MINT 709 Capstone Project Report

Spectrum Sensing with Improved Energy Detector in Interference

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Submitted to
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April 25, 2014

Abstract

A cognitive radio (CR) came into existence as a solution to the radio frequency spectrum underutilization (scarcity) problem. A CR promotes dynamic spectrum utilization and enables increase in the spectrum usage efficiency. For a CR to be highly efficient, the foremost task is to identify the possible communication opportunities, called spectrum holes through a process called spectrum sensing. Fundamentally, spectrum sensing should be highly reliable for accurately track those communication opportunities. The energy detector, which offers a simple solution to the spectrum sensing task is one of the most popular devices used for detecting spectrum holes. However, the energy detector performance degrades in a multi-user environment, where a large number of wireless devices are omnipresent. The energy detector performance degrades due to reception of interfering signals from other users. Thus, quantification of such degradation and its possible mitigation is needed for robust spectrum sensing performance. With these goals in mind, we first characterize the spectrum sensing performance of the energy detector in fading channels with interference. Second, an adaptive energy detector is used to achieve significant performance gains compared to the traditional energy detector. Third, to further boost the performance of the improved energy detector, multiple antenna diversity is considered and found to produce remarkable gain in the reliability of spectrum sensing.

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List of Acronyms

ADC analog-to-digital converter

AF amplify-and-forward

BS base station

CAF cyclic autocorrelation function

CPU central processing unit

CR cognitive radio

DF decode-and-forward

DSP digital signal processing

ED energy detector

FCC Federal Communications Commission

GPS global positioning system

LOS line-of-sight

MS mobile station

PDF probability density function

PU primary user

QoS quality of service

RF radio frequency

ROC receiver operating characteristic

SINR signal-to-noise plus interference ratio

SNR signal-to-noise ratio

SCF spectral correlation function

TDMA time division multiple access

UWB ultra-wideband

WSN wireless sensor network

List of Symbols

Listed below are the notations used throughout the report.

ξ	Power of transmitted signal
σ^2	Variance
β	Relay gain
λ	Detection threshold
Ω	Average fading power
H_0	Hypothesis 0
H_1	Hypothesis 1
I_0	0th order modified Bessel function of the first kind
K	Rice factor
L	Total number of receiver antennas
N	Total number of signal samples
$n(t)$	Additive white Gaussian noise
P_d	Probability of detection
P_f	Probability of false alarm
P_e	Probability of error
P_{md}	Probability of missed detection
$p(r)$	Probability Density Function (PDF) of Rayleigh fading model
p	p-norm detection parameter
r	Channel fading amplitude
$s(t)$	Signal transmitted by PU
T	Detector decision variable
u	Time-bandwidth product of the energy detector (ED)
$x(t)$	Signal observed by CR
Y_k	Energy from kth square-law device

Chapter 1

Introduction

The number of users interconnected through wireless technology is expected to exceed 50 billion [1] over the next decade, thus asking for more radio frequency (RF) spectrum, which is the fundamental resource to accommodate those users. As shown in Figure 1.1 the development of the networked world is progressing mainly through three waves with the first encompassing networked consumer electronics, second covering networked industries and the third wave ultimately interconnecting everything. Also modern-day communication devices are getting smarter and increasing number of devices have high multimedia processing capability thus increasing

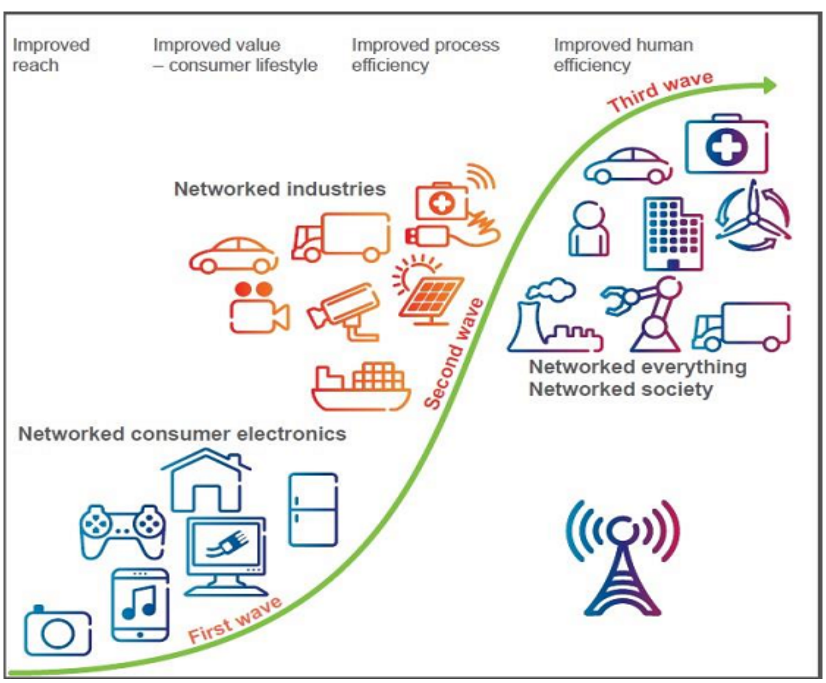

Figure 1.1: The Waves of Connected Device Development [1]

Region	2013	2018
North America	65%	93%
Western Europe	45%	83%
Cen tral and Eastern Europe	15%	61%
Latin America	14%	55%
Asia Pacific	17%	47%
Middle East and Africa	10%	36%

Table 1.1: Regional share of Smart devices and connections (Percent of the Regional Total) [3]

their popularity. Table 1.1 gives a forecast of the number of smart devices and connections globally during the 5-year period of 2013-2018. North America leads the growth forest with over 90% of its installed base converted to smart devices and connections which is followed by Western Europe with 83% of the same. Such increase in the number of users is bound to result in an intense competition for the use of the available RF spectrum. This will lead to further scarcity of the precious RF spectrum which has already been allocated to specific services by government agencies all over the world. For example, recent studies of the Federal Communications Commission (FCC) Spectrum Policy Task Force have reported vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85% [2]. Thus, the scarcity is actually a perceived one due to such strict spectrum allocation policies.

To deal with the spectrum underutilization problem, and thus accommodate more users in the available RF spectrum, a new type of technology called cognitive radio (CR) emerged [4], [5]. A cognitive radio (CR) is a device capable of changing its transmitted and received parameters according to its interaction with the environment [4]. The CR technology provides the capability to share the RF spectrum with the licensed users in an opportunistic manner. CR networks allow the unlicensed users, also known as secondary users, to utilize a licensed band when the primary user (PU) is absent or idle, thus significantly improving the spectrum utilization. By sensing and adapting to the environment, a CR is able to communicate through the unused spectrum spaces (also known as spectrum holes) without causing interference to the PU [6]. However, CR networks face several challenges. Among them, spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility are the four major challenges in spectrum management that CR networks need to meet [4]. In order to address these challenges, CR networks should efficiently detect the spectrum holes, select the best channel according to the required services, share the access of the channel with other users and vacate the channel as soon as the PU reappears. Out of these, spectrum sensing is the first and the most fundamental step to promote spectrum underutilization [7]. It is an inherent requirement for dynamic spectrum access. Thus, CR networks are highly dependent on the reliability of detection of spectrum holes due to which efficient spectrum sensing is always the first priority.

There are several methods for spectrum sensing which essentially requires detection of spectrum holes. Out of them, the most popular ones are matched filter detector, energy detector (ED) and feature detector. Among these techniques, ED is the most widely used detector because of its quick sensing decision, ease of implementation and low complexity. However, ED is adversely affected by factors such as receiver noise and multipath fading. Multipath fading is an omnipresent phenomenon in wireless propagation which occurs due to scattering, reflection and diffraction of the transmitted waves and results in rapid variations in the envelope of the received signal [8]. Apart from multipath fading, the sensing CR may also be subject to interference from other secondary users looking for possible opportunities to communicate or from PUs users which are already communicating in the band of interest thus causing power leakage into the sensing CR receiver [9]. In such situations, the reception of unwanted signals at the CR is likely degrade its detection performance. Thus, the ED performance in presence of a number of interfering users in fading channels needs investigation. Further, improvement of its performance in such situation requires attention. In order to address these issues, the following objectives are set up for investigation in this research project.

1.1 Objectives

The major objectives of this project are stated as follows.

1. Analyze the performance of ED and improved energy detector in fading channels with interfering users.

2. Further investigate the ED performance enhancements by using improved energy detector equipped with multiple antennas.

   These objectives are further elaborated as problems stated below.

1.2 Problems

Problem1. A highly reliable spectrum sensing performance is needed for effectively promoting dynamic spectrum access. However, the spectrum sensing capability of an ED is adversely effected by multipath fading and more importantly, by interference from other users [10]. The presence of interference is likely to degrade the ED sensing reliability. This degradation needs to be quantified. Further, countermeasures to such degradation need to be designed. With these goals in mind, a more generalized version of ED, called the improved ED (IED) [11], will be considered in this study. With the motive of attaining better reliability of detection, the role of IED in mitigating the effects of interference will be investigated.

Problem2. It is well known that antenna diversity enhances wireless link performance by providing the receiver with multiple replicas of the same information bearing signal [8]. Motivated by this fact, we will investigate the effect of multiple antennas on the performance of the IED. Possible improvements in spectrum sensing performance of IED will be explored and quantified.

1.3 Potential impact and significance of the research

Since, the available spectrum is scarce, the need to get dynamic spectrum access has become prominent. The dynamic spectrum access is promoted by spectrum sensing which can be achieved through CR networks. The simple spectrum sensing techniques mainly focus on low complexity and ease of implementation. ED is one such detector that fits in well enough and has found widespread applications for spectrum sensing in CR networks. However, ED degrades in performance in multipath fading, noise and interference. Thus, an improvement in spectrum sensing quality of ED is required under these circumstances without much increase in complexity. Furthermore, for any system designer, performance analysis of such detection systems is of utmost importance for assessing the viability of these techniques in CR networks. Moreover, the techniques developed in this research can also be utilized in other areas such as target detection in radar and signal detection in ultra-wideband (UWB) communication networks. This research study can also possibly contribute to the betterment of the society since the increase in the availability of the RF spectrum will result in the innovation of new smart devices. For example, intelligent transport solutions can help in speeding up the traffic flows and use of remote control appliances can lead to the introduction of smart houses. Not just for the society, but this study may also provide an aid to the government in military area by allowing an uninterrupted transmission of data or in space research where low interference is the key requirement.

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Chapter 2

Literature Review

2.1 Cognitive Radio

Currently in wireless communications, the available spectrum is allocated on the basis of some static spectrum assigning policies. Recently it has been found that the available spectrum is not used efficiently, or, it can also be said that the PU having a specific amount of spectrum allocated to them are no using it efficiently. It has been observed that the licensed spectrum is not being used continuously all the time, as a result leaving spectrum holes behind. Thus CR comes into existence. A CR facilitates an unlicensed user to use licensed spectrum when a PU is not using it, thereby increasing the efficiency of the available spectrum. However, CR networks impose some unique challenges due to high fluctuation in the available spectrum, as well as the diverse quality of service (QoS) requirements of various applications. The four major challenges of CR network are [4], [5] spectrum sensing (determining which portions of the spectrum are available), spectrum decision (selection of the best available channel), spectrum sharing (coordinate access to the selected channel with other secondary users) and spectrum mobility (vacate the channel when a licensed user is detected) [4], [5]. In order to meet these challenges, a CR needs to have a RF transceiver architecture as shown in Figure 2.1. In the RF front-end the received signal is amplified, mixed and converted from analog-to-digital using an analog-to-digital converter (ADC) and in the baseband processing unit, the signal is modulated/demodulated [4]. Certain terms required to understand a CR and its working properly are discussed in the following subsections.

2.1.1 RF spectrum

The term RF can be defined as any of the electromagnetic wave frequencies that lie in the range extending from below 3 kHz to about 300 GHz which include the frequencies used for commu-

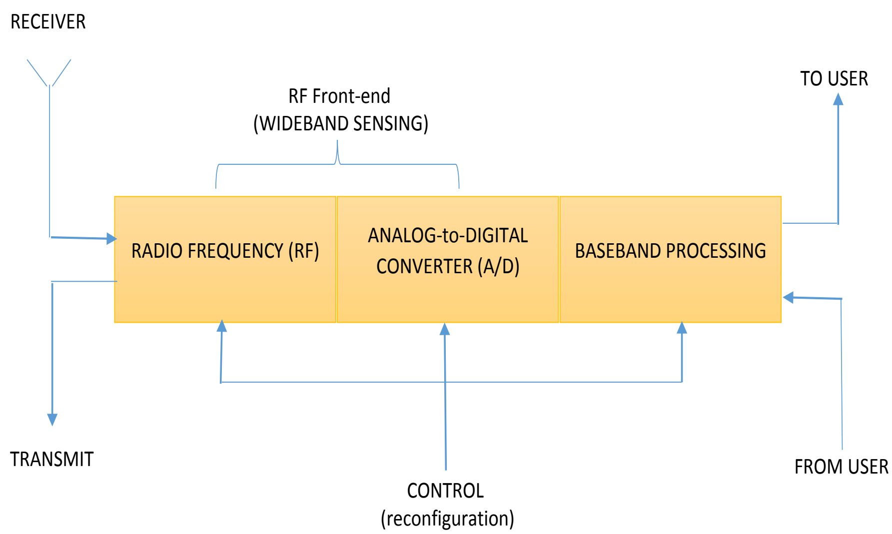

Figure 2.1: Cognitive Radio Transceiver Architecture [4]

nications signals (as for radio and television broadcasting and cell-phone and satellite transmissions) or radar signals [12].

Not all radio frequencies are equal. In general, lower frequencies can reach far beyond the visible horizon and are better at penetrating physical obstacles such as rain or buildings. Higher frequencies have greater data-carrying capacity, but less range and low ability to pass through obstacles. Capacity is also dependent on the amount of spectrum a service uses. For many wireless applications, the best trade-off of these factors occurs in the frequency range varying from 400 MHz to 4 GHz. Since the number of wireless devices and services are increasing constantly, there is a great demand for this portion of the radio spectrum.

2.1.2 Spectrum underutilization

General observations and preceding data shows that certain portions of radio frequency are either not used or are used for a very short time period. For an instance, FCCs Enforcement Bureau measured spectrum use below 1 GHz in Atlanta, Chicago, New Orleans, San Diego, and in a Washington, DC suburb during various periods in July 2002 [13]. These statistics show that, while some bands are heavily used, such as those bands used by cellular base stations, many other bands are not in use or are used only on the part time basis. Spectrum underutilization occurs in two types - spatially and temporally where spatial spectrum underutilization means that the

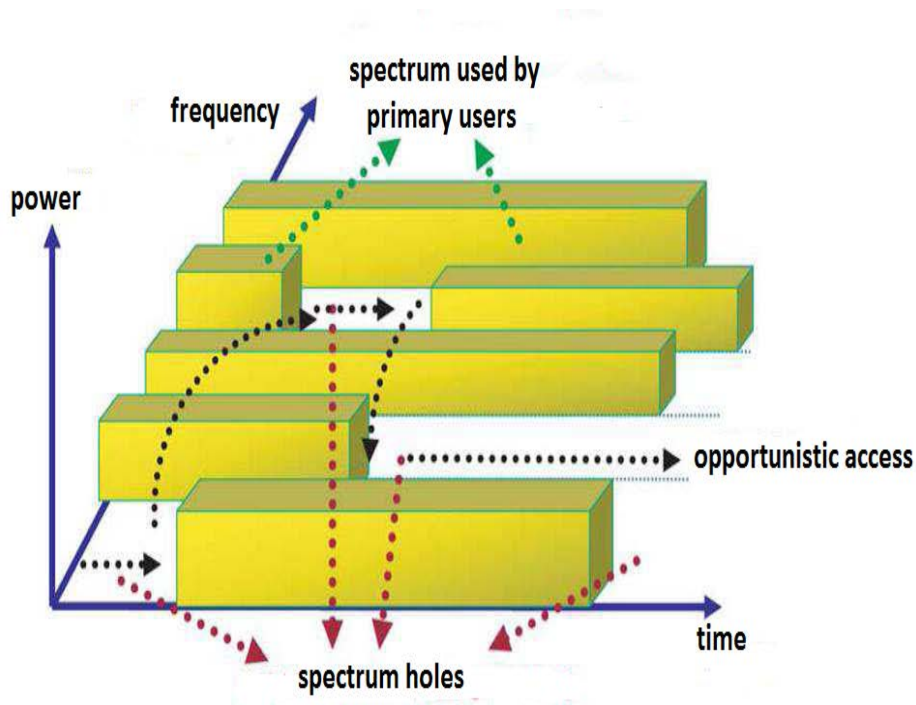

Figure 2.2: The principle of spectrum holes [4]

spectrum is not used or used in certain geographical areas and temporal spectrum underutilization means that the spectrum is used or not used for certain time period. The utilization of available spectrum is thus highly inefficient, leading to apparent (or artificial) spectrum scarcity.

2.1.3 Spectrum holes

A band of spectrum can be considered under-used if it can accommodate secondary users without harming the transmission of PU This underutilization of radio spectrum leads us to think of a new term called spectrum holes. The region of space-time-frequency in which a particular secondary use is possible is called a Spectrum hole [14]. Figure 2.2 provides an overview of spectrum holes concept. Allowing a secondary user to access a spectrum hole, when it is unoccupied by a PU, helps in significantly improving spectrum utilization [15].

2.2 Spectrum sensing

Spectrum sensing is the key enabling technology for CR networks. The main objective of spectrum sensing is to provide more spectrum access opportunities to CR users without interfering with the operations of the licensed network. For a better communication and low interference to the primary user, a CR is required to sense the spectrum holes as accurately as possible. The most effective way to sense a spectrum hole is by detecting the primary receiver, however it is not feasible since it works on the exploitation of local oscillator power at receiver end which is very weak indeed [5], [4]. Therefore the existing sensing algorithm is primary transmitter detection. Some of the many techniques, based on primary transmission detection, for detecting spectrum holes are described as follows.

1. Energy Detection: An energy detection is a non-coherent detection in which the prior knowledge of the primary signal is not required [16]. In this technique, ED detects the energy of the signal to determine whether the channel is idle or not. Although this technique has certain drawbacks such as inability to differentiate whether PU or another CR user is using the channel and poor performance for low signal-to-noise ratio (SNR), it is still preferred over other techniques because of its simplicity and ease in implication.

2. Matched Filter Detection: Unlike energy detection, matched filter detection requires the prior knowledge of primary signal. In this type of detection, secondary users should have full prior knowledge of modulation type, pulse shaping and packet format. In this scenario, secondary users should provide separate dedicated receiver for each primary user class, which is impractical. Other drawbacks of this approach are susceptibility to frequency offsets and the resultant loss of synchronization [17]. However, on the positive side, Matched Filter detection requires very little sensing time.

3. Cyclostationary Detection: This type of detection facilitates the fact that modulated signals have periodicities by default. In this technique first a cyclic autocorrelation function (CAF) of the observed signal is calculated, then a spectral correlation function (SCF) is obtained by discrete Fourier transformation of CAF and then the detection is done by searching for a unique cyclic frequency with respect to peak in SCF plane [5]. The major advantage of this technique is that it has very good performance even at very low SNR.

4. Wavelet Detection: In this type of detection, the input signal is subdivided into different frequency components. In order to locate spectrum holes, the entire spectrum band is modeled as a sequence of continuous frequency sub bands in which power spectral characteristics are sharp at the borders and smooth in the center. By employing a wavelet transform of power spectral density of input signal, vacant frequency bands can be detected by finding singularities of power spectral density. One critical challenge of implementing the wavelet

approach in practice is the high sampling rates for characterizing the large bandwidth. Also, the wavelet approach offers advantages in terms of both implementation cost and flexibility in adapting to the dynamic spectrum [18].

2.3 Hypothesis Testing

The characteristics of spectrum sensing are generally determined with the help of binary hypothesis-testing problem. There are two possibilities in spectrum sensing with respect to PU. These are H_0 representing the absence of PU and H_1 representing the presence of PU.
The key matrices of the spectrum sensing are the probabilities of correct detection given by Prob (decision = H_1/H_1) and Prob(decision = H_0/H_0), the probability of false alarm given by Prob(decision = H_1/H_0) and the probability of missed detection given by Prob(decision = H_0/H_1). There are generally following two hypothesis for spectrum sensing to decide among [5].

$$x(t) = \begin{cases} n(t), & : H_0 \\ hs(t) + n(t), & : H_1 \end{cases} \tag{2.1}$$

Here $x(t)$ is the signal observed by the CR, $s(t)$ is the signal transmitted by the PU, $n(t)$ is the additive white Gaussian noise, and h is the complex channel gain of the transmission channel between CR and PU.

2.4 Wireless Sensor Networks

A wireless sensor network (WSN) is a collection of nodes organized into a cooperative network [19]. Each node consists of a processing capability (one or more microcontrollers, central processing units (CPUs) or digital signal processing (DSP) chips, may contain multiple types of memory (program, data and flash memories), have a RF receiver (usually with a single omni-directional antenna), have a power source (e.g., batteries and solar cells), and accommodate various sensors and actuators. Figure 2.3 shows the complexity of a WSN. In this figure, we have just shown the connectivity of smartphone users to WSN in order to ease the understanding of the reader, however more number of devices such as computers, Vehicle global positioning system (GPS), etc., can also be added. The plethora of available technologies makes even the selection of components difficult, let alone the design of a consistent, reliable, robust overall system. In contrast, for wireless sensor networks, the systems are wireless, have scarce power, are

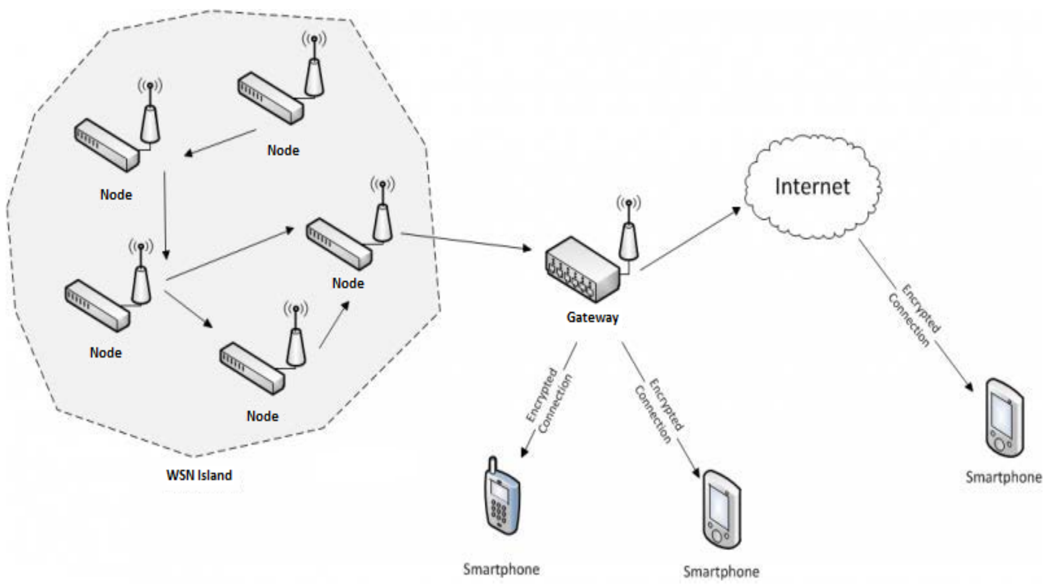

Figure 2.3: The Wireless Sensor Network

real-time, utilize sensors and actuators as interfaces, have dynamically changing sets of resources, aggregate behavior is important and location is critical. Many wireless sensor networks also utilize minimal capacity devices which places a further strain on the ability to use past solutions

2.5 Energy detector

Energy detection also called as period gram [20] is a basic approach for spectrum sensing since it has low implementation complexities, its easy to use and also it is more generic compared to other methods. As shown in Figure 2.4, ED works on the principle of comparing the received signal from PU to a predetermined threshold value and making decision whether the PU is present or not. The decision statistic(T) for ED is given as:

$$Y = \frac{1}{N} \sum_{i=1}^{N} |y_i|^2 \quad \gtrless^{H_1}_{H_0} \lambda \tag{2.2}$$

where N is the number of samples received during the sensing time and y_i is the input signal to the ED.

2.5.1 Performance metrics

In order to detect the PU signal, the ED compares the energy of the received signal with the predefined threshold λ. The time-bandwidth product over here is given as $u = TW$ where T is

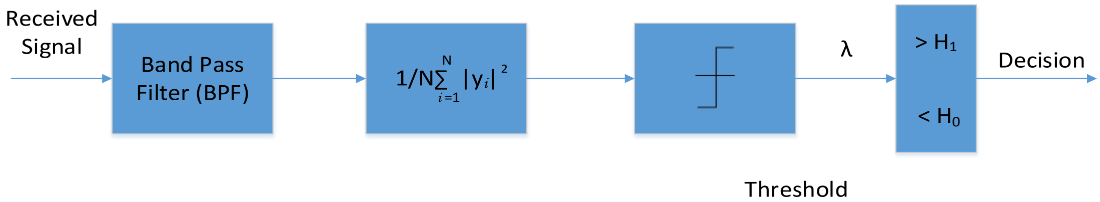

Figure 2.4: Energy Detector Block Diagram

the time period and W is predefined bandwidth. While detecting the presence of PU signal, the key metrics of an ED namely probability of detection (P_d) and the false alarm probability (P_f) are given as [5].

$$P_d = \mathbb{P}(Y > \lambda | H_1) \tag{2.3}$$

$$P_f = \mathbb{P}(Y > \lambda | H_0) \tag{2.4}$$

An important performance index for the ED is the complementary receiver operating characteristic (ROC) curve obtained by plotting P_f against probability of missed detection P_m where $P_m = (1 - P_d)$. The probability of error P_e of the ED is calculated as [21].

$$P_e = P_f.(\mathbb{P}(H_0)) + P_m.(\mathbb{P}(H_1) \tag{2.5}$$

where Pr(H_0) and Pr(H_1) are the respective probabilities of obtaining the hypothesis H_0 and H_1. The performance of an ED fascinates us and is therefore discussed as one of the objectives of this report in Chapter 3.

2.6 Improved energy detector

In order to improve the performance statistics of ED, a new kind of detector is proposed knows as IED. The decision statistic for an IED is given as [11]

$$Y = \frac{1}{N} \sum_{i=1}^{N} |y_i|^p \quad \gtrless^{H_1}_{H_0} \lambda \tag{2.6}$$

where $p > 0$ is an arbitrary constant. The only difference between the decision statistic of ED and IED is that in ED the value of p is fixed to 2 and in IED, p is an arbitrary positive value. Also the detection threshold in IED is changed according to the value of p. It can also be seen that the conventional ED is a special case of IED when the value of p is set to 2. The performance of an IED is the area of our interest and is discussed later in this report in Chapter 3.

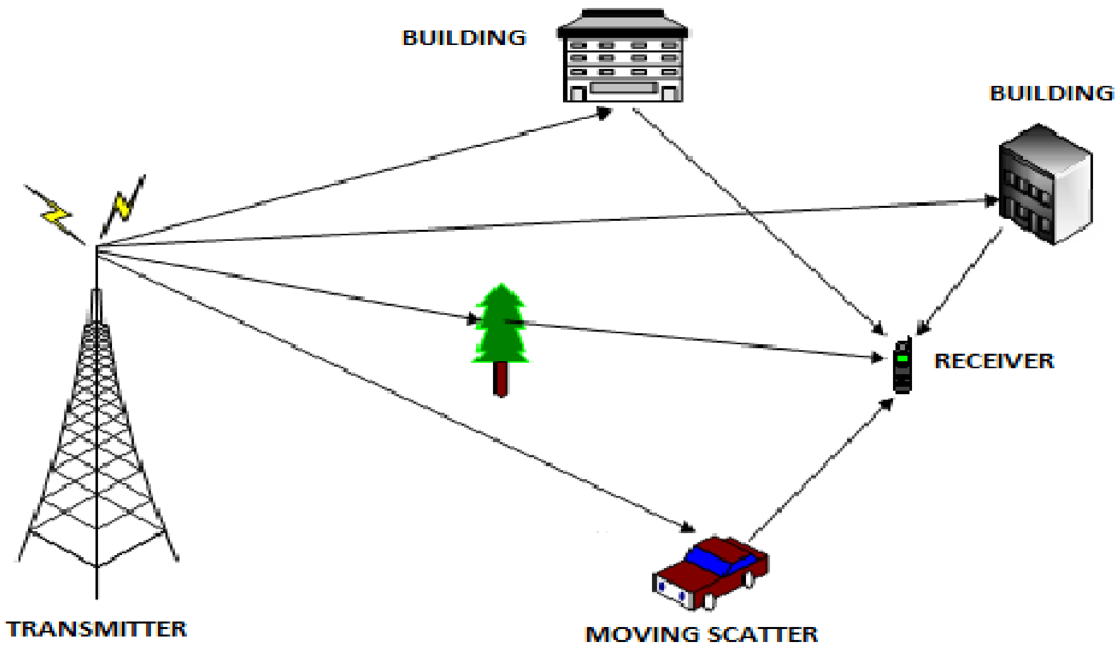

Figure 2.5: Multipath Fading

2.7 Multipath fading

In a wireless communication channel, when a signal is transmitted from transmitter to receiver, there is a very high probability that it gets reflected over multiple reflected paths as shown in Figure2.5. Due to this, certain uncertainties in the signal, such as fluctuations in phase, amplitude and angle of arrival of the received signal occur. This is termed as Multipath fading. It can be best explained with the example that when a signal is transmitted from base station (BS) to mobile station (MS), it may suffer from multiple reflections from buildings nearby, trees or any other environmental factors.

2.7.1 fading channel models

There are a number of fading models that predict the effects of this fading properly in order to mitigate its effects. Some of these are

1. Rayleigh Fading Model: The Rayleigh fading model is normally viewed as a suitable approach to take when analyzing and predicting radio wave propagation performance for areas such as cellular communications in a well built up urban environment where there are many reflections from buildings, etc.. As per the Rayleigh fading model, their will be a random variation in the magnitude of the signal, that has traveled through a communication channel, according to the continuous probability distribution [8]. The probability density

function (PDF) of the channel fading amplitude as per the rayleigh fading model is given as

$$p(r) = \frac{2r}{\Omega} exp(-r^2/\Omega) \tag{2.7}$$

where r is the channel fading amplitude and Ω is the average fading power. The Rayleigh distribution is frequently used to model multipath fading with no direct line-of-sight (LOS) path.

2. Rician Fading Model: In Rician fading, a strong dominant component is present. Similar to the case of Rayleigh fading, the in-phase and quadrature phase component of the received signal are independent and identically distributed Gaussian random variables. However, in Rician fading the mean value of (at least) one component is non-zero due to a deterministic strong wave. A Rician fading channel can be described by two parameters: K and Ω, where K, the Rice factor, is defined as the ratio of the specular power to the scattered power and Ω is the average envelope power. The resulting PDF for Rician fading is:

$$f(x) = \frac{2(k+1)x}{\Omega} exp(-K - \frac{(K+1)x^2}{\Omega}) I_0(2\sqrt{\frac{K(K+1)}{\Omega}}x) \tag{2.8}$$

where I_0 is the 0th order modified Bessel function of the first kind. This type of fading is often observed in microcellular and mobile satellite applications [8].

3. Nakagami-m Fading Model: The Nakagami fading or the Nakagami-m fading gives a probability distribution related to the gamma distribution. It has two parameters: a shape parameter m and a second parameter controlling spread, Ω. The PDF for Nakagami-m fading model is given as:

$$f(x; m, \omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1} exp(\frac{-m}{\Omega} x^2) \tag{2.9}$$

where m ranges from 1/2 to ∞. The Nakagami-m distrubution is found to provide a better match to experimental data than Rayleigh and Rician distributions [22]. The Nakagami distribution matches some empirical data better than other models. The Nakagami-m distribution often gives the best fit to landmobile and indoormobile multipath propagation, as well as scintillating ionospheric radio links [23].

2.8 Antenna Diversity

Diversity is one very effective remedy that exploits the principle of providing the receiver with multiple faded replicas of the same information bearing signal. There are several methods by which diversity can be achieved and antenna diversity is one of them [8]. Antenna diversity, also known as space diversity is achieved by using multiple transmit and/or receiving antennas. Antenna diversity is especially effective in mitigating multipath situations. This is because, now the receiver is able to receive the same signal from multiple sources and is able to chose the one with the best quality among them. Cellularization or sectorization, for example, is an antenna diversity scheme that can have antennas or BSs miles apart. The signals arriving at the antenna diversity reception are required to be subsequently combined so that an improved version of the signal, when compared to that of the single antenna system, is formed. Some of the well known combining techniques used in antenna diversity are as follows

1. Selective Combining: In this type of combining, the branch or received signal from an antenna that has the highest SNR is selected and all others are discarded [8]. The selected branch is then used for the duration of the entire burst. Such an approach is only useful if the channel does not change significantly over a time division multiple access (TDMA) burst.

2. Maximal Ratio Combining: The main principle behind maximal ratio combining is the combination of all the signals in a co-phased and weighted manner so as to have the highest achievable SNR at the receiver at all times [8]. In this combining technique, all the branches are used simultaneously. Each of the branch signals is weighted with a gain factor proportional to its own SNR.

3. Square Law Selection: In square law selection, the inputs from different antennas are fed into separate square law devices, where square and integrate operations are performed, and then the outputs of these square law devices are added to yield a new decision statistic. This decision statistic is then used to determine whether a PU is present or not. The probability of detection and probability of false alarm are given as [24]:

$$P_{d_{SLS}} = 1 - (1 - P_d)^L \tag{2.10}$$

$$P_{f_{SLS}} = 1 - (1 - P_f)^L \tag{2.11}$$

2.9 Cooperative Diversity

In order to reduce the fading over the quality of the transmitted signal, cooperative diversity can be used to transfer the different samples of the same signal over essentially independent channels. There are many approaches to achieve cooperative diversity in wireless communications. Multiple Antennas is also one of the methods but the multiple antennas are not always available or the destination is just too far to get a good quality signal. Some of the other approaches to achieve cooperative diversity are

1. Amplify and Forward: Whenever a signal is transmitted from sender to receiver, it gets faded or loses its quality with respect to time and space. The amplify-and-forward (AF) method takes this fact into consideration and amplifies the received attenuated signal at relay before it can be sent forward again. This method is often used when the relay has only limited computing power/power available or the time delay, caused by the relay to decode and encode the message, has to be minimized. In order to send the data with the same power as the sender did, the relay needs to use the gain of [25]

$$\beta = \sqrt{\frac{\xi}{|h_{(q,b)}|^2\xi + 2\sigma^2_{(q,b)}}} \tag{2.12}$$

   where q denotes the sender, b the relay, ξ as power of the transmitted signal and σ^2 as variance. one of major drawbacks of this technique is that along with the signal, the noise is also amplified.

2. Decode and Forward: Nowadays a wireless transmission is very seldom analogue and the relay has enough computing power, so decode-and-forward (DF) is most often the preferred method to process the data in the relay. In this technique, the recived signal is decoded at the relay and then again encoded prior to transmitting to the receiver. This way the original signal is transmitted without noise. DF can be done by two methods, either decode the content fully or decode it partially. Decoding the signal fully, although, requires an ample amount of time, but it also provides numerous of advantages such as errors in the message could be checked and corrected by using certain error correcting algorithms or erroneous message might not be sent to the receiver if error detection techniques are used. However, this large amount of delay is not accepted in practice. Therefore, relay, instead of

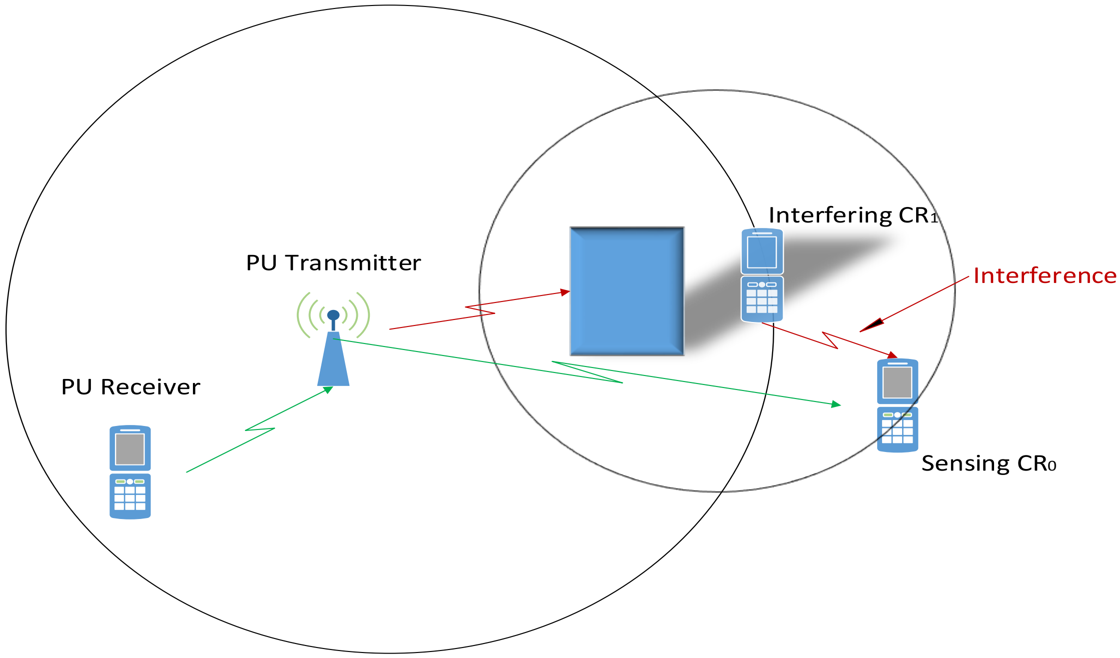

Figure 2.6: Shadowing uncertainty [4]

undergoing full decoding and encoding process, decodes and encodes the signal symbol-by-symbol, shredding all the error correction and detection techniques.

2.9.1 Hard Decision Combining

In this type of technique, the CR user makes a one-bit decision regarding the presence of PU and then this one-bit decision is forwarded to a fusion center where the final decision is made. Inside the fusion center, either OR rule is used or an AND operation is used to make a decision. According to [5], the common receiver fuses all the one-bit data by using the following rule

$$Z = \sum_{i=1}^{K} D_i \begin{cases} \geq n, & H_1 \\ < n, & H_0 \end{cases} \tag{2.13}$$

where H_1 and H_0 denote the inferences drawn by the common receiver that the PU signal is transmitted or not transmitted, respectively.

2.9.2 Soft Decision Combining

In soft decision combining, CRs forward their entire data to the common receiver instead of just forwarding their decision bits [26]. The common receiver then takes the linear combination of the data received from various CRs in order to make a decision between the two hypothesis.

2.10 Interference in CR networks

Due to the limited availability of the wireless spectrum, it is not possible in large wireless networks to separate concurrent transmissions completely. Thus, the signals from many undesired (interfering) transmitters get added up to the desired signal at the receiver. Hence, interference is one of the main performance-limiting factors in a wireless communication network. In case of CR networks, an effective spectrum sensing algorithm enables the cognitive radio to transmit without causing harmful interference to the licensed user. However, in a multi-user environment, the sensing CR may itself be subject to interference resulting from the other users which may adversely affect the CR's sensing performance [21]. The sensing CR may, for example, receive interfering signals in the following situations.

1. In cellular mobile based CR networks, the sensing CR may receive interference from other users operating in the same frequency band (co-channel interference) [27]. The co-channel interference in wireless networks depends upon the number of interferers and wireless channel propagation characteristics such as path loss and multipath fading [28].

2. From other users operating nearby such that their transmit powers leak into the sensing CR receiver. The leaking transmit powers depend upon the spatial locations, number of transmitters and the path loss which depends on the propagation channel. In this situation, the sensing CR is mainly affected by interferers which lie within its close proximity.

3. From other contemporary (operating in the same spectrum band) sensing CR nodes which may have miss detected the PU and start to transmit thus harmfully interfering with the sensing CR's reception. As shown in Figure 2.6, a practical scenario may arise when a CR_1 has a good LOS to CR_0 but may not be able to detect the PU, even though if PU is in CR_1 user's range, due to say, shadowing, which occurs when a large obstacle disrupts the transmitter-receiver communication link. So CR_1 assumes that the PU is absent and starts transmitting and thus CR_0, which is looking to detect the PU, receives the interfering signal from CR_1.

   In order to effectively utilize the spectrum, a CR should have high sensing reliability. However, the presence of interference is likely to degrade the sensing performance of a CR. Some of the possible solutions to mitigate the effects of interference could be the use of multiple antennas, using detectors robust to interference for CR and possibly, cooperative spectrum sensing.

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Chapter 3

Performance of energy detector and improved energy detector in presence of interference

3.1 Introduction

In this chapter, the performance of an ED based CR is studied in the presence of multipath fading, noise and interference. Multipath fading channel is modeled using the popular Rayleigh fading. As the spectrum sensing performance of ED is likely to degrade in interference, with the goal of degrading the mitigation, the IED is considered and its detection performance in interference is characterized. We exploit the adaptive tuning of the parameter p of the IED to achieve possible performance benefits compared to the ED. In order to further explore possible performance improvements, the scenario is extended to a situation when IED is equipped with multiple antennas. The recently proposed p-law selection (pLS) scheme [29] is utilized for combining signals received at the multiple antennas. The performance is analyzed via numerical results obtained using Monte-Carlo simulations Numerical results will be generated via semi-analytical Monte Carlo simulations.

The remainder of this chapter is organized as follows. The system model and the simulation model are described in Section 3.2 and Section 3.3, respectively. The Numerical results are discussed in Section 3.4 where Section 3.4.1 elaborates the performance of ED and IED in interference and Section 3.4.2 describes the performance of IED with multiple antennas in the presence of interference. Concluding remarks are made in Section 3.5.

3.2 System Model

We consider a network with a PU, a sensing CR and K interfering users U_1, U_2,... U_K dispersed within a given geographical region as shown in Figure 3.1. The PU holds the highest priority

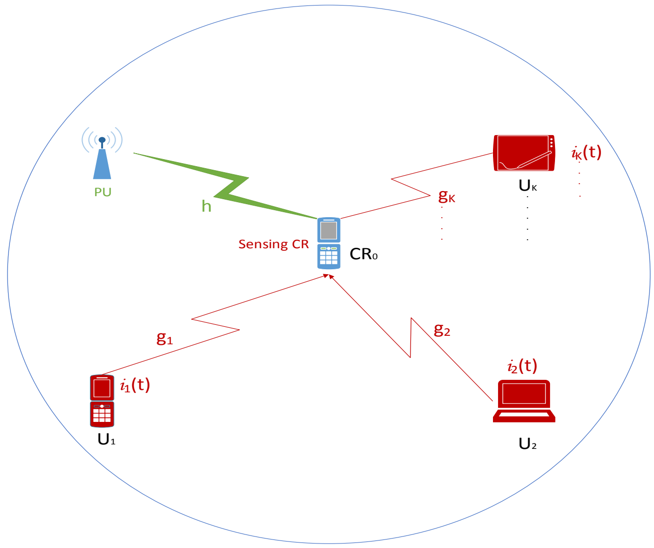

Figure 3.1: Interference in CR

for communicating in the band of interest while network policy allows sensing CR to randomly access the band only when the PU is idle. Meanwhile, the interfering devices $U_1, U_2, ...U_K$, which could be other PUs or even secondary CR users that operate in proximity to the desired PU-CR$_0$ link, may be transmitting/receiving in the same space-time or frequency instances. The CR$_0$ thus receives interfering transmissions from these users. In this case, the signal observed at the ED is in the form

$$y(t) = \begin{cases} n(t) + \sum_{k=1}^{K} g_k i_k(t), & : H_0 \\ hs(t) + n(t) + \sum_{k=1}^{K} g_k i_k(t), & : H_1 \end{cases} \tag{3.1}$$

where $h \sim CN(0,1), g_k \sim CN(0,1), \forall k \in \{1, 2, ...K\}$ are fading channel coefficients from PU and from interfering users to the sensing CR, respectively, which are Rayleigh faded[1], $s(t)$ is the PU transmit signal, $n(t)$ is the additive white Gaussian noise and $i_k(t)$ is the kth interfering signal. In order to sense the PU presence, the signal $y(t)$ is sampled and fed to the ED such that the detection decision variable is given by

$$Y = \frac{1}{N} \sum_{i=1}^{N} |y_i|^2 \quad \gtrless_{H_0}^{H_1} \lambda \tag{3.2}$$

where $y_i \forall i \in \{1, 2, ..., N\}$ is the ith sample of the signal $y(t)$ and N is the total number of samples, and λ is the detection threshold. Similarly, the IED decision rule can be obtained to be

$$Y = \frac{1}{N} \sum_{i=1}^{N} |y_i|^p \quad \gtrless_{H_0}^{H_1} \lambda \tag{3.3}$$

[1]Here $CN(m,\sigma)$ is a complex normal random variable with mean m and variance σ

where $p > 0$ is the tuning parameter of IED.

3.3 Description of simulation model

The numerical results are obtained using semi-analytical Monte Carlo simulation, which is an iterative process that relies on repeated random sampling of an unknown probabilistic entity to obtain numerical results using a broad class of computational algorithms [30]. These simulations are performed in MATLAB using 10^5 iterations. The Monte Carlo simulation technique is

3.3.1 Performance metrics

The performance metrics needed for quantifying the detection performance are computed using the following rules.

$$P_d = \mathbb{P}(Y \geq \lambda | H_1), \tag{3.4}$$

$$P_f = \mathbb{P}(Y \geq \lambda | H_1) \text{ and} \tag{3.5}$$

$$P_e = \mathbb{P}(H_0) P_f + \mathbb{P}(H_1) P_{md} \tag{3.6}$$

where $P_{md} = 1 - P_d$ is the probability of miss detection and H_1/H_0 are the hypothesis denoting the presence/absence of a PU, respectively.

3.3.2 Fading channel generation

Rayleigh fading is an appropriate model in order to employ the real-world phenomena of wireless communications, since it can reasonably model multipath scattering effects, time dispersion, and Doppler shifts arising from relative motion between the transmitter and receiver. Rayleigh fading channel coefficient h can be generated as.

$$h = a_I + j b_Q \tag{3.7}$$

where a_I and b_Q are independent Gaussian random variables with mean zero and variance 1/2. The channel coefficient is assumed to remain constant over the sampling interval (slow-fading) [8].

3.3.3 Multiple antenna combining scheme

To further improve the performance of an IED in the presence of interference, L number of antennas are assumed at the detector. The pLS scheme is used for IED which is an equivalent version of the SLS combining in the traditional ED with multiple antennas [29]. The pLS scheme is shown in Figure 3.2 where the received signal at each branch is passed through its p-norm device after which the branch with the largest decision variable is selected. The resulting decision

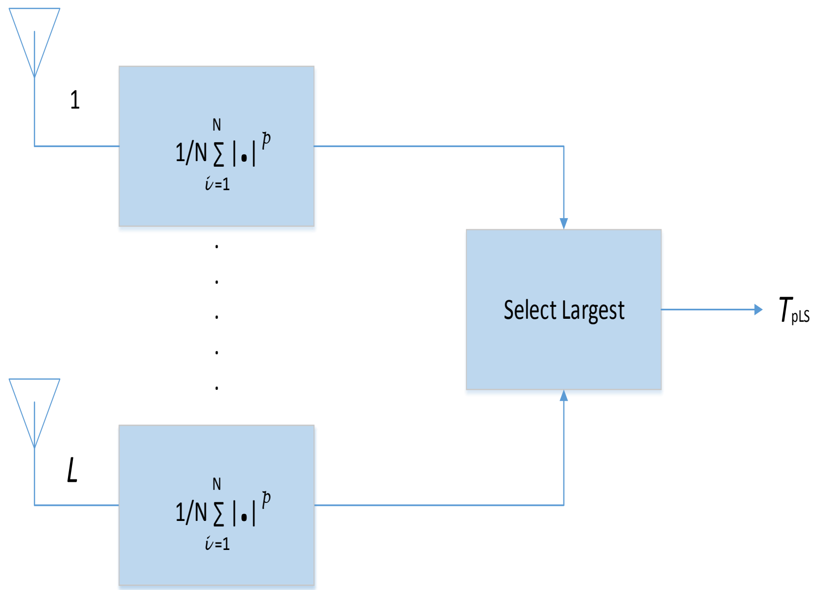

Figure 3.2: p-law selection (pLS) scheme

variable is given by $Y_{\text{pLS}} = \max\{Y_1, Y_2, ..., Y_L\}$ where $Y_1, Y_2, ..., Y_L$ are the L decision variables obtained from the corresponding p-norm devices. Then the detection probability and false alarm probability for the pLS scheme, denoted by $P_{d_{pLS}}$ and $P_{f_{pLS}}$ respectively, are given by

$$P_{d_{pLS}} = 1 - (1 - P_d)^L \tag{3.8}$$

$$P_{f_{pLS}} = 1 - (1 - P_f)^L \tag{3.9}$$

where P_d and P_f are the detection probability and false alarm probability for a detector with single antenna.

3.4 Numerical Results: Performances of ED and IED in interference

Next, we discuss the performances of ED and IED in interference. A low probability of false alarm is always desired. For example, CR networks require $P_f \leq 0.1$ for reliable detection of spectrum holes [31]. Thus, we fix P_f= 0.01, by varying λ, for generating all of our graphical results other than the ROC curves, which are the plots of P_d vs P_f. The numerical results are described as follows

3.4.1 Effect of interference on ED performance

Figure 3.3 illustrates the performance of an ED in the presence of various number of interferers. Clearly, as the number of interferers increase, the performance of ED degrades. For example,

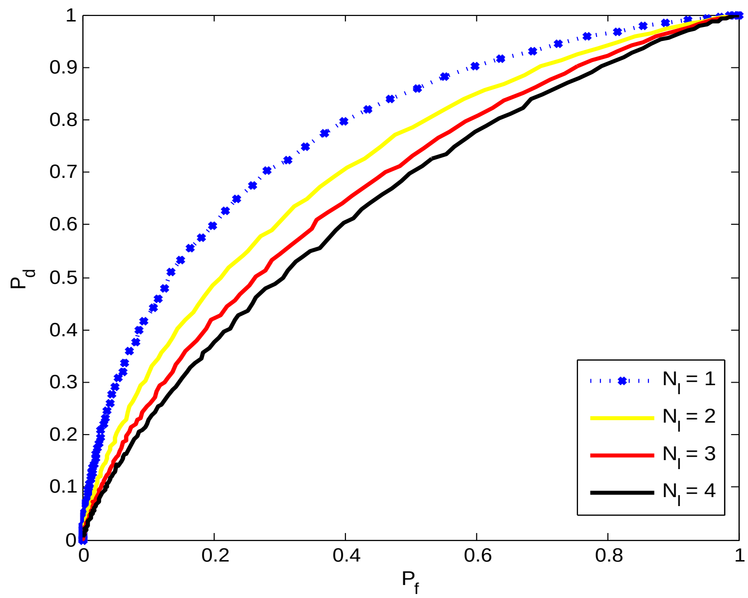

Figure 3.3: ROC curves for varying interferers, u = 2, SINR = 5 dB

when the number of interferers decrease from 2 to 1, about 33% of gain is observed at a constant P_f of 0.01. Also when the number of interferers reduces from 3 to 2, about 27% of increase in the performance of ED is observed. Hence it can said that lower the number of interferers, the better the ED performance.

3.4.2 Effect of N_I over P_e for varying λ

In Figure 3.4, P_e for an ED is plotted against different values of threshold (λ) for varying interferers. We can see that as the number of interferers increase, P_e also increases which means that there are more chances for an ED to give an error while sensing a spectrum. According to the numbers, P_e would increase by 23% when number of interferers increase from 1 to 2 and by 11% when number of interferers increase from 2 to 3, at a fixed λ of 2. Also we can see that the optimal λ required for an ED changes with the change in number of interferers. For eg., the optimal threshold for an ED with one interferer is 2.4 whereas for two interferers is 3.3. Therefore, lower the number of interferers, lower will be the error probability for ED while sensing a spectrum.

3.4.3 P_{md} vs. N_I for fixed P_f

Figure 3.5 shows a graph plotted between probability of missed detection(P_{md}) and N_I for various values of SINR. As it was expected, with an increase in SINR, P_{md} decreased for fixed number of interferers. For an instance, P_{md} decreased by 31% when SINR is increased from 5 to 10 for

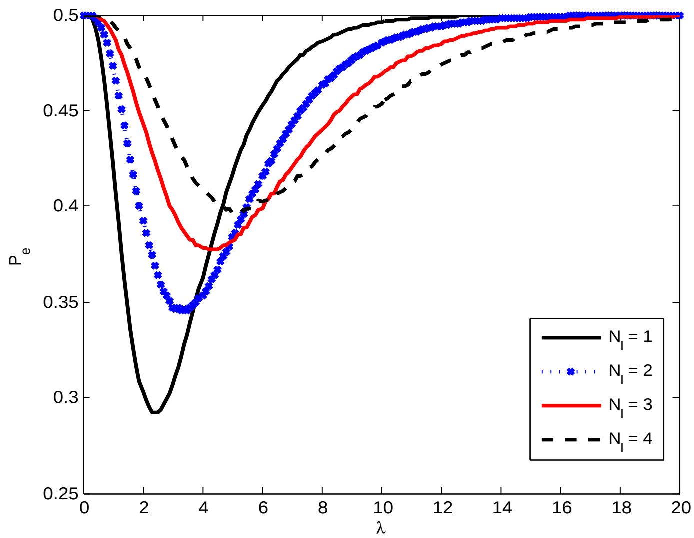

Figure 3.4: P_e vs. λ for varying interferers with p = 2, u = 2, SINR = 5 dB

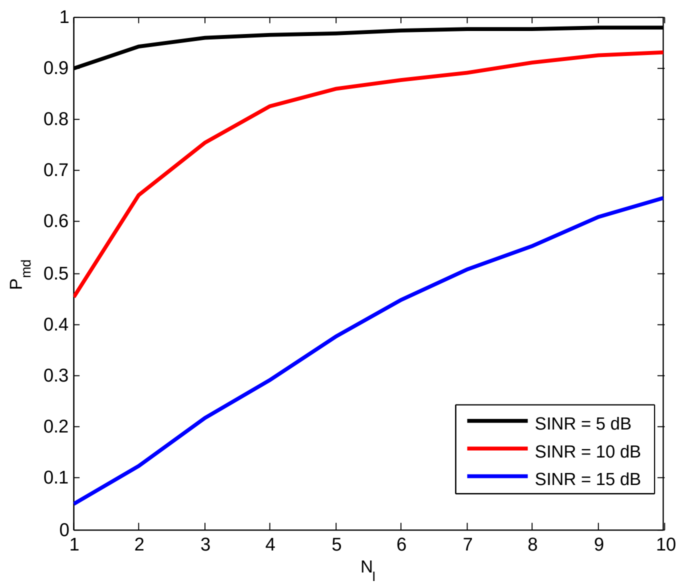

Figure 3.5: P_{md} vs. N_I for varying SINR at P_f = 0.01

2 interferers. Also It can be very clearly seen from the graph that as N_I increases, P_{md} increases. For example, P_{md} increases by 6% when N_I is increases from 1 to 2. Similar observations were made when N_I was further increased. Thus we conclude that, lower the number of interferers and higher the SINR, the lower are the chances that an ED would miss detect a PU.

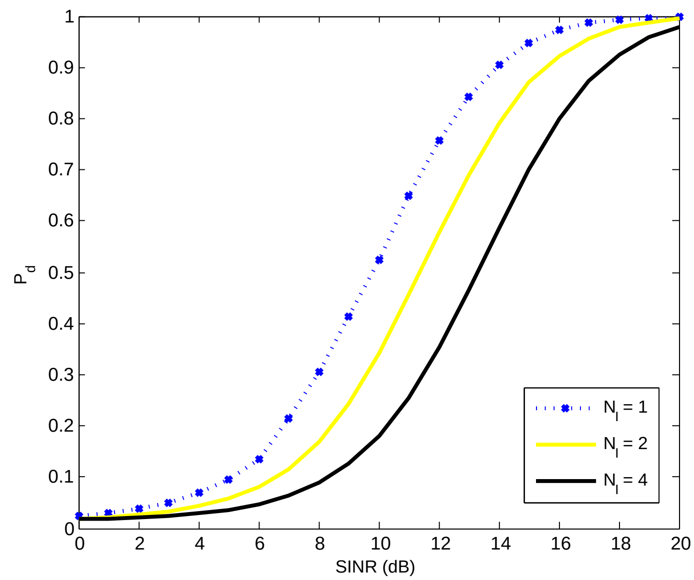

Figure 3.6: P_d vs. SINR for varying interferers with P_f = 0.01

3.4.4 Effect of N_I over P_d for varying SINR

Figure 3.6 shows the effect of interference over ED's probability of detection P_d for varying signal-to-noise plus interference ratio (SINR). Our results and calculations have shown that as the number of interferers $N_I$are increase, P_d decreases for a fixed value of SINR. In order to support this comment, we observed that when SINR is fixed to 10 dB, P_d degraded by 65% when N_I was increased from 1 to 4. The value of P_d in this case changed from 0.5 for one interferer to 0.18 for four interferers. It is also seen that if by varying SINR, same P_d could be achieved for different interferers but this is not feasible in practice since SINR can not be varied as per our needs. Hence, it can be said that as the number of interferers are increased, probability of detection of an ED decreases untill and unless SINR is increased.

3.4.5 Effect of N_I over P_e for varying SINR

In order for an ED to provide high performance, it is very important that its probability of error P_e should be as low as possible. Figure 3.7 depicts the relation of P_e to SINR with respect to varying interferers N_I. There are two aspects that can be observed from the figure. One is that as SINR increases, P_e decreases for particular number of interferers. For example P_e decreases by 31% when SINR is increased from 8dB to 10dB for one interferer. Second is that for a fixed value of SINR, P_e increases with the increase in N_I. For an instance, P_e increases by 37% when

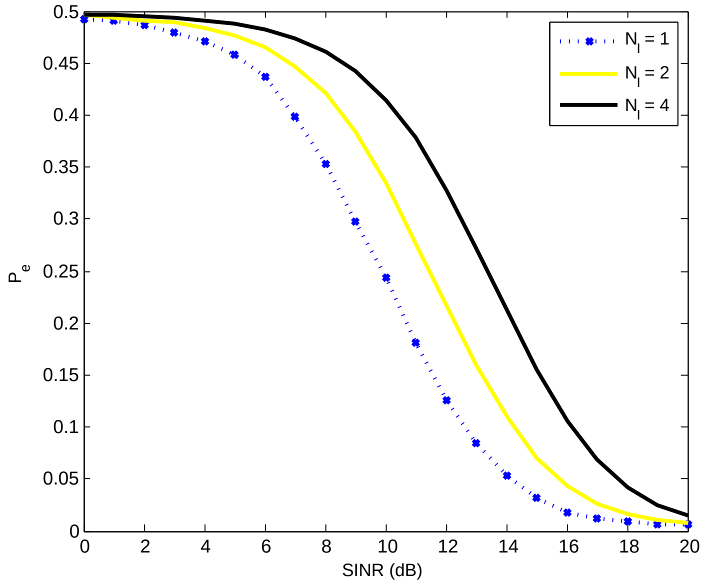

Figure 3.7: P_e vs. SINR for varying interferers, p = 2, P_f = 0.01

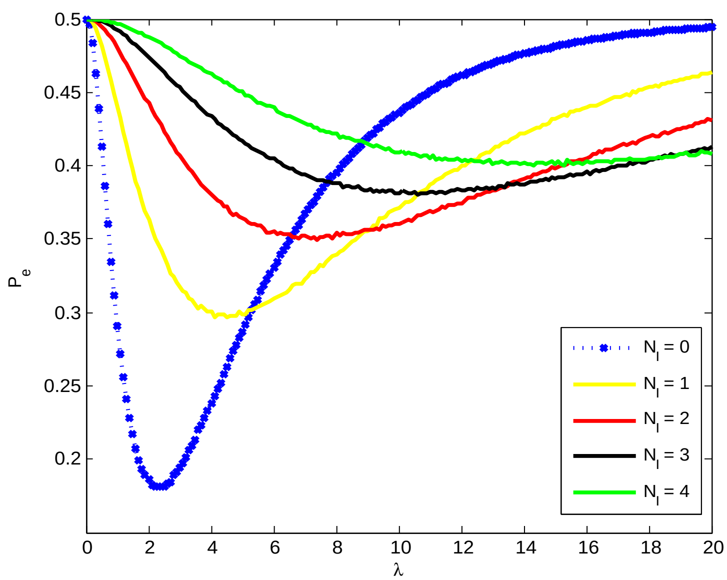

Figure 3.8: P$_e$ vs. λ for varying interferers, p = 3, SINR = 5 dB

the number of interferers are increased from 1 to 2 and by 24% when N_I is increased from 2 to 4. Therefore, we conclude that, lower the value of N_I, lower the P_e is and better an ED would perform.

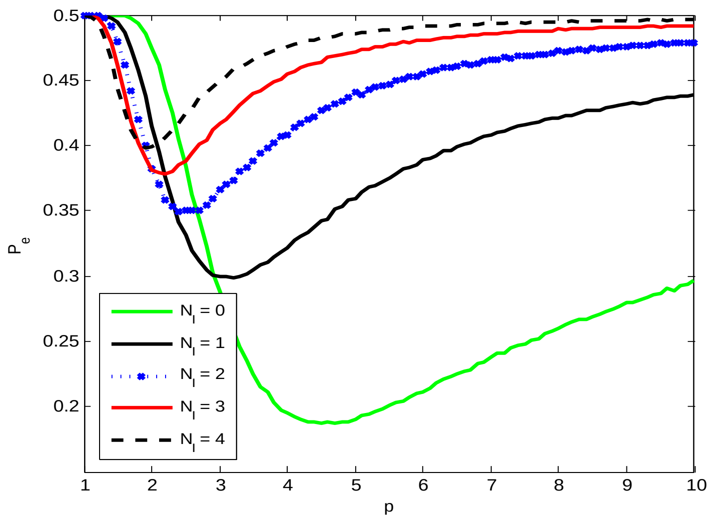

Figure 3.9: P_e vs. p for varying interferers, λ = 5, SINR = 5 dB, u = 2

3.4.6 Effect of N_I over P_e for varying λ

From Figure 3.8, which gives a graph of P_e vs λ for varying interferers for an IED, it can be seen that as the number of interferers increase, P_e and λ increase as well. This can be supported with our observation that, while λ is kept constant to 2, P_e increases by 95% and 21.8% when N_I increases from 0 to 1 and 1 to 2, respectively. On the other hand, the optimal value of λ increases as the number of interferers are increase. For example, the optimal value of λ increased from 2.4 to 4.5 and from 4.5 to 7.4 when N_I incrases from 0 to 1 and 1 to 2, respectively. Therefore from the above calculations, we can conclude that lower number of interferers would be beneficial for a better performance of an IED.

3.4.7 Effect of N_I over P_e for varying p

For an IED, p is one crucial factor that can decide performance characteristics. Figure 3.9 shows the influence of p over P_e under the presence of interference. From the figure, we calculated that P_e decreases only until a certain optimal value of p for particular number of interferers but after that, it gradually increases. For example, the optimal value of p when N_I is 1 is 3.3 and is 2.3 when N_I is 3. We also noticed that this optimal value changes with a change in N_I, which generally decreases with increase in N_I. We also deduced that as N_I increases, P_e decreases. About 22% and 8% of increase was recorded in P_e when N_I increased from 1 to 2 and 2 to 3,

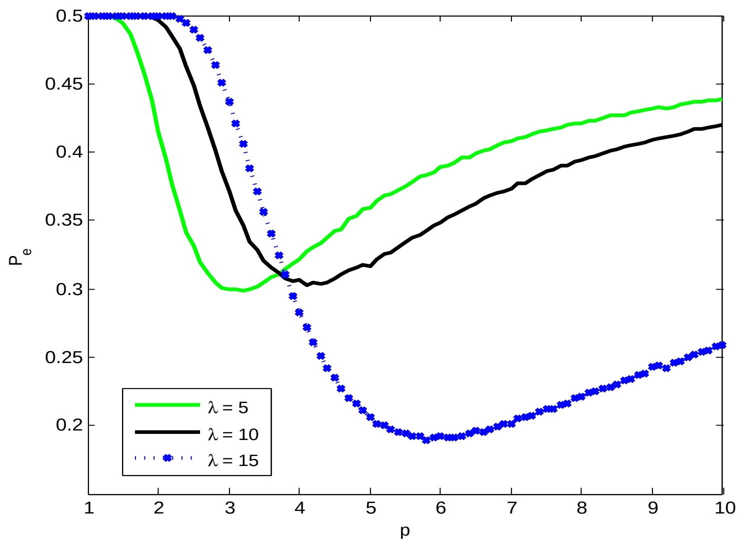

Figure 3.10: P_e vs. p for varying λ, SINR = 5 dB, u = 2

respectively. Therefore it can be concluded that an IED should be used at the optimal value of p under low interference for a low error rate.

3.4.8 Effect of λ over P_e for varying p

Figure 3.10 depicts the relation of P_e to p with respect to varying λ. It can be clearly seen from the figure that for a particular value of λ, P_e decreases up to certain value or the optimal value of p after which it starts increasing. Also it can seen that this optimal value of p differs for different values of λ. From the simulation results we saw that optimal value of p varies from 3.2 when λ is 5 to 4.1 when λ is 10. Another thing that we recorded was that for a fixed value of P_e, p increased when λ was increased. Thus from the above results we infer that optimal values of p for an IED result in lower P_e for a given λ.

3.5 Numerical Results: Performance of IED with multiple antennas in interference

3.5.1 Effect of L over P_d for varying SINR

Recently, the antenna diversity has emerged as an important factor in spectrum sensing. Figure 3.11 shows the relationship of P_d and SINR as the number of antennas L are varied. It can be clearly seen from the figure that for a fixed value of SINR, P_d increases as L increases. We

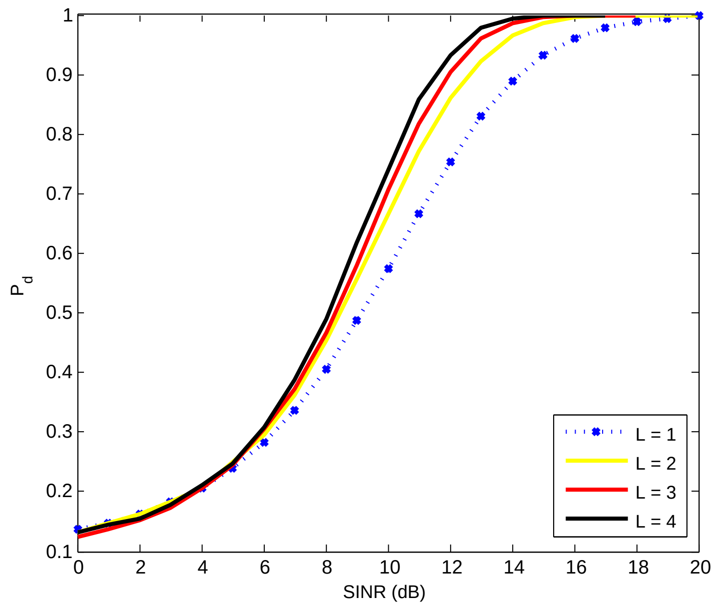

Figure 3.11: P_d vs. SINR for various number of antennas, p = 2, P_f = 0.01

calculated that P_d increases by 16% when L increases from 1 to 2 and by 6% when L increases from 2 to 3. Also for a fixed value of L, P_d increased as SINR is increased. For example, P_d increased by 41% when SINR is increased from 8 to 10. However, increasing SINR is not always in our hands. Thus we concluded that probability of detection can be improved if number of antennas are increased.

3.5.2 Effect of N_I over P_{md} for varying L

Figure 3.12 shows the impact of interference over probability of missed detection P_{md} for varying number of antennas L for an IED. According to this figure, if we keep N_I to any constant value, P_{md} decreases with an increase in L. About 5% of decrement was recorded in P_{md} when L increased from 2 to 4 for a single interferer. Another thing that we noticed was that $P_m d$ increased with an increase in N_I for fixed L. This could be verified with our calculations where we saw an increase of 18% in $P_m d$ when N_I increases from 1 to 2 and an increase of 8% when N_I increases from 2 to 3. So we can say that for an IED to have low probability of missed detection, it is very important that it has more number of antennas and low interference.

3.5.3 Effect of p over P_e for varying λ

Figure 3.13 gives us the behavior of P_e with respect to λ for different values of p. The number of antennas and the number of interferers are kept constant to 2 in this graph. We observed that for a

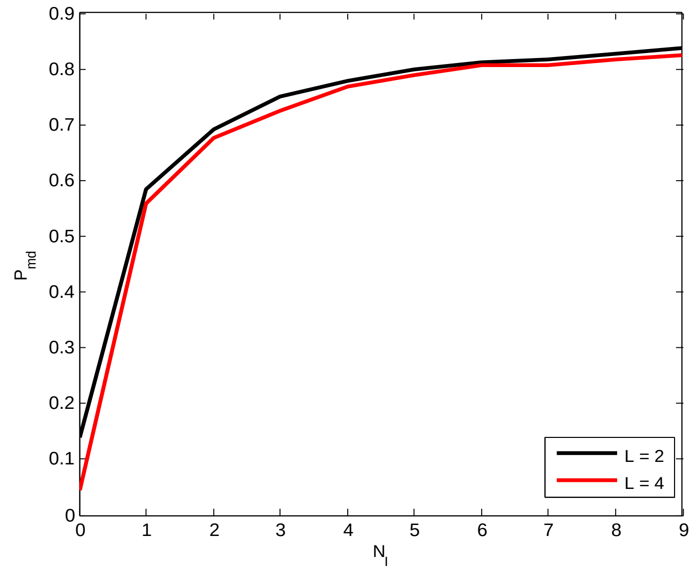

Figure 3.12: P_{md} vs. N_I for various number of antennas, p = 3.5, u = 2, P_f = 0.01

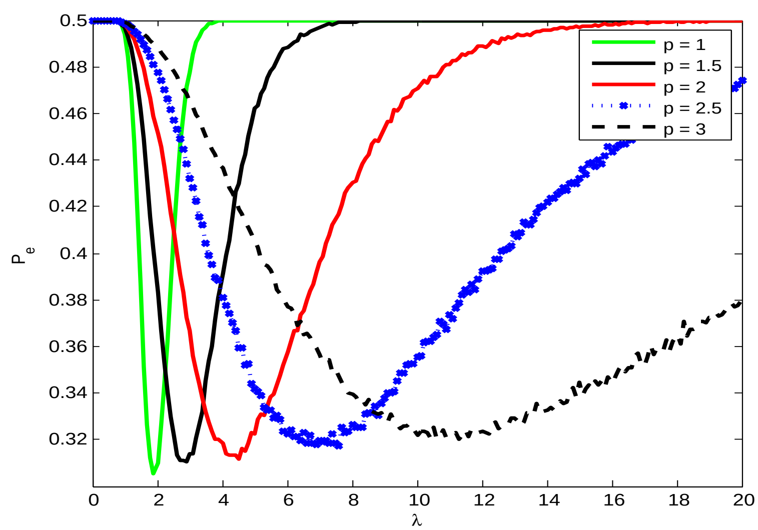

Figure 3.13: P_e vs. λ for varying p with two antennas, SINR = 5 dB, u = 2, N_I = 2

particular value of p, P_e decreases only up to a certain optimal threshold value and increases after that. It can also be seen that different values of p have different optimal threshold values which increases with an increase in p. For an instance, when p is 1.5, the minimum λ is 2.9 and when$p$ is increased to 2, λ becomes 4.5. From these result we inferred that p equals to 1 had minimum

P_e as compared to other p values. Thus we can conclude that an IED provides lower probability of error as compared to ED where the value of p is always 2.

3.6 Conclusion

In this chapter, the performance of ED in Rayleigh fading channels in presence of interference is characterized with the help of extensive simulations performed in MATLAB. Intuitively, the reception of unwanted signals at the ED degrades its sensing performance, which was indeed the case as observed from our numerical results. With the goal of alleviating such degradation, next, the IED is considered. Interestingly, our results reveal that significant gain in reliability of spectrum sensing can be achieved by adaptively tuning the IED parameter p. To further exploit spatial diversity in the form of multiple-antennas, the IED performance with pLS combining scheme is considered. The IED is found to perform better as the number of antennas is increased. Thus, our findings clearly suggest that the use of multiple antennas are indeed desirable to further enhance the reliability of detection of the IED, which in turn helps to achieve the overall goal of having a robust spectrum sensing performance of CR networks in presence of interference.

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Chapter 4

Conclusion and Future Work

This project focuses on simple detectors for addressing the spectrum sensing problem in cognitive radio networks. The effect of interference on the spectrum sensing quality of the well-known energy detector is considered. With the goal of promoting robust spectrum sensing, application of two state-of-the art wireless signal detection techniques, the energy detector and the improved energy detector are investigated.

In Chapter 1, a brief overview of the problem of ever increasing demand of limited available spectrum is presented. Cognitive radio networks are considered as a solution to this problem, however these networks have their own challenges among which spectrum sensing is the fundamental one. In order to sense the spectrum, an energy detector is a popular detection device due to its ease of implementation and low hardware complexity. However, its performance is likely to degrade in presence of interference, which is a common unwanted nuisance in multi-user wireless communication systems. Interference may arise, for example, from: (i) other users operating in the same frequency band (co-channel interferers), (ii) leakage of power from other transmitters located in the same space at the same time, and/or (iii) contemporary cognitive users looking for possible communication opportunities. Thus, the characterization of the energy detector performance in presence of interference is pivotal to identify the effect of interference as well as to devise effective detection techniques to enhance its reliability of detection in modern day communication network. With the purpose of achieving possible enhancements in ED performance, recently, a more generalized version of the energy detector called the improved energy detector came into existence. Thus, the possible spectrum sensing gains attainable using the improved energy detector needs further investigation. Additionally, the role of multiple antennas in further enhancing the improved energy detector performance would be interesting to research.

Chapter 2 mainly familiarizes the reader to the area of wireless signal detection in context of spectrum sensing in cognitive radio networks. A detailed overview of the relevant literature pivotal to provide a background on the cognitive radio technology, spectrum sensing techniques, the energy detector, the improved energy detector, wireless propagation channels and interference, among others is thus provided in this Chapter.

In Chapter 3, the system model, simulation model, as well as the major findings and results are presented. Spectrum sensing performance of energy detector and improved energy detector is examined by statistically modeling the wireless channel as Rayleigh faded and a finite number of interferers are considered. Semi-analytical Monte Carlo simulations performed in MATLAB are used to characterize the interplay of various parameters of interest such as the number of interferers, signal-to-interference noise ratio, detection threshold, improved energy detector parameter p, and multiple antennas on the detection performance of the energy detector/improved energy detector. In summary, interference is found to degrade the energy detector performance. However, the impact of interference can be countered by fine-tuning the improved energy detector parameter p. It is discovered that further performance gains can be achieved by using multiple-antenna based improved energy detector. These gains are quantified numerically. Ultimately, these analysis and results may serve as an initial basis for designing a detection system robust to interference.

There are some inherent assumptions made in the project. Relaxing some of these assumptions would lead to formulation of some very interesting problems that might be of interest for researchers working in this area in future. They are highlighted as follows.

1. In all of the above cases, the activity of the primary user is assumed to be equally-likely. In other words, the probability of the primary user being present or absent is equal. However, in practice, the PU activity may not be equally-likely since some of the PU may be present in a chunk of spectrum almost all of the time while some other portion of the spectrum may be mostly unoccupied (e.g. TVs at the subscribers homes may not switched ON all the time but spectrum occupation by cell phone users is more). Thus, modeling the PU activity and studying its effect on the spectrum sensing performance of energy detector and improved energy detectors would be more realistic than the case with equally-likely PU activity.

2. All the user terminals: the primary users, the cognitive radios as well as the interfering

users are assumed to be static. Inclusion of mobility factor and its effect on spectrum sensing is a more practical situation in modern-day wireless networks, where almost all of the wireless devices are portable and likely to be in motion.

3. The wireless channel, in addition to multipath fading, also suffers from path loss (decay of the received signal strength with distance from the transmitter). Formulating and solving the spectrum sensing problem with inclusion of path loss will more realistically model the wireless propagation space and help to quantify its role on the reliability of spectrum sensing.

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