



Genetic Algorithm for Selecting Optimal Secondary Users to Collaborate in Spectrum Sensing

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Abstract

Cognitive Radio is an innovative technology that allows the secondary unlicensed users to share the spectrum with licensed primary users to utilize the spectrum. For maximum utilization of spectrum, in cognitive radio network spectrum sensing is an important issue. Cognitive user under extreme shadowing and channel fading can't sense the primary licensed user signal correctly and thus to improve the performance of spectrum sensing, collaboration between secondary unlicensed users is required. In collaborative spectrum sensing the observation of each secondary user is received by a base station acting as a central entity, where a final conclusion about the presence or absence of the primary user signal is made using a particular decision and fusion rule. Due to spatially correlated shadowing the collaborative spectrum sensing performance decreases, and thus optimum secondary users must be selected to, not only improve spectrum sensing performance but also lessen the processing overhead of the central entity. A particular situation is depicted in the project where according to some performance parameters, first those optimum secondary users that have enough spatial separation and high average received SNR are selected using Genetic Algorithm, and then collaboration among these optimum secondary users is done to evaluate the performance. The collaboration of optimal secondary user providing high probability of detection and low probability of false alarm, for sensing the spectrum is compared with the collaboration of all the available secondary users in that radio environment. At the end a conclusion has been made that collaboration of selected optimum secondary users provides better performance, then the collaboration of all the secondary users available.

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In the name of ALLAH, most Gracious, most Compassionate.

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Chapter 1

Cognitive Radio Networks

1. Introduction

From the last ten to twelve years wireless communication has developed to a great scope. This boost in communication devices such as mobile and computer etc and in communication technologies such as UMTS, Wi-Fi, WiMax, LTE, MIMO, establishes a path for the future expansion of wireless systems. All those wireless technologies, used for diverse services requires specific spectrum range that may be allocated to it by a particular government organization and it varies from region to region for example in Pakistan for telecommunication a company by the name “Wateen Telecom” which is a UAE company, uses a spectrum band of 3.5 GHz.

With the increase in usage, these wireless technologies have also caused some problems such as spectrum scarcity which crop up when the allocated spectrum is not used to its best possible potential and is most of the time unutilized. Because of not utilizing the spectrum to its full potential and being in the era where new technologies are developed frequently, the researchers have started to think and develop ways to effectively utilize the spectrum [1].

An organization by the name “The Spectrum Policy Task Force”[3] was established in June 2002 to help “Federal Communication Commission (FCC)” in identifying and evaluating spectrum policy after a study reported in Nov. 2002[5][2][4] it was comprehended that a great geographical variations are observed in the spectrum that has been allocated to the user for usage and the utilization varied from some 14.3% to 85.7% under 3 GHz[4].

Spectrum measurements were also taken in Berkeley [2][6] showing that upto 30% spectrum was utilize at 3GHz but above 3GHz and below 6GHz this utilization was measured to be 0.5%. After observing such results in 2003, the FCC tried to resolve these tribulations by allowing a license band to secondary users. This way the allocated band for a particular process could be used to its best possible potential, if

the secondary users are allowed to use it to any length of time and coverage area unless no intervention is caused with the primary licensee [7].

Another study was made by the “Spectrum Task Force and Shared Spectrum Company” to comprehend spectrum allocation for diverse regions that exposed different results i.e. a band of 30MHz to 3000MHz was considered for the test and according to the study for Dublin, Ireland in 2007, average spectrum occupation was 13.6% [8] but in New York City for the same band in 2004 the spectrum usage was 13% [10]. The results revealed numerous white spaces, demonstrating the underutilization of the spectrum and a general conclusion was made that if a fixed frequency is allocated to users, it will result in spectrum insufficiency which can only be removed if a spectrum is efficiently used by making use of the white spaces in the band [9] [11].

How to use the spectrum efficiently and reduce number of white space? To answer the problem, and come with a best solution, number of techniques were developed and one among them is “Opportunistic Spectrum Access” using Cognitive radio [12]. The Cognitive Radio can also be referred to as a smart system and it is a kind of wireless communication representation, where communication of a primary licensed and secondary unlicensed user is sustained by a wireless node and it alters its transmission such that it does not cause any intervention between the licensed and unlicensed users. This technology allows the unlicensed users to access the spectrum opportunistically when the spectrum is free and when primary licensed users are inactive or idle. In such technique secondary user regularly checks for the primary user signal in order to avoid the interference between each other, thus leaving the spectrum as soon as primary user signal is sighted. A mechanism must be there allowing the secondary users to perfectly spot both the presence of primary user signal and its arrival if the secondary user is operating in the primary user band thus reducing the chances of interferences. The secondary user initially checks if a communication channel is not in use, and if idle it moves into that liberated empty space thus using that radio frequency without interfering with the licensed users.

To build up techniques for well-organized spectrum sensing, following techniques were anticipated by different research groups [15] and they were divided into three different categories namely “primary receiver detection”, “primary transmitter detection”, and “interference temperature management” [15].

1.1 Spectrum Sensing with Primary Receiver Detection

In Primary Receiver Detection approach the communication channel throughout which the primary users receives the data are used to identify the holes within the spectrum [13]. The primary user when receives the primary transmitted signal its radio frequency front end emits power leakage from the local oscillator. In this scheme the same leakage power is calculated to know if the spectrum is obtainable for use but since the signal is too weak the implementation is tricky and is only used in TV receiver.

1.2 Spectrum Sensing with Interference Temperature Management

In Interference temperature management model which has in recent times been introduced by “Federal Communications Commission” [12], identifies the extent of new interference that a user can tolerate. In this technique a bound is set in form of interference temperature, and user using the spectrum must not cross that precise boundary, but what will be an acceptable interference temperature is a complex matter because of not having a practical approach and the cognitive users using this scheme cannot tell apart between SNR and interference temperature, especially if the SNR is condensed due to interference [13].

1.3 Spectrum Sensing with Primary Transmitter Detection

In Primary Transmitter Detection, in contrast to other detection method the transmitted signal of the primary user is detected and consequently three methods are used for such detection namely e.g “cyclostationary feature detection”, “matched filter detection”, and “energy detection” [12].

Energy detection is a procedure that is also used in this project as it is most commonly used, being most favorable for detecting any unidentified signal when the secondary user need not to assemble sufficient information about the signal such as its modulation type or pulse shape[14]. This approach is also effortlessly integrated on mobile devices, but it has some drawbacks such as distinguishing the signal category is difficult for it, also its performance in a condition where there is fading and shadowing can degrades [16]. In phenomena such as shadowing, since the

received SNR alters and reduces, so a secondary user sensing the spectrum can't make a distinction between noise and signal, and an opportunity for utilizing the spectrum vanishes causing the performance to degrade [9].

In case of tribulations such as fading and shadowing the cognitive radio must have such scheme that helps it to easily differentiate between noise and signal. For this purpose different ideas have been anticipated by different researchers for collaboration or cooperation between secondary user to improve the sensing performance [18][20] and reduces multipath fading and shadowing effects. In such collaboration between secondary user to spot the primary user signal, conclusion is based on individual secondary user inspection and if there are numerous secondary users their individual results and observations are then send to a base station also known as Band Manager, which can also be a common secondary user. The band manager also known as a base station, uses diverse fusion techniques to inspect the results and after examining the outcome from the entire secondary users the band manager then makes a judgment about the existence or nonexistence of primary user signal. If the collaborative users that are involved in collaboration have high received SNR and no fading and shadowing, then the effects on the overall system are immense as the sensing performance enhances [18][17].

Increasing the number of secondary user to improve the energy detection performance is not spot on all the time. If the number of secondary users collaboration increases from a particular threshold depending upon the surroundings in which the secondary users are collaborating, it does not enhances the sensing performance [19]. The degrade performance is because, after a specified threshold collaboration will slowdown the band manager processing time for results, mainly when the bandwidth is also low, or a number of users are under the influence of fading, and independent as well as correlated shadowing being near to each other thus effecting there outcome. In case of large number of secondary user, selecting optimum amount of secondary user is vital for collaboration, as they can contribute in the conclusion, to come to a decision wheather a primary user signal existence, is detected or not. To select finest secondary user, a capable procedure is needed, that can pick only those secondary users that can provide accurate results about the existence of the primary user signal thus improving on the whole, performance of the system.

1.4 System Model

The main idea of our project was to select best combination of few optimum secondary users for collaboration to determine the presence of primary user signal using Genetic Algorithm along with energy detection technique, such that results of those selected users are the same as the combine results of all the users involved in collaboration. To have a clear idea of what kind of radio environment we want to study and simulate we have develop a system model given in fig:1, and in our system model we have shown a solid circular area which is our region of interest having a primary transmitter outside it transmitting the signal and some primary user (PU) shaded as green along with secondary cognitive radio users (SU) shaded as black and a common secondary user acting as a Base station or Band manager represented by a box in the center of the circle. The model also shows those secondary users that are affected by some phenomena such as fading and shadowing and in case of collaboration spatially correlated shadowing on secondary users are depicted by a small circle with brown shaded secondary users in that circle. The causes of fading and shadowing are also depicted in the form of a building and tree. Some secondary users (SU) are also considered to be optimum for selection as their results improves and enhances the performance of the system and they are shown with a blue dotted line around them.

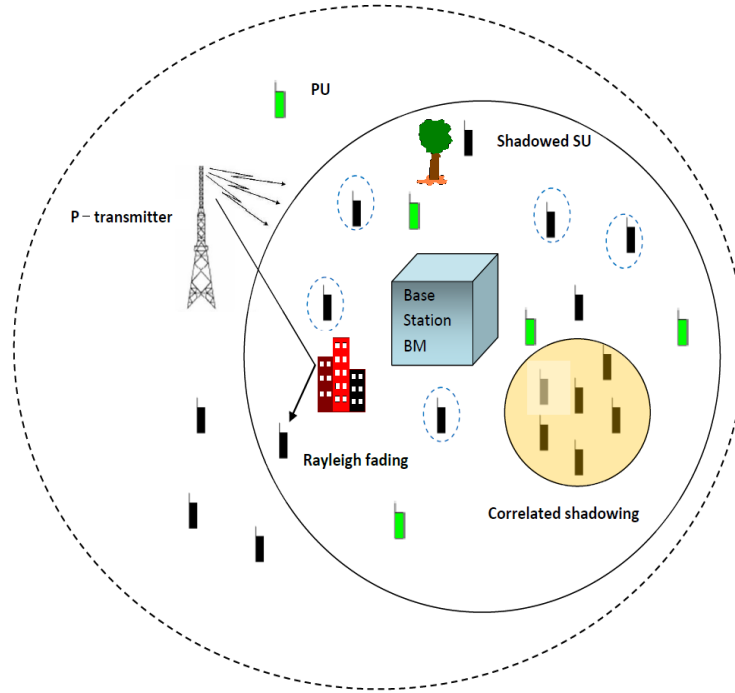


Figure 1: System model with secondary and primary users.

1.5 Goals and Achievements

In this project our aim was to study the behavior of secondary users who are trying to detect the primary user signal using energy detection technique and the performance of the energy detection especially in cases where it is affected by fading and shadowing. The second phase of the project was concerned with the collaboration of secondary users and their operation. Simulation were done to show how the performance of energy detection technique enhances or degrades in different areas especially when distance between collaborative secondary users increases or decreases, having their received SNR same and constant and how it effects the collaborative spectrum sensing.

To achieve all this, simulation in MATLAB tool with version 2008(a) was done. Energy detection technique with different combination of secondary user was simulated to detect the presence of primary user signal both in the attendance and absence of fading and independent shadowing. Collaborative spectrum sensing was also simulated, and then an evaluation was made to demonstrate how collaborative spectrum sensing improves the energy detection performance in fading and shadowing but also faces another problem known as correlated shadowing. Then the correlated shadowing effects in urban and suburban area were also simulated to show how it degrades the system performance.

In the third phase of the project at the end Genetic Algorithm was used to construct such a scheme that take some values as parameters for secondary users and then construct random population using these values that are required for efficient secondary users. The generated population of secondary users is then used to select optimum secondary user combination for spectrum sensing that provides better results.

Chapter 2

Dynamic Spectrum Access

2. Introduction

The spectrum scarcity and its allotment in the existing circumstances do not fulfill the authorized claim for new broadband technologies. It also confine and deny various companies to build up something innovative such as producing new wireless services with more spectrum requirement. Such problems guide us entering into a new era of allowing unlicensed users to access licensed spectrum know as the Dynamic spectrum access initially introduced in 2006 by DARPA Defense Advanced Research Projects Agency [21].

A conclusion has been reached by cautious speculations that radio spectrum that we have in the present, will be inadequate soon and the 20MHz frequency for European 3G spectrum with a billion dollar price is an obvious confirmation to the claim[15]. FCC spectrum Policy Task Force with their inspection and measurement in different countries and cities have seen that the exploration they carried for the frequency band measurement substantiate the statement that more often than not, idle spectrum is resulted when spectrum is allocated for various services [22]. The idle spectrum shows the deficiency of a spectrum but this is because a static policy is use for managing the spectrum, meaning that the real problem is not because there is not enough physical frequencies but is, because the spectrum usage in not proper.

Realizing the dilemma the researchers started working on innovative spectrum management schemes that may result in a proficient utilization of spectrum. This resulted in number of new techniques and so a famous scheme came into origin called Dynamic Spectrum Access which is far more competent and more diverse from the current static spectrum policy. It has three more models to go with it. The hierarchical model of the Dynamic spectrum access is given in fig:2 [12] below:

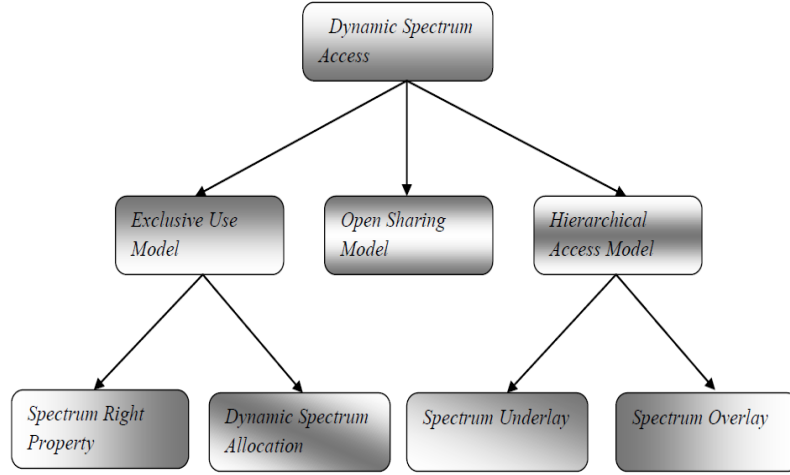


Figure 2: Dynamic spectrum access, hierarchical model [12].

2.1 Hierarchical Model for Spectrum Access

The hierarchical makeup of this model helps to split the users into two categories explicitly Primary user which are licensed users and have high priority and Secondary user which are unlicensed, the licensed spectrum is open for access, for the secondary unlicensed users [29]. This helps the secondary users to take maximum utilization of the spectrum but only if there is no primary licensed user using the spectrum at that instance or that band has limited intervention, because the secondary users should not hamper with the primary users in that area, allowing the primary system to operate normally. The model is further divided into two approaches [29].

2.1.1 Ultra Wideband Spectrum Underlay

Transmission power of secondary user plays an important part in this approach. This scheme works by applying restriction on the power of the secondary user that allows it to transmit, so it means that for secondary users the noise level of primary user is the criteria and they must do their operation below it [12]. If the transmitted

signal is spread over a wide frequency band then to keep away from interference, the secondary users communicate only through small ranges but an improvement is that they can also achieve a high data rate by using Ultra Wide Band for the transmitted signal [29].

Since the secondary user in this approach is not confined to sense the spectrum for primary user signal, thus eliminating all added burden on secondary user to initially detect the primary user signal using diverse techniques for detection [12].

Considering a supposition, that primary user will all the time be transmitting on all probable frequencies accessible to it, then to detect white spaces for usage and exploit the spectrum, it is very difficult to achieve [29].

2.1.2 Opportunistic Access or Spectrum Overlay

Mitola [33] introduced this approach using a term spectrum spooling and is considered to be one of the most well-known, of all the approaches. DARPA also studied it in program for Next Generation (*XG*) and gave it the name Opportunistic Spectrum Access [29]. In this approach the secondary unlicensed user can work with any normal power since not having any restraint on its transmission power. The secondary user initially performs the discovery of the primary user signal on the licensed band on a particular region of interest but at the same time the secondary user must stay away from any interference to the primary user signal, if there is any signal detected during the course of detection. If there is no signal detected then the secondary user can transmit till the primary user signal is detected, and at that instance the secondary user must depart the spectrum almost immediately in order to stay away from intervention and for this, the secondary user must have competent signal detection techniques [12]. Because of this approach it is compared to be well-suited and more compatible with the offered spectrum policies for wireless system and research is going on in this area to put into practice this approach and improve it more.

2.2 Exclusive Use Model for Dynamic Access

Even though similar in stature to that of existing spectrum policy, still there are various innovative features introduced in the model which makes it rather more flexible as compared to the aged static model. In this model licensing bands are introduced for explicit services and exclusive use [12] and this model also have further two approaches.

2.2.1 Spectrum Property Rights

The property rights for spectrum use was originally initiated in a seminal paper publishes in 1959 by Ronald Coase [23] and Arthur De Vany [24], after sometime Lawrence White [25] also mentioned three parameters for the spectrum right policy including time, geographic area and spectrum band. In this scheme the licensees who are allotted the spectrum, are free to trade the spectrum, and they also can decide whichever technology they want to deal with, which allows the spectrum to be used to its best potential [26].

The model with this approach though must deal with some tribulations that may hinder its performance, the first problem is that defining spectrum rights for the user to operate under it are difficult to put into practice because of channel interferences being adjoining and also because radio wave propagation are extremely erratic and unpredictable in both frequency and space [27]. The other problem that this model faces is that this model does not entirely eliminates the white spaces in the spectrum by not utilizing the spectrum and it is because in a digital wireless communications data are send in small but sudden periods. From the management position the model faces an additional problem which is the regulation authorities, since they does not support the spectrum sharing, despite the fact that it is profit rewarding [28],[29].

2.2.2 Spectrum Allotment

Being best fitting with the commercial applications such as UMTS and DVB-T dynamic exclusive use model with dynamic spectrum allotment approach also tries to enhance the spectrum competency in time and space-dependent spectrum sharing,

between radio services that are synchronized [27]. The approach was brought by the European DRIVE project [30] because it assigns spectrum on temporal and statistics of traffic dynamically. The major thought behind this approach is that if a service requires extra bandwidth and have limited bandwidth, then it is allotted require bandwidth for certain time, along with a timer and after that time period as the timer expires, the extra bandwidth is then not permissible to the service but the one which was allotted to it in the start is still allowable [30].

This approach as compared to dynamic spectrum allocation has an added advantage that is, the frequency allotment in this approach is incredibly rapid and as compared to the stationary static approaches. This approach also provides flexibility by minimizing the spectrum depletion to an immense amount however the approach also faces the same problem of white spaces which is desirable to be resolved [29][30].

2.3 Open Sharing Model

This is a diverse model that has been developed, also known as “Spectrum Commons Approach” bearing in mind that it helps the spectrum to be considered open for sharing and is used for spectral region management[29], in addition to this, also in this approach the user owns no fraction of the spectrum by considering it as its property. Being a motivation of the ISM (Industrial, Scientific and Medical) it is considered to be extremely proficient, however still the approach does not addresses or deals with all the band access issues and has some inadequacy to be solved [29][31][32].

2.4 Cognitive Radio

Software Defined Radio (*SDR*) and Cognitive Radio (*CR*) expression were first put forward by Mitola in a seminar at The Royal Institute of Technology KTH, in 1998 and then published by Mitola and Gerald Q in an article [34][35].

Software Defined Radio being a multi band radio can hold multiple protocols and air interfaces, it is reconfigured through software being a radio and have all the

signal properties including carrier frequency, modulation type, and signal bandwidth integrated in it. The network's entrance is distinct by software and modern SDR can also initiate features such as cryptography, and forward error correction coding, also source coding of voice, video and data additionally [29]. Since a cognitive Radio is usually implemented on the basis of Software Defined Radio and is considered as an intelligent system, it can reconfigure itself according to the surroundings and also experts to new environment. The three important properties that make an SDR in CR are given as:

- i) How can the spectrum be supervise and utilized to its complete potential
- ii) Wireless network interface, to construct use of network resources
- iii) An interface for human dealings so that they can get complete use of the resources.

The Dynamic Spectrum Access is an important part of the Cognitive Radio [29] [12] and it uses Spectrum Overlay scheme.

2.4.1 Technology

Opportunistic spectrum access reduces the depletion of spectrum as compared to the contemporary rigid static spectrum supervision policy and the cognitive radio technology take advantage of the same opportunistic spectrum approach [36]. Features and capabilities such as flexibility, agility, radio frequency, and networking are implemented by cognitive radio technology for enabling the use of spectrum [37].

Flexibility of this technology changes the configuration and waveform of a signal so that it can be used for two diverse roles. Using the flexibility feature, the radio reflect characteristics such as data range, latency, and packet error rate and extra feature such as agility attribute [37] which allows cognitive radio to modify the spectral band in which a device will maneuver to operate.

RF sensing is its skill to examine the system status linking both the radio and the surrounding and helps to evaluate its impact and effect on the surrounding [37] while networking is the capability of cognitive radio to converse with various nodes and thus facilitate merge sensing [37].

2.4.2 Capability and Re-configurability of Cognitive Radio

It is that attribute of the cognitive radio which allows it to have authentic interactions with the surrounding of the radio environment and assist it to access the vacant segment of the spectrum and it has the following three features [15][38].

- i) ***Sensing and identifying White spaces:*** A cognitive radio can sense spectrum for white spaces which are frequency bands either unemployed by licensed users or having partial intervention [38].
- ii) ***Sharing the Band:*** A license involving two parties, permit the spectrum to be used and depending on the agreement the spectrum can be used in real time also as compared to makeshift basis [38].
- iii) ***Identifying the location:*** The ability to recognize other transmitter site for decent selection of parameters for instance power and frequency in that particular location [38].

The uniqueness of a cognitive radio to transmit on diverse frequencies and also facilitating variety of access techniques make it first choice for current circumstances [15].

2.4.3 Architecture of Primary Network

Known as the existing network the users of this network are called primary user and they have licensed to employ the frequency band for their operation having high priority and such a network have a Band manager to be in charge of the network operation [15],[36].

2.4.4 Architecture of Secondary Network

Also called Cognitive Radio Network, such a network have each and every one as unlicensed users identified as secondary user, furthermore the secondary user uses the primary licensed user frequency band for their operation but must also tries to steer clear of any intrusion with the users whose frequency band, it is trying to use[36].

In some cases the Secondary Network also have common secondary user substitute as a Secondary Base Station called Cognitive Radio Base Station (CRBS) or Band manager which helps the spectrum resources to be scattered among various Secondary Network users [36].

2.5 Cognitive Radio Network Operation

The Cognitive Radio Network can access equally the primary licensed network and unlicensed fraction of spectrum. Based on the operation that Cognitive Radio Network can carry out it can be categorized in two subsequent types [15].

2.5.1 Operation on the Licensed Band

In this method the secondary user initially spot the primary user signal since they are the licensed user that can employ the licensed band plus have more priority than the secondary user, and if no primary user signal is detected the secondary user then uses the white spaces of the band for their operation [15]. However during their processing if they notice the presence of the primary user signal the band must be emptied to stay away from any kind of clash. This type of operation requires a very cautious consideration on the secondary user side. In some cases if the interference is partial then base on the network operation for a while the secondary users are permitted to use the band [15].

2.5.2 Operation on Unlicensed Band

In unlicensed band operation secondary users require not to be concerned regarding the primary user signal and obstruction with it, as the secondary user in the network has the same rights to employ the spectrum for their operation and there is no primary user. The secondary user sense to avoid interfering with other secondary users and then the spectrum is employed, also diverse access methods are used by the cognitive radio network for communication among different users [15].

Cognitive radio can resolve numerous harms of spectrum depletion and a vital component of this technology is the spectrum sensing as the performance of Cognitive Radio Networks entirely depends on how perfectly has the band for spectrum access have been detected. The fig:3 below gives an idea of how the occupied band have some white spaces that need to be utilize by secondary users without having hindrance with primary user signal.

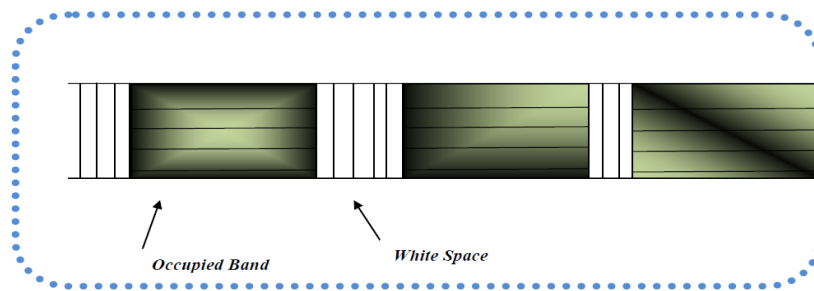


Figure 3: Occupied spectrum with white spaces.

Chapter 3

Sensing Techniques for Spectrum

3. Introduction

The most excellent exploitation of the spectrum is to identify the white spaces [35] in the spectrum and in Cognitive radio technology an efficient approach for it is a well-known practice called opportunistic access. The likelihood to do so is completely reliant on how the cognitive radio assembles information regarding its environment of operation for which the obvious choice is careful sensing. Depending upon the consequences then using certain communication parameters, so that the adjusted parameter then helps to perform the transmission and reception in an enhanced manner. In cognitive radio technology the most obvious concern is that of sensing, while precise sensing to the highest degree improves by and large the performance of the cognitive radio network since the operation can be continued until an accurate sensing is made continuously [39]. Due to diverse variety of modulation types and having extensive range of power schemes, primary user have diversity of choices to utilize any of these to access the band, and in such cases to properly sense spectrum for use by the secondary user is a tricky job. The secondary user might also possibly face several harms of fading and shadowing themselves and in such scenarios to spot the presence of primary user signal is incredibly tough [18] thus leading to underutilization of the spectrum and performance hindrance due to erroneous sensing.

A binary hypothesis problem [40] given as H_0 and H_1 can be in use as a testing scheme for sensing the spectrum precisely and this helps to spot the existence and nonexistence of primary user prior to using the spectrum.

In this method H_0 imply that the primary users are not in attendance and the spectrum can be use, whereas H_1 signify that the primary user is in attendance on the band, and based on these testing the secondary user can sketch the conclusions whether to employ or not exploit the spectrum.

H0: {Primary User not in Attendance}

H1: {Primary User in Attendance }

3.1 Different Spectrum Sensing Techniques

There are diverse techniques that can be used by the secondary users to sense the spectrum such as detection technique for primary receiver and transmitter along with measurement of temperature cause by interference [15] however the one frequently used because of its competence is primary transmitter detection which is additionally separated into three types.

3.1.1 Matched Filter Method for Detection

A match filter is a different scheme used for the discovery of primary user signal and the basic aim of this approach is to take benefit of the white spaces of the band. In this technique a linear match filter is obtained so that for a prearranged input signals, maximize the SNR ratio [41] and it is done when, a signal which is not known to the detector is allied with the device known signal. This technique helps to identify the presence of the acknowledged signal in the signal which is not familiar to the detector [41].

For the method to work the preliminary information concerning the primary user signal such as arrangement of the packet, order and shape of pulse with modulation type[41] is obligatory but is extremely difficult, nevertheless the technique is exceedingly appropriate for sensing as it boost the SNR in AWGN.

3.1.2 Energy Detection Procedure

For the reason of its simplicity energy detection is regarded as one of the finest of all the primary transmitter detection schemes and is used to detect zero mean signals [16]. In this technique energy that have been received because of the received radio frequency is measured and an already specified threshold, which is

chosen depending on the surrounding radio environment where the operation is to be done, is used as a judgment parameter which is then used to conclude whether there is a primary user signal at hand or not.

A significant matter in energy detection scheme is to set the threshold which is exceptionally complicated task because in must deal with the susceptibility of the radio environment being especially flexible and might changes soon.

Because of its simplicity energy detection is the main preference for spectrum sensing and there are number of factors that construct it as one of the most attractive pick, because in order to become aware of the primary user signal, the energy detection do not requires any preliminary knowledge of the detected signal [29].

The energy detection scheme for the primary user signal detection was the primary option for the project and has been used with a conclusion declaration given in equation (3.1) [50].

$$r(t) = \begin{cases} n(t) & H_0 \\ hs(t) + n(t) & H_1 \end{cases} \quad (3.1)$$

This conclusion statement shows the received signal with $r(t)$, and the received signal will have two supposition about it, one is whether the received signal is a AWGN with amplitude having that of a Gaussian distribution denoted by $n(t)$, and this proposition is given by H_0 viewing the nonattendance of Primary user signal and the other assumption is H_1 which shows the attendance of Primary user signal i.e transmitted signal denoted by $s(t)$ with a gain in amplitude mentioned by h , and some mutilation in the form of AWGN adding to the signal.

The energy detection mechanism for the detection of the signal is given by the block diagram in fig: 4. [40]

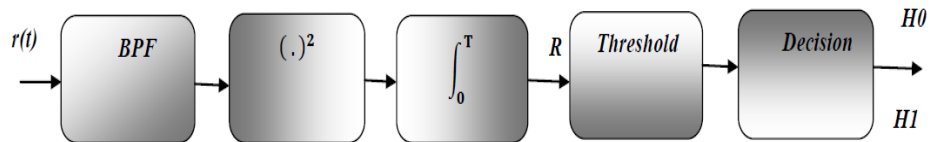


Figure 4: Energy detector block diagram [40].

The procedure of energy detection starts when a signal is received, which is then passed through a band pass filter, so to choose only those frequencies that are preferred bypassing all other undesired frequencies. The received energy is considered by a squaring device after the filter selects the frequency and bandwidth denoted by W and then after the squaring device, there is an integrator which is used to measure the observation time over an interval T [18]. The final output from the integrator denoted by R , is then compared with the threshold denoted by λ (λ) which is defined on subject to the radio surroundings, and subsequent to the evaluation the results are send to the conclusion or decision device, where based on the outcome the verdict is taken to decide whether a primary user signal is in attendance or not [18],[43],[42].

In customary circumstances when there is no fading and shadowing it means that the secondary users are not exaggerated by any phenomena and because of non fading environment, thus the probability of detection (P_d) and probability of false alarm (P_{fa}) can be given by the subsequent equations given in (3.2) and (3.3)[16],[40].

$$P_d = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) \quad (3.2)$$

$$P_{fa} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \quad (3.3)$$

In the above equation the probability of detection (P_d), is symbolized by $Qm(.,.)$ and is characterize as generalized Marcum Q function having its parameter (γ) being the received SNR and (λ) corresponds to the threshold used for detection and assessment [40][45].

The generalized Marcum Q function is given in equation (3.4) as [40][45].

$$Q_m(a, b) = \int_b^\infty \frac{x^m}{a^{m-1}} e^{\frac{-x^2+a^2}{2}} I_{m-1}(ax) dx \quad (3.4)$$

$I_{m-1}(.)$ is the $(m-1)th$ order tailored Bessel function of the first kind with (a) and (b) being non negative real numbers and (m) symbolizes an integer number

[45][40]. Likewise for the probability of false alarm $\Gamma(\cdot)$ suggests the complete Gamma function, and $\Gamma(\cdot, \cdot)$ stand for incomplete Gamma function [45][40].

In various books such as the one written by Johnson and Kotz books on distributions, the Marcum's Q-function is also acknowledged as the non-central chi-square distribution. According to Urkowitz [42] the nonexistence of the primary user signal can be represented by a decision statistic as given in equation (3.5).

χ^2_{2TW} which is central chi square distribution having $2TW$ as the degree of freedom and the attendance of the primary user signal can be signify by $\chi^2_{2TW}(2\gamma)$ which is non central chi square distribution with $2TW$ being the degree of freedom and (2γ) being the non central parameter having (γ) as the SNR that has been received [42][40]. Both these decision statics are obtained from the integrator as its output and can be denoted by R , so the final depiction would be

$$R = \begin{cases} \chi^2_{2TW} & \text{H0 (White band)} \\ \chi^2_{2TW}(2\gamma) & \text{H1 (occupied Space)} \end{cases} \quad (3.5)$$

In the equation (3.5) the TW characterizes the bandwidth plus the time product, and we have denoted it by and integer number (m) [40].

A chi square distribution being central and non central can be defined as random variable that are altered by Gaussian distribution given in equation (3.6) [44]

$$Y = \sum_{i=1}^n X_i^2 \quad (3.6)$$

where the X_i , $i = 1, 2, \dots, n$ are all Gaussian distributed random variables being indistinguishable and having mean (m_i) and variance (σ_i). With the two form of chi square distribution in non central chi square distribution the X_i , have at least one mean (m_i) not equivalent to zero but in central chi square distribution all the X_i , random variables has zero mean which is the only disparity among them and (n) is referred to as degree of freedom [44].

3.1.3 Cyclostationary Detection for Sensing

For the detection of feeble primary user signal the energy detection is not extremely competent technique in scenarios where secondary users are under intense shadowing and fading. Also since initial knowledge of the primary user's signal is required in the match filter scheme to sense the spectrum for the absence or presence of primary user signal the method is difficult to implement.

In order to remove such problems Cyclostationary feature method have been projected for the exposure of the primary user signal and it is a recognition system for two dimensional complex signal with the procedure of processing modulated signal even in scenarios of fading, obstruction and noise [46].

If the primary signal has cyclostationary properties then it can effortlessly be detected in small values of SNR and the modulated signal can in addition be modeled as cyclostationary process. By means of this technique the cyclic spectrum can also be of assistance to be familiar with the spectral redundancy [46].

This scheme is more efficient than the energy detection however the main hurdle in this scheme is that, it is extremely complex and the processing time that it takes to sense the primary user signal, when used in comparison with the other two techniques discussed earlier, is very high [46].

3.2 ROC Performance Metric Curve

Receiver Operating Characteristics also mentioned as ROC was primarily used in World War II as an analytical tool for examining images of radar [48]. Nowadays ROC is used as an analytical curve in different fields of technology and medicine for gauging the performance in phrase of sensitivity [48].

ROC curve can as well be used for investigating the performance of the spectrum sensing by making an assessment between two probabilities i.e the probability of false alarm signified by (P_{fa}) and probability of detection (P_d) or probability of miss detection denoted by (P_m) [12]. This curve gives an improved understanding of how the expansion in one probability have impact on other plus what are the conducts of the system under the effects of shadowing and fading and how it affects the spectrum sensing by simulating various scenarios curves.

3.2.1 Probability of Detection and Miss Detection

As the name specifies Probability of Detection (P_d) is the probability to spot in the area of operation of a secondary user, whether there is a primary user signal in attendance or not. Larger the probability of detection (P_d) the odds are that more exact will be the sensing and thus extremely little chances of intervention as secondary user will classify the existence of primary user signal and will not use the band consequently avoiding the interference. However if the probability of detection (P_d) declines then the probability of miss detection (P_m) which is in reality the inverse of probability of detection (P_d), increases indicating that there are added likelihood of missing the primary user signal which is at hand, in the area of operation and it increases the chances of interferences between the primary user and secondary user. The Probability of miss detection can be written as given in equation (3.7) [40]

$$P_m = 1 - P_d \quad (3.7)$$

so for better performance of Cognitive Radio Network the probability of detection must be elevated [12].

3.2.2 Probability of False Alarm

Sometime there is a white space in the spectrum which can be utilized by the secondary users but the secondary users formulates a wrong ruling by identifying it as, already packed space of spectrum by another signal which escorts to an erroneous verdict and such a probability is known as probability of false alarm (P_{fa})

If the probability of false alarm (P_{fa}) enlarges then it results in a very low utilization of spectrum as the white spaces of the band which can be use by the secondary users, are identified as all ready filled space due to erroneous sensing resulting in the performance degradation.

For an ideal system the probability of miss detection (P_m) and probability of false alarm (P_{fa}) must be extremely low and the probability of detection (P_d) must have a higher value [29].

3.3 AWGN

AWGN stands for Additive White Gaussian Noise and is a model of a channel with uniformity in the spectral density on a bandwidth furthermore its amplitude is distributed Gaussianly having no fading and hindrance. AWGN can transpire due to number of factors such as thermal noise due to atoms in conductor, and from sun and earth as radiation of a black body [12].

3.4 Rayleigh Fading

A fading that crop up due to number of reflection in an environment is referred to as Rayleigh fading and is evaluated using various statistical method. In urban areas plus in scenarios where diverse paths are used by a signal, to check the performance of radio wave propagation Rayleigh faded model is foremost alternative because of reflection from obstacles[47]. A disperse signal between receiver and transmitter also demonstrate to be a good case to study Rayleigh fading as the received signal might be an arrangement of the all the signals reaching to the receiver through diverse paths and depending upon the phase they might either add or subtract from the received signal. Rayleigh fading is also referred to as non line of sight fading [47].

3.5 Shadow Fading

Shadowing is the deviation and disparity in the power of received signal when it is received at some distance on the receiver side at an intermediate scale and is caused while the user is in the shadow of something such as being inside a room, in the rear of a door, or at the back of a building, or some other physical obstacles, due to shadow an extremely squat valued SNR is received at the receiving side.

Because of shadow fading there is a great decline in the power of a signal that is received at the receiver side and due to this, in cognitive radio the secondary user cannot tell apart between white space and primary user signal when they are in a shadow.

3.6 Simulation and Explanation

The simulation for this section of the project was done using MATLAB and in the initial part emphasis was to show, how the energy detection works by sensing the primary user signal so to make use of the spectrum, a graphical observation of the probability of miss detection (P_m) verses probability of false alarm (P_{fa}) was shown with Monte Carlo simulation, plotting in the MATLAB in receiver operating curve (ROC) with all the required parameters.

The energy detection method was preferred in this project and an assumption was made that no preceding awareness of the signal is obtainable, also because for mobile devices the accomplishment of energy detection is especially appropriate plus its complication is, as well very small.

3.6.1 Energy Detection with Diverse SNR Values

A complementary ROC curve was obtained by simulating energy detection technique in occurrence of AWGN and after that on the foundation of the resulted curves conclusion regarding the performance of the energy detection was made.

For the simulation average received SNR was considered to be $10dB$ and the Matlab function for chi square distribution was used plus the degree of freedom which in this case is the time and bandwidth product denoted by (m), was taken as 5. The simulated graph in fig:5 having the curve for probability of miss detection (P_m) versus probability of false alarm (P_{fa}) showed that as the (P_m) raise (P_{fa}) declines for a certain SNR lacking any fading effects. Bearing in mind it as an ideal curve or close to it, all the other obtained curves are subsequently matched with it to demonstrate how the performance of energy detection technique degrades.

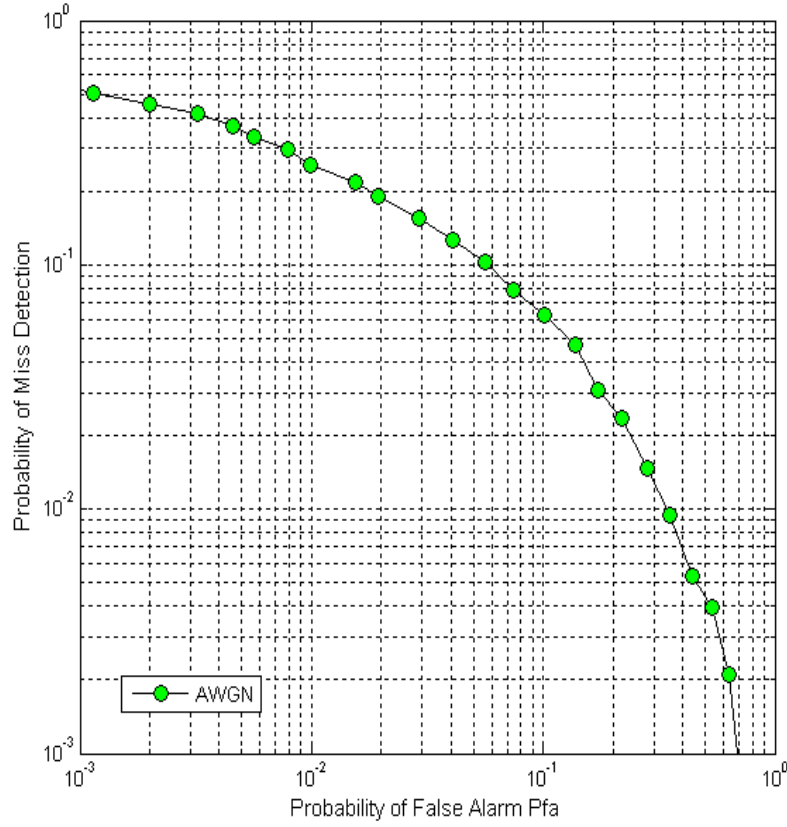


Figure 5: ROC curve for Energy Detection with (P_m) vs. (P_d) in AWGN with $\bar{\gamma} = 10dB$, and $TW(m) = 5$

In fig:6 energy detection performance is exposed with diverse values of SNR to inspect, what is influence of low and elevated SNR values on energy detection performance. Average received SNR with values of 5 dB, 10 dB and 15 dB and time and bandwidth product m with 5, has been used to simulate the energy detection performance and a conclusion has be made that superior the value of SNR, more improved the performance of the energy detector will be and as the average received SNR diminish it degrades the performance of the energy detector and the cause behind it is that with larger value of SNR the secondary user using the energy detection technique with a specified threshold can effortlessly make a distinction between noise and primary user signal, however if the average received SNR is low then differentiating between the noise and primary user signal is extremely thorny for the secondary user decision statistic and this can be revealed from the resultant curves showing that for an agreed value of probability of miss detection (P_m) there is

a immense disparity in the value for probability of false alarm (P_{fa}) which is independent of the received SNR indicating tainted energy detector performance.

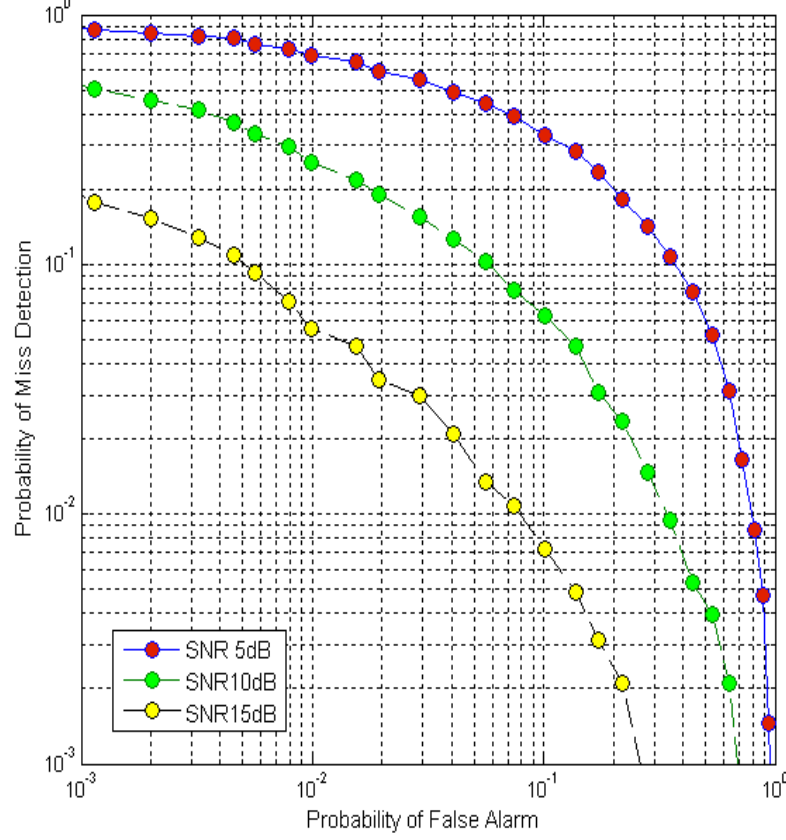


Figure 6: A (P_m) vs. (P_{fa}) plotted ROC curves for Energy Detection in AWGN with $\bar{\gamma} = 5, 10$ and 15 dB, and $TW (m) = 5$.

3.6.2 Rayleigh Fading Effects on Energy Detection

When a secondary user is under effect of fading then the channel gain denoted by “ h ” might diverge to some level depending upon what sort of phenomena it is exaggerated by, and the detection procedure in addition is also affected by this expand thus the detection probability (P_d) then depends upon that instantaneous SNR. If instantaneous SNR is the consequential of fading then the received SNR pursue a particular probability distribution function which is used to obtain average detection probability (P_d) given by the equation in (3.8) [40],

$$P_d = \int_x Q_m(\sqrt{2\bar{\gamma}}, \sqrt{\lambda}) f_{\gamma}(x) dx \quad (3.8)$$

With fading being the factor for that instantaneous SNR the probability distribution function (PDF) for that received SNR by secondary user is signify by the function $f_{\gamma}(x)$ and if the fading is Rayleigh fading then since the Rayleigh faded signals follows exponential distribution [40] the probability of detection can be specified by the following equation given in (3.9) [40].

$$P_d = e^{-\lambda/2} \sum_{j=0}^{m-2} \frac{1}{j!} \left(\frac{\lambda}{2}\right)^j + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{m-1} \times \left(e^{\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\lambda/2} \sum_{j=0}^{m-2} \frac{1}{j!} \left(\frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})}\right)^j \right) \quad (3.9)$$

In this simulation energy detection practice for two secondary users with average received SNR of 10 dB and time and bandwidth product m of 5 is exposed but one of the secondary user is affected by Rayleigh fading and the other has no fading associated to it plus (P_m) along with (P_{fa}) is publicized in an ROC curve which is shown in fig:7 for these two secondary user and an evaluation have been made as how the fading factor effects the performance of the energy detector.

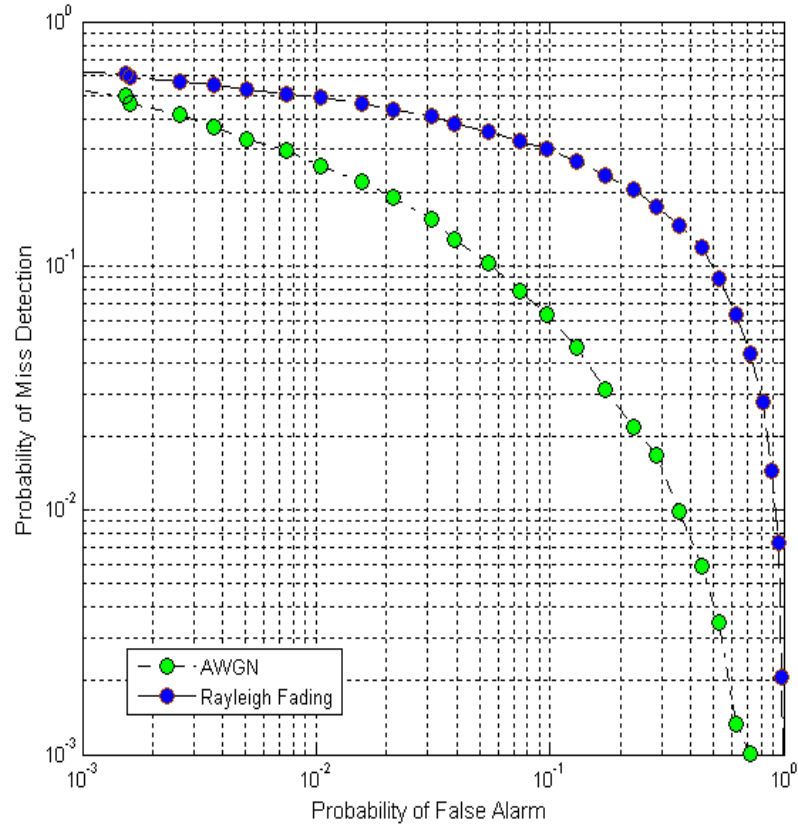


Figure 7: (P_m) vs. (P_{fa}) plotted ROC curves for Energy Detection under Rayleigh fading, and AWGN with $\bar{\gamma}=10dB, m=5$

3.6.3 Log Normal Shadowing Effects on Energy Detection

In this simulation the shadowing factor that might affect the secondary user sensing, is simulated and this causes the secondary user to sense the spectrum imprecisely because of power disparity being in the shadow of some physical object and consequently not being capable to tell apart, whether a received signal is noise or primary user signal.

In case of shadow fading the received SNR power varies and as a result it follows a particular distribution depending upon what kind of shadow fading it is effected by.

In case of log normal shadowing the power of the received SNR might pursue a normal distribution that is uttered in dB [40][16], so the expand that the channel possibly will receive too has a log normal distribution which can be symbolized by log normal random variable (e^x) with X being Gaussian random variable with the mean happening to be zero and the variance is given as σ^2 [49].

Usually dB spread (σ_{dB}) is used to catalog the Log normal distribution which is allied with (σ) being the standard deviation which is given in the equation (3.10) [40].

$$\sigma = 0.1 \ln(10) \sigma_{dB} \quad (3.10)$$

By means of the equation, a simulation for four diverse values of the dB spread given in fig:8, has been simulated and its effects have been shown on the energy detector with average SNR taken as $10\ dB$ and time bandwidth product m taken as 5 the curve demonstrates that for low value of dB spread of 6 the probability of miss detection (P_m) is low but as the dB spread increases to a value of 8 and 12, the probability of detection (P_d) diminish as revealed in the ROC curve, resulting in low energy detection performance due to the fact, that in case of shadowing since the users are in the shadow of some obstacle so the average received SNR that it receive is on the low plus the secondary user capability to make a distinction between the primary user signal and noise in order to access and use the spectrum also hampers due to intense dB spread [29]. An AWGN curve is also shown for comparison.

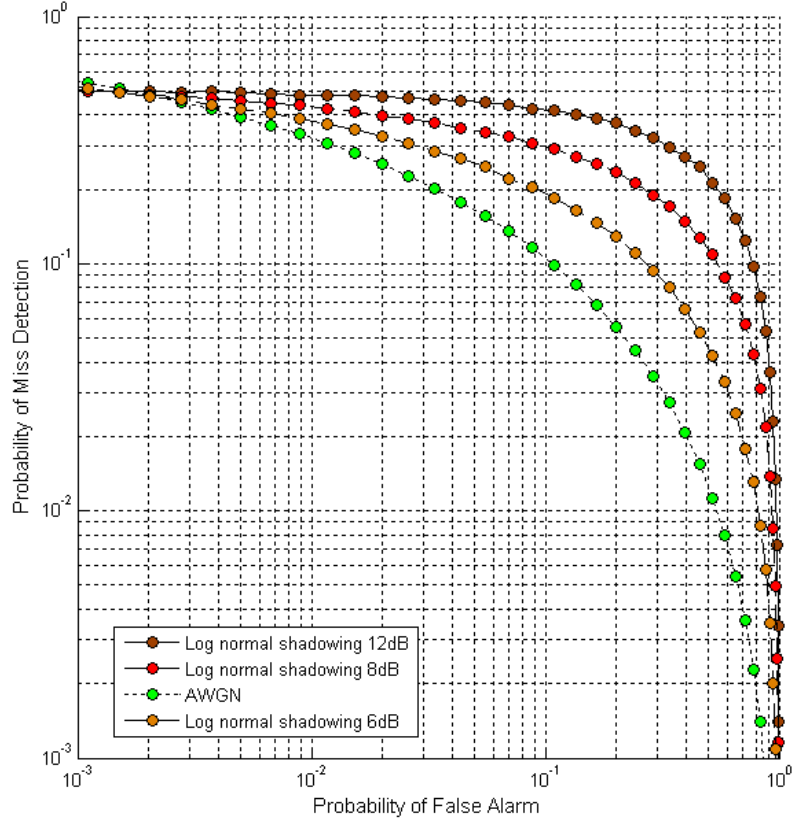


Figure 8: (P_{fa}) vs (P_m) plotted ROC curves for Energy Detection with Log Normal Shadowing, and AWGN $\bar{\gamma} = 10dB$, $m=5$, and $\sigma_{dB}=6, 8$ and $12dB$.

In a further simulation given in fig:9, three secondary users under dissimilar affects have been taken with the average received SNR as 10 dB and the bandwidth and time product m as 5 . One secondary user is under log normal shadowing with dB spread of 12 dB , while the other secondary user is effected by Rayleigh fading, the last user is not affected by any phenomena and then an evaluation has been exposed by plotting an ROC curve with probability of miss detection (P_m) versus probability of false alarm (P_{fa}) and it has been observed that if there is no fading and shadowing then the energy detection has superior performance however under fading and shadowing because of the deviation in the received signal power the energy detector performance is affected showing that this procedure in fading and shadowing in not trust worthy.

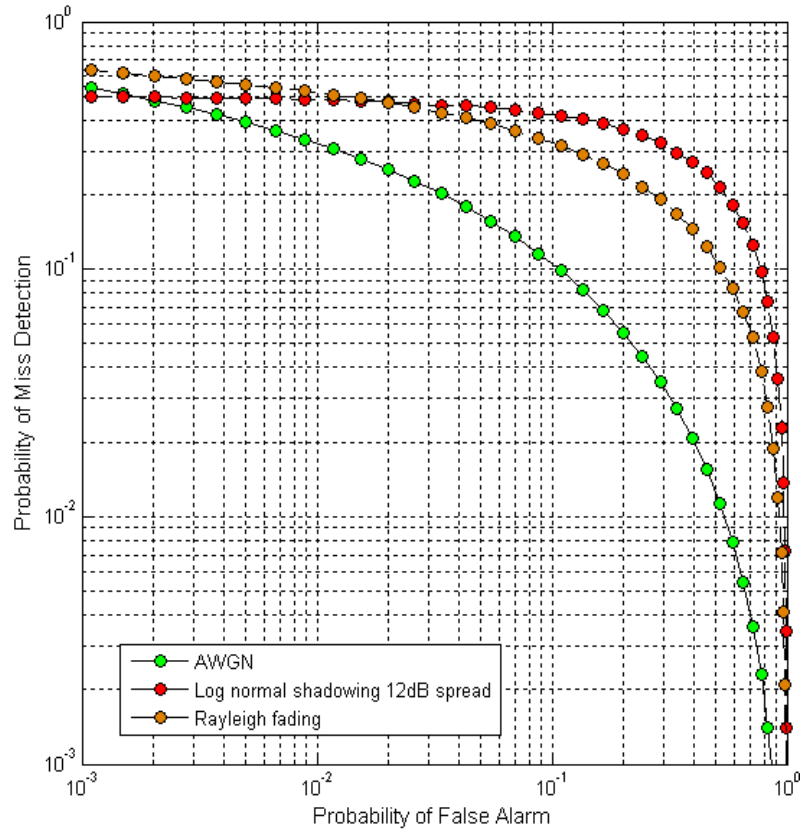


Figure 9: (P_{fa}) vs (P_m) plotted ROC curves for Energy Detection under Log normal shadowing Rayleigh fading and AWGN with $\sigma_{dB}=12B$, and $\bar{\gamma}=10dB$, with $m=5$

Chapter 4

Collaboration between Secondary Users

4. Introduction

Sensing the spectrum to employ the white band is affected in existence of fading, and the performance of an energy detection procedure in such case is not reasonable as revealed by previous simulation results. Likewise if the secondary users are blocked by various obstacles or if they are in some shadow by not having a direct line of sight (LOS) with the primary transmitter, spotting the primary signal nonexistence or attendance is extremely complex. Because of wrong sensing existence of a primary user signal may be mistakenly examine as the nonexistence of the signal and causes intervention with the primary user [17]. Similarly the concealed terminal problem causing intervention can be seen in system model diagram. In case of fading and shadow of an obstacle, which causes the intensity of SNR to be extremely low, the performance of energy detection degrades and to deal with this hindrance a procedure called collaboration of secondary users is suggested. Such a sensing involving the collaboration of secondary user with each other sharing their individual experiences is acknowledged as Collaborative Spectrum Sensing [17].

In such a technique there is a central decision station called band manager and the decision taken by a band manager does not depend upon only one secondary user result instead a group of secondary user contribute in the verdict by sending their outcomes and the overall consequence is based upon individual results of all the collaborative users [17].

4.1 Conclusion Combining Methods

The final decision that the band manager takes to conclude whether a primary user signal is at hand or not is usually taken by following some explicit rules and these rules are acknowledged as decision combining rules. Using these

combining rules the individual outcome of all the secondary users that are part of teamwork are taken into consideration by the band manager or base station and then a concluding result is taken depending upon the sort of fusion rule that it follows.

4.1.1 Hard Verdict Combining Scheme

To deal with the difficulty of clogging when there is restricted bandwidth, an additional decision combining technique is used called as hard decision combining technique which solves the obstruction problem in a case of low bandwidth. In this method the secondary user after using particular detection technique for sensing the spectrum, converts their individual outcomes into binary form represented as 1 and 0[40] and in most case 1 is used to classify the existence of primary user signal and 0 is used to point out nonexistence of primary user signal, these bits are then send by all the secondary users that participates in the collaboration for sensing the spectrum, to the base station which after collecting the individual results then construct a final decision[40].

The bits generated by secondary users requires less bandwidth since each secondary user will send only one bit to the base station to designate the attendance or absence of the primary user signal and this method is considered to be extra efficient in case when group effort for sensing the spectrum requires large number of secondary users to participate. This method solves the overcrowding problem to some degree but it also faces the common problem of performance degradation when the common channel is a faded one [40].

4.1.2 Soft Verdict Combining Scheme

In soft verdict combining scheme, the threshold is of immense significance as in this practice all the individual outcomes that are obtained from the different collaborative secondary users are then drive to the band manager [51]. The band manager which sometime happens to be a common secondary user then merges all the received outcomes and after combining all these results they are then evaluated with a threshold to see the combine result. If the combined results are superior than the threshold, it means that the primary user signals are at hand, so the secondary users are not permitted to use the band and cause intervention with the primary user,

however the collective results when compared with the threshold, happens to be below the threshold it suggests that there is no primary user signal in attendance and the secondary users are permissible to exploit the band [51].

If there are large number of secondary users participating in the collaboration and the bandwidth is low, then since the secondary user may require large amount of bandwidth for sending their individual results to the band manager, less bandwidth may increase the processing time of this decision combining technique because all the secondary user will be using the similar frequent channel for sending their individual results to the band manager causing the channel to be overcrowded. The collaborative spectrum sensing technique although is extremely constructive in fading however if the channel is also effected by fading then it's worth is not of great deal assistance [29] and because of it hard decision combining rule is preferred in most cases.

4.2 Fusion Policy

After the secondary users individual results are send to the band manager, then depending upon which method is used for decision combining, the band manager can use diverse fusion rule along with any of the above mention decision combining method for effective decision making. There are number of rule for fusion that the base station or band manager can use.

4.2.1 AND Regulation for Fusion

In AND fusion procedure if any of the secondary user, in a group of all the participating collaborative secondary user, sends a “0” bit to the band manager, indicating the nonexistence of primary user signal, then the ultimate verdict of the band manager is the absence of the primary user signal, nevertheless on the other hand the band manager concluding choice for the attendance of the primary user signal occurs, if all the secondary users that contribute in the collaborative spectrum sensing send a “1” to the base station to point out that they all have detected the existence of the primary user signal. In such case the probability of false alarm (P_{fa}) and probability of detection (P_d) is given by equation (4.1) and (4.2) [13].

$$Q_d = \prod_{i=1}^n P_d \quad (4.1)$$

$$Q_{fa} = \prod_{i=1}^n P_{fa} \quad (4.2)$$

4.2.2 OR Regulation for Fusion

This technique is the reverse of that of the AND fusion rule and is that sort of fusion rule in which the secondary user sending a binary “1” to designate the occurrence of primary user signal has high priority. In this rule the band manager after collecting all the individual results of the secondary user inspects if there is any secondary user with the result “1” and if there is any than the overall result of the band manager is “1” indicating the existence of the primary user signal, but if there is no such secondary user with result as “1” bit and all the secondary user designates the nonexistence of primary user signal by sending “0” as their individual result, the band manager then gives the ultimate verdict as the absence of primary user signal [13].

If in collaborative sensing all the secondary user gives their individual results then the two probabilities, the probability of detection (P_d) and probability of false alarm (P_{fa}) is given by equation (4.3) and (4.4) [13]

$$Q_d = 1 - \prod_{i=1}^n (1 - P_d) \quad (4.3)$$

$$Q_{fa} = 1 - \prod_{i=1}^n (1 - P_{fa}) \quad (4.4)$$

If the probability of false alarm (P_{fa}) and probability of detection (P_d) is the same for the entire collaborative secondary users participating in the collaboration then the two probabilities are given by equation (4.5) and (4.6) [40].

$$Q_d = 1 - (1 - P_d)^n \quad (4.4)$$

$$Q_{fa} = 1 - (1 - P_{fa})^n \quad (4.6)$$

4.2.3 (n, k) Regulation for Fusion

This is an additional kind of majority voting scheme having predefined rules and this rule states that for a conclusion to work a particular section of total population must be on one side so that the fusion rule can work [13].

The rule has two parameters “ n ” and “ k ” where as “ n ” stands for incidence of primary user, and both these parameter have their values totally reliant on the radio environment, plus in the scenarios where the radio environment is detailed to be extra faded then the “ n ” value is kept very high.

4.2.4 Majority Fusion Law

As the name recommends in this practice, final conclusion is taken on the basis of majority and the rule works when a large number of inhabitants of secondary users are involved in collaboration by sending their individual consequences, pointing out that they have spotted the existence of primary user signal [13]. The band manager then take its ultimate decision as the existence of the primary user. This rule is also called as voting rule and to be affective at least more than half of the whole inhabitants in a radio environment must be on the same opinion with the verdict [13].

4.3 Efficient Techniques for Joint Spectrum Sensing

Collaborative spectrum sensing is extremely efficient practice in fading and independent shadowing, however sometime because of common channel being faded one also affects this method since it may happens that the secondary user involved in the group effort when sending their individual outcomes of their sensing may alter due to faded common channel and the binary bit “1” and “0” send by participating secondary users to the base station alters from “1” to “0” and “0” to “1”.

Consequently the base station after receiving the outcomes when takes the last choice to decide the attendance and nonattendance of primary user signal proves to be erroneous.

To deal with this problem several techniques can be used.

4.3.1 Censored Decision Scheme

The practice necessitates that a vague region threshold must be defined in order to permit only those secondary user that are measured to be more dependable than other secondary user to chip in association, and it helps reducing the processing time of base station since less but more dependable secondary user participating in the collaboration helps get better the performance even if the bandwidth is low [29].

4.3.2 Selection Diversity Process

When there are many secondary user participating in the group effort and majority of them are distant from each other as well as from the base station then the practice called selection diversity [54] can be used. In this procedure the secondary user having most excellent common channel condition with other secondary user and band manager are only elected for sensing.

4.3.3 Cooperative Diversity Process

If in cognitive radio for reception, numerous antennas are used it would be efficient however it cost too much, but virtual antenna scheme as in MIMO when space and time coding is done, can be use [52] [53].

The thought is only functional when a secondary user is nearer and shares their outcomes with neighboring secondary users. In this technique the secondary user sends the outcome of its near secondary user and its own to the band manager using two diverse time slots. In this way the base station will receive the results in two diverse channels with independent fading thus improving the performance [29].

4.3.4 Relay Diversity Scheme

The secondary user sometime cannot send the outcomes to the base station because of extremely concentrated shadowed common channel, so the base station concludes the ultimate choice randomly having some 50% to 60% probability to be correct. Therefore there has to be a system that the band manager could be familiar with and then label those secondary users which are under shadowing. But this technique shows very good results only in shadowing affects [29].

4.4 Spatially Correlated Shadowing

With collaboration flanked by different secondary users to sense the spectrum the performance increases even in case of independent shadowing and fading but when the secondary user that might contribute in group effort are at a small distance from each other then the secondary user might face spatially correlated Log normal shadowing [55]. Because of spatially correlated shadowing the collaborative spectrum sensing performance also suffers as the secondary users will then have indistinguishable shadowing effects and thus they will then face reduce collaborative gain causing the entire system to suffer [40].

When the secondary user close to each other suffers from correlated shadowing then the resulting shadowing follows an exponential correlation function given in equation (4.7) [55]. When secondary users are nearer to each other facing alike shadowing, then the outcome resulting from the collaboration of these secondary users will degrade the whole performance.

$$R(d) = e^{-ad} \quad (4.7)$$

The equation (4.7) have $R(d)$ as the correlation function and “ d ” is the distance between secondary users with “ a ” being a constant that depends upon the radio environment with a value of 0.1204 for urban environment where the area is populated with more tall structure then in suburban environment where the value of “ a ” is calculated to be 0.002 [55].

4.5 Simulation and Explanation

In this section we have shown the simulation results for collaborative spectrum sensing using energy detection as the primary detection technique for the secondary user and we have simulated various scenarios with different number of users participating in the collaboration.

The hard decision combining method along with *OR* fusion rule is used and phenomena such as Rayleigh fading, Log Normal shadowing and Correlated shadowing are studied and simulated to show the enhancement in performance of secondary users in collaborative spectrum sensing.

4.5.1 Collaborative Spectrum Sensing in AWGN

In the simulation in fig:10, three different curves are shown with average SNR $10dB$ and time and bandwidth product (m) as 5, one simulated curve shows three collaborative secondary users using energy detection practice and hard verdict combining with OR fusion rule to perceive the primary user signal in AWGN channel, the second curve shows five collaborative secondary user that are participating and an additional curve is also shown for comparison with one secondary user sensing the spectrum in AWGN channel, and the results clearly indicates that as the number of collaborative secondary user boosts the overall performance to sense the spectrum.

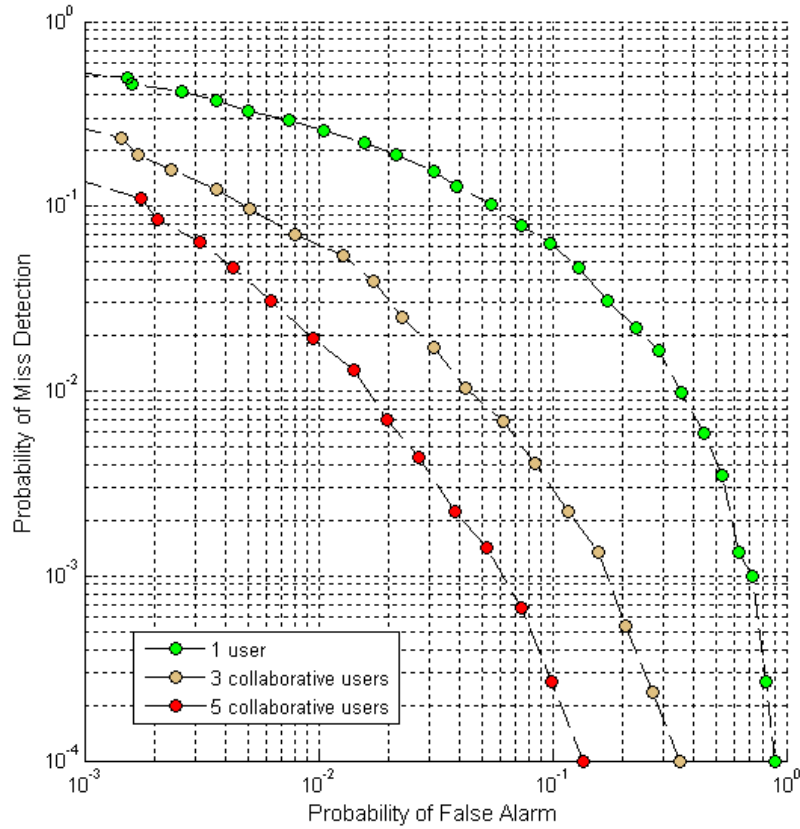


Figure 10: (P_{fa}) vs (P_m) ROC bends for Collaborative Spectrum Sensing in AWGN with secondary users varying having $\bar{\gamma}=10dB$, and $TW(m) = 5$.

4.5.2 Rayleigh Fading Affected Collaborative Spectrum Sensing

In the previous chapter secondary user under Rayleigh fading was simulated and it was observed that in the presence of fading the performance for sensing the spectrum

by the secondary user degrades because the SNR that the secondary user receives varies because of fading having an exponential distribution.

In this simulation shown in fig:11, collaborative secondary users under Rayleigh fading with each having its observation independent of the other, have been simulated. Four curves have been shown with instantaneous SNR of $10dB$ and TW product (m) is 5. The simulation shows three cases of Rayleigh fading with one secondary user having no collaboration affected by Rayleigh fading and then the outcomes of two collaborative secondary users that have autonomous fading are simulated, similarly results for four secondary users with independent fading involved in collaboration for sensing the spectrum are simulated at the end it is viewed that, the more secondary user contribute in group effort, the more it improves the performance of the system even in cases of fading.

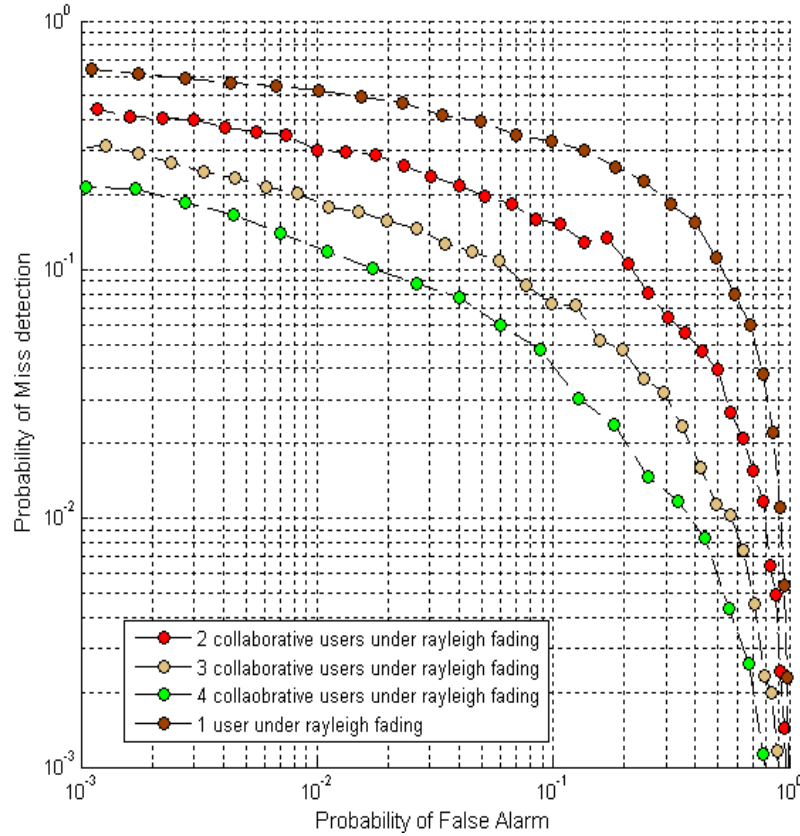


Figure 11: Curves for Collaborative Spectrum Sensing in Rayleigh fading with the number of secondary users varying having $\bar{\gamma}=10dB$, and $TW(m) = 5$.

4.5.3 Log Normal Shadowing Affected Collaborative Spectrum Sensing

In this simulation shown in fig:12, those collaborative secondary users are shown that are exaggerated by Log normal independent shadowing and then there spectrum sensing performance is studied. Four simulated curves are obtained with 1 secondary user having no collaboration and is under log normal shadowing with $12 (\sigma_{dB})dB$ spread. The simulation also shows 3 collaborative users with $8 (\sigma_{dB}) dB$ spread, and 4 collaborative secondary users with $6 (\sigma_{dB}) dB$ spread, AWGN curve is also shown for comparison and average SNR of $10dB$ and time bandwidth product m of 5 is taken for the simulation, at the end it have been comprehended that increasing the number of collaborative users with less $(\sigma_{dB})dB$ spread, the performance of the secondary user for sensing the spectrum increases.

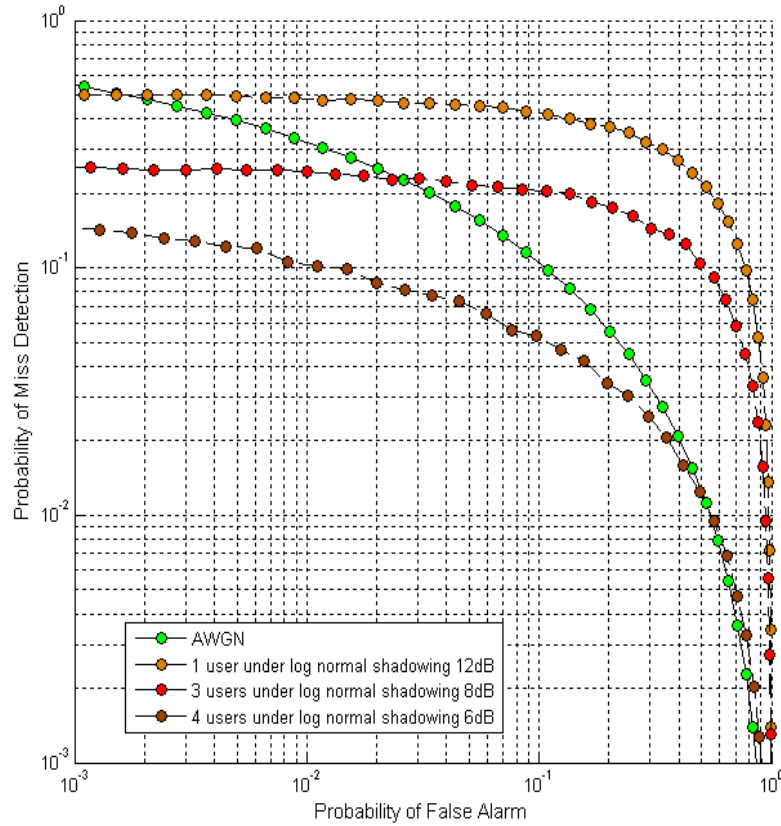


Figure 12: A (P_{fa}) vs (P_m) ROC bends in Collaborative Spectrum Sensing with Log Normal Shadowing having number of secondary users varying with $\bar{\gamma}=10dB$, and $TW(m) = 5$ and $\sigma_{dB} = 12, 8$ and $6 dB$ respectively.

4.5.4 Collaborative Spectrum Sensing in Suburban Area under Correlated Shadowing

The simulation shown in fig:13, depicts the ROC curve between two major probabilities e.g. detection probability (P_d) and false alarm probability (P_{fa}). The curves are simulated for secondary user collaborating in a radio environment, and these secondary users are affected by spatially correlated shadowing. In this simulation the average received SNR in use is $10dB$ and the time bandwidth product denoted by (m) has a value of 5. The curve are the results of three collaborative secondary users sensing the spectrum, that are affected by spatially correlated log normal shadowing within the premises of not much populated suburban region with the distance “ d ” between them as $100m$. For comparison three secondary collaborative users with independent shadowing having $6dB$ spread is also shown along with a single secondary user having no shadowing and fading and it have been observed that in case of spatially correlated log normal shadowing the effects are more degrading as evaluated when the secondary users are under independent and uncorrelated shadowing.

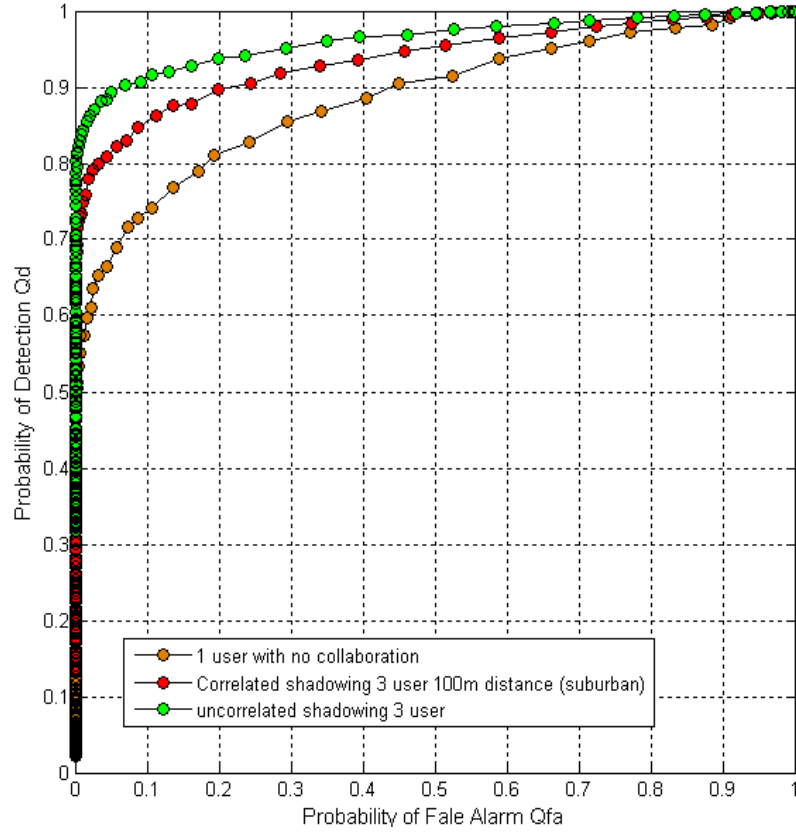


Figure 13: A (Q_{fa}) vs (Q_d) curve with Collaborative Spectrum Sensing in suburban area under spatially correlated Log normal shadowing and independent Shadowing with the number of secondary users varying having $\bar{\gamma}=10dB$, and $TW(m) = 5, \sigma_{dB} = 6dB$ and distance $d = 100m$ respectively

4.5.5 Collaborative Spectrum Sensing in Urban Area under Correlated Shadowing

This simulation results shown in fig:14, depicts two collaborative spectrum sensing secondary users under spatially correlated shadowing in urban area, with average received SNR of $10dB$, and $TW(m)$ is 5 and distance “ d ” between them is taken as $10m$ and $20m$ respectively. For comparison two secondary collaborative users are also shown that have independent log normal shadowing with $6dB$ spread and it is observed that correlated shadowing degrades the performance of secondary collaborative user more, however as the distance between secondary users in urban areas increases the performance enhances to some degree.

Also from the two simulations for secondary collaborative users affected by spatially correlated log normal shadowing in both urban and suburban areas it has

been realized that the performance of sensing degrades much in suburban area as compared to urban areas and the reason for this is that users in urban area are more affected by independent shadowing because of large obstacle but in suburban since the area is not much populated so the secondary user close to each other are affected by spatially correlated shadowing but as the distance between the secondary users increases the sensing performance gets better.

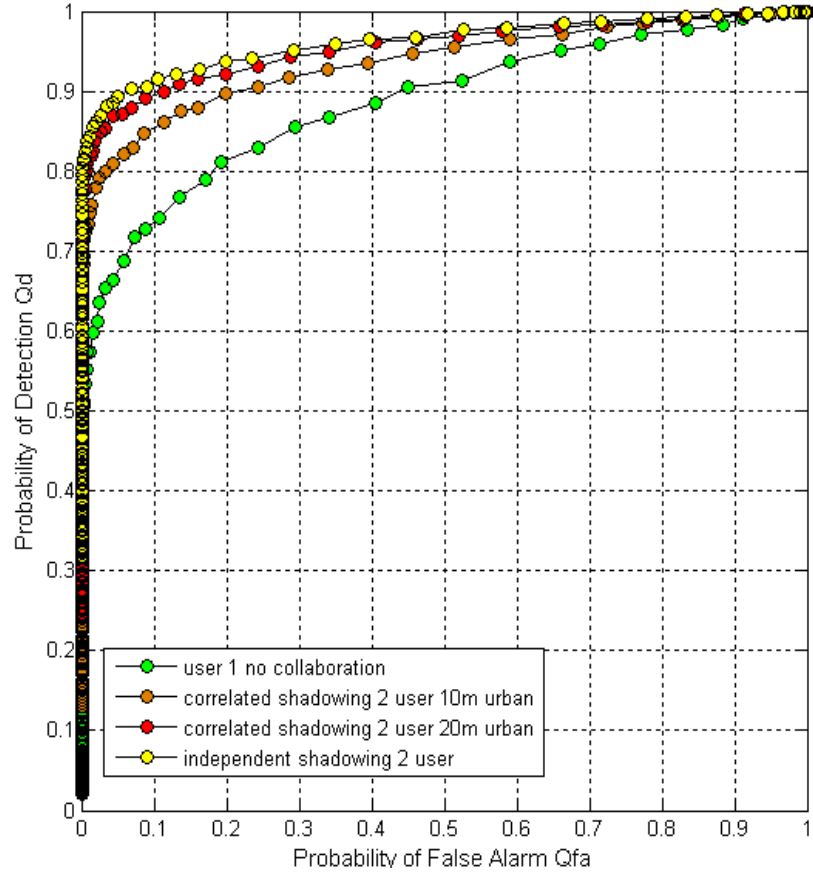


Figure 14: Curves with (Q_{fa}) and (Q_d) with Collaborative Spectrum Sensing in urban area under spatially correlated Log normal Shadowing and Independent Shadowing with the number of secondary users varying having $\bar{\gamma}=10dB$, and $TW(m) = 5$ $\sigma_{dB}=6dB$ and distance $d = 10m$ and $20m$ respectively.

Chapter 5

Selection of Cognitive Radio

5. Introduction

To sense the spectrum collaboratively in cognitive radio, an optimization scheme is required that helps to improve the performance of the cognitive radio. If the collaboration of secondary users for the spectrum sensing involves many secondary users better performance can be achieved [40]. In a group effort with many secondary users to collaboratively sense the spectrum, it also sometime degrades the performance of the system instead of improving it because if all the secondary users are using the same common channel then much bandwidth is required to collect the individual results of all the secondary users, which causes the processing to take much time [29].

If number of secondary users participating in collaboration to sense the spectrum are under spatially correlated log normal shadowing then the performance of the collaboration between secondary users for sensing the spectrum also degrades [19], similarly the base station will also need more processing power if the secondary users are many in number.

The solution to such problems would be, to have such cognitive radio users that have high average received SNR and a large separation between them, so when used in collaboration for sensing spectrum they will improve the performance. Also instead of using all the available secondary users only those best fitted for sensing the spectrum can be used to get better the performance of the system. By using all the cognitive secondary users in collaboration for spectrum sensing, it will not only increase the processing time, but because of having spatially correlated shadowing between some of them could cause the overall result to be degraded [56].

The main idea is to have such a group of secondary users selected from the pool of all available secondary users that provides enhanced performance or in some cases gives better results when used for collaboration to sense the spectrum, as compared to when all the available secondary user in that radio environment are

used. So to have such a combination of secondary user, an optimization scheme is required that can help to select optimal secondary user for a particular radio environment improving the performance of spectrum sensing. A combination of minimum number of secondary users for spectrum sensing also depends upon what performance bound is imposed by the network.

An optimization technique that can help to perform a quick search and give optimum secondary users given the parameters of the radio environment is Genetic Algorithm.

5.1 Genetic Algorithm for Optimization

Charles Darwin in his theory of natural evolution stated that a natural principle is retained by organisms for their selection after some generation and he named it as the “Survival of the fittest” [58], it means that the organisms that are more flexible to their environment and can resist changes will survive through generation but the one that are rigid to the environmental changes will vanish [58].

This evolutionary technique was used to develop many algorithms in order to search for optimal solution and select those best suited for a particular environment. Since most of these evolutionary algorithms are based on a population, the optimal results are then found by creating generations of this population [58].

John Holland used the same idea of the “Survival of the fittest” proposed by Charles Darwin and he describes Genetic Algorithm as an evolutionary algorithm in 1975 because it is an efficient optimization technique and gives fast searching results.

Genetic algorithm selects a part of the initial population and evolves it through generation to find optimum solution [57]. Being a robust algorithm it handles population for all possible solutions where as each solution is named a chromosome. Each of these chromosomes is made of some genes. The initial population is also used for reproduction, in order to produce new generations for finding those chromosomes which have survived through different generations. The reproduction is carried out by using parameters such as Cross over and Mutation.

Cross over are used to produce child chromosome from the parent chromosome by the genetic algorithm and the technique works by selecting two parent chromosomes and then generating children from these parent chromosomes. Different

combination of genes of two parent chromosomes are interchanged to produce child chromosome by maintaining a fix crossover rate for it. For example if a chromosome consists of four genes then suppose gene two and three of one parent chromosome is interchanged with the same gene of another parent chromosome to produce a child chromosome which will be a combination of genes from both parent chromosome.

Mutation means that a chromosome might be mutated with certain probability by changing bits or an integer entry in the genes of the chromosome and it is done to preserve diversity in genetic of chromosomes [58].

To perform a cross over the selection of the chromosomes can either be done randomly or the parent chromosomes can be ranked to select only those chromosome that are best fitted to produce new child chromosome. The selection of chromosome is usually dependent on a particular objective function also known as fitness function.

The fitness function is used to produce a particular value and then this value are then used to show the chromosomes with their fitness level. Genetic algorithm selects initial population when fitness and reproduction function for generating next generation is defined properly and it is selected in the following way [58].

- i) **Individual selection:** first best individuals as parents are selected for the production new child.
- ii) **Producing new generation:** Then the crossover and mutation functions are used to produce next generation.
- iii) **Assessment:** The fitness level of the next generation chromosomes is assessed by using the fitness function.
- iv) **Substitution:** New generated individuals then take place of old chromosome. Also the new generation formed may have individual from previous generation.

5.2 Simulation

The purpose of this part of the project was to select some optimum secondary users for collaboration, from the list of all available cognitive radio and then simulate the result using these cognitive users and compare it with simulation of all the secondary users present in that radio environment.

The scenario is explained below for simplicity some secondary users along with average received SNR are considered to be in a straight line, and the distance of all the secondary users from the transmitter are calculated by a formula,

$$d = k/\gamma \quad (5.1)$$

whereas γ denoted the average received SNR of the secondary users and k being a constant considered to be 100, so to calculate the distance of secondary users from the transmitter, and after that then the distance of secondary users from each other is calculated.

To use the genetic algorithm the first step was to construct chromosome which are made up of genes, and in the project the gene were taken as those factors of the secondary users that have direct relation with the secondary users and its performance. So the chromosomes which are secondary users, in this project had three genes or parameters namely average received SNR, distance from transmitter, and the σ_{dB} the dB spread for correlated log normal shadowing considering that all the secondary users are under spatially correlated log normal shadowing having different dB spread but the intensity of this shadowing is different on each secondary user. The table below describes each gene with its values represented by a decimal number, thus performing value encoding of each gene for simplicity.

5.2.1 Received SNR of secondary users having value encoding

The table (5.1), below shows different values of SNR with step size of 1.5 *db* that the different secondary users in that radio environment have, where as each value of SNR acted as gene for a chromosome.

Decimal value	0	1	2	3	4	...	15
Received SNR	25db	23.5db	22db	20.5db	19db	...	2.5db

Table 5. 1: Value encoding of SNR values

5.2.2 Distance from transmitter value encoding

The distance of secondary users from the transmitter is calculated, with respect to their SNR by using the formula in equation (5.1) and then value encoding of these values is done given in table (5.2). This is the second gene of the chromosome. Using this distance then the distance of secondary user from each other can easily be calculated assuming that they are all in a straight line.

Decimal value	0	1	2	3	4	...	15
Distance from transmitter	4m	4.2m	4.5m	4.8m	5.2m	...	40m

Table 5. 2: Value encoding of distance from transmitter.

5.2.3 Different values of dB spread

The different values of dB spread for correlated log normal shadowing with step size of $1dB$ are represented by decimal numbers from 0 to 14 with total of 15 decimal values. These values are given in table (5.3) below.

Decimal value	0	1	2	3	4	...	14
dB spread for shadowing	2dB	3dB	4dB	5dB	6dB	...	16dB

Table 5. 3: Value encoding of dB spread for log normal shadowing

After all the genes are define then the chromosome configuration in decimal form is given as describe in table (5.4) below.

Gene Number	Gene Name	Decimal value range
1	received snr	0-15
2	distance from transmitter	0-15
3	dB spread	0-14

Table 5. 4: Chromosome configuration

For process such as mutation, the chromosome along with its genes needed to be converted to bits because if a bit is altered it will change chromosome only, but if a decimal value is used for mutation and then it is changed, it will change the whole gene. The table (5.5) below describes configuration of chromosome in case of binary encoding.

Gene Number	Gene Name	Number of bits required
1	received snr	4 bits
2	distance from transmitter	4 bits
3	dB spread	4 bits

Table 5. 5: Chromosome configuration in binary format

After the chromosome is constructed then initial population of the chromosomes are generated randomly.

5.3 Initial Population

The initial population for Genetic algorithm involves individual also known as chromosome that are the solutions, and the chromosome that is the most optimal for the performance is considered. Each entity represents a cognitive radio that can be used for collaboration to sense the spectrum. For the simulation initial population of hundred chromosomes is generated randomly.

5.4 Fitness Function

After the chromosomes are constructed, and an initial population is generated then comes the fitness measure which is used to determine the stability of a chromosome from a population and how fit it is in solving the problem [59]. Since the solution set may have worse and fit chromosome therefore such a fitness function is require that can accept fit chromosome for the next generation.

As in the project secondary user are considered as chromosome and each chromosome is constructed from a combination of genes. Each gene of a chromosome has some specific weight in the chromosome represented by the number

of bits it requires to represent a gene in binary form. The weight of each gene is given in the table (5.6) below.

Gene Weight	Gene Name	Number of bits required
Wt1	received snr	33.3%
Wt2	distance from transmitter	33.3%
Wt3	dB spread	33.3%

Table 5. 6: Weight of each gene in chromosome

Now to calculate the fitness function for a chromosome the fitness function of each gene must be calculated first, and to define fitness function of a gene it must have a fitness point, whereas a fitness point of a gene is central point of each gene and is used to cover the full decimal range of gene in both direction in order to select genes with optimal values. Different values as a central point for all the genes have been verified and the one given in the table(5.7), are the most fitting because it helps to select the most favorable values for a chromosome.

Fitness point	Gene Name	Value for Fitness point
F1	Received snr	6
F2	Distance from transmitter	6
F3	dB spread	5

Table 5. 7: Fitness point of each gene

After the fitness point is chosen then, the parameter of secondary user for a particular radio environment which is desired for better performance is compared with that gene of a chromosome generated from initial population, and then fitness function of each gene is calculated by using the equation (5.2) given below.

$$\text{Absolute Difference(ABS)} = |\text{Chromosome gene} - \text{Requested gene}| \quad (5.2)$$

When the absolute difference value is obtained, it is then compared with the fitness point of each requested gene and if the absolute value is greater than that of fitness

point of a particular gene, then fitness function of the gene is given as the weight of that particular gene given in equation (5.3)

$$\text{Fitness function of a gene} = \text{Weight of that gene} \quad (5.3)$$

On the other hand if the absolute difference value is less than that of the fitness point of a particular gene, then the fitness function of a gene is given by equation (5.4)

$$\text{Gene fitness fun} = [(\text{Weigh of gene} \times \text{Absolute diff}) \div \text{gene fitness point}] \quad (5.4)$$

After the fitness function of all the genes of chromosome are calculated then the fitness function of the chromosome is derived also defined as the “total fitness function” of the a chromosome. The require total fitness function of the chromosome is calculated by using aggregated weighted sum [60], approach by adding the fitness function of all the genes given in equation (5.5)

$$\text{Aggregated weighted sum} = \text{sum of the fitness fun of all genes in a chromosome} \quad (5.5)$$

and then subtracting it from 100, since the total fitness function of a chromosome can't go beyond 100. The total fitness function of a chromosome is given in equation (5.6) describe below.

$$\text{Total FF of chromosome(tff)} = 100 - \text{Aggregated weighted sum} \quad (5.6)$$

The total fitness function is used to have an optimal solution.

5.5 Selection of Chromosome for Next Generation

Selection is that part of genetic algorithm which is used for building the next generation of a population, and for processes such as cross over and mutation. It is dependent upon fitness function of a chromosome [61] and chromosome with better fitness functions are selected depending upon the selection method used.

In this project we have consider roulette wheel selection method that works on the probability distribution method given in equation (5.7) describe below,

$$p(i) = \frac{f(i)}{\sum_{j=1}^n f(j)} \quad (5.7)$$

whereas $p(i)$ is the probability of chromosomes to be selected and $f(i)$ is the fitness function of chromosome and $\sum_{j=1}^n f(j)$ the sum of all the “ n ” number of chromosomes in the population. After the probabilities of the chromosomes are calculated then depending on their percentage they are allotted place on roulette wheel and then the chromosome having the higher probability taking more space on the on the wheel has higher chances of selection on a spun and the chromosome having low probability thus occupies less space on the wheel has very little chance of selection, causing the selection of unfit chromosome almost impossible for the next generation.

Simulation for the roulette wheel selection shows some chromosome along with their percentages in the table below

Selected chromosome	Total fitness function (tff)	Selection Probability p(i)
1	70	25%
2	96	35%
3	23	8%
4	88	32%
All chromosome total	277	100%

Table 5.8: Selection probabilities of chromosomes

The table (5.8) shows four chromosome from the initial population along with their fitness function values and there probabilities, now to understand the roulette wheel selection all the four chromosome are given place on the roulette wheel and the one with greater probability for selection takes more space on the wheel e.g chromosome number two having higher probability of selection will take more space on roulette

wheel but chromosome number three on the other hand will take less space on the wheel having very low probability for selection and thus it has very low chance of selection when a roulette wheel spun for the selection of chromosome is performed . Using this technique the worse chromosomes are selected rarely.

5.5.1 Crossover Process

The crossover is used for reproduction and in this process the genes of two parent chromosomes are exchanged with each other in such a way in order to form new child chromosome [62]. In this project the two point crossover technique is used to create new child chromosome from two parent chromosome by exchanging their genes in a particular order as given in fig:15, and for crossover technique the value encoding technique for the genes of chromosomes are used. The crossover rate is kept to 90% and it results in a selection of 45 random pairs that are selected for two point crossover process.

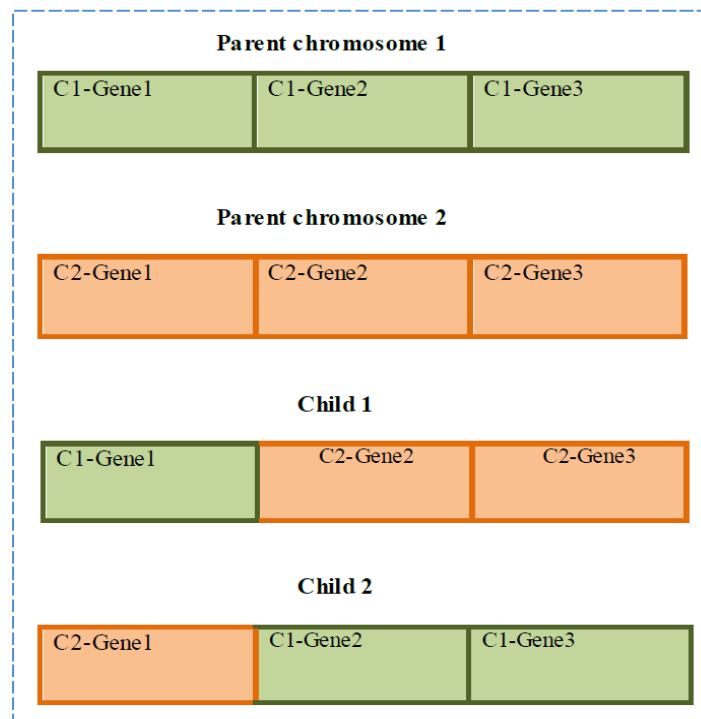


Figure 15: Crossover operation of two parent chromosome

5.5.2 Mutation Process

After the crossover process, the mutation process is performed and it is that kind of process in genetic algorithm in which the characteristics of a gene of a chromosome are alter before it is used for reproduction. In this project the gene value for mutation process is represented in binary form, so the mutation process occurs when a binary 1 of a gene is replaced by a binary 0 or a binary 0 is replaced by binary 1[61].

In the project the randomly generated initial population is of 100 chromosomes and the mutation rate for a given population is considered as 2%, which means out of all the chromosomes created by crossover only two will go under mutation process to carry on with the diversity. Fig:16 shows in detail the mutation process of a gene in which the bits of the genes are changed and thus the gene is mutated causing a new chromosome to be form.

Gene1	Gene2	Gene3
4	6	3
Chromosome with decimal value for each gene		
Gene1	Gene2	Gene3
0100	0110	0011
Chromosome with binary value for each gene		
Gene1	Gene2	Gene3
0100	0110	0111
Gene 3 mutated with one bit changed marked as red		
Gene1	Gene2	Gene3
4	6	7
New chromosome developed due to mutation of its gene		

Figure 16: Shows the mutation process

The genetic algorithm process is performed till thirty generations with each generation having hundred chromosome or secondary users having different parameters associated with it and then the most optimum secondary users are

selected from it and used for collaboration to give lowest probability of false alarm and higher probability of detection.

Optimum Solution	Chromosome 1	Chromosome 2	Chromosome 3	Chromosome 4	Chromosome 5
SNR gene	8	6	7	9	11
Distance from transmitter	6	8	3	4	4
dB spread	4	4	4	4	4
Fitness measure	88%	88%	93%	89%	86%

Figure 17: Five optimum secondary users for collaboration

The fig:17 show those final set of 5 secondary users that are considered to be the optimum one for collaboration to sense the spectrum having sufficient spatially separation between them and have high received SNR values and each of these five user have result similar to other four secondary users but all of these five secondary users shows better performance. After the distance of each secondary user from the transmitter is obtained, then distance of these secondary neighboring users from each other is calculated, considering that they are in a straight line. Then a correlation matrix is generated showing the correlation coefficients between these users. In case of 5 users this matrix is a 5 by 5 matrix and is obtained by using equation (4.7) for urban area.

$$\text{corr martrix} = \begin{bmatrix} su_{1,1} & \cdots & su_{1,5} \\ \vdots & \ddots & \vdots \\ su_{5,1} & \cdots & su_{5,5} \end{bmatrix} \quad (5.8)$$

In the matrix $su_{1,5}$ means secondary users and it shows the coefficient of correlation between secondary user one and five. Then simulation of these five optimum secondary users for sensing the spectrum is performed and compared with

ten secondary user also selected randomly for collaboration but they all have high correlated shadowing and are very close to each other so they all have almost the same result and have low received SNR values. For the simulation hard verdict rule with OR fusion technique is used and the simulation is performed for urban areas, and the simulation results shows that the optimum selected secondary users have better performance, having low probability of false alarm and high probability of detection, with the optimum user less than that of the total available user thus saving bandwidth and reducing processing time.

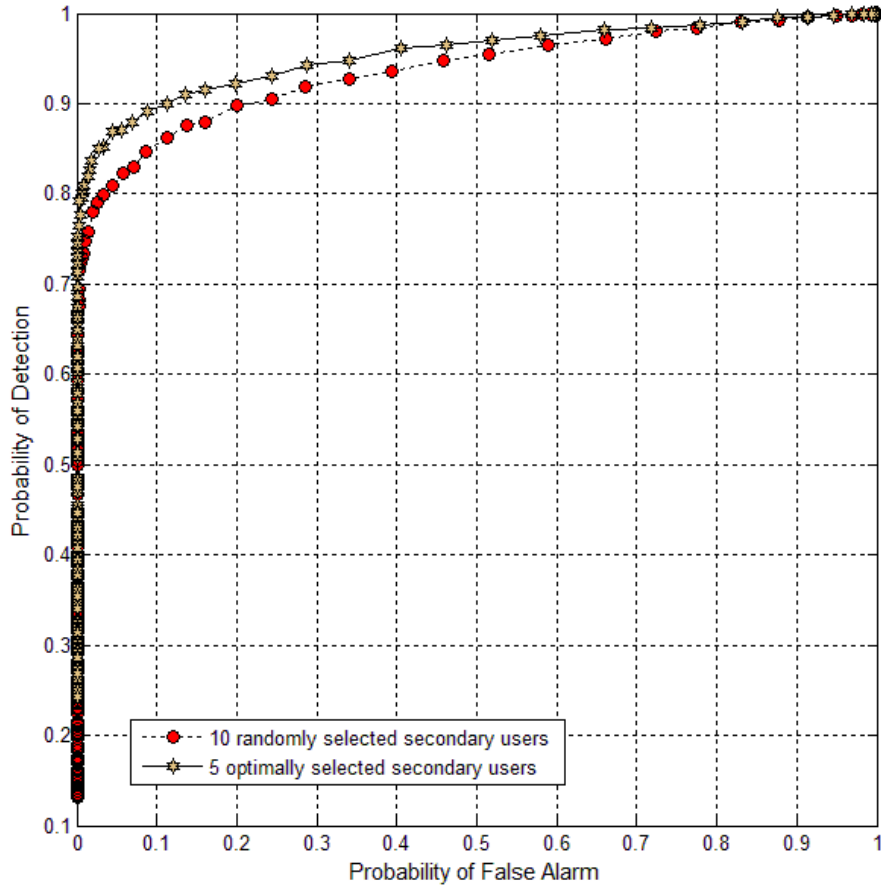


Figure 18: Curves with (Q_{fa}) and (Q_d) with optimally selected secondary users for collaborative Spectrum Sensing in urban area under spatially correlated Log normal shadowing each having different SNR and dB spread.

Chapter 6

Conclusion

Cognitive radio can solve the spectrum under utilization problem, using opportunistic approach to use the unused licensed bands using an efficient spectrum sensing technique. A sensing approach which provides sensing information having high probability of detection and low probability of false alarm would then not cause any intervention with the primary user signal. The technique that would be used for sensing must not be too complex and it can be incorporated in the secondary user hardware easily being cost effective.

Sensing technique such as energy detection, for detecting the primary user signal is a less complex technique and it does not require any initial knowledge about the primary user's signal, which makes it the first choice. It can also be easily incorporated into the cognitive radio hardware. Shadowing and fading are some phenomena's that causes the performance of energy detection to be degraded.

To handle problems such as fading and shadowing, collaboration between secondary users was considered to be the best option that can deal with these factors and the energy detection performance degradation was also reduce to some extent. The energy detection performance was enhanced when the number of secondary users collaborating to sense the primary user signal was increased. All the cognitive users that are together in group effort for collaboration, sends their outcomes to the base station or band manager because it is a central entity in the network, also all the secondary user uses the similar familiar channel for sending their outcomes. However with large number of secondary users participating in the collaboration, and with limited bandwidth it is very difficult to collect the results of the entire secondary users through the common channel and also the band manager require more power for processing to make a final decision.

Spatially correlated shadowing is mostly experienced in radio environment and because of this correlated shadowing, the secondary users that are collaborating for sensing the primary user signal experiences similar results about primary user signal and the collaborative gain decrease to some extent resulting in a degraded

performance. In such a scenario selecting optimum secondary users for collaboration improves the sensing performance.

The last part of the project was concerned with the selection of specific secondary users from a pool of available secondary users with parameters that might improve the performance, and to achieve this, an optimization technique was required to select optimum secondary users for collaboration in order to sense the spectrum. For optimization, genetic algorithm was used along with some parameters for performance and fitness function was used to select optimum secondary users from a population and then the collaboration of these secondary users was simulated to show the improvement in the performance.

The results revealed that instead of using all the available secondary user, if a certain combination of secondary users is used the spectrum sensing performance improves to a great deal, on the other hand if all the available secondary users are used for collaboration to sense the spectrum, in most cases the performance does not enhances.

Future Work

The performance of the energy detection in the project was evaluated in case of shadowing and fading only and in case of a collaborative spectrum sensing spatially correlated log normal shadowing was considered. Also genetic algorithm was used as an optimization technique for calculating the optimum secondary users for collaboration to sense the spectrum, and combination of 5 collaborative users was evaluated to see the performance in the urban area of a radio environment. For future work the number of collaborative secondary users for sensing the spectrum can be increase or decrease and different combination of secondary users, with different parameters for performance can be evaluated. For example from the available population of ten secondary users a combination of more than five or less than five can be selected to evaluated the performance both in urban and suburban radio environment especially in environment with intense fading and shadowing. Other optimization technique can also be tried to have a clear understanding of these techniques. In the project the threshold and the bandwidth was kept fix for simplicity, a technique of two threshold with upper and lower limit can also be tried to evaluate

the spectrum sensing performance in case of threshold constraint for energy detection.

Along with selecting optimum secondary users for spectrum sensing, extensive work is also required to enhance on the whole sensing of the spectrum by using cooperation between cognitive radio for collaboration in which the secondary user not only collaborate but also cooperate, as it is an efficient technique.

Cooperation among secondary users allows the secondary users to share their individual outcomes with the other nearby secondary users and in cases where the secondary user is unable to send its outcome to the band manager, the neighboring secondary user can forward the result of that secondary user to the central entity using a particular routing algorithm that can select a best lane among all the available paths leaving those paths that are congested.

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