IMPROVED SPECTRUM SENSING USING MULTIPLE ENERGY DETECTORS

Dissertation Submitted in partial fulfillment of the requirement for the degree of

MASTER OF TECHNOLOGY
IN
ELECTRONICS AND COMMUNICATION ENGINEERING

By

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CERTIFICATE

This is to certify that the work titled **"IMPROVED SPECTRUM SENSING USING MULTIPLE ENERGY DETECTOR WITH OPTIMIZED THRESHOLD"** submitted by "ANURAG CHAUHAN" in partial fulfillment for the award of degree of Master of Technology in Electronics & Communication Engineering, Jaypee University of Information Technology, Waknaghat has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree or diploma.

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I would like to thank my supervisor Assistant Professor, Department of Electronics & Communication Engineering, Jaypee University of Information technology, Waknaghat, "**Dr.NEERU SHARMA**" for her constant help and guidance and provided me the idea and related material for the project proposal. She indeed guided me to do the task for my thesis in such a way that it seems to be research work. Her continuous monitoring to support me and my research work encouraged me a lot for doing my thesis in very smooth manner.

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ABSTRACT

Cognitive radio is an exciting promising technology which not only has the potential of dealing with the inflexible prerequisites but also the scarcity of the radio spectrum usage. Such an innovative and transforming technology presents an exemplar change in the design of wireless communication systems, as it allows the efficient utilization of the radio spectrum by spectrum allocation based on the cognitive cycle. The basic idea in cognitive radio is to permit some unlicensed (secondary) users to operate in a licensed frequency band, without causing interference to the licensed (primary) user. The aim of this study is to focus on spectrum sensing in cognitive radio which is a recently introduced technology in order to increase the spectrum efficiency. Increasing efficiency of the spectrum usage is an urgent need as an intrinsic result of the rapidly increasing number of wireless users and also the conversion of voice oriented applications to multimedia applications. Static allocation of the frequency spectrum does not meet the needs of current wireless technology that is why dynamic spectrum usage is required for wireless networks. Cognitive radio is considered as a promising candidate to be employed in such systems as they are aware of their operating environments and can adjust their parameters. Cognitive radio can sense the spectrum and detect the idle frequency bands, thus secondary users can be allocated in those bands when primary users do not use those bands in order to avoid any interference to primary user by secondary user. There are several spectrum sensing techniques proposed in literature for cognitive radio based systems. In this thesis, conventional energy detection and multiple energy detector with optimized threshold based spectrum sensing systems for cognitive radios is examined in detail and comparative performance results are obtained.

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CR	Cognitive Radio
CFAR	Constant False Alarm Rate
CSD	Cooperative Spectrum Detection
FCC	Federal Communication Commission
ITU	International Telecommunication Union
LOS	Line-Of-Sight
LRT	Likelihood Ratio Test
MAI	Multi-User Access Interference
ML	Maximum likelihood
NB	Narrow Band
NBI	Narrow Band Interference
PDF	Probability Density Function
PSD	Power Spectral Density
PU	Primary user
SU	Secondary user
BS	Base station
QoS	Quality of service
SNR	Signal to Noise Ratio

SINR	Signal to interference ratio
SDR	Software Defined Radio
CED	Conventional Energy Detector
MED	Multiple Energy Detector

CHAPTER 1
INTRODUCTION

Communication is mainly classified as wired and wireless. It is commonly believed that there is a scarcity of spectrum availability at frequencies that can be economically used for wireless communications; this misconception has arisen from the intense competition for use of spectra at some bands of frequencies. At some other frequencies there is actually very little spectrum usage. The ever increasing utilization of radio spectrum has resulted in an apparent spectrum scarcity. It is obtained from the analysis that this scarcity can be attributed to the inefficient fixed spectrum allocation techniques. These techniques are easier to implement but mainly result in great variations in spectrum utilization in different frequency bands [1][4]. This non-uniform distribution of users in different bands creates the notion that the spectrum is a finite resource about to become overly congested with potential users. Dynamic spectrum access (DSA) or Next Generation (xG) Networks have been suggested as few of the most effective remedial measures. DSA advocates use of less congested spectrum bands by the users from more congested frequency bands. The concept has evolved from a definition to a proposed IEEE standard (IEEE 802.22) in just over a decade. The Federal Communication Commission (FCC) has suggested exploration of the Digital Television (DTV) band for the purpose of DSA [3]-[5] and it is a popular research area. In the proposed approach it allows the secondary users (or non-licensed users) to utilize the frequency band which is licensed to the primary users (PUs), only when if it can be ensured that the band is not being currently used by the PUs, causing no interference to primary user. Cognitive Radio (CR) is the key enabling technology for the implementation of DSA. A CR is an evolved Software Defined Radio (SDR) that, in addition to the capability to change itself, also possesses the ability to analyze its surrounding radio environment and decide the best way to adapt itself. The CR has the ability to identify any opportunities that exist in the spectrum band of interest and utilize them without causing any interference to the PUs. These opportunities exist in the form of spectrum holes. A spectrum hole is the part of the spectrum which is unoccupied by the PU.

This seems totally in contradiction to the concern of spectrum shortage, since in fact we have spectrum abundance, and the spectrum shortage is in part an artificial result of the regulatory and licensing process. Therefore, the spectrum usage is inconsistent with different regulatory agencies (e.g. Federal Communication Commission (FCC) in the United States) frequency chart that indicates there are multiple allocations over all of the frequency bands [1] [2]. It is this discrepancy between these agencies allocations and actual usage which indicates that a new approach to spectrum licensing is needed. What is clearly needed is an opportunistic usage of this licensed spectrum. An approach, which can meet these goals, is to develop a radio system that is able to reliably sense the spectral environment over a wide bandwidth, detect the presence or absence of primary users and use the spectrum only if communication does not interfere with any primary user. These radios are lower priority secondary users**,** which exploit cognitive radio (CR) techniques, to ensure non interfering co-existence with the primary users**.** Regulatory domains are also realizing the need for new technologies in order to efficiently use available spectral resources. Recent studies by the FCC spectrum policy task force have reported vast temporal and geographic variations in the usage of allocated spectrum [2]. In order to utilize these ‘white spaces’, the FCC has issued a notice of proposed rulemaking advancing CR technology as a candidate to implement negotiated or opportunistic spectrum sharing [3]. A radio or system that senses and aware of its operational environment and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly is called cognitive radio.

Cognitive radio is a new concept of reusing licensed spectrum in an unlicensed manner. The unused resources are often referred to as spectrum holes or white spaces. These spectrum holes could be reused by cognitive radios in an opportunistic way called as opportunistic access.

It is shown in Fig. 1.1 that some band of frequency is in heavy use; some band is used sparsely while some frequencies come under the medium use. This shows that spectrum band is not utilized efficiently.

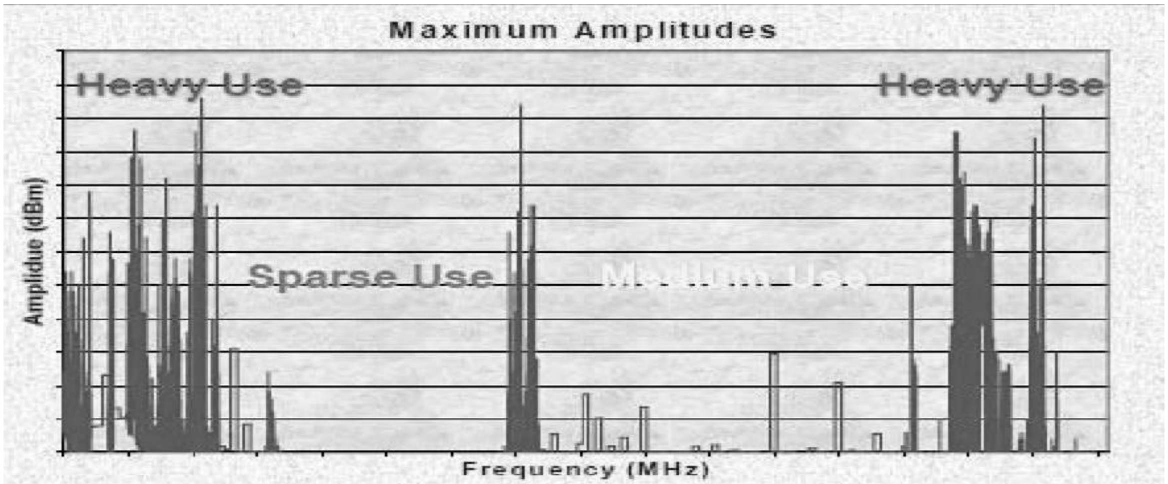

Fig. 1.1 Spectrum Utilization

1.1 Motivation

Most of today's radio systems bands are using a specific spectrum band that function in a particular frequency. Spectrum utilization investigations indicate that the entire spectrum is not used in space (geographic location) or time. So, a radio which can identify and sense its local radio spectrum situation, to recognize temporarily vacant spectrum and make use of it, posses the potential to present higher bandwidth services, enhance spectrum competence and lessen the need for centralized spectrum organization. This might be achieved through a radio which can formulate autonomous decisions regarding how it accesses spectrum. Cognitive radios have the potential to jump in and out of unused spectrum gaps to enhance the spectrum competence and make available wideband services. At different locations or at different times of the day, 70 percent of the allocated spectrum might be in idle state. It is recently suggested by the FCC that significantly greater spectral efficiency might be realized by deploying wireless devices which can coexist with the licensed users.

1.2 Objective

Spectrum sensing plays an important role for implementation of the cognitive radio because on spectrum allocation totally depends on the spectrum sensing. We know that Cognitive radio technology is aware of its surrounding frequency environment, in order to provide the quality of service to the primary user, sensing should be accurate and filling the discovered gaps of unused licensed spectrum with their own transmissions. Precise spectrum awareness is the main concern for the cognitive radio system (secondary user). In this regard it is a proposal that transmission should be adaptive in accordance with spectrum sensing in unused spectral bands without causing interference to the primary user. The transmissions of licensed users have to be detected without failure and the main goal for adaptive transmission is the detection of vacant frequency bands. A scheme is propose to form a cognitive radio that works intelligently to detect vacant frequency bands professionally with better probability of error and detection reliability.

1.3 Outline of Dissertation

Chapter 1 includes the brief introduction of the subject of spectrum sensing cognitive radio, motivation behind this thesis and the objectives of this research.

Chapter 2 describes detailed information about cognitive radio. A detailed architecture, operation and applications of cognitive radio are described.

Chapter 3 A literature review of the research that has been done in the related areas of spectrum sensing, cognitive radio networks and spectrum sensing in standards is discussed.

Chapter 4 deals with the spectrum sensing and various existing techniques used.

Chapter 5 contains the detection theory and hypothesis based on which decision is to be made.

Chapter 6 consists of types of antenna diversity and broadly used diversity combining techniques.

Chapter 7 describes the convention energy detector and the noise uncertainty criteria.

Chapter 8 considered the problem of spectrum sensing in Cognitive radio. To deal with problems of sensing proposed work which is improved spectrum sensing using multiple energy detector is explained.

Chapter 9 deals with the simulation and results where simulation parameters, corroborating simulations with results are provided.

Chapter 10 proposed work is concluded in chapter 10 with some future work suggestion in brief.

CHAPTER 2
COGNITIVE RADIO

Cognitive radio is an intelligent wireless communication system. It realizes spectrum sharing and dynamic spectrum allocation by the spectrum sensing and intelligent learning ability of the system. It is visible that spectrum allocation is an important content in the cognitive radio. Spectrum allocation refers to allocate spectrum to one or more given nodes based on the node number which needs to access system and its service requirements. The choice of spectrum allocation strategy directly determines the system capacity, spectrum utilization rate and whether it will meet users' continuous changing needs because of different business.

2.1 Different Definitions of Cognitive Radio

Different groups have given different definitions for cognitive radio. To better understand the definitions by the different groups, it is important to present them in brief as follows. In 1999 the paper that first coined the term "cognitive radio", Joseph Mitola III defines a cognitive radio as [3]:

> *"The term cognitive radio identifies the point at which wireless personal digital assistants and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to: detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs."*

The other reputable author in the communication areas and a life fellow of IEEE, Simon Haykin, defines cognitive radio as [1]:

> *"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 Radio frequency (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."*

Coming from a background where regulations focus on the operation of transmitters, the FCC has defined a cognitive radio as [4]:

> *"A cognitive radio goes one step further from software defined radio, and empowers the radio to alter its transmitter parameters based on interaction with the environment in which it operates."*

Meanwhile, the other primary spectrum regulatory body in the US, the NTIA [10], adopted the following definition of cognitive radio that focuses on some of the applications of cognitive radio:

> *"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, and access secondary markets."*

While aiding the FCC in its efforts to define cognitive radio, IEEE USA offered the following definition [4]:

> *"A radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorized users."*

The broader IEEE tasked the IEEE 1900.1 group to define cognitive radio which has the following working definition [12]:

> *"A type of radio that can sense and autonomously reason about its environment and adapt accordingly. This radio could employ knowledge representation, automated reasoning and machine learning mechanisms in establishing, conducting, or terminating communication or networking functions with other radios. Cognitive radios can be trained to dynamically and autonomously adjust its operating parameters."*

The Virginia Tech Cognitive Radio Working Group which has a large involvement in the development of the technology has adopted the following capability- focused definition of cognitive radio [13]:

"An adaptive radio that is capable of the following:

- *Awareness of its environment and its own capabilities*

- *Goal driven autonomous operation,*
- *Understanding or learning how its actions impact its goal,*
- *Recalling and correlating past actions, environments, and performance."*

These definitions reveal some commonalities among these definitions. First, all of these definitions assume that cognition will be implemented as a control process, presumably as part of a software defined radio. Second, all of the definitions at least imply some capability of autonomous operation.

2.2 Cognitive Radio Network

Cognitive radio networks do not have the permission to operate in the required band. The CR networks can be deployed both with infrastructure and without infrastructure networks as illustrated in Fig. 2.1.The components of the network are as follows:

• **Cognitive Radio user:** The CR user (the unlicensed user) has no spectrum license, so extra functionalities are needed for sharing the spectrum band.

• **Cognitive Radio base-station:** The CR base-station (the unlicensed base station) has a fixed infrastructure component with CR abilities. Cognitive Radio can access the different networks by providing the single hop network connection to CR user [5]. Single hop connection is used to reduce the propagation delay; it has now become essential to have single hop network connection which connects the user terminals.

The CR network architecture in Fig. 2.1 shows different types of networks primary network access, with infrastructure based CR network, without infrastructure based CR network (ad-hoc network). The CR networks operate both in licensed and unlicensed bands (mixed spectrum environment). There are three access types are:

- **CR network access:** The CR users can access the CR base-station not only the licensed bands but also the unlicensed spectrum bands.
- **CR ad hoc access:** The CR users communicate with different CR users through the ad-hoc connection on licensed and unlicensed bands.
- **Primary network access:** The licensed bands are means for the CR users through which they access the primary base-station.

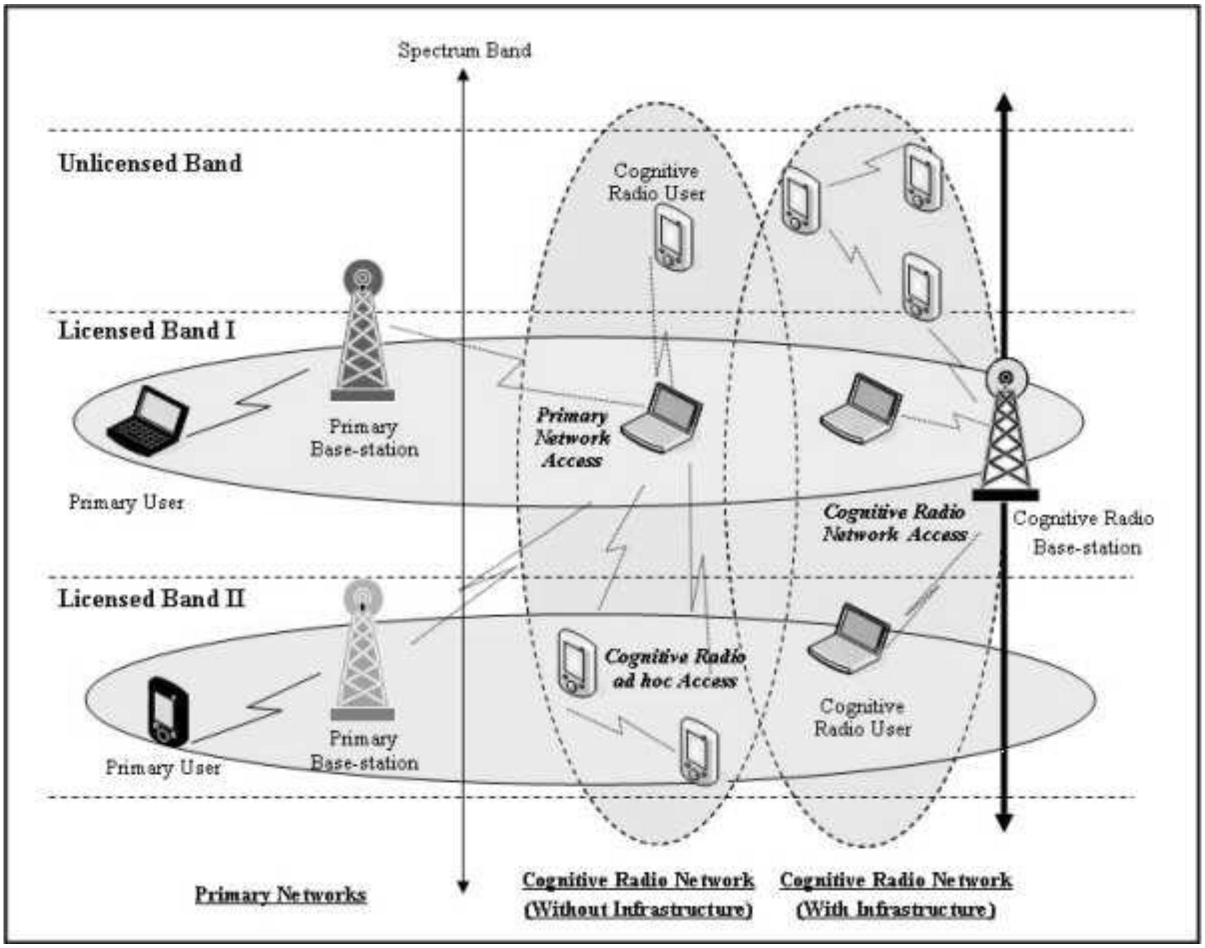

Fig. 2.1 Cognitive Radio Architecture

2.3 Software Defined Radio

Wireless technology basically depends on the signals, physical hardware and their attributes. In the past communication technology had straightforward signaling, analog hardware and very limited functionality. The Software Defined Radio (SDR) was introduced for handling more than one communication technology (e.g. GSM and CDMA) [3]. such that the terminals can change their operation with respect to the software. In recent times different signaling methods have been proposed and used in various communication technologies all over the world.

Software defined radio enhances the wireless devices with cognition abilities like awareness, learning, sensing and reasoning. Also, it has the capability to resolve the emerging interoperability issue by providing a global seamless connection. Before the invention of cognitive radio, SDR was focused on multi-mode and multi-standard devices. SDR plays a vital role, to realize the features of cognitive radio [3].

2.3.1 SDR and Its Relationship with Cognitive Radio

Previously there was discussion about the adaptability of being the main property of the cognitive radio where frequency, power, modulation and bandwidth can be changed according to the current radio environment. To avoid analog circuits and components, SDR provides variable radio functionality. The cognitive radio is basically a SDR which already knows the condition, state, position and automatically adjusts its functions according to the desired objectives.

The relation between the SDP and the cognitive radio can be demonstrated in Fig.2.2 .It is clear from the below diagram that the cognitive radio encompasses the SDR. The SDR is developed in software based on Digital Signal Processing with the modifiable Radio Frequency components .Hence, the SDR is a generic radio platform which has the capability to operate in different bandwidths over a large number of frequencies as well as using different modulation schemes and waveform formats. As a result of this, the SDR can support multiple standards such as GSM, WCDMA, WIMAX etc., and multiple access schemes such as TDMA, OFDM and SDMA etc.

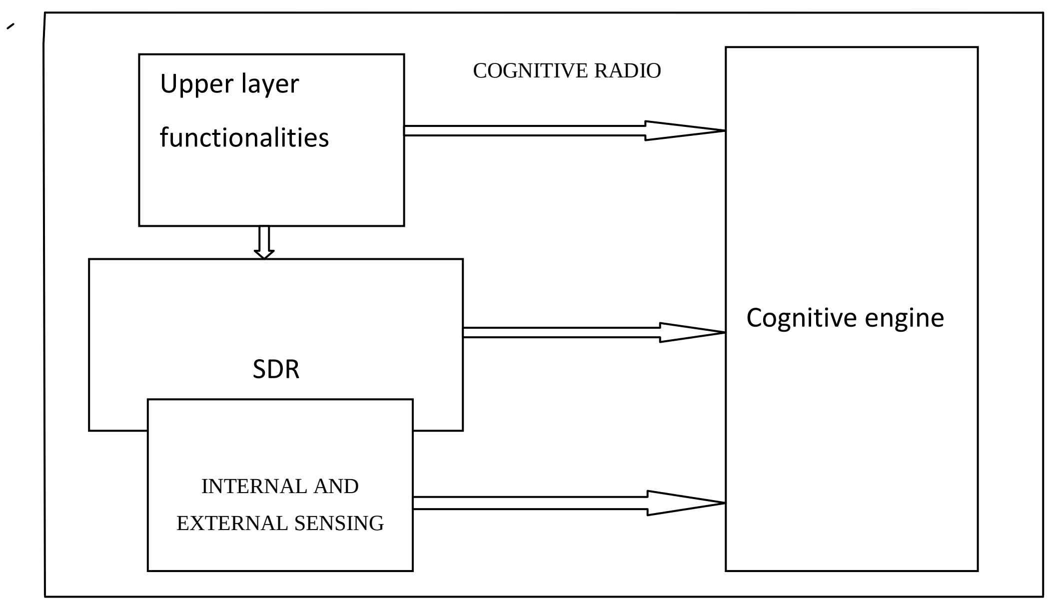

Fig.2.2: SDR and Cognitive Radio

2.4 Cognitive Cycle

In cognitive radio its operation is mainly described according to the basic cognitive cycle as shown in Fig. 2.3

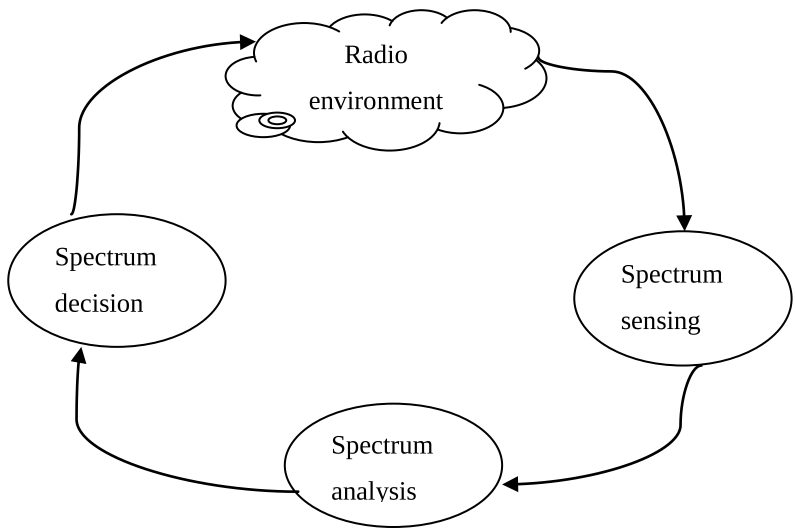

Fig. 2.3 Basic Cognitive Cycle

Spectrum Sensing

In spectrum sensing it mainly deals with perception or awareness about the spectrum. Spectrum sensing is the basic functionality of the cognitive radio. It gives the information about whether the spectrum is available or being used by some other users. Spectrum sensing should be highly robust to make cognitive radio functional.

Spectrum analysis

Spectrum analysis discovers the different functionalities of the spectrum bands, to make productive use of the spectrum band according to the requirements. Each spectrum hole (Band of frequencies assigned to the primary user, but at a specific time and geographic location, these bands is not fully utilized by that user [2].) should be defined according to the time varying environment and the information of the band like frequency and bandwidth. To represent the quality of the spectrum band, parameters are defined such as interference, holding time, path loss, link layer delay, wireless link errors etc.

- **Interference:** The interference characteristics of the channel can be determined from the spectrum band in used. The permissible power of a CR user can be calculated, from the amount of interference which is use for the calculation of the channel capacity.
- **Holding time:** Holding time is an expected time, from which the CR user occupy the licensed band before its interruption. For better quality holding time should be as long as possible.
- **Path loss:** If the operating frequency increases, the path loss will also be increased. If the cognitive users have the constant transmission power then at higher frequencies their transmission range decreases. In order to compensate the increased path loss if we increase the transmission power this yields in higher interference to the other users.
- **Wireless link errors:** This error rate of the channel changes according to the change in modulation scheme and interference level of the spectrum band.
- **Link layer delay:** Different link layer protocols are required to address path loss, interference and wireless link errors [4][7].

Spectrum decision

When an analysis of all the spectrum bands is completed, a spectrum band should be selected for the transmission according to the QoS requirements. The decision rules are focused on the cost of communication and fairness [6].

2.5 Applications of Cognitive Radio

More efficient and flexible use of spectrum in the near future will open up exciting opportunities for cognitive radio to support a variety of applications, ranging from public safety and broadband cellular, to medical applications. Some of the applications are given below and a brief view on how cognitive radio would support such applications, the benefits that cognitive radio would bring, and also some challenges that are yet to be resolved are explained.

2.5.1 Public Safety networks:

We know that wireless communication system is being widely used by the emergency responders e.g., fire, police, and emergency medical services. Also, this wireless service is not limited to the voice or messaging. It has extended to web browsing, email, picture and video transfer etc. The radio frequencies being used in the public safety environment have become congested. This congestion is more in urban areas. Sometime the agencies and first responders from different jurisdictions are not able to communicate during the emergency. This hampering in interoperability is because of by the use of multiple frequency bands, lack of standardization and incompatible radio equipment.

Cognitive radio is the best technology that can overcome all the above challenges and can increase the efficiency of spectrum usage. With CR additional spectrum such as license-exempt TV band can be used by the public safety users. But to access licensed spectrum of commercial operator there is a need of appropriate spectr.um sharing partnerships. For example, the public safety community will be allowed to roam on the commercial networks in 700 MHz in the areas where public safety broadband wireless networks will be unavailable or there will be requirement of more capacity to respond to an emergency. [19]

During natural disasters, existing communication infrastructure may get destroyed. In such situations emergency personnel and public safety user working in the disaster areas needs immediate established emergency networks. As these emergency networks deal with the critical information, so there is need of reliable communication with minimum latency. Also there is requirement of a significant amount of radio spectrum for handling huge volume of traffic including voice, video and data. Cognitive radio networks are capable of enabling the usage of the existing spectrum without the need for an infrastructure [20, 21].

2.5.2 Wireless Medical Networks

In recent years interest for the implementation of ubiquitous monitoring of patients in hospitals is increasing mainly for vital signs such as temperature, pressure, blood oxygen, and electrocardiogram (ECG) etc. This monitoring is done using the on-body sensors that are connected by wires to a bedside monitor. The MBANs are used in eliminating the wires.

So the MBANs would help in increasing the patient comfort and mobility, and improve quality of medical decision making.

The main priority for MBAN's is to maintain quality of service, this can be possibly attained if spectrum is not more crowded. For medical applications usually WMTS band is used but due to bandwidth scarcity the desired need cannot be met. As there is a lot of interference present in the ISM band it is not suitable to use it for the applications where QoS is a critical factor. There is one more option i.e. the 2.4 GHz industrial, scientific, and medical (ISM) band but it is not suitable for life-critical medical applications. The reason is the interference and congestion from IT wireless networks in hospitals. By using the 2360–2400 band allocated for MBANs on a secondary basis, Qos for these monitoring applications can be respected. Also the 2360–2400 MHz band is immediately adjacent to the 2400 MHz band for which there exist many devices today that could easily be reused for MBANS, such as IEEE 802.15.4 radios and it makes low-cost implementations easy which leads to wider deployment of MBANs.[20]

2.5.3 Cellular Networks

There have been lots of changes in the use of cellular in recent years. Because of the expectation of consumer of being connected always, anywhere and anytime is high. The popularity of smart phones, social networks, growing media sites such as YouTube, devices such as e-readers, is responsible for the addition to the already high and growing use of cellular networks that was needed for conventional data services such as email and web-browsing. This can be taken as opportunity as well as a challenge for cellular operators. This is opportunity because it will lead to increased average revenue per user due to added data services and it is challenge is because in certain geographical areas, cellular networks are overloaded, due partly to limited spectrum resources owned by the cellular operator

With the ruling FCC's TVWS, the new spectrum becomes available to cellular operators. In near future television band spectrum which is not declared white space yet, may also become available to cellular operators according to National Broadband Plan. This plan discusses the possibility of voluntarily auction of their licenses by current license holders of television spectrum, in return for part of the proceeds from the auction. The vision of the plan is to use this newly freed spectrum for cellular broadband applications.

Rural areas i.e. areas with low population density distribution are known for poor coverage. Cellular operators have been given rights to use their spectrum nationwide, but they choose not to deploy their networks in rural areas[11]. The reason is that infrastructure costs is a significant part of the costs of a cellular operator. It is not possible to recover this cost in rural areas because of lack of number of subscribers in a given area. With white space spectrum, the problem can be solved. For example, by making white space spectrum available for unlicensed use, this white space spectrum can be used by cellular operators for backhaul, for connecting their cell towers to their backbone networks, and thus provide coverage to more customers in not served and underserved areas. For using additional spectrum some design considerations should be kept in mind given that the transmission requirements associated with the additional spectrum are varying significantly from that of the primary cellular spectrum [20].

2.5.4 Military Network

Cognitive radio can play an interesting role in military application especially in a military radio environment [14]. It can be used to enable the military radio to choose arbitrary modulation scheme, coding scheme, intermediate frequency according to the variable radio environment of battlefield. Military networks need security and protection of communication in hostile environment. Cognitive radio network will allow the spectrum handoff to find secure spectrum.

2.6 Limitations of Cognitive Radio

As there are significant advantages of CR, there are a number of key challenges. Ideally a CR should have no impact on other radio users, but in reality some impact is expected particularly on non-cognitive primary radio users. The autonomous adaptive nature of CR means that it could be difficult to predict and control the spectrum behavior of individual radios: a concern for anyone who might suffer from CR interference. A method may be required to audit and trace CR spectrum usage in legacy bands. The communications industry’s greatest concern with CR is the hidden node problem. This situation arises when a CR is unable to detect all of the radios with which it might interfere, not because its own spectrum sensing is ineffective, but because some radios are hidden from it. The hidden node problem is a big challenge facing the widespread market deployment of spectrally aware CR. CR is located far away from a transmitting contemporary user, but is very close to a receiving contemporary user. The receiving contemporary user is at the edge of its cell.

CR will suffer from the same security issues as SDR such as malicious use, leading to unexpected or problematic behavior of individual CRs or potentially entire networks.

CHAPTER 3
LITERATURE REVIEW

3.1 Overview

The radio spectrum scarcity is a fundamental dilemma which greatly limits the growth of wireless access. However, still there is a possibility to improve the spectrum efficiency by using unoccupied bands and thereby providing a solution to alleviate the spectrum scarcity [1][8].

In order to control the radio spectrum usage and to protect the primary users (PUs), international and local regulatory bodies impose strict rules on radio resource and access. Though these regulations and standards help safeguard the resource and licensed users, in contrast, these command-and-control rules forbid the access of unoccupied resource even when there is no harm to the PUs. However, radio access technology is not developed to utilize such unoccupied spectrum bands which must perform some additional tasks. The cognitive radio technology is proposed to carry out these additional tasks and to make use of these unused spectrum bands.

In this context, by passive sensing of the radio spectrum, frequency bands can be mainly classified into three types as shown in Fig. 3.1, namely,

1. Black spaces - occupied by high power local interferers
2. Grey spaces - partially occupied by low power interferers
3. White spaces - unoccupied free band (except the surround noise).

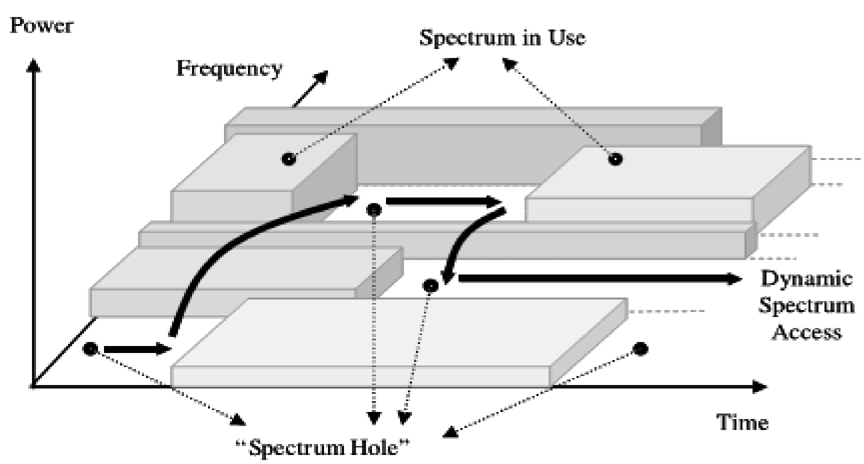

Fig. 3.1 Spectrum Holes

Cognitive users (CUs) can occupy white spaces and grey spaces with the promise to avoid disturbances to the PU. Thus, CUs require releasing the radio resource totally or partially giving the priority to PUs.

Recent literature proposes three main techniques to detect the presence of spectrum holes; matched filtering, energy detection and cyclostationary feature detection. Out of these three techniques, energy detection is of particular interest due to its simplicity in implementation and the capability to detect any shape of waveforms. Further, the primary user transmission is modeled as a signal with known power, and hence the energy detector (ED) is optimal [17][18]. In addition to applications in cognitive radio, the energy detector finds many applications in ultra wide-band technologies.

Thus, the analysis of the performance of energy detector in different wireless environments and with variety of integrated techniques is of particular interest in these two fields. The underutilization of spectrum bands leads to the definition of term spectrum hole. The spectrum hole is formally defined as below [1].

Spectrum Hole

A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.

The cognitive radio is proposed as a mean to access such spectrum holes opportunistically by the CUs, after exploiting its existence, with the intention to improve the spectrum efficiency.

3.2 Cognitive Tasks

In order to build a cognitive radio system, following cognitive tasks must be performed.

1. Radio-scene analysis consists of:
    - Estimation of interference temperature of surrounding radio environment
    - Detection of spectrum holes
2. Channel identification consists of:
    - Estimation of channel state information (CSI)
    - Estimation of channel capacity
3. Transmitter power control and dynamic spectrum management

The functions in 1 and 2 are carried out at the receiver while 3 are performed at the transmitter. In order to exchange information between the transmitter and receiver, there should be a feedback channel [1]. In this research work, we will focus on the “Detection of spectrum holes”.

3.3 Detection of Spectrum Holes

As listed in section (2.2), the detection of spectrum holes is one main task to perform by cognitive users in analyzing the radio scene. There are three main methods proposed in literature for spectrum sensing, and thereby detect the available spectrum holes[6][7].

1. Detection through an Energy Detector
2. Matched Filter Detection
3. Cyclostationary Feature Detection.

All three methods possess unique properties which are appropriate in different environment settings. These techniques intend to detect the presence of PU transmissions and thereby with priory knowledge of the available total range of frequency bands, spectrum holes can be identified[8].

In [3], it shows that the matched filter can maximize the received SNR, it requires demodulation of a primary user signal and it can perform coherent detection. The advantage of matched filter is that according to consistent, to get high processing gain less time is needed. However, a significant disadvantage of a matched filter is that a special receiver is necessary for every primary user. So the utilization of the matched filter is restricted by the drawback mentioned above.

The energy detector simplifies the matched filter to perform non-coherent detection. It detects the received signals‟ energy to compare with the threshold and then deduce the status of the primary signals. The disadvantage is that a threshold we used will be easily influenced by unknown or changing noise levels, so the energy detector will be confused by the presence of any in-band interference [3].

It is investigated that within a special modulation type, the cyclostationary feature detector is able to exploit the inherent periodicity in the received signal to detect primary signals since most signals vary with time periodically [14]. There is also a disadvantage that longer processing time and higher computational complexity is needed with the cyclostationary feature detector [11].

3.4 Spectrum Sensing In Current Wireless Standards

In this section, wireless technologies which involve a short kind of spectrum sensing for dynamic frequency access (DFA) are summarized.

3.4.1 IEEE 802.11k

An anticipated expansion of the IEEE 802.11 pattern is IEEE 802.11k which describes a number of types of measurements. In order to make its own measurements, AP collects information from each mobile unit. This data enables the AP to control access to a given channel. Thus the sensing (or measured) information is used to perk up the traffic allocation in a network as well. WLAN devices generally connect to that AP which has the strongest signal level. Sometimes, such an arrangement could not be optimal and can cause overloading on one AP and causing the underutilization of others. Whereas in 802.11k, when an AP is loaded to its full capacity with the strongest signal, regardless of the fact that the received signal level is weaker, new subscriber units are assigned to one of the underutilized AP.

3.4.2 Bluetooth

To reduce interfering between wireless technologies which are sharing the 2.4GHz unlicensed radio spectrum, a new feature named as adaptive frequency hopping (AFH) is integrated to the Bluetooth standard.

AFH is used for identification for transmissions in the industrial, scientific and medical (ISM) band but remains away from their frequencies. Therefore transmit power is reduced, better bit error rate (BER) performance is achieved and narrow band interference can be avoided. Fig. 3.2 depicts a representation of Bluetooth communication with AFH and without AFH. This example in Fig. shows that by utilizing AFH, collisions with the signals of WLAN are restricted [25].

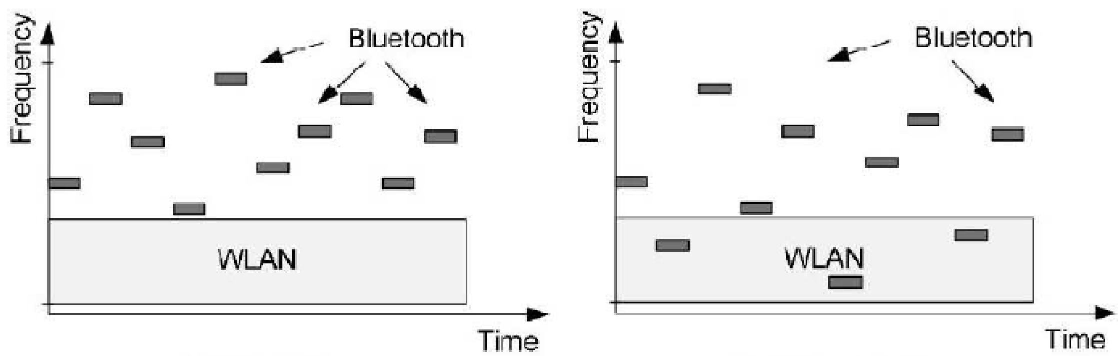

Fig. 3.2 Bluetooth transmission with and without AFH

3.4.3 IEEE 802.22

The IEEE 802.22 standard is recognized as the cognitive radio standard because it contains the cognitive features although this standard is still in development age. The vision of sensing is based upon two stages [13]:

- Fast Sensing
- Fine Sensing

In the fast sensing stage, a common sensing algorithm like as energy detector is employed. The fine sensing stage is initiated based upon the results of fast sensing. Fine sensing consists on a more detailed sensing and usage of more powerful methods. Many schemes have been projected and integrated in the draft standard like energy detection, waveform-based sensing, cyclostationary detection, and matched filtering. Subscriber Stations (SSs) are used for distribution of sensing load from the base station (BS). The BS receives the returned results and uses these results for managing the transmission [13]. It is also a practical example of centralized collaborative sensing.

CHAPTER 4
SPECTRUM SENSING

4.1 Overview

Spectrum sensing is the first stage in cognitive radio in which the radio scans a section of the frequency spectrum for any active signal. There are two main applications of spectrum sensing: Scanning for white space, and scanning for signals. These two applications are closely associated with each other. The former is typically for a transmitter design where the system looks at a range of frequency spectrum and uses internal algorithm to decide if there is any white space, and if so, where is it in the spectrum. This allows the system to transmit without interfering another existing signal at the same frequency. The latter is more commonly found in a receiver system where the purpose is to detect any active signal. Spectrum sensing is also involved in determining the type of the signal like carrier frequency, the modulation scheme, the waveform etc [5]. The conventional definition of spectrum opportunity is "a band of frequencies which are not used by the primary user at a particular time and a particular geographic area" [12] and it only exploits three dimensions: frequency, time and space of the spectrum space. Conventional sensing methods usually undercount the three dimensions (frequency, time and space) during spectrum sensing however for good spectrum opportunity there are some other dimensions also like multi-antenna which can be referred to multi-dimensional sensing which includes the knowledge of frequency, space, time, location and angle.

The mostly used spectrum sensing techniques are given as [5]

- Matched Filtering
- Waveform-Based Sensing
- Cyclostationary Based Sensing
- Energy Detector Based Sensing
- Radio Identification
- Other Sensing Methods

4.2 Challenges

Before a detailed description of spectrum sensing techniques will be given, spectrum sensing challenges associated with cognitive radio are discussed in this section.

4.2.1 Hardware Requirements

Analog to digital converters (ADCs) with high speed signal processors, high resolution and with larger dynamic range are required for spectrum sensing for cognitive radio networks[14]. Noise variance estimation techniques have been widely used for optimal receiver designs like channel estimation, soft information generation *etc.*, as well as for channel allocation techniques, and improved handoff power control [14]. As receivers are tuned to receive signals which are transmitted over a desired bandwidth that's why problem of interference is also an easy case in this scenario. Furthermore, receivers are able of processing the narrowband baseband signals with sensibly low complexity and low power processors. In cognitive radio, terminals are essential for processing transmission for any opportunity over a much wider band.

Hence, in order to identify any spectrum opportunity, the CR should be in a position to capture and analyze a larger band. Radio frequency (RF) components are imposed on additional requirements by larger operating bandwidths such as antennas and power amplifiers. There are two architectures for the sensing process: single radio and dual radio [15].

4.2.2 Hidden primary user problem

Here, unwanted interference is generated by cognitive radio devices to the primary user because due to the location of the devices, the primary transmitter's signal could not be detected. It is shown in Fig. 4.1 that how this kind of problem arises in the cognitive radio network.

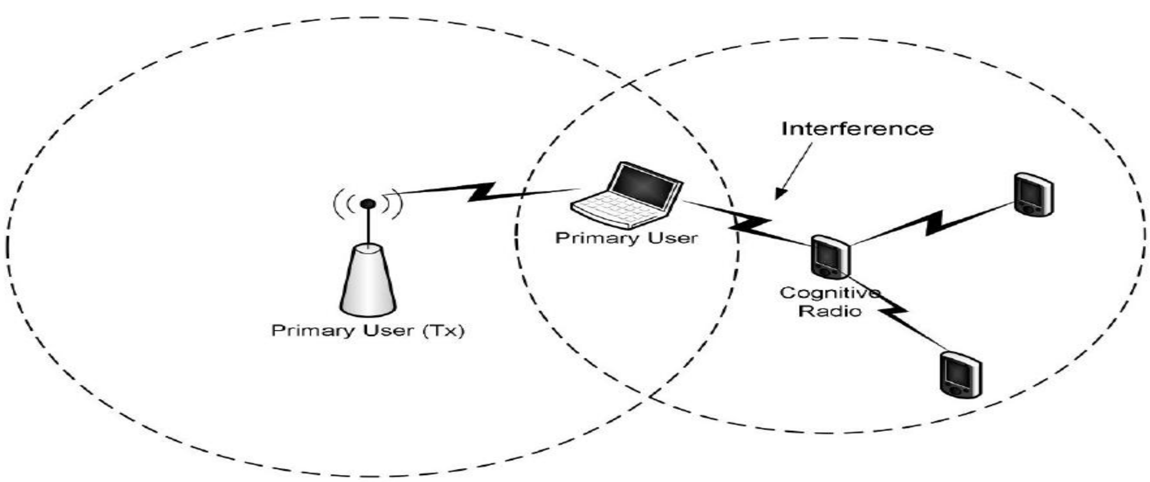

Fig. 4.1 Hidden Primary User Problem

4.3 Sensing Duration and Frequency

As the CR operates in the bands of primary users, these bands can be claimed by primary users at any time so in order to avoid interference to and for the PU, the CR should be so sensible that it could identify the presence of the PU and leave the band immediately. Hence within certain duration, the CR should identify the presence of the PU. Although this kind of condition puts some complexity and challenges for the design of CR. The sensing frequency (how often sensing should be performed by the cognitive radio) is a key parameter which should be chosen carefully. Sensing frequency requirements can be relaxed if you know that the status of the PU is going to change slowly. For example in the case of TV channel detection, in a geographic area presence of a TV channel does not change frequently unless an existing channel goes off or a new channel starts broadcasting. Sensing period for IEEE 802.22 draft standard is 30 seconds.

Except sensing frequency, other timing related parameters like channel move time and channel detection time etc, are also defined in the standard [18].

Interference tolerance of the primary license holder is another factor which affects the sensing frequency. In order to avoid any interference, sensing should be done as often as possible in the case when the CR is operating in public safety bands and it should vacate the bands immediately if required by public safety units. A channel which is being used by the SU cannot be used for sensing procedure, that's why before the spectrum sensing interpretation by the SU should be done for data transmission. Due to this spectrum efficiency of the overall system is decreased. To mitigate this dilemma, a technique known as dynamic frequency hopping (DFH) is proposed in [19]. This DFH method relies on the assumption of comprising more than a sole channel. In the operation on a functioning channel, the anticipated channel is sensed in parallel and if there is an available option, switching takes place and one of the anticipated channels becomes the operating channel. The Channel-hopping pattern is decided by an access point (AP) and this information is broadcasted to connected stations.

4.4 Sensing Techniques

4.4.1 Energy Detection

If the previous information of the PU signal is anonymous, then this energy detection method is optimal for detecting any zero-mean constellation signals [26]. In this energy detection approach, in order to determine whether the channel is occupied or not, the received signal strength indicator (RSSI) or radio frequency (RF) energy in the channel is measured. Firstly, in order to select the bandwidth of interest; the input signal is filtered by a band pass filter. After getting the square of the output signal, it is integrated over the observation interval. At the end, the output from the integrator is compared to a predetermined threshold value to conclude the presence or not of the PU signal.

Fast Fourier transforms (FFT) based methods are used when the spectral is analyzed in the digital domain. Specifically, the received signal **X(t)** sampled in a time window are first passed through an FFT device, in order to get the power spectrum ***X*(*f*)**. Then the peak of this power spectrum is located and after windowing the peak of spectrum we obtain ***Y* (*f*).** Then the signal energy in the frequency domain is collected and the binary decision is made.

Rather than that this method can be implemented without prior knowledge of PU, it has still some drawbacks also. The first hitch is that it shows poor performance under low SNR conditions because at low SNR noise variance is not accurately known [26]. Another issue is about the ability to differentiate between the other secondary users which are sharing the same channel and the primary user [27]. The threshold selection is also knotty since it is highly vulnerable to the changing background noise and interference level.

4.4.2 Matched Filter

A matched filter is the finest detection technique as it maximizes the signal to noise ratio (SNR) of the received signal in the existence of additive Gaussian noise [26][28]. It is obtained by correlating a known signal with an unknown signal in order to detect the existence of the known signal or template in the unknown signal. It is the same as convolving the unknown signal with a time-reversed version of the template. Radar transmission has common use of a matched filter but its usage in CR is limited because of little available information of primary user signals in cognitive radio. Its usage is possible for coherent detection if partial information of PU signals is known. For example, in the case of Digital Television, to detect the presence of DTV signals, its pilot tone can be detected by passing the DTV signal through a delay- multiply circuit. Then the square of magnitude of the out4put signal is taken and if this square is larger than a threshold, the presence of the DTV signals can be detected.

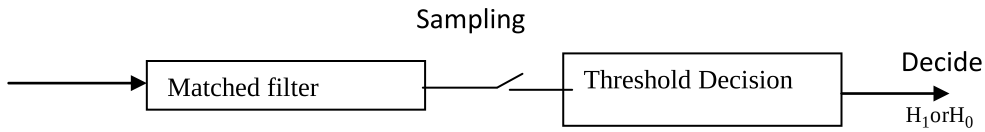

Fig. 4.2 Matched Filter

4.4.3 Cyclostationary Detection

Man made signals are normally not stationary but some of them are cyclostationary, showing periodicity in their statistics. This periodicity can be utilized for the detection of a random signal which has a particular modulation type in a background of noise. Such detection is called cyclostationary detection. The signal of the PU can be detected at very low SNR values if it exhibits strong cyclostationary properties. If the autocorrelation of a signal is a periodic function of time t with some period then such a signal is called cyclostationary and this cyclostationary detection is performed as shown in Fig.4.3 and follows,

$$Rx(\tau) = E[x(t+\tau)x^*(t-\tau)e^{-2\Pi\alpha t}] \qquad (4.1)$$

Here **α** is cyclic frequency and E[**.**] is the statistical expectation operation. The spectral correlation function (SCF) denoted by S(f,α), also called the cyclic spectrum is obtained by computing the discrete Fourier transformation of the cyclic auto correlation function(CAF). Detection is completed finally by searching for the unique cyclic frequency corresponding to the peak in the SCF plane. This approach is vigorous to interference and random noise from other modulated signals, because different modulated signals have different unique cyclic frequencies while noise has only a peak of SCF at zero cyclic frequency.

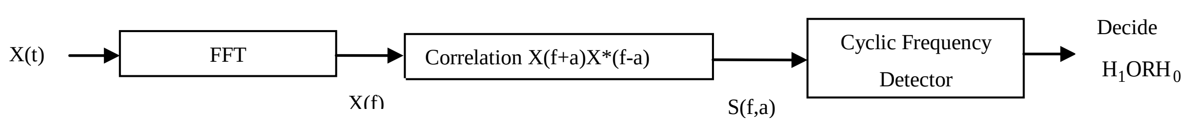

Fig. 4.3 Cyclostationary Detection

4.4.4 Wavelet Detection

The wavelet approach offers advantages in terms of both implementation cost and flexibility for signal detection over wideband channels, in adapting to the dynamic spectrum in contrast to the conventional implementation of multiple narrowband band pass filters (BPF) [28]. By employing a wavelet transform of the power spectral density (PSD) of the observed signal $x(t)$, the singularities of the PSD $S(f)$ can be sighted and thus the vacant frequency bands can be found as shown in Fig.4.4.

One major issue in the implementation of this approach is the high sampling rates characterizing larger bandwidths.

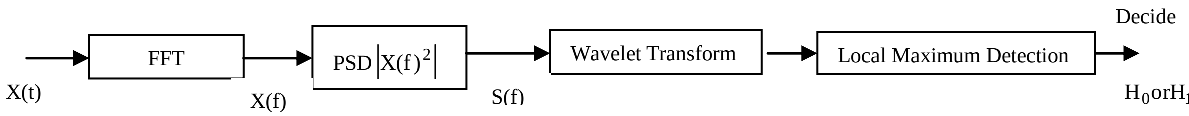

Fig. 4.4 Wavelet Spectrum Sensing

4.4.5 Cooperative Spectrum Sensing

Cooperation sensing is a proposed solution to the problems that arise during spectrum sensing like fading, shadowing and noise uncertainty [29]. Cooperative sensing has decreased the miss detection and false alarm problem up to a satisfactory level. In addition cooperative sensing can solve one of the most critical issues of spectrum sensing, hidden terminal problem. This problem occurs when the CR is shadowed or in severe multipath fading [29].

Here access to cognitive radio is allowed while on the other hand the PU is still in operation. To deal with this problem, multiple CRs can be organized in order to perform spectrum sensing cooperatively. Due to recent research, cooperative sensing is able to greatly increase the probability of detection in fading channels [29]. In general cooperative spectrum sensing consists of the following steps.

• Every CR independently performs measurements for its local spectrum sensing and then makes a binary decision to check on whether the PU is present or not.

• These binary decisions by all CR are forwarded to a common receiver which is a base station (BS) in a cellular network or an access point (AP) in a wireless LAN.

• Those binary decisions are combined by a common receiver and a final decision is made in order to infer the absence or presence of the PU in the observed band.

To build a cooperative sensing network, cooperation among CRs and external sensors can be made. Cooperation in the former case is implemented in two fashions: centralized or distributed [29].These methods are external sensing and are discussed as follows:

4.4.5.1 Centralized Sensing

In centralized sensing, sensing information from the cognitive devices is collected by a central unit. The available spectrum is identified and this information is broadcasted to other CRs or directly controls the CR traffic. At AP, all hard sensing results are gathered. The goal is to increase detection performance by alleviating the fading effects of the channel. Local observations of CRs are quantized to one bit in order to decrease the sharing bandwidth.

Furthermore, only the CRs with trustworthy information are approved to account their decisions to the central unit and some sensors are censored. This censoring is performed by applying two threshold values instead of only one. Analytic presentation of this scheme is considered for both perfect and imperfect coverage channels.

4.4.5.2 Distributed Sensing

In distributed sensing although cognitive nodes share information between each other they formulate their personal decisions as to which component of the spectrum they are able to utilize.

Distributed sensing is more useful than centralized sensing in cases where there is no requirement for backbone transportation and it has less cost. Collaboration is performed between two SUs, then the user which are nearer to a primary transmitter, and who has a better possibility of detecting the PU transmission, cooperate with far-off users. An algorithm used for pairing SUs without a centralized mode is projected. In order to reduce the network overhead because of collaboration, only ultimate decisions are pooled and in order to advance detection capability of the system features gained at different radios are shared along with cognitive users[36].

4.4.5.3 External Sensing

External sensing is another technique used for obtaining the spectrum information. In this technique sensing is performed by an external agent and information about the channel occupancy is forwarded to CRs. With the help of external sensing some problems regarding internal sensing are solved where sensing is performed internally by cognitive transceivers.

Collocated sensing is another name for internal sensing. The main advantage of external sensing is to prevail over fading, uncertainty because of shadowing and to overcome the hidden primary user problem. As the CR does not spend time for sensing, as a result spectrum efficiency is increased. The power utilization dilemma of internal sensing can also be addressed because sensing network does not require being mobile and is not essentially powered by batteries [12].

Sensor node detector architecture is used by determining the local oscillator (LO) power leakage in presence of passive receivers is detected. Sensor node notifies CRs in the area of passive PUs via a control channel when a receiver and the utilized channel are detected.

Spectrum is sensed continuously or periodically by a dedicated network which is composed of only spectrum sensing units. A sink (central) node attains the communicated results which additionally process the sensing statistics and shares the data with opportunistic radios related to spectrum occupancy in the sensed vicinity. The information obtained from the sensing network is utilized by these opportunistic radios for the selection of bands (and time durations) used for their data transmission. A pilot channel like the network access and connectivity channel (NACCH) can also be used for sharing the sensing results [38].

CHAPTER 5

DETECTION THEORY

The field of signal detection is concerned with the analysis of received signals to determine the presence or absence of signals of interest, to classify the signals present, and to extract information either purposefully or inadvertently included in these signals. For example, in active radar, electromagnetic pulses or pulse trains are transmitted and the reflected signals are analyzed to determine the nature of air traffic (small airplanes, commercial airplanes, or hostile aircraft), to extract information such as distance, speed, and possibly to form an image that would allow the identification of the airplane type. Most signal detection problems can be cast in the framework of M-ary hypothesis testing, in which we have an observation (possibly a vector or function) on the basis of which we wish to decide among M possible statistical situations describing the observations. For example, in an ,M-ary communications receiver we observe an electrical waveform that consists of one of M possible signals corrupted by random channel or receiver noise, and we wish to decide which of the M possible signal is present. Obviously, for any given decision problem, there are a number of possible decision strategies or rules (like Bayes, minimax, Neyman-Pearson, etc) that could be applied[25][30].

5.1 Observation and Types of Error

The structure of Fig. 5.1 is specified by a partition of the set of all possible observations into a set R and its complement RC. The null hypothesis is rejected if the realized value of the observation falls in the rejection region. Similarly, hypothesis H1 is accepted if the realized value of the observation falls in the acceptance region. In testing hypothesis Ho versus H1, there are two types of errors that can be made .These errors are:

Type I Error: This type of error is called false rejection. Decide H1 is true, when actually Ho is true.

Type II Error: It is false acceptance. Decide H_0 is true, when actually H_1 is true. This type of error causes miss detection. The tradeoff between probability of error type I and error type II is shown below in Fig 5.1.

It shows a graph of two hypothetical probabilities versus power curve. The curve on the left is for the noise-alone trials, and the curve on the right is for the signal-plus-noise trials. The horizontal axis is labeled internal response and the vertical axis is labeled probability.

Notice also that the curves overlap, that is, the internal response for a noise-alone trial may exceed the internal response for a signal-plus-noise trial. An example criterion is indicated by the vertical lines in Fig. 5.1. The criterion line divides the graph into four sections that correspond to: hits, misses, false alarms, and correct rejections. On both hits and false alarms, the power is greater than the criterion. Hits correspond to signal-plus-noise trials when the power is greater than criterion, as indicated in the Fig. 5.1. False alarms correspond to noise alone trials when power response is greater than criterion, as indicated in the Fig. 5.1.

Similarly, on both misses and correct rejection, the power is less than the criterion. Miss corresponds to signal-plus-noise trials when the power is less than criterion, as indicated in the Fig.5.1. Correct rejection corresponds to noise-alone trials when power response is less than criterion.

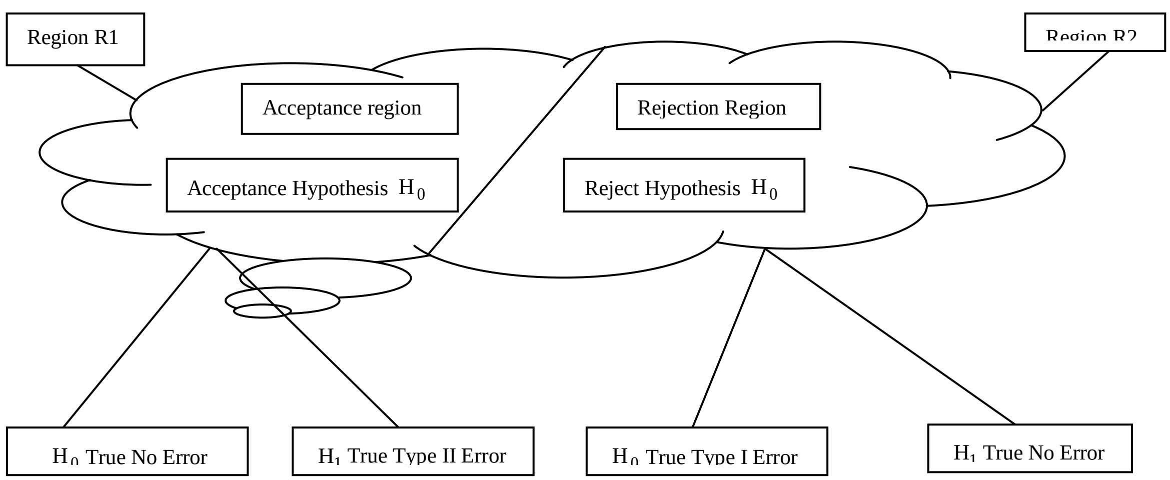

Fig. 5.1 Hypothesis Testing

5.2 Bayesian Binary Hypothesis Testing

The goal of binary hypothesis testing is to decide between two hypotheses H0 and H1 based on the observation of a random vector **Y**. We consider the cases where **Y** takes continuous or discrete values over a domain Y. In the continuous-valued case, Y =Rn, and depending on whether H0 or H1 holds, **Y** admits the probability densities

$$H_0 : y \approx f(y/H_0) \quad (5.1)$$

$$H_1 : y \approx f(y/H_1) \quad (5.2)$$

In the discrete-valued case, **y** = {**y**i, i ε I} is a countable collection of discrete values **y***i* indexed by i ε I and depending on whether H_0 or H_1 holds, **Y** admits the probability mass distribution functions

$$\begin{aligned} H_0 &: P(Y/H_0) = p[Y = y/H_0] \\ H_1 &: p(y/H_1) = p[Y = y/H_1] \end{aligned} \tag{5.3}$$

Then, given Y, we need to decide whether H_0 or H_1 is true. This is accomplished by selecting a decision function δ(Y) taking values in {0, 1}, where δ(y) = 1 if we decide that H_1 holds when Y = y, and δ(y) = 0 if we decide that H0 holds when Y = y.

5.3 Maximum Likelihood Decision Rule

In the absence of a-priori knowledge about the frequency of occurrence of each hypothesis and by assuming the two hypotheses are equally likely ($x_0 = x_1$), the LRT can be expressed as the maximum-likelihood (ML) decision rule for continuous-valued observations and discrete-valued observations are given respectively by

$$\begin{aligned} p[H_1 \mid y] &\overset{H1}{\geq} p[H_0 \mid y] \\ p[H_0 \mid y] &\overset{H0}{\geq} p[H_{\grave{}1} \mid y] \end{aligned} \tag{5.4}$$

5.4 Neyman-Pearson Testing

In hypothesis testing, as in all other areas of statistical inference, there are two major schools of thought on designing good tests: Bayesian and classical. In the Bayesian setup, a prior probability $\Pi_j = P_r[H_j]$ of each hypothesis occurring is assumed known. In some applications, however, it may not be reasonable to assign a priori probability to a hypothesis. For example, what is the a priori probability of a supernova occurring in any particular region of the sky? What is the prior probability of being attacked by a ballistic missile? In such cases we need a decision rule that does not depend on making assumptions about the a priori probability of each hypothesis. Here the Neyman-Pearson criterion offers an alternative to the Bayesian framework.

The Neyman-Pearson criterion is stated in terms of certain probabilities associated with a particular hypothesis test. The Neyman-Pearson criterion says that we should construct our decision rule to have maximum probability of detection while not allowing the probability of false alarm to exceed a certain value α.

CHAPTER 6

SPECTRUM SENSING WITH DIVERSITY RECEPTION

6.1 Introduction

The diversity reception is one of promising methods to overcome the inevitable fading effects and to benefit from the multipath effects inherent in the wireless environment. Thus the energy detector can obtain the advantages of diversity reception schemes to overcome the fading effects and signal-to-noise ratio (SNR) wall experienced by the detector.

Detection over maximal ratio, selection and switch-and-stay diversity receivers are analyzed in [23] while [24] considers the square-law combining schemes. Moreover the results obtained in [16] consider selection and maximal ratio receiver combining schemes. However, all diversity combined detector performance analyses are limited to Rayleigh fading branches. The integrals of Marcum-Q found in evaluating diversity combining techniques with other fading branches such as Rician and Nakagami-m are complicated and cannot be solved by available limited integral results [32]-[34]

6.2 Different types of diversity

- Space diversity: antennas are separated in space.
- Frequency diversity: multiple copies are transmitted at different frequencies
- Time diversity: multiple copies are transmitted in different time slot.
- Polarization diversity: multiple copies having different field polarization

Hence different diversity forms are normally efficient in different scenarios. A diversity form is efficient if multiple copies of signals are uncorrelated or independent. These multiple copies of signal are combined using some combining techniques.

6.3 Diversity Combining Techniques

1. Selection combining
2. Square law combining
3. Maximum ratio combining
4. Equal gain combining
5. Switched combining

6.3.1 Selection Combining

In selection combining diversity techniques it consists of a selection combiner which generally selects the maximum SNR out of the all signal from multipath signal component In Ref.(Digham, et al. 2003) and (Ashish and Linnartz 2007), selection combining method is applied to an energy detection based spectrum sensing system. In this method cognitive radio is assumed to have the knowledge of channel state information and thus chooses the branch with the highest channel gain and receives the data from that antenna. Then simply the received data is applied to an Energy Detector.

One of the most promising advantages of this method can be the fact that the threshold does not change as the noise level remains constant. As cognitive radio chooses one of the branches, it acts like a SISO system, that’s why the threshold remains exactly as same as it is set for SISO systems. In selection combining it keeps on monitoring the SNR from different multipath or channels and selects the maximum SNR accordingly at the receiver. In Fig. 6.1 it is shown that how selection combining works

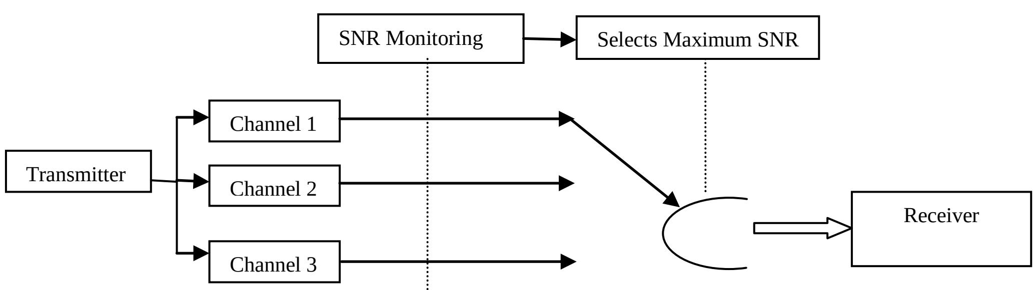

Fig.6.1 Selection Combining Technique

6.3.2 Square Law Combining

In this scheme proposed in [23] the outputs of the square-law devices (energy detectors) are combined and compared with a threshold to set a certain level of False Alarm probability as shown in Fig. 6.2. In [15] it is shown that this technique achieves better performance by using diversity reception.

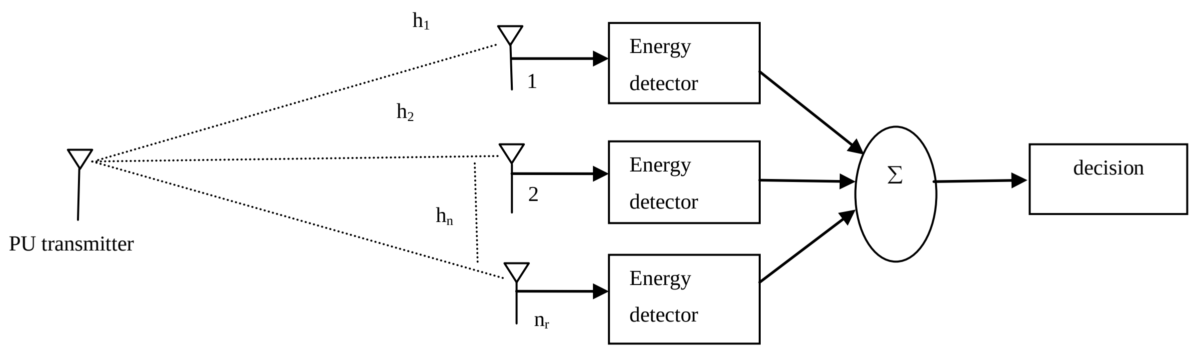

Fig.6.2 Square Law Combining

The equations for Square Law Combining can be derived as follows:

$$E_j = \sum_{k=1}^{N} \left| x_j(k) \right|^2 \tag{6.1}$$

$$E_{slc} = \sum_{1}^{n_r} E_j \tag{6.2}$$

It's straightforwardly seen that an energy detector must be allocated to each antenna.

6.3.3 Maximum Ratio Combining (MRC)

In the MRC combining technique needs summing circuits, weighting and co-phasing. The signals from different diversity branches are co-phased and weighted before summing or combining. The weights have to be chosen as proportional to the respective signals level for maximizing the combined carrier-to-noise ratio (CNR). The applied weighting to the diversity branches has to be adjusted according to the SNR. For maximizing the SNR and minimizing the probability of error at the output combiner, signal of d^{th} diversity branch is weighted before making sum with others by a factor, $C_d^* / \sigma_{n,d}^2$. Here $\sigma_{n,d}^2$ is noise variance of the diversity branch d^{th} and C_d^* is complex conjugate of channel gain.

As a result the phase-shifts are compensated in the diversity channels and the signals coming from strong diversity branches which has low level noise are weighted more comparing to the signals from the weak branches with high level of noise. The term $\sigma_{n,d}^2$ in weighting can be neglected for the condition that $\sigma_{n,d}^2$ has equal value for all d. Then the realization of the combiner needs the estimation of gains in complex channel and it does not need any estimation of the power of noise and performs as shown in Fig.6.3

This is a very useful combining process to combat channel fading. This is the best combining process which achieves the best performance improvement comparing to other methods. The MRC is a commonly used combining method to improve performance in a noise limited communication systems where the AWGN and the fading are independent amongst the diversity branches[7][40].

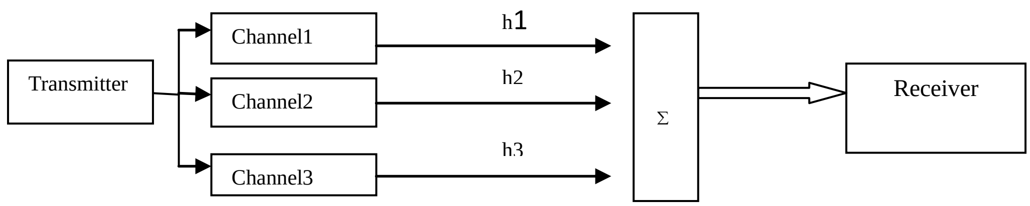

Fig.6.3 Maximum Ratio Combining

6.3.4 Equal-Gain Combining (EGC)

The EGC is similar to MRC with an exception to omit the weighting circuits. The performance improvement is little bit lower in EGC than MRC because there is a chance to combine the signals with interference and noise, with the signals in high quality which are interference and noise free. EGC's normal procedure is coherently combined the individual signal branch but it non-coherently combine some noise components.

MRC is the most ideal diversity combining but the scheme requires very expensive design at receiver circuit to adjust the gain in every branch. It needs an appropriate tracking for the complex fading, which very difficult to achieve practically. However, by using a simple phase lock summing circuit, it is very easy to implement an equal gain combining.

The EGC can employ in the reception of diversity with coherent modulation. The envelope gains of diversity channels are neglected in EGC and the diversity branches are combined here with equal weights but conjugate phase. The structure of equal-gain combining (EGC) is as following since there is no envelope gain estimation of the channel.

6.3.5 Switched Combining (SWC)

It is impractical to monitor the all diversity branches in selection combining. In addition, if we want to monitor the signals continuously then we need the same number of receivers and branches. Therefore, the form of switched combining is used to implement selection combining. The switching from branch to branch occurs when the signal level falls under threshold. The value of threshold is fixed under a small area but the value is not the best necessarily over the total service area. As a result the threshold needs to be set frequently. It is very important to determine the optimal switching threshold in SWC. If the value of threshold is very high, then the rate of undesirable switching transient increases. However, if the threshold is very low then the diversity gain is also very low. The switching of switch combining can be performed periodically in the case of frequency hopping systems.

CHAPTER 7

CONVENTIONAL ENERGY DETECTOR

7.1 Energy Detector

Energy detector is the most common way of spectrum detection because of its low computational and implementation complexities [20]. It is based on the principle that, at the reception, the energy of the signal to be detected is always higher than the energy of the noise. The energy detector is said to be a blind signal detector because it ignores the structure of the signal. The decision is made by comparing the decision statistics which corresponds to energy collected in the observation time, to an appropriate threshold [21, 22 and 23], that is traditionally selected from the statistics of the noise to satisfy the false alarm rate specification of the detector based on Constant False Alarm Rate (CFAR) principle.

The energy detector relies completely on the variance of the noise which is taken as a fixed value. This is generally not true in practice, Essentially this means that the energy detector will generate errors during those variations, especially when the signal to noise ratio (SNR) is very low where we see an area of uncertainty surrounding the threshold in contrast with the case in which perfect noise knowledge is considered. The system model for energy detection which is used to identify the presence or absence of primary signal is shown below in Fig. 7.1 From the given block diagram, in order to measure the energy of the received signal, the output signal of band pass filter, used to limit the noise power and to normalize the noise variance, with bandwidth W is squared and integrated over the observation interval T. Finally, the output of the integrator, Y, is compared with a threshold, to decide whether a licensed user is present or not.

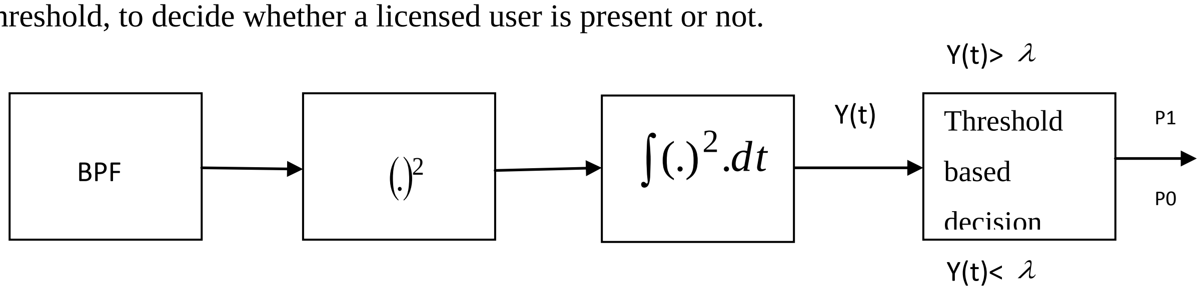

Fig.7.1 Energy Detector

Where system is modeled as

$$y(n) = \begin{cases} w_0(n), P_0, \\ s_0(n) + w_0(n), P_1 \end{cases} \tag{7.1}$$

Here y(n) denotes the signal which is received by secondary user or cognitive radio user. $s_0(n)$ denotes the primary user signal and $w_0(n)$ is the zero mean additive white Gaussian noise. In signal detection we consider three cases

1. Probability of detection (P_d) occurs when P_1 is declared for case of P_1.
2. Probability of false alarm (P_{fa}) occurs when P_1 is declared for case of P_0.
3. Probability of miss detection (P_m) occurs when P_0 is declared for the case of P_1.

The flow chart which is used to describe the block diagram shown in Fig.7.2 is shown below.

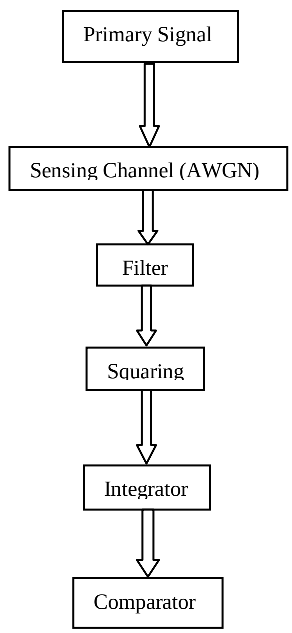

Fig.7.2 Flowchart Representing Conventional Energy Detector

The generated signal is passed through white Gaussian noise (AWGN) channel, according to Performance evaluation on transmitter detection techniques for cognitive radio the above block diagram the energy of signal plus noise will be calculated and finally the evaluated energy will be compared with the threshold value to decide on the presence or absence of the primary signal which passes through additive white Gaussian noise channel.

Generally, we took the threshold value for the cost of probability of false alarm of less than or equal to 10% and different values of noise variance ranging from 0.5 to 1. At the comparator, if the energy is greater than the threshold value, it shows that the transmitted signal is present and it is not possible to use the cognitive radio as a secondary user with in the coverage area of the primary users. Whereas, if the energy is less than the predefined threshold value, the primary signal is not accessing its spectrum and it is time to use the cognitive radio in an opportunistic way until the presence of the primary signal is detected.

In case of single energy detector performance of spectrum sensing is limited to high SNR. In case of single energy detector it is not able to detect signal under low SNR value[4]. In conventional case the threshold value is also affected by the changing noise levels and is not able to detect the primary user's signal in case of fading and shadowing.

7.2 Noise Uncertainty

Although it is generally assumed for simplicity that the variance of the receiver noise is known, noise variance is never exactly known in the case of real systems even if the system is calibrated. There are several factors that contribute to the existence of noise uncertainty. For example, thermal noise due to change in temperature, change in amplifier gain due to change in temperature, calibration error etc. As noise uncertainty in the receiver in unavoidable, it is very important to analyze its effect on the detection performance.

Let us model the noise process w[n] to have any distribution W from a set of possible distributions w. This set is called the noise uncertainty set. Although the actual noise variance might vary over distributions set w, let us assume that there is a single nominal noise variance σ_n^2 associated with the noise uncertainty set w. As energy detector evaluates the detection performance based of the incoming signal, the distributional uncertainty of noise can be summarized in a single interval $\sigma_w^2 \in [(\frac{1}{\rho})\sigma_n^2, \rho\sigma_n^2\ ]$ where σ_n^2 is the nominal noise power and $\rho > 1$is the parameter that quantifies the size of the noise uncertainty. The parameter is often considered in its dB equivalent as$10\log_{10}(\rho)$. To understand the noise uncertainty for the detector the shaded area in the Fig.7.3 represents the uncertainty in the noise power.

From the figure it is clear that if the test statistic falls within the shaded region, there is no way to distinguish between the two hypotheses. By including the noise uncertainty factor shown in Fig 7.3, probability of false alarm, threshold and probability of detection can be written as:

$$P_f = Q\left(\frac{\lambda - N\rho\sigma_n^2}{\sqrt{2N\rho^2\sigma_n^4}}\right) \tag{7.2}$$

$$\lambda = \sqrt{N\rho^2\sigma_n^4}\,(Q^{-1}(P_f) + N\rho\sigma_n^2) \tag{7.3}$$

$$P_d = Q\left(\frac{\lambda - N(\frac{1}{\rho}\sigma_n^2 + \sigma_s^2)}{\sqrt{2N\frac{1}{\rho}(\sigma_n^2 + \sigma_s^2)^2}}\right) \tag{7.4}$$

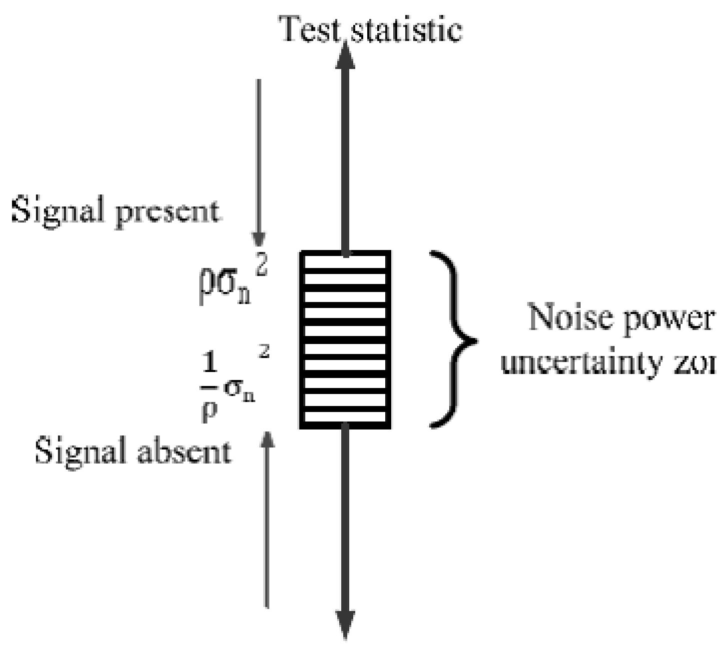

Fig. 7.3 Noise Uncertainty

Noise level uncertainty renders robust detection below certain SNR impossible [27, 28]. To constraint the resulting false alarm rate, the detection threshold has to be set based on the worst case noise level uncertainty. Consequently, if the signal power is below a certain level, the energy detector cannot distinguish the signal from a slightly larger noise power regardless of the detection time. This threshold is called the SNR wall in [28]. Consequently, the energy detector performance depends heavily on the accuracy and reliability of the noise level estimate. The noise uncertainty factor can be expressed in terms of SNR wall as

$$\mathrm{SNR}_{\mathrm{wall}} = \frac{\rho^2 - 1}{\rho} \tag{7.5}$$

CHAPTER 8

IMPROVED SPECTRUM SENSING USING MULTIPLE ENERGY DETECTORS

8.1 Multiple Energy Detectors

A key challenge in cognitive radio is unreliability of CR which affects its performance also. Here in our approach we proposed an analytical model called multiple energy detectors(MEDs) to overcome this problem.

For spectrum sensing multiple energy detectors with optimized threshold is proposed to reduce the effect of multipath and shadowing . The concept of multiple energy detector is mainly used with the cooperative and diversity combining scenarios. Here we assumed that if we have a fading channel then there is possibility that one out of the multiple components through different multipath will have high SNR(signal which is less faded) .

Here in our approach we have used multiple energy detectors with selection combining diversity technique which combines the signal in such a way that the maximum value of energy computed out of the number of detectors is considered and followed by test hypothesis in the same way like in single energy detector with optimized threshold. Each energy detector is having its own individual antenna to achieve diversity.

In fading environment when we receive a signal then in case of single energy detector it may happen that the received signal is highly faded and attenuated so when we calculate its energy it will be less than the threshold value. So number of miss detection increases which also results in high probability of error. We know that channel characteristics are changing with time and space. When we transmit a signal it follows multiple paths and some component may follow highly attenuated paths and some may pass through very low attenuated paths. So when we use multiple number of energy detectors then each energy detector receive its own component for computation of energy and due to different channel gain one of the three gets the best signal component from the three signal. Here we are considering Rayleigh fading channel. Rayleigh fading is modeled by Rayleigh distribution which is given by

$$f(a,\phi) = 2ae^{-a^2} \tag{8.1}$$

From distribution function we got that when value of fading coefficient is zero then gain also tends to zero which show deep fades and as the fading coefficient increases , then the gain of the channel also increases.

Here we have used selection combining technique to combine the signals using concept of SIMO(single input multiple output). In selection combining diversity technique it takes the maximum valued SNR signal from the multiple antennas and ignore other signals. It gives output or chooses a signal in such a way that max (E(SNR)).

Here E0 is the maximum energy from the multiple energy detector obtained using selection combining technique. Now, this is followed by test hypothesis using optimized threshold. Threshold optimization is used to combat with changing noise levels. Based on the changing noise level also known as noise uncertainty, the probability of detection and probability of false alarm kept in constraint considering tradeoff between probability of false alarm and probability of miss detection

8.2. Optimization of threshold

In wireless communication system, noise is considered as undesired disturbance caused by summation of different independent components with thermal effect and interference effect caused by weak signals.

We are optimizing threshold considering the changing noise levels and making threshold adaptive in the sense that secondary user should transmit aggressively when the SNR is large, which also maximize the capacity. Threshold optimization is very important because noise is uncertain and its levels keep on changing. So, because of these changing noise levels , the performance of energy detector will deteriorate. Here to deal with the effect of noise uncertainty, we need to model the distributional uncertainty for the noise as $(s_0^2 \in (s_{min}^2, s_{max}^2))$, here we are considering the s_0^2 as the actual noise power, whereas lower bound uncertainty is represented by the $(s_{min}^2 = (s_n^2 / a))$ and upper bound uncertainty is represented by the $(s_{max}^2 = (a \times s_n^2))$. Here s_n^2 is expected or nominal noise power[7][8][9].

Now, on the bases of central limit theorem when the samples are large enough the noise uncertainty can be represented as Gaussian distribution

$$TH_D \approx N(m_{0,}s_0^2) = \begin{cases} N(Na \times s_n^2, 2 \times a^2 s_n^4)), P_0 \\ N(m_1, s_1^2\ ) = N((Ns_n^2(\gamma + \frac{1}{a}), 2Ns_n^4(\gamma + \frac{1}{a})^2), P_1 \end{cases} \tag{8.2}$$

Where a is the noise uncertainty factor. We know that $PH_0 + PH_1 = 1$[12]. Based on this we can obtain the formula for probability of error as

$$P_e = PP_0 P_f + PP_1 P_m \tag{8.3}$$

When we consider a as the noise uncertainty factor then we should take a* as the constrained noise uncertainty factor greater than a, which is based on the observation. So probability of detection and probability of false alarm can be formulated as

$$P_D = \frac{1}{2}\operatorname{erfc}\left[\frac{\lambda/a* - m_1}{\sqrt{2}s_1}\right] \tag{8.4}$$

$$P_f = \frac{1}{2}\operatorname{erfc}\left[\frac{a*\lambda - m_0}{\sqrt{2}s_0}\right] \tag{8.5}$$

Now using probability of error and differentiating the equations using values of P_f and P_D we will get optimized threshold as

$$\lambda^{opt} = \frac{-B + \sqrt{B^2 - AC}}{A} \tag{8.6}$$

with parameters expressed as

$$A = a*s_1^2 - \left(1/a*^2\right)s_0^2 \tag{8.7}$$

$$B = \left(\frac{1}{a*}\right) s_0^2 m_1 - a* s_1 m_0 \quad (8.8)$$

$$C = s_1^2 m_0^2 - s_0^2 m_1^2 - 2 s_0^2 s_1^2 \ln\left(\frac{a*^2 s_1}{s_0} \right) \quad (8.9)$$

Flow diagram of the proposed scheme is shown in the Fig.8.1 considering one primary user transmission (SIMO case). It is shown that signal is passed through fading channel and received at number of energy detectors with individual antenna. Further diversity combining scheme is applied which is done using a selection combiner. Output from the selection combiner is used for the test hypothesis. Now in test hypothesis optimized threshold is used for the detection.

8.3 Flow Chart

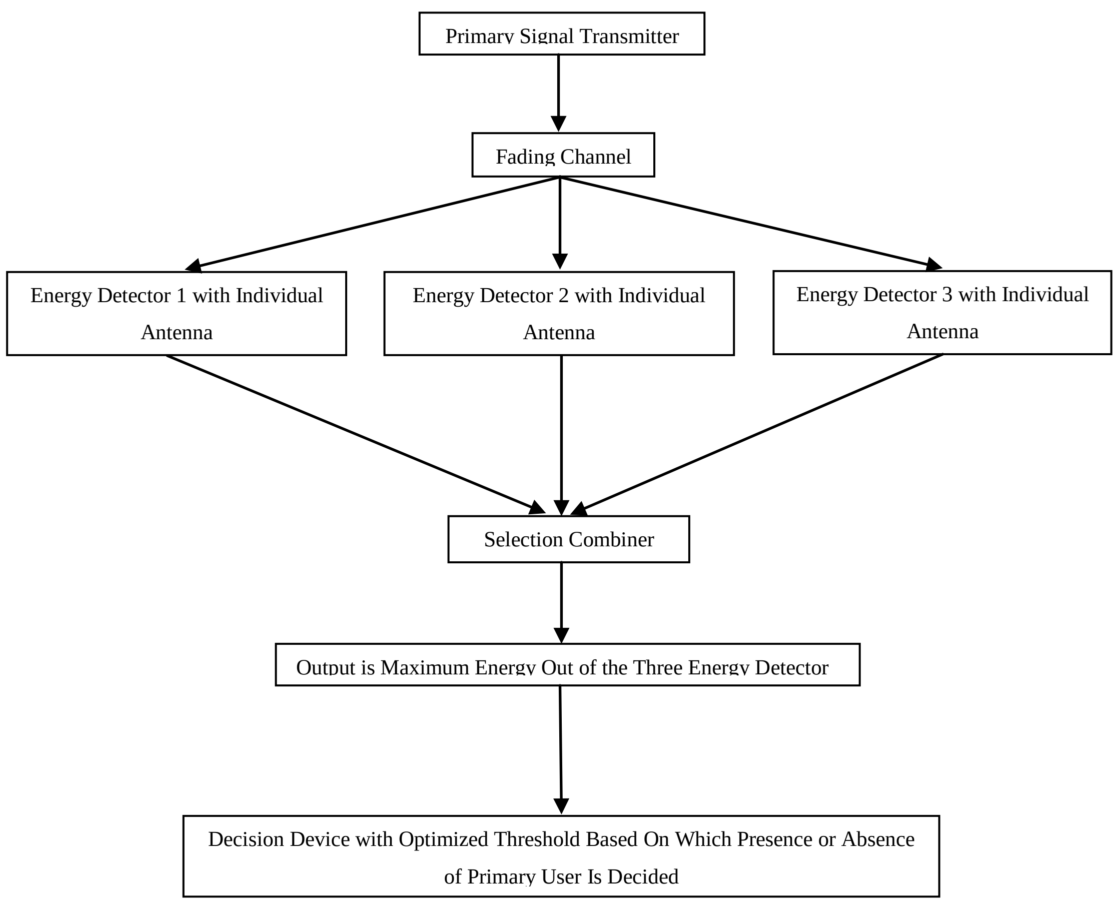

Fig.8.1 MED Flow Chart

CHAPTER 9

SIMULATION AND RESULTS

9.1 Introduction

This chapter deals with the methodology and simulation results for the two techniques, namely the conventional energy detector and multiple energy detector. It defines the approaches adopted, the scenarios set-up, the assumptions made and the methods used. Comprehensive simulation results derived using MATLAB to simulate these two techniques. Comparison analyses are done using performance measure such as probability of detection and false alarm.

9.2 Methodology

The formulation of the conventional and the multiple energy detectors is performed using the step-by-step approach, as discussed in chapter 8. For simulations we have used MATLAB software. Firstly the conventional energy detector is simulated and results are derived. Secondly the multiple energy detectors scheme is simulated.

As we know that CR promises the secondary users access the spectrum which is allocated to a primary user, so avoiding interference to potential primary users is a basic requirement. Therefore we should detect the primary user status through the continuous spectrum sensing.

9.3 Simulation Results for Conventional Energy Detector

We use MATLAB to encode the output signal from the integrator with zero-mean AWGN. The output signal is in Chi-square distribution. We assume the Chi-square distribution as Gaussian distribution when samples are large, so we can encode the output signal from the integrator as:

```
Sig = sqrt(sigmas^2+sigman^2)*randn(100,N)
```

which obeys the Gaussian distribution. Sigmas^2 is the variance of the signal waveform, sigman^2 is the variance of AWGN, the operation randn distributes random numbers and arrays. Then we set the values of parameters according to the Table 9.1:

Table 9.1 System Parameters for CED

SNR	-10dB
Bandwidth	1×10^{-5}
Observation time	1×10^{-2} s
Variance of the signal	$\left(\sigma_n \times10^{-1}\right)^2$
Variance of the noise	1×10^{-12}

In Fig.9.1 it is shown that the number of detection are increasing as the value of SNR increasing.

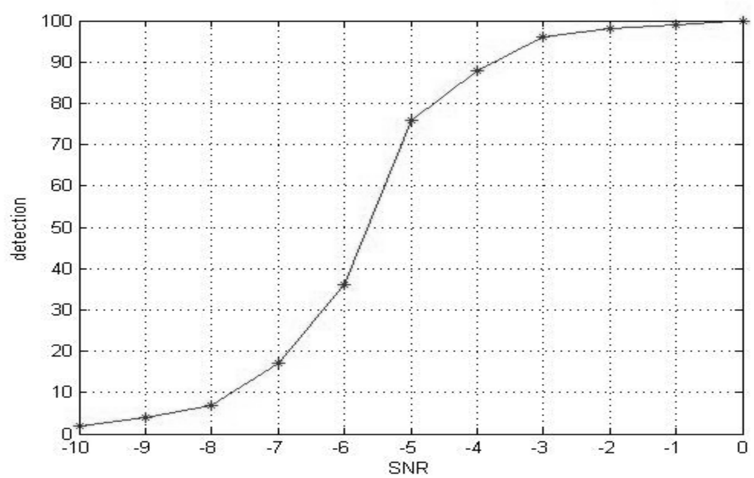

Fig. 9.1 Number of Detection vs SNR

- We change the SNR from -10 dB to 0 and then calculate the false alarm probability
- Here we are having 100 samples.
- When we vary the value of SNR we get different detection so we get different values of probability of false alarm.
- Here we notice that probability of false alarm is 0.01 at SNR of -1 which says that there will be 99 detections for 100 samples.

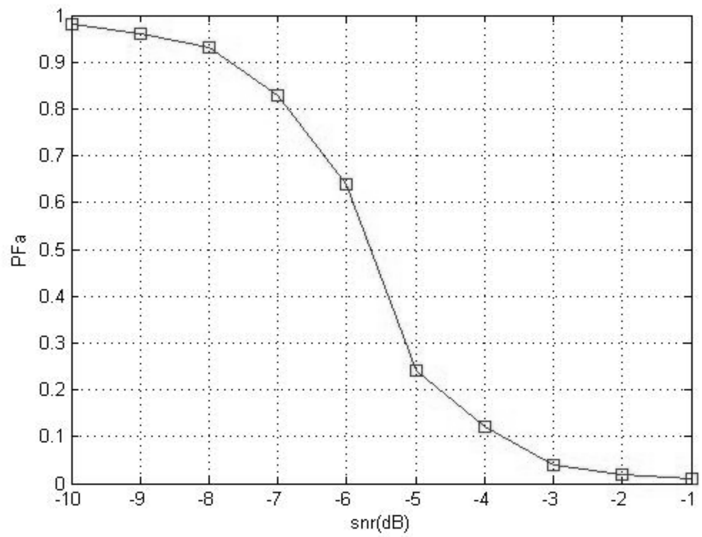

Fig. 9.2 P_{fa} vs SNR Plot

- On changing the sensing time we get different detections for different sensing time.
- As we increases the sensing time, the number of detection also increases as shown in Fig.9.3.
- When sensing time is large as 0.1s then the number of detection are 7 and when we start decreasing the sensing time number of detection also starts decreasing shown for time less than 0.01s the number of detections comes out to be 3 and decreases further with time.

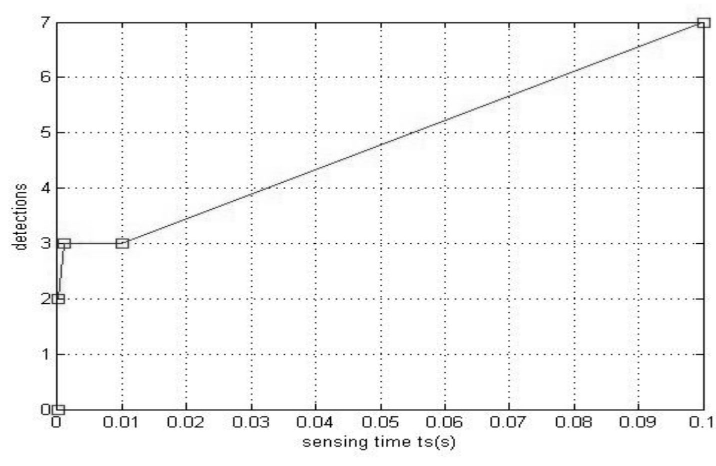

Fig. 9.3 Sensing Time vs Detection

For efficient detection sensing time plays an important role so it is always necessary to set an observation time to achieve better performance as shown in Fig. 9.3.

9.4 Simulation Results for Multiple Energy Detector

We have shown the performance of MED using curve for probability of error and SNR (dB). Here we consider that the noise power is known completely, and the Pf and Pm are constrained to o.1 and the noise uncertainty factor (a) is considered to be greater than 1.Based on the different number of samples N=500,1000 and 1500, probability of error is computed. N can also be represented as time bandwidth product.

The probability of error is observed for SNR values ranges from -25dB to 5dB. It is observed in Fig. 9.4 that the number of samples required to obtain reliable detection reduces with the same probability of error as in case of conventional energy detector.

Here from simulation results we observe that when we increase the number of samples probability of error decreases. In case of conventional energy detector as in [11] for same probability of error 2000 samples are used but with multiple energy detector scheme number of samples are reduced to 1500 for same probability of error. We observe from the simulation that to improve detection in low SNR region large sensing time is required which is done by increasing the N number of samples.

When we consider the case of noise uncertainty factor we observed that changing noise factor affect the detection performance in such a way that probability of error increases for low uncertainty factor for a=1.0, P_e increases slightly with decrease of SNR and remains same. Here we have considered noise uncertainty factor $a^* \geq a$.

Table 9.2 System Parameters In MED

Number of samples considered(N)	500,1000 and 1500
SNR range	-25dB to 5Db
Noise uncertainty factor a*	1.5

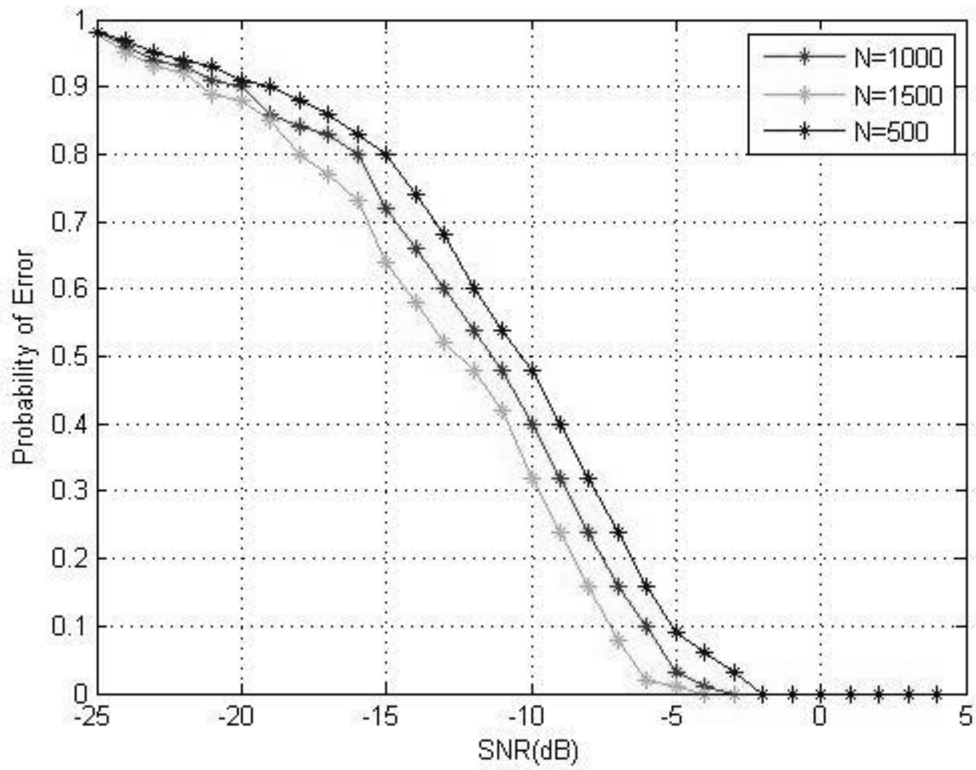

Fig. 9.4 Probability of Error vs. SNR

Here in the Fig. 9.4 it's shown that P_e is decreasing as the number of samples are increased. When we take the case of conventional energy detector it requires more than 2000 samples to achieve the nearby probability of error. So better probability of error is achieved using the multiple energy detection scheme with optimized threshold.

Table 9.3 Simulation Parameters For MED To Obtain Detection Performance

Number of Energy Detector with individual Antenna	3
Number of Samples(N)	1000
Probability of False Alarm(constraint)	0.1
SNR Range	-20dB to 0 dB
Noise Uncertainty Parameter(a*)	1.5

In Fig.9.5, it is shown that performance of detection is improved comparing with single energy detector. Here for N=1000 we have considered that probability of false alarm P_{fa}=0.1, number of energy detector N_r=3 with individual antenna and Rayleigh fading channel. We assume different channel gain for different multipath considering changing channel characteristics.

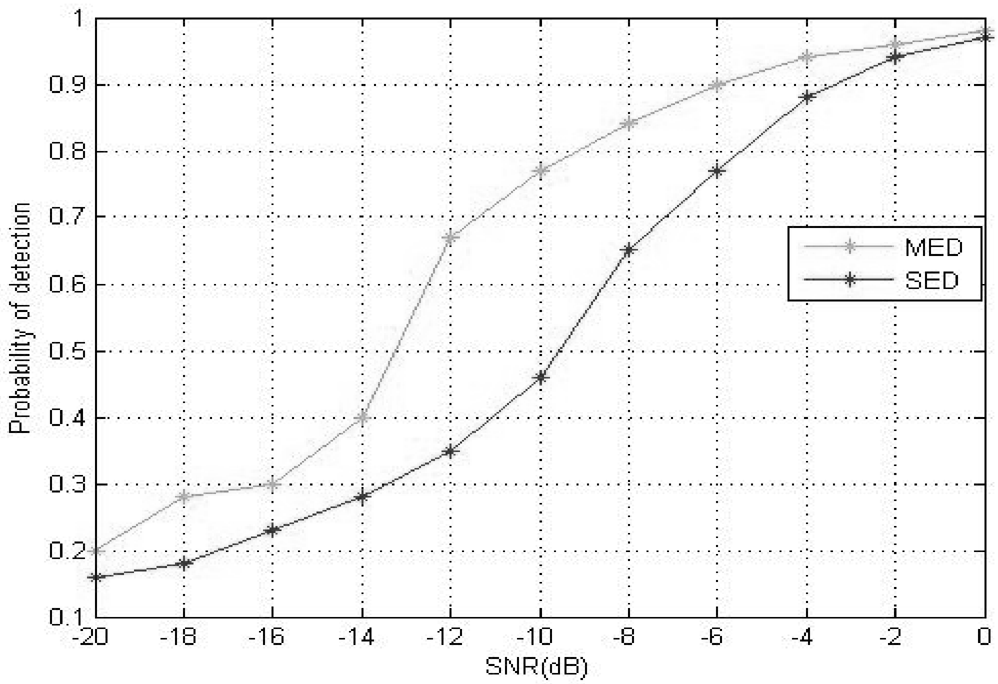

Fig. 9.5 Comparison of SED Vs MED Based on Probability of Detection

Here we observe that for different values of SNR we are getting different probability of error and we got that our proposed scheme will give better performance in low SNR region also. In accordance to the IEEE 802.22, the probability of detection should be 0.9 at SNR of -10dB and it is somewhere near in our case. It helps to avoid problem of shadowing and fading because of assumption that one of the detector will get less faded signal because of changing channel characteristics.

CHAPTER 10

CONCLUSION AND FUTURE SCOPE

In this thesis, we have focused on spectrum sensing techniques for Cognitive Radio Systems with multiple energy detectors. We have aimed to propose multiple antenna techniques in order to increase the performance of the spectrum sensing systems in literature and reduce the implementation costs.

We have studied some spectrum sensing techniques proposed in literature and obtained simulation performance of Energy Detection and multiple energy detectors Detection methods. We have studied different ways of energy detection implementation.

The main focus is detection of primary user signal and keeping probability of false alarm constraint improving system performance. Our approach is good for the case of changing channel characteristics or multipath scenario because for system having same channel characteristics only one detector can be used to give reliable performance. We have optimized the threshold based on effect of changing noise level on the threshold because it affects the detection and leads to non-reliable sensing.

Using this approach we are able to overcome the problem of sensing failure and hidden terminal problem. Sensing performance is improved in a simplest way by keeping constraint on probability of false alarm and miss detection. Although this system increases the complexity if we consider the line of sight communication or channel.

Our future work will includes analysis of different diversity combining technique which can be further implemented with energy detector to obtain better spectrum sensing performance.

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