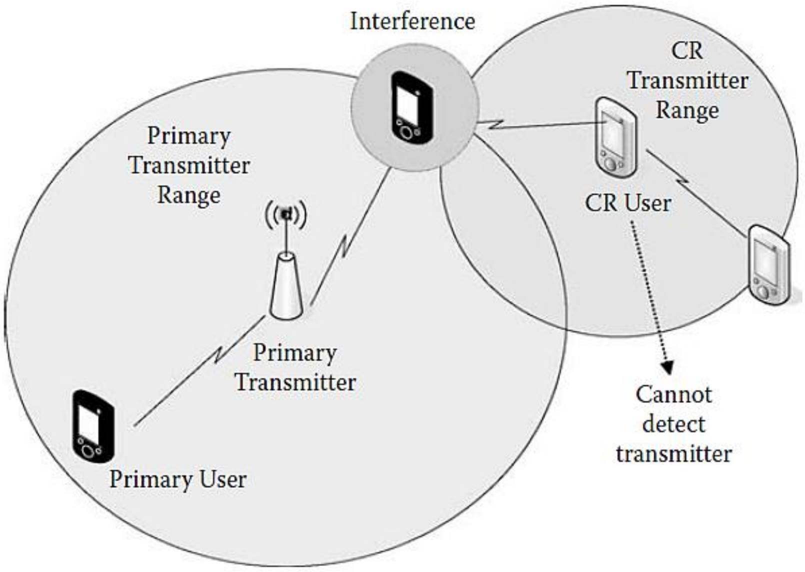

Figure 3-5: Transmitter Detection Problem (a) Receiver Uncertainity

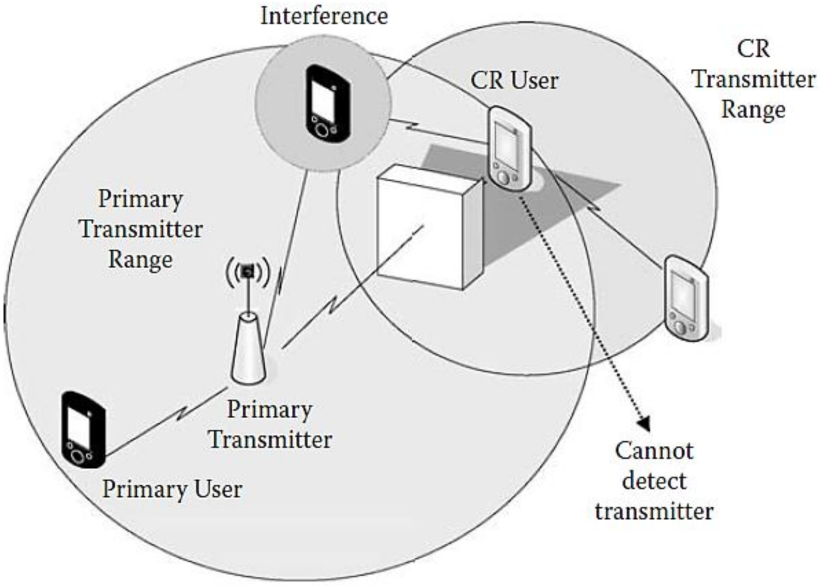

Figure 3-6: Transmitter Detection Problem (b) Shadowing Uncertainity

3.9 Primary Receiver Detection

Although cooperative detection reduces the probability of interference, the most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of a CR user. As depicted in Figure 3-7, the primary receiver usually emits Local Oscillator (LO) leakage power from its RF front-end when it receives signals from the primary transmitter. In order to determine the spectrum availability, a primary receiver detection method exploits this LO leakage power instead of the signal from the primary transmitter, and detects the presence of the primary receiver directly [32]. Such an approach may be feasible for TV receivers only, or need further hardware such as a supporting sensor network in the area with the primary receivers.

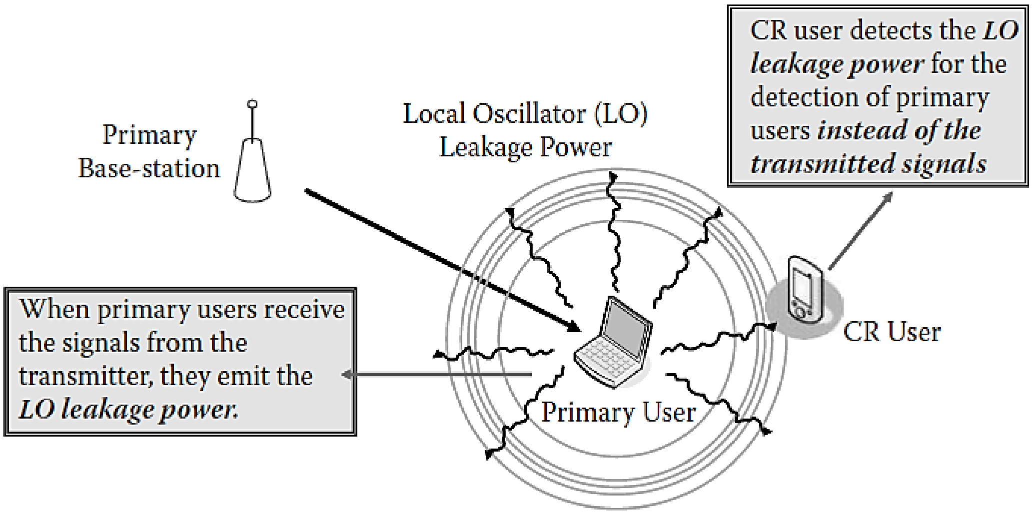

Figure 3-7: Primary Receiver Detection

3.10 Interference Temperature Management

Traditionally, interference can be controlled at the transmitter through the radiated power, out-of-band emissions, and location of individual transmitters. However, interference actually takes place at the receivers, as shown in Figure 3-5. Recently, a new model for measuring interference, referred to as *interference temperature*, has been introduced by the FCC [33].

Figure 3-8 shows the signal of the primary transmitter designed to operate out to the distance at which the received power approaches the level of the noise floor. The noise floor is location-specific depending on the additional interfering signals at that point. As shown in Figure 3-8, this model suggests an interference temperature limit, which is the amount of new interference that the primary receiver could tolerate. As long as CR users do not exceed this limit, they can use the spectrum band.

Although this model is best fitted for the objective of spectrum sensing, the difficulty lies in accurately determining the interference temperature limit for each location-specific case. There is no practical way for a CR user to measure or estimate the interference temperature, since CR users have difficulty in distinguishing between actual signals from the primary user and noise/interference. Also, with the increase in the interference temperature limit, the SNR at the primary receiver decreases, resulting in a decrease in the primary network's capacity and coverage.

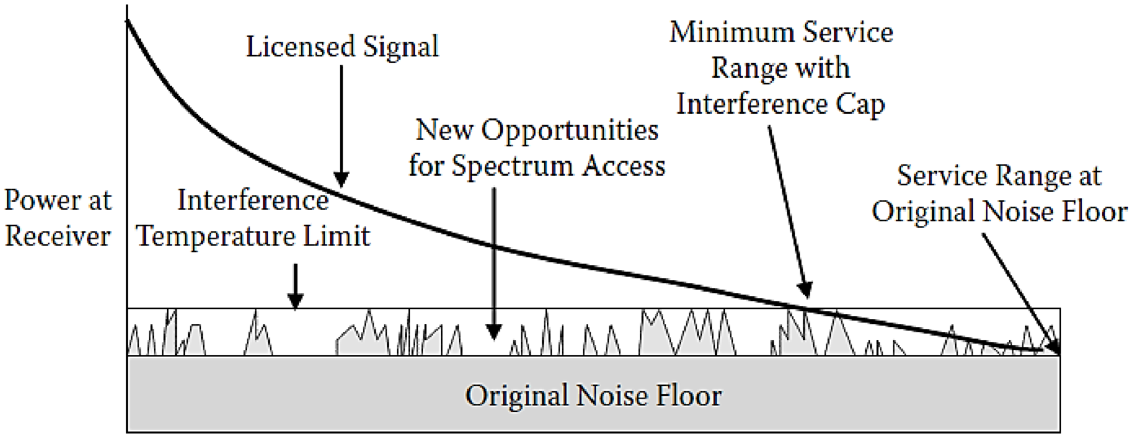

Figure 3-8: Interference Temperature Management

3.11 Spectrum Sensing Framework

Generally, CR networks have multiple cooperating CR users. This multi-user environment helps CR users to enhance the sensing accuracy, which is time-varying and is a function of the number of users. Furthermore, CR users are allowed to exploit multiple spectrum bands. Practically, CR users do not have enough sensing transceivers to sense all the available spectrum bands. In order to adapt these various sensing environments efficiently, we introduce an optimal spectrum sensing framework, which is illustrated in Figure 3-9. This framework consists of the *optimization of sensing parameters* in a single spectrum band, *spectrum selection and scheduling*, and an *adaptive and cooperative sensing* method [34].

The detailed scenario for the optimal sensing framework is as follows. According to the radio characteristics, base stations initially determine the optimal sensing parameters of each spectrum band through the *sensing parameter optimization phase*. When CR users join the CR networks, through *spectrum selection and scheduling* methods, the base stations select the best spectrum bands for sensing and configure sensing schedules according to the number of transceivers and the optimized sensing parameters. Then, CR users begin to monitor spectrum bands continuously with the optimized sensing schedule and report sensing results to the base station. Using these sensing results, the base station determines the spectrum availability. If the base station detects any changes that affect the sensing performance, sensing parameters need to be re-optimized and announced to the CR users through the *adaptive and cooperative sensing phase*.

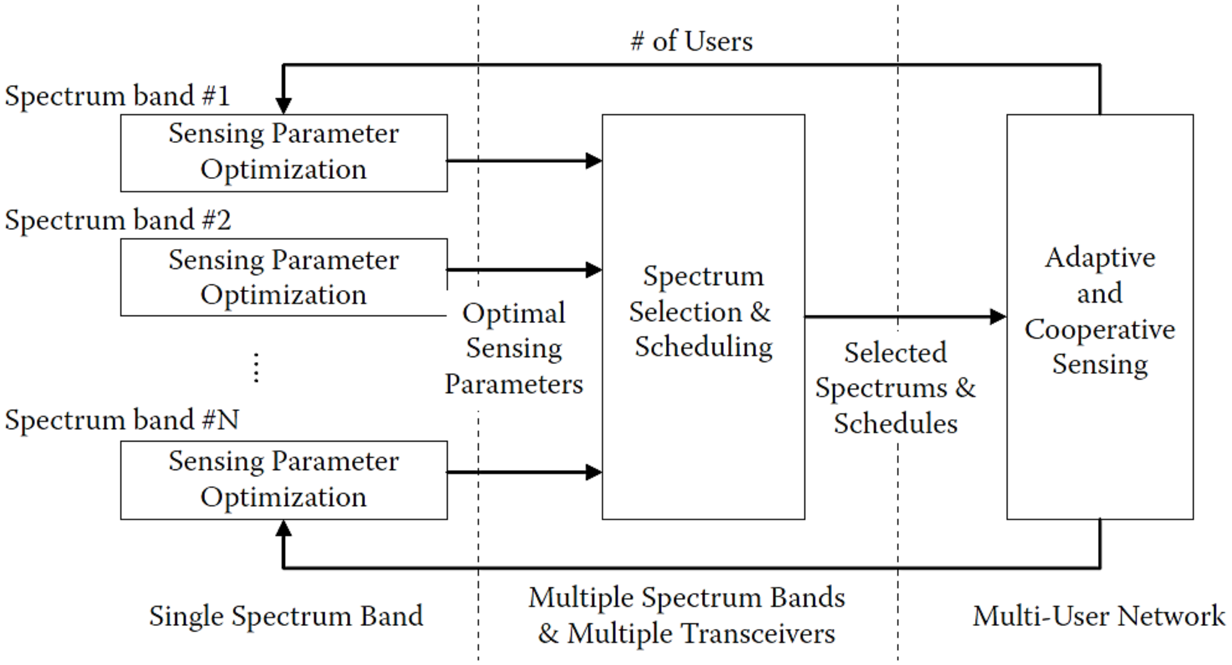

Figure 3-9: Overall Architecture of the Optimal Sensing Framework

3.12 Spectrum Sensing Challenges

Spectrum sensing constitutes one the most important components of the cognitive radio. The accuracy and the overhead of the spectrum sensing are two main issues in this area. The solutions discussed here provide valuable insight into the challenges and potential solutions in spectrum sensing. Nevertheless, there still exist several open research challenges that need to be investigated for the development of accurate and efficient spectrum sensing solutions. We discuss these challenges in detail in this section.

3.12.1 Interference Temperature Measurement

Interference temperature measurement techniques provide a way of interference avoidance without the need for accurate primary transmitter detection techniques. Instead, the interference at the primary receivers is limited through an interference temperature limit. The difficulty of this receiver detection model lies in effectively measuring the interference temperature and determining the limit.

A CR user is naturally aware of its transmitted power level and can determine its precise location with the help of a positioning system. With this ability, however, its transmission could cause significant interference at a neighboring receiver on the same frequency. Currently, there exists no practical way for cognitive radios to measure or estimate the interference temperature at nearby primary receivers. Since primary receivers are usually passive devices, a CR user cannot be aware of the precise locations of primary receivers. Furthermore, if CR users cannot measure the effects of their transmissions on all possible receivers, a useful interference temperature measurement may not be feasible.

Another important challenge is the determination of the interference temperature limit. Since CR users try to control their transmissions according to this limit, an accurate model for the determination of the interference temperature limit is necessary. However, the optimal value of this limit may depend on the density and the traffic characteristics of the primary users. Furthermore, the physical layer characteristics, such as the modulation and transmitted power, as well as the operating frequency of the primary users, also affect the limit. Consequently, adaptive techniques for the determination of the interference temperature limit are necessary.

3.12.2 Multi-User Cognitive Radio Networks

CR networks usually reside in a multi-user environment, which consists of multiple CR users and primary users. Furthermore, CR networks can also be co-located with other CR networks competing for the same spectrum band. However, current interference models [35, 36] do not consider the effect of multiple CR users. A multi-user environment makes it more difficult to sense the primary users and to estimate the actual interference. First, the effects of the transmissions of other CR users are unknown to a specific CR user. Consequently, it is hard to estimate the total interference that would be caused at a primary receiver. Second, the transmissions of other CR users may prevent a specific CR user from detecting the activity of a primary transmitter and lead the CR user to regard the primary user transmission as noise. This leads to degradation in sensing accuracy. Spectrum sensing functions should be developed considering the possibility of a multi-user/network environment. In order to solve the multi-user problem, the cooperative detection schemes can be considered, which exploit the spatial diversity inherent in a multi-user network.

3.12.3 Physical Layer Constraints

Spectrum sensing techniques require efficient physical layer capabilities in terms of wideband sensing and rapid spectrum switching. However, the constraints of the physical layer need to be known to design practical sensing algorithms. As discussed in Section 1.4, the fact that the cognitive radio cannot sense and transmit simultaneously is one of the factors in the design of spectrum sensing algorithms. This fact has been considered in [37] to optimally schedule the transmission and sensing without degrading the sensing accuracy. As an alternative, the effect of using multiple radios has been investigated in [38], where a two-transceiver operation is considered such that a transceiver always listens to the control channel for sensing. This operation improves the system performance; however, the complexity and device costs are high.

3.12.4 Cooperative Sensing

Cooperative sensing constitutes one of the potential solutions for spectrum sensing in CR networks. Spectrum sensing accuracy for a single user increases with the sensing time. Considering the sensing capabilities of CR radios, however, an acceptable accuracy may be reached only after very long sensing times. The uncertainty in noise, however, prevents even infinite sensing times from being accurate in some cases [39]. This theoretical finding motivates cooperative sensing schemes.

Cooperative sensing, although more efficient, creates additional challenges for accurate spectrum sensing in CR networks. The communication requirement of the cooperating nodes necessitates cross-layer techniques that support joint design of spectrum sensing with spectrum sharing. Efficient communication and sharing techniques are necessary to alleviate the effects of communication overhead in cooperative sensing. To this end, dynamic common control channel techniques, which provide a common control channel for the CR users to exchange spectrum sensing information, may be required [40]. Moreover, efficient and distributed coordination solutions that partition the spectrum sensing tasks to various co-located CR users are required.

3.12.5 Mobility

Spectrum sensing techniques aim to provide a map of the spectrum in a CR user’s vicinity. Consequently, efficient spectrum decision techniques can be used. However, if a CR user moves, the spectrum allocation map may change rapidly. Therefore, the spectrum allocation map constructed by the sensing algorithm may become obsolete with high mobility. Consequently, the CR user may need to perform spectrum sensing as they change location. This necessitates an adaptive spectrum sensing technology that is responsive to the mobility of the CR user.

3.12.6 Adaptive Spectrum Sensing

The requirements of spectrum sensing solutions may depend on the network architecture. While centralized solutions focus on efficient information collection from multiple sensing devices and optimally allocating spectrum for users, distributed architectures lead to frequent information exchange between CR users. Consequently, the nature of the spectrum sensing solution may differ depending on the architecture. However, considering that CR user devices will need to adapt to any network setting, whether it is centralized or distributed, adaptive spectrum sensing solutions are crucial for rapid proliferation of the CR technology. As a result, a single CR device can be used in different network settings with a single, adaptive spectrum sensing solution.

Adaptive techniques are also necessary for different underlying physical layer functionalities. As explained above, physical layer constraints significantly affect the performance of spectrum sensing solutions. Moreover, it is clear that the realization of cognitive radio networks will lead to the implementation of different CR devices by different companies, similar to the current case with WLANs. To provide seamless spectrum sensing for higher networking layers, spectrum sensing solutions need to be adaptive to the physical layer capabilities.

3.12.7 Security

From the primary user point of view, CR users can be regarded as *malicious* devices that *eavesdrop* on the channel that the primary user is transmitting. In a sense, spectrum sensing techniques resemble eavesdropping attacks. In order to preserve the privacy of the users, spectrum sensing techniques need to be designed carefully. This is particularly important considering the economics that lie behind the primary networks. Since each primary user owns the particular spectrum, the traffic flowing through this spectrum needs to be protected. Spectrum sensing techniques, however, necessitate the knowledge of the existence of primary users for efficient operation. Consequently, spectrum sensing techniques should be designed in such a way that they are aware of the *existence* of the ongoing traffic but cannot determine the *content* of the traffic. Moreover, these techniques need to be implemented so that any CR user that performs spectrum sensing will not be regarded as malicious by the already existing security protocols in primary networks.

Chapter-4

System Model

4.1 Introduction

We are considering the situation where there is a single PU and one CR. Assume that the PU sends a pilot signal with data to perform timing and carrier synchronization. The CR has a perfect knowledge of the pilot signal and can perform its coherent processing. The channel between primary transmitter and CR is considered AWGN channel. With a complex baseband equivalent discrete signal representation, the related hypothesis testing problem is,

$$r[n] = \begin{cases} h[n]s[n] + w[n] & H_1 \\ w[n] & H_0 \end{cases} \tag{4.01}$$

where $r[n]$ denotes complex baseband equivalent of the nth sample of the received signal by CR, $s[n]$ is the nth PU transmitted pilot baseband sample which is deterministic and complex and is to CR, $w[n]$ is assumed to be Independent and Identically Distributed (IID) and zero-mean Complex Additive White Gaussian Noise (CAWGN) with known variance σ_w^2 at CR and $h[n]$ is the nth complex zero-mean Gaussian channel gain of the sensing channel between PU and CR. We define $x[n] = h[n]s[n]$ and express the sensing hypothesis test (1) into a vector form as follows,

$$r = \begin{cases} x + w & H_1 \\ w & H_0 \end{cases} \tag{4.02}$$

where $r = \left[r[0],...,r[N-1]\right]^T$, $w = \left[w[0],...,w[N-1]\right]^T$ is the additive noise at the CR receiver, modeled as an Circularly Symmetric Complex Gaussian (CSCG) vector with zero-mean and the covariance matrix $\sigma_w^2 I$, with $\mathbf{I}$ denoting an identity matrix. Channel gain vector with zero-mean and the covariance matrix denoted by,

$$C_h = E\left[hh^H\right] = \begin{pmatrix} h_{0,0} & h_{0,1} & \cdots & h_{0,N-1} \\ h_{1,0} & h_{1,1} & \cdots & h_{1,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N-1,0} & h_{N-1,1} & \cdots & h_{N-1,N-1} \end{pmatrix} \tag{4.03}$$

Distorted pilot vector $x = \left[x[0],...,x[N-1]\right]^T$ has CSCG distribution with zero-mean and the covariance matrix,

$$C_x = E\left[xx^H\right] = \begin{pmatrix} |s[0]|^2 h_{0,0} & \cdots & s[0]s[N-1]^H h_{0,N-1} \\ s[1]s[0]^H h_{1,0} & \cdots & s[1]s[N-1]^H h_{1,N-1} \\ \vdots & \ddots & \vdots \\ s[N-1]s[0]^H h_{N-1,0} & \cdots & |s[N-1]|^2 h_{N-1,N-1} \end{pmatrix} \quad (4.04)$$

where $(.)^H$ denotes the Hermitian operator. C_h and C_x are Hermitian and positive-semidefinite matrix, with real numbers in the main diagonal and complex numbers off-diagonal. We assume that $\mathbf{x}$ and $\mathbf{w}$ are independent, which is reasonable from a practical perspective. In addition, we assume that channel parameters σ_w^2 and C_h are known to CR under H_1 and H_0 have the following distribution,

$$p(r) = \begin{cases} CN\left(0, C_x + \sigma_w^2 I\right) & H_1 \\ CN\left(0, \sigma_w^2 I\right) & H_0 \end{cases} \quad (4.05)$$

where, $CN\left(m, \mathbf{C}\right)$ represents CSCG distribution with mean m and covariance matrix $\mathbf{C}$.

4.2 Optimum Detector

To detect optimally the presence of the PU signal, Likelihood Ratio Test (LRT) must be applied. LRT methodology would decide H_1 if the likelihood ratio exceeds a threshold:

$$T(r) = \frac{p(r|H_1)}{p(r|H_0)} > \gamma \qquad (4.06)$$

By substituting (4.05) into (4.06), the LRT decides H_1 based on the following statistics:

$$T(r) = \frac{\frac{1}{\pi^N \left|C_x + \sigma_w^2 I\right|} \exp\left[-\tfrac{1}{2} r^H \left(C_x + \sigma_w^2 I\right)^{-1} r\right]}{\frac{1}{\pi^N \left|\sigma_w^2 I\right|} \exp\left[-\tfrac{1}{2} r^H (\sigma_w^2 I)^{-1} r\right]} > \gamma \qquad (4.07)$$

After taking logarithm and discarding terms that are independent of the hypothesis, we have,

$$T(r) \;=\; -\tfrac{1}{2} r^H \left[\left(C_x + \sigma_w^2 I\right)^{-1} - (\sigma_w^2 I)^{-1}\right] r \;>\; \gamma$$

$$T(r) = \sigma_w^2 r^H \left[(\sigma_w^2 I)^{-1} - \left(C_x + \sigma_w^2 I\right)^{-1}\right] r > 2\gamma\sigma_w^2 \qquad (4.08)$$

From Matrix Inversion Lemma we know,

$$(\mathrm{A} + \mathrm{BCD})^{-1} = \mathrm{A}^{-1} - \mathrm{A}^{-1}\mathrm{B}\,(\mathrm{DA}^{-1}\mathrm{B} + \mathrm{C}^{-1})^{-1}\mathrm{DA}^{-1} \qquad (4.09)$$

Let,

$$\mathrm{A} = \sigma_{\mathrm{w}}^2 \mathrm{I}, \mathrm{B} = \mathrm{D} = \mathrm{I}, \mathrm{C} = \mathrm{C}_{\mathrm{x}}$$

So we can write,

$$\left(\sigma_w^2 I + C_x\right)^{-1} = (\sigma_w^2 I)^{-1} - (\sigma_w^2 I)^{-1} I \left[I(\sigma_w^2 I)^{-1} I + C_x^{-1}\right]^{-1} I(\sigma_w^2 I)^{-1}$$

$$\left(\sigma_w^2 I + C_x\right)^{-1} = \frac{1}{\sigma_w^2} I - \frac{1}{\sigma_w^4}\left(\frac{1}{\sigma_w^2} I + C_x^{-1}\right)^{-1}$$

Substituting this to (4.08) we find,

$$T(r) = \sigma_w^2 r^H \left[\frac{1}{\sigma_w^2} I - \frac{1}{\sigma_w^2} I + \frac{1}{\sigma_w^4}\left(\frac{1}{\sigma_w^2} I + C_x^{-1}\right)^{-1}\right] r > 2\gamma\sigma_w^2$$

$$T(r) = r^H \left[\frac{1}{\sigma_w^2} \left(\frac{1}{\sigma_w^2} I + C_x^{-1} \right)^{-1} \right] r \qquad (4.10)$$

Now let

$$\hat{S} = \frac{1}{\sigma_w^2} \left(\frac{1}{\sigma_w^2} I + C_x^{-1} \right)^{-1} r \, .$$

We can rewrite this as,

$$\begin{aligned} \hat{S} \quad &= \frac{1}{\sigma_w^2} \left(\frac{1}{\sigma_w^2} I + C_x^{-1} \right)^{-1} r \\ &= \frac{1}{\sigma_w^2} \left[\frac{1}{\sigma_w^2} C_x C_x^{-1} + C_x^{-1} \right]^{-1} r \\ &= \frac{1}{\sigma_w^2} \left[\frac{1}{\sigma_w^2} \left(C_x + \sigma_w^2 I \right) C_x^{-1} \right]^{-1} r \\ &= \frac{1}{\sigma_w^2} \frac{1}{\frac{1}{\sigma_w^2} \left(C_x + \sigma_w^2 I \right) C_x^{-1}} r \\ &= \frac{C_x}{\left(C_x + \sigma_w^2 I \right) C_x C_x^{-1}} r \\ &= C_x \left(C_x + \sigma_w^2 I \right)^{-1} r \end{aligned}$$

We can write (4.10) as,

$$T(r) = r^H C_x \left(C_x + \sigma_w^2 I \right)^{-1} r \ > \ \gamma' \qquad (4.11)$$

Let the eigen-decomposition of $C_x = U_x \Lambda_x U_x^H$, where U_x is and $N \times N$ unitary matrix $\left({U_x}^H = {U_x}^{-1} \right)$, consisting of eigenvectors as $U_x = \left[u_0 .....u_{N-1} \right]$and Λ_x is a diagonal matrix of N eigenvalues as $\Lambda_x = \mathrm{diag}\left(\lambda_0 .....\lambda_{\mathrm{N-1}} \right)$.

Let $\mathrm{g} = {\mathrm{U}_\mathrm{x}}^H \mathbf{r}$. We have,

$$\begin{aligned} T(r) \quad &= r^H C_x \left(C_x + \sigma_w^2 I \right)^{-1} r \\ &= r^H U_x {U_x}^H C_x U_x {U_x}^{-1} \left(C_x + \sigma_w^2 I \right)^{-1} U_x {U_x}^H r \end{aligned}$$

$$= g^H \Lambda_x \left(\Lambda_x + \sigma_w^2 I)\right)^{-1} g \tag{4.12}$$

Since the right hand side of (4.12) is a function of g, we can replace $T(r)$ with $T(g)$ and the test statistics can be written as:

$$T(g) = \sum_{n=0}^{N-1} \frac{\lambda_n}{\lambda_n + \sigma_w^2} \left| g[n] \right|^2 > \gamma' \tag{4.13}$$

It can be easily shown that,

$$p(\mathbf{g}) = \begin{cases} CN\left(0, \Lambda_x + \sigma_w^2 I\right) & H_1 \\ CN\left(0, \sigma_w^2 I\right) & H_0 \end{cases} \tag{4.14}$$

In the detection process the received samples are first linearly transformed to white samples, after which a weighted energy detector is applied to whiten samples and then the final decision about the presence or absence of primary user signal is taken.

Chapter-5

Analytical Performance Evaluation

5.1 Detection Performance of the Estimator-Correlator

Now we derive the detection performance for the estimator-correlator. The detector decides H_1 if,

$$T(x) = \mathbf{x}^T \mathbf{C_s} (\mathbf{C_s} + \sigma^2 \mathbf{I})^{-1} \mathbf{x} > \gamma^H \tag{5.01}$$

Where we assume $\mathbf{x} \sim N(0, \sigma^2 \mathbf{I})$ under the H_0 and $\mathbf{x} \sim N(0, \mathbf{C_s} + \sigma^2 \mathbf{I})$ under H_1.

As shown previously,

$$T(x) = \sum_{n=0}^{N-1} \frac{\lambda_{s_n}}{\lambda_{s_n} + \sigma^2} y^2[n] \tag{5.02}$$

Where $y = V^T x$ for **V** the modal matrix of C_s and λ_{s_n} the *n*-th eigenvalue of C_s. Now under either hypothesis **y** is a Gaussian Random Vector, being a linear transformation of **x** and since $E(y) = 0$ under either hypothesis:

$$C_y = E\left(yy^T\right) = E\left(V^T xx^T V\right) = V^T C_x V \tag{5.03}$$

This becomes,

$$C_y = \begin{cases} \sigma^2 I & H_0 \\ \Lambda_s + \sigma^2 I & H_1 \end{cases} \tag{5.04}$$

Thus

$$y \sim \begin{cases} N\left(0, \sigma^2 I\right) & H_0 \\ N\left(0, \Lambda_s + \sigma^2 I\right) & H_1 \end{cases} \tag{5.05}$$

Let us consider the probability of false alarm:

$$\begin{aligned} P_F &= P_r\left\{T(x) > \gamma^H; H_0\right\} \\ &= \mathrm{P}_r\left\{\sum_{n=0}^{N-1} \frac{\lambda_{s_n}}{\lambda_{s_n} + \sigma^2} y^2[n] > \gamma^H; H_0\right\} \\ &= \mathrm{P}_r\left\{\sum_{n=0}^{N-1} \frac{\lambda_{s_n}\sigma^2}{\lambda_{s_n} + \sigma^2} z^2[n] > \gamma^H; H_0\right\} \end{aligned} \tag{5.06}$$

where $z[n] = y[n]/\sigma$.

Now we need to find the CDF of $T(x)=\sum_{n=0}^{N-1}\alpha_n z^2\left[n\right]$, where the $z\left[n\right]$'s are IID $N(0,1)$ random variables. We can use characteristic functions to accomplish this. If the characteristic function is defined as $\phi_x(\omega)=\mathrm{E}\left[\exp(j\omega x)\right]$.

Then by using the independence of $z\left[n\right]$'s we have,

$$\begin{aligned}\phi_T(\omega) &= E\left[\exp(j\omega T)\right]\\ &= E\left[\exp\left(j\omega\sum_{n=0}^{N-1}\alpha_n z^2\left[n\right]\right)\right]\\ &= \prod_{n=0}^{N-1}E\left[\exp\left(j\omega\alpha_n z^2\left[n\right]\right)\right]\\ &= \prod_{n=0}^{N-1}\phi_{z^2}(\alpha_n\omega)\end{aligned}$$

The PDF of *T* is obtained as the inverse Fourier transform of the characteristic function or,

$$p_T(t)=\begin{cases}\int_{-\infty}^{\infty}\phi_T(\omega)\exp\left(-j\omega t\right)\frac{d\omega}{2\pi} & t\ge 0\\ 0 & t\le 0\end{cases} \tag{5.08}$$

Since $T\ge 0$ and hence $p_T(t)=0$ for $t<0$. Now $z^2\left[n\right]\sim\chi_1^2$ and the characteristic function can be shown to be:

$$\phi_{\chi_1^2}(\omega)=\frac{1}{\sqrt{1-2j\omega}} \tag{5.09}$$

Thus,

$$\phi_T(\omega)=\prod_{n=0}^{N-1}\frac{1}{\sqrt{1-2j\alpha_n\omega}} \tag{5.10}$$

where,

$$\alpha_n=\frac{\lambda_{s_n}\sigma^2}{\lambda_{s_n}+\sigma^2} \tag{5.11}$$

So we can write the Probability of False Alarm as,

$$P_F = \int_{\gamma^H}^{\infty} \int_{-\infty}^{\infty} \prod_{n=0}^{N-1} \frac{1}{\sqrt{1-2j\alpha_n\omega}} \exp\left(-j\omega t\right) \frac{d\omega}{2\pi} dt \tag{5.12}$$

Similarly, we can show that Probability of Detection is,

$$P_D = \int_{\gamma^H}^{\infty} \int_{-\infty}^{\infty} \prod_{n=0}^{N-1} \frac{1}{\sqrt{1-2j\lambda_{S_n}\omega}} \exp\left(-j\omega t\right) \frac{d\omega}{2\pi} dt \tag{5.13}$$

5.2 Analysis of Results

Analytical values of equation parameters:

Term	**Denoted by**	**Value**
Number of Samples	N	10, 15, 30, 40
Channel Variance	σ	0.42
n-th Eigenvalue	$\lambda_n = 0.30\left(\frac{N.4}{n(N-n)+N}\right)$	$n = 0 \ldots N-1$
Coefficient of the Random Variable	$\alpha_n = \frac{\sigma_w^2 \lambda_n}{\lambda_n + \sigma_w^2}$	$n = 0 \ldots N-1$
Integration Upper Limit	R	12
Integration Lower Limit	γ	1,1.25,…,12

Equation for Probability of Detection:

$$P_D = \int_{\gamma^H}^{\infty}\int_{-\infty}^{\infty}\prod_{n=0}^{N-1}\frac{1}{\sqrt{1-2j\lambda_{s_n}\omega}}\exp(-j\omega t)\frac{d\omega}{2\pi}dt$$

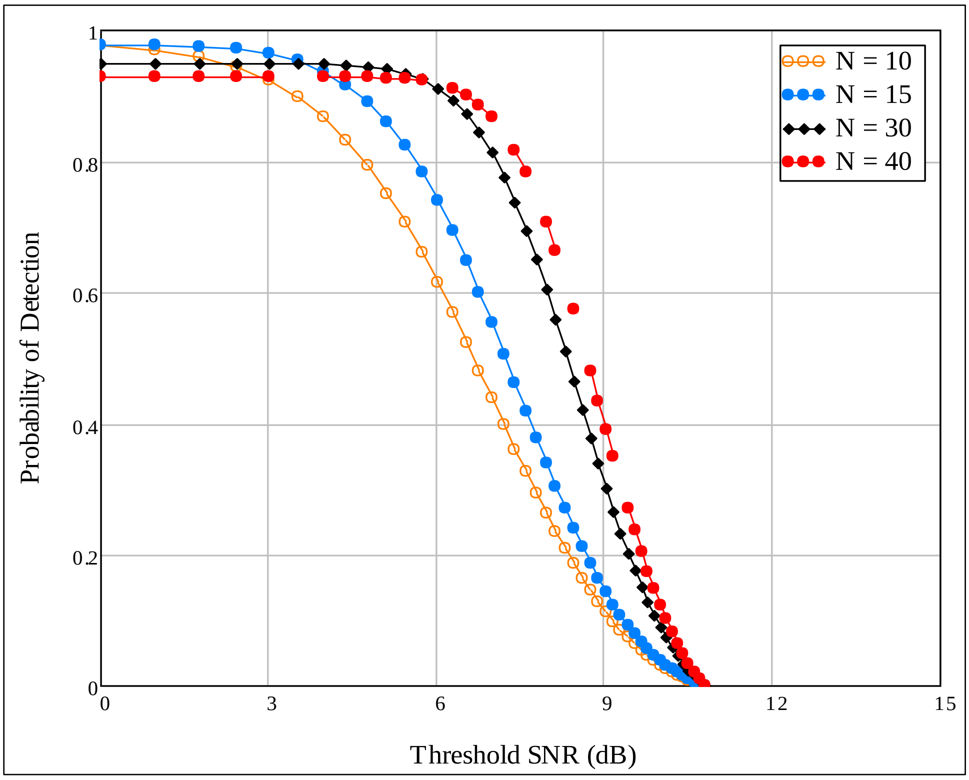

Figure 5-1: Probability of Detection with four sample values

In Figure 5.1 P_D is plotted against threshold SNR in dB taking four samples values N . We observe that for the value $N = 40$ the curve is discontinuous so we keep the upper limit of our analysis up to $N = 30$. The plotted graph is as follows:

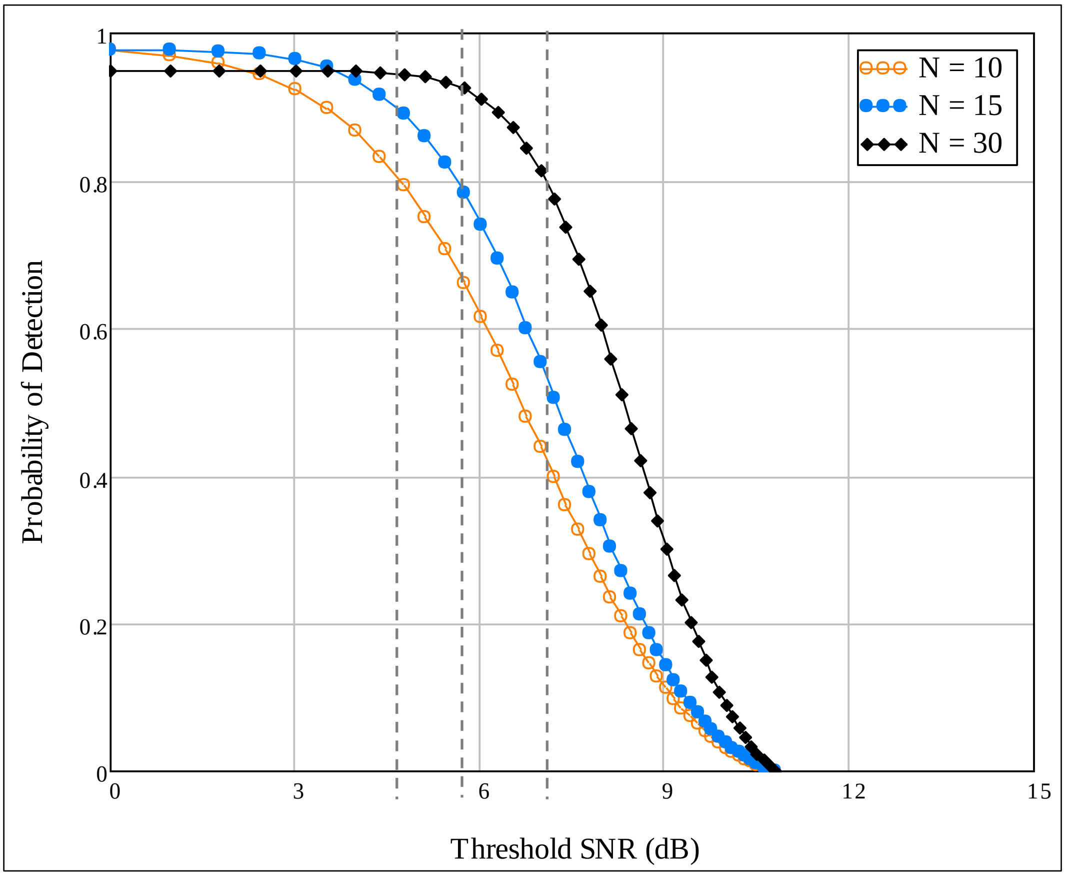

Figure 5-2: Probability of Detection with three sample values

From Figure 5.2 we observe that P_D decreases with increasing threshold SNR but increase with higher number of sample value N . To get P_D above 80% we have to select threshold SNR < 7.1 dB for $N = 30$, < 5.7 dB for $N = 15$ and < 4.6 dB for $N = 10$.

Equation for Probability of False Alarm:

$$P_F = \int_{\gamma^H}^{\infty} \int_{-\infty}^{\infty} \prod_{n=0}^{N-1} \frac{1}{\sqrt{1-2j\alpha_n \omega}} \exp(-j\omega t) \frac{d\omega}{2\pi} dt$$

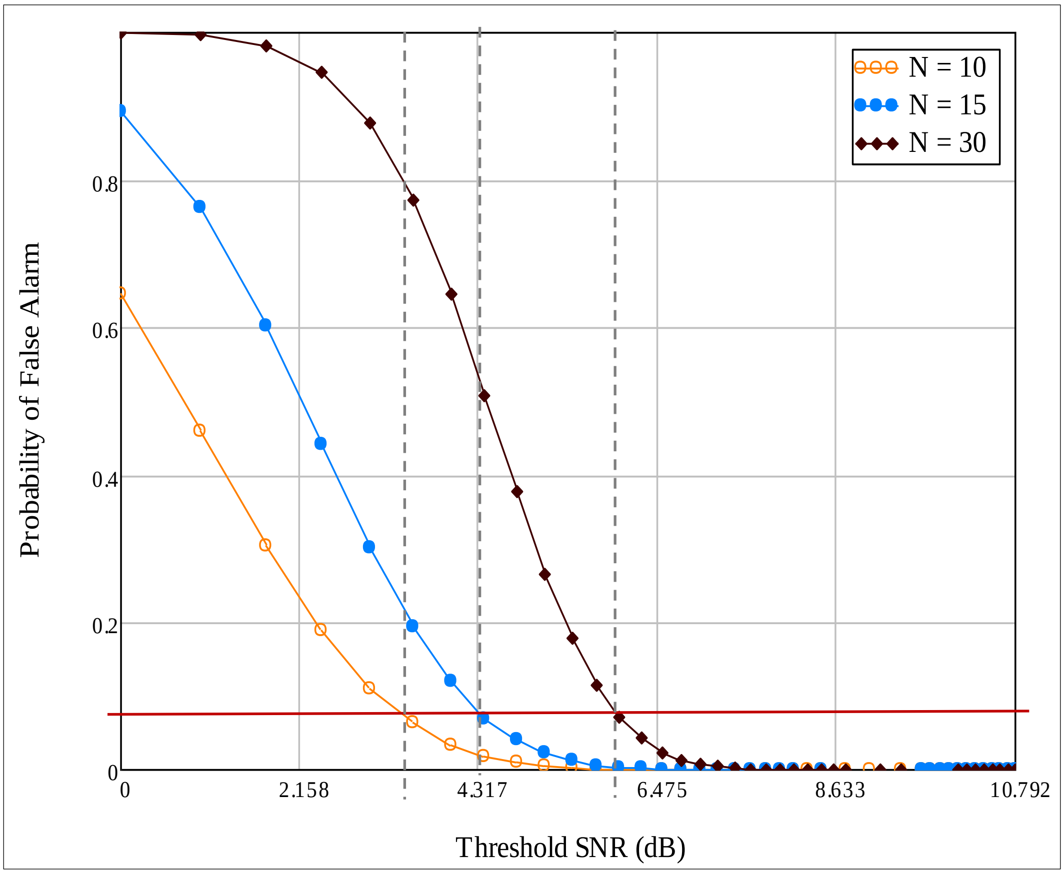

Figure 5-3: Probability of False Alarm with three sample values

In Figure 5.3 P_F is plotted against threshold SNR taking three sample values of N. To keep P_F less than 8% we have to keep threshold SNR ≥ 3.5 dB for $N = 10$, SNR≥ 4.3 dB for $N = 15$ and SNR > 6.0 dB for $N = 30$.

Therefore, for optimum detection maintining the condition (P_D > 80% and P_F < 8%) the threhsold SNR value should be:

for $N = 10$: 4.0 dB

for $N = 15$: 4.5 dB

for $N = 30$: 6.0 dB

Conclusion and Future Work

The objective of this project work was to calculate the threshold SNR value for Gaussian AWGN channel with MIMO system by maintaining P_D above 80% and P_F less than 8%. We have met or objective by changing some parameters and set the condition for AWGN channel. Here lower number of samples were required for MIMO system but if Single-Input-Single-Output (SISO) system were considered then larger amount of samples (>100) were required.

Also as we considered only AWGN channel, this model is applicable only for pico cell or famto cell scenario. For micro cell environment large scale fading parameters have to be taken into consideration. Also different channel fading characteristics like Rayleigh fading, Rician fading, Nakagami-m fading etc. are needed to be analyzed. We can further compare the performance deterioration due to large scale fading and determine the threshold SNR for different channel characteristics for similar parameters.

Our further work also includes to analyze this scenario with independent and identically distributed central chi-square function with n-degree of freedom. We will compare the performance incorporating with different fading channels and analyze the output.

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