COGNITIVE RADIOS – SPECTRUM SENSING ISSUES

A Thesis

presented to

the Faculty of the Graduate School

at the University of Missouri-Columbia

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

By

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DECEMBER 2007

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Acknowledgements

I feel immense pleasure in thanking my thesis advisor Dr. Chengshan Xiao for his constant support, encouragement and helping me in selecting my thesis topic. I thank him for imparting his knowledge, without which this work would have not been possible. I would also like to thank Dr. Zhihai He and Dr. John Fresen for readily accepting to be in my thesis examining committee and for providing valuable suggestions and reviews on my thesis report. My special thanks to Dr. Fresen for his support while recovering from a major surgery.

I am thankful to Martin for showing confidence on my work and helping me whenever required.

Finally I would like to thank my parents and sisters for their continuous moral support and encouragement. I thank all my friends specially Milind, Sridhar, Karthik, for their constant support throughout my Graduate studies.

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Abstract

Today’s wireless networks are characterized by fixed spectrum assignment policy. With ever increasing demand for frequency spectrum and limited resource availability FCC decided to make a paradigm shift by allowing more and more number of unlicensed users to transmit their signals in licensed bands so as to efficiently utilize the available spectrum. The motivating factor behind this decision was the findings in a report by Spectrum Policy Task Force, in which vast temporal and geographic variations in spectrum usage were found ranging from 15% to 85%. FCC was now open to new approaches for efficient spectrum sharing techniques with unlicensed users; one of them is Cognitive Radios.

Cognitive Radio can smartly senses and adapts with the changing environment by altering its transmitting parameters, such as modulation, frequency, frame format etc. The main challenges with cognitive radios are that it should not interfere with the licensed users and should vacate the band when required. For this it should sense the signals faster. For this purpose various detection schemes like energy detector, matched filter and cyclostationary feature detector are discussed in this report and performance evaluation of these is calculated. Besides this a performance evaluation is done between cooperative and non cooperative spectrum sensing schemes which uses Amplify-and-Forward algorithm is also discussed. All simulations are done in MATLAB.

Chapter 1 Introduction

1.1 Motivation and Background

With the increasing number of wireless users, scarcity of electromagnetic spectrum is obvious. Taking this into consideration, the Federal Communications Commission (FCC) published a report prepared by Spectrum Policy Task Force (SPTF) [1]. This report recommends certain rules and regulations for the efficient use of radio spectrum and the ways to improve the existing spectrum usage. In relation to the spectrum utilization this report illustrates that there is significant inefficient spectrum utilization than the actual spectrum scarcity due to the legacy system and the rules imposed by FCC. Most of the allotted channels are not in use most of the time; some are partially occupied while others are heavily used.

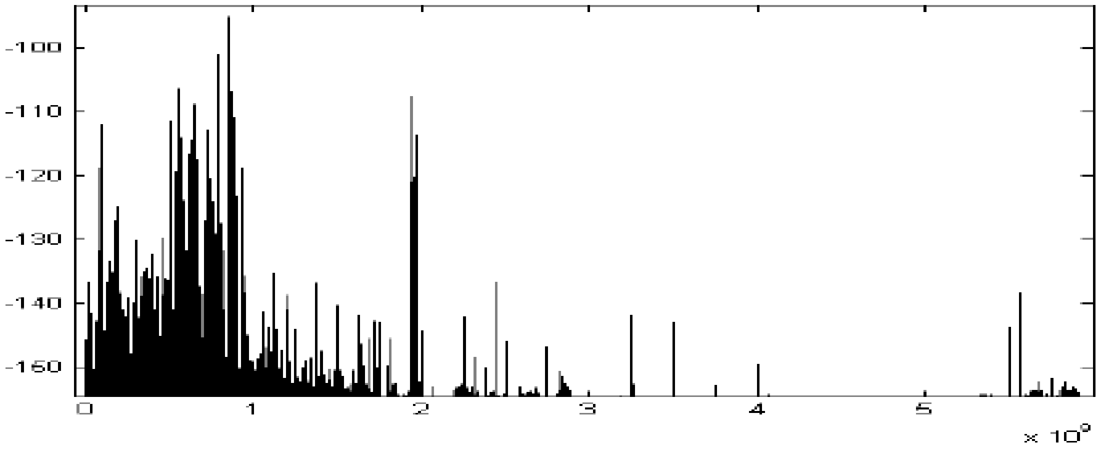


Figure 1.1 Measurement of 0-6 GHz Spectrum Utilization at BWRC

Frequency (GHz)	0-1	1-2	2-3	3-4	4-5	5-6
Utilization (%)	54.4	35.1	7.6	0.25	0.128	4.6

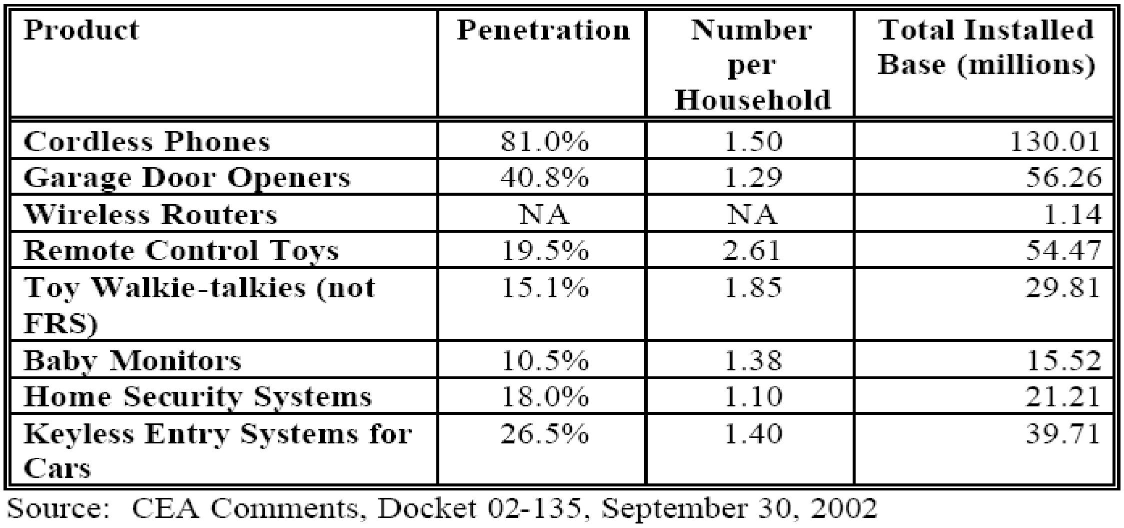
Table 1.1 Frequency utilization

Spectrum Holes

Figure 1.1 above reveals the spectrum utilization from 0-6 GHz band. The lower frequency band is densely populated while at the higher frequencies utilization is not adequate. We call these regions as Spectrum Holes or White space.

Frequency bands restricted only to licensed users and at any particular time or location which are underutilized.

FCC was interested in making these holes or white space to be freely used by unlicensed users for the best spectrum utilization because of the growth in 802.11/Wi-Fi unlicensed consumer devices market which is estimated to be Billions of US Dollars per year [1].



Product	Penetration	Number per Household	Total Installed Base (millions)
Cordless Phones	81.0%	1.50	130.01
Garage Door Openers	40.8%	1.29	56.26
Wireless Routers	NA	NA	1.14
Remote Control Toys	19.5%	2.61	54.47
Toy Walkie-talkies (not FRS)	15.1%	1.85	29.81
Baby Monitors	10.5%	1.38	15.52
Home Security Systems	18.0%	1.10	21.21
Keyless Entry Systems for Cars	26.5%	1.40	39.71

Source: CEA Comments, Docket 02-135, September 30, 2002

Table 1.2 Unlicensed consumer device market

In May 2004, FCC released a report [2] in which it took an initiative which allows the use of this underutilized spectrum to unlicensed users (Users that are not been served by the primary license holders) to operate in television spectrum in areas where the spectrum is not in use. However, these unlicensed users should not create interference to the licensed user and at times the licensed user wants to transmit its signal the unlicensed user should vacate the spectrum and should look for some other free space. This could be achieved by incorporating “Cognitive Radios” to sense unused spectrum.

Cognitive Radios

Cognitive radios [13] [14] is a new term in wireless communication technology which interacts with real time environment to dynamically alter its operating parameters such as transmit power, carrier frequency, modulation to acclimate itself with the environment whenever there is a statistical change in the incoming radio frequency with the sole purpose to take advantage of the available spectrum without causing interference to primary users.

Cognitive Cycle

The figure below shows various phases of a cognitive cycle which are described below:

- Radio Scene Analysis

  This deals with the estimation of interference temperature and detection of spectrum holes.
- Channel Identification

  Deals with estimation of Channel State Information and channel capacity.
- Transmit power control and spectrum management.

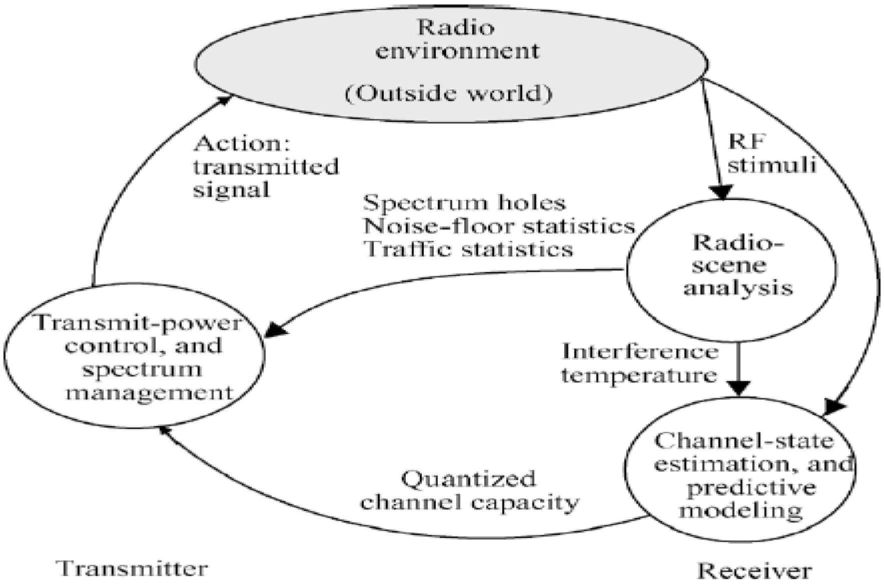


Figure 1.2 Simplified Cognitive cycle

Chapter 2 Literature Review

In this chapter a background of Cognitive Radios, its issues and literary review of previous work has been discussed besides definitions of frequently used terminologies.

2.1 Unlicensed Devices

According to FCC's rules part 15 for the usage of radio spectrum, three types of unlicensed devices are defined [1]

Intentional Radiators

Radio devices which intentionally generate and emit RF energy by radiations are known as Intentional Radiators. Typical examples are cordless phones, remote controls etc.

Unintentional Radiators

A device that generates or uses RF energy but do not emits. Laptops, radio receivers, digital clocks etc are good examples of such devices.

Incidental Radiators

Devices that generate RF energy during their operations, however these are not designed to do so. Motors and switches fits under this category of devices.

If these unlicensed devices cause harmful interference to licensed devices then these are subject to abduction. So taking this into consideration specific measures should be taken to minimize such interference to an acceptable level.

Presently the transmitters are designed in such a way that they can overcome the prescribed noise floor. However because of these new interferers the noise floor could rise from its prescribed limits thereby causing degradation in the coverage of signal transmitted. Due to this FCC in its SPTF report suggested that Interference Temperature limit should be used as a metric to estimate and manage the amount of interference present. Interference Temperature limit provides a worst case scenario in a particular frequency band and its geographic surroundings. The transmitter and receiver should adapt according to the change in surrounding Interference Temperature. The main benefit of using Interference Temperature (IT) as a metric is that if the IT is less than the prescribed limits then that particular band could be used by Unlicensed Devices as long as they maintain the permissible noise floor set by FCC.

2.2 Calculation of Interference Temperature

Interference Temperature is defined as the temperature equivalent of the total interference present in RF environment for a particular frequency band and a geographic location. Its unit is *degrees Kelvin* and its mathematical equation is as follows:

$$T = P / (k*B) \tag{2.1}$$

Where T = Interference Temperature in degrees Kelvin

P = Average Interference Power in Watts

K = Boltzmann’s constant = 1.3807×10^{-23} joules per degree Kelvin

The product of Interference Temperature with Boltzmann's constant gives the maximum power spectral density that could be permitted in a particular frequency band.

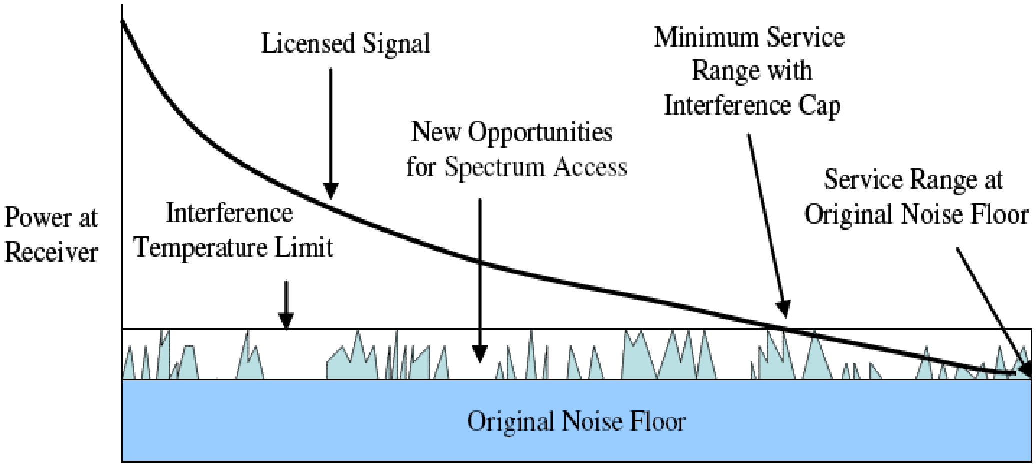


Figure 2.1 Interference Temperature Model [6]

2.3 Estimation of Interference Temperature

For the reliable estimate of Interference Temperature we must satisfy two important requirements,

- Using Multi-Taper-Method(MTM) [3] for estimating the power spectrum of IT due to the internal noise and external devices producing RF energy.
- Using large number of sensors wherever required to detect RF environment to compensate the spatial variations from one place to another.

Deploying multiple sensors at critical positions is required estimate the IT more accurately where the coverage area is large as in a building whereas only a single sensor would work at places with smaller coverage areas like in a cordless phone.

2.4 Multi Taper Spectrum Estimation

This method of spectrum estimation expands a part of the time series in a frequency band f - W to f + W where f is the centered frequency and W the bandwidth, into a special form of sequence known as *Slepian Sequence* whose property is that its Fourier Transforms have its maximal energy concentration in that bandwidth stated above for a finite number of samples. This helps in reducing the variance of the spectral estimate and keeping the estimates unbiased.

This technique for a given time series say $\{x_t\}_{t=1}^{N}$ determines,

- Orthonormal sequence of K Slepian tapers denoted by $\{w_t^{(k)}\}_{t=1}^{N}$.
- And the eigenspectra associated with this defined by the Fourier Transform of time series.

$$Y_k(f) = \sum_{t=1}^{N} w_t^{(k)} x(t) e^{-j2\pi f t} \quad \text{where } k = 0, 1 \ldots N-1 \tag{2.2}$$

The energy distribution is concentrated inside the bandwidth 2W known as the resolution bandwidth and its product with the total number of samples of time series N is the time bandwidth product which determines the degrees of freedom for controlling variance.

$$p = 2WN \tag{2.3}$$

The parameters K and p are responsible for the variance and spectral resolution tradeoff.

The estimate is unbiased if

$$K = 2WN - 1 \tag{2.4}$$

Now suppose that the total number of sensors used for estimating the power spectrum is M and let $Y_k^{(m)}(f)$ denotes the kth eigenspectrum associated with the sensor m then we define an M by K complex valued matrix

$$A(f) = \begin{bmatrix} w_1\, Y_1^{(1)}(f) & w_1 Y_2^{(1)}(f) & w_1 Y_3^{(1)}(f) & \cdots & w_1\, Y_K^{(1)}(f) \\ & \vdots & & \ddots & \vdots \\ w_M\, Y_1^{(1)}(f) & w_M Y_2^{(1)}(f) & w_M\, Y_3^{(1)}(f) & \cdots & w_M\, Y_K^{(1)}(f) \end{bmatrix} \qquad (2.5)$$

Here each column of the matrix is the result of the RF energy sensed at different points where the sensors are installed, while each row is computed using a different Slepian sequence tapers and the coefficients $\{w_m\}_{m=1}^{M}$ represents their corresponding weights [4]

Elements of this $A(f)$ matrix is generated from the internal additive sensor noise and the and the incoming RF stimuli. However we are concerned with the incoming RF stimuli so for denoising we perform its Singular Value Decomposition (SVD) [5]

$$A(f) = \sum_{k=0}^{K-1} \sigma_k\,(f)\, u_k\,(f) v_k^h\,(f) \qquad (2.6)$$

Where, $\sigma_k\,(f)$ is the kth singular value of $A(f)$ whereas $u_k\,(f)$ and $v_k^h\,(f)$ are the left and right singular vector and the subscript h shows that it is the Hermitian Transpose. The above decomposition gives the principle modulation of the RF stimuli and $\sigma_k\,(f)$ gives the amplitudes of kth principle modulation of matrix $A(f)$.

Calculating the K-by-K square matrix using $A(f)$ and its Hermitian we find the diagonal elements which represent the eigenspectrum due to each Slepian tapers. If the singular matrix is ordered in a way,

$$|\sigma_0(f)| \geq |\sigma_1(f)| \geq |\sigma_2(f)| \geq \cdots |\sigma_{k-1}(f)| \geq 0 \tag{2.7}$$

then the kth eigenvalue of the square matrix is $|\sigma_k(f)^2|$. The following statements could be made:

- The largest eigenvalue $|\sigma_0(f)^2|$ gives the information about interference temperature.
- The left and the right singular vectors give the information about spatial distribution of interferers and multitaper coefficients of interfering waveforms respectively.

2.5 Spectrum Sensing

In this we discuss about the techniques used in spectrum sensing. Three different signal processing techniques that are used in the systems are matched filter, energy detector and cyclostationary feature detection.

Consider a hypothesis test for signal detection:

$$H_0: \quad Y[n] = W[n] \qquad n = 0,1 \ldots . N-1$$

$$H_1: \quad Y[n] = X[n] + W[n] \qquad n = 0,1 \ldots . N-1 \tag{2.8}$$

Here it is assumed that $W[n]$ are the samples of additive white Gaussian noise with spectral density σ^2 i.e. $W[n] \sim N(0,\sigma^2)$ and $X[n]$ is the input sample sequence.

2.5.1 Matched Filter

It is a linear filter which maximizes the signal to noise ratio. The main advantage of this filter is that it requires less time to achieve high processing gain because of the coherency [7]. If $X[n]$ is completely known to the receiver then the optimal detector for this case is [18]:

$$T(Y) = \sum_{n=0}^{N-1} Y[n]X[n] \lessgtr_{H0}^{H1} \gamma \tag{2.9}$$

here γ is the detection threshold, then the number of samples required for optimal detection are

$$\begin{aligned} N &= [Q^{-1}(P_D) - Q^{-1}(P_{FD})]^2(snr)^{-1} \\ &= O(snr)^{-1} \end{aligned} \tag{2.10}$$

where P_D and P_{FD} are the probabilities of detection and false detection respectively.

Thus the number of samples required for optimal detection is O(1/SNR). However it requires a priori knowledge of primary signal such as modulation scheme, pulse shape, packet format. All this information can be saved in cognitive radio memory, however if this information is not accurate i.e. not coherent then the results could be poor. Performance could be improved by using pilot symbols, preambles, synchronization codes, equalization in the primary signal and thus could be used for coherent detection. For example CDMA systems use spreading codes for pilot and synchronization channels, OFDM systems use preambles. The main disadvantage with this technique is that it would require a dedicated receiver for every primary user.

2.5.2 Energy Detector

If the receiver does have prior knowledge of the primary signal then for the non-coherent method Energy Detector is the optimal way for spectrum sensing below [7]. In order to measure the energy of the received signal the output signal of bandpass filter with bandwidth W is squared and integrated over the observation interval T. Finally the output of the integrator is compared with a threshold to detect weather the primary or licensed user is present or not. It can also be computed in frequency domain by averaging bins of a Fast Fourier Transform. In this the processing gain is proportional to FFT size N and the averaging time T. Increase in the size of FFT improves the frequency resolution which is helpful in detecting narrowband signals. Also if we reduce the averaging time it improves the SNR by reducing the noise power.

$$T(Y) = \sum_{n=0}^{N-1} Y^2[n] \lesseqgtr_{H0}^{H1} \gamma \tag{2.11}$$

$$N = 2[(Q^{-1}(P_{FA}) - Q^{-1}(P_D))(snr)^{-1} - Q^{-1}(P_D)]^2 \tag{2.12}$$

$$= O(snr)^{-2} \tag{2.13}$$

The number of samples required to optimally detect the incoming signal is O(1/SNR^2) [7]

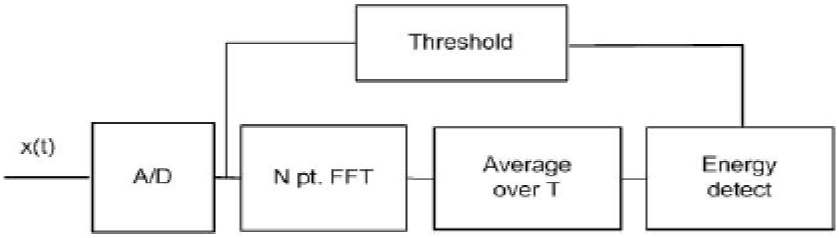


Figure 2.2 Energy detector using Welch Periodogram method

The problems in using energy detector is the threshold that is used for detecting primary signal is prone to unknown changes in noise levels. If the noise level is changed adaptively still the presence of in-band interference can cause poor detection of signal energy. If the channel is not flat it is not possible to set the threshold with respect to the notches caused by its frequency selectivity. Since the energy detector is only concerned with the energy of the incoming signal it does not differentiate between noise and interference. In context to cognitive radios interference and noise should be treated differently because of the presence of unlicensed and licensed users. Due to these problems energy detector becomes prone to false detection.

The hypothesis model for transmitter detection can be defined as:

$$x(t) = \begin{cases} n(t) & H_0 \\ h * s(t) + n(t) & H_1 \end{cases} \tag{2.14}$$

Here $x(t)$ is the signal received by the unlicensed user, $s(t)$ is the signal transmitted by the licensed transmitter, $n(t)$ is the noise introduced by AWGN and h is the channel gain. H_0 is the null hypothesis when there is no primary signal and H_1 indicates the presence of primary signal [8]The probability of detection P_d and false alarm P_f are given as follows [9]

$$P_d = P\{Y > \lambda | H_1\} = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{2.15}$$

$$P_f = P\{Y > \lambda | H_0\} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{2.16}$$

In these equation γ is SNR, λ is threshold. A low detection of probability will result in absence of primary signal and a high P_f would result in inefficient spectrum utilization.

Besides other limitations energy detector cannot be used for spread spectrum signals [10] and hence more sophisticated algorithms should be employed for signal detection.

2.5.3 Cyclostationary Feature Detection

An alternative method for the detection of primary signals is Cyclostationary Feature Detection in which modulated signals are coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. This results in built-in periodicity. These modulated signals are characterized as cyclostationary because their mean and autocorrelation exhibit periodicity. This periodicity is introduced in the signal format at the receiver so as to exploit it for parameter estimation such as carrier phase, timing or direction of arrival. These features are detected by analyzing a spectral correlation function. The main advantage of this function is that it differentiates the noise from the modulated signal energy. This is due to the fact that noise is a wide-sense stationary signal with no correlation however modulated signals are cyclostationary due to embedded redundancy of signal periodicity [11]. Analogous to autocorrelation function spectral correlation function (SCF) can be defined as:

$$S_x^{\alpha}(f) = \lim_{T\to\infty} \lim_{\Delta t\to\infty} \frac{1}{\Delta t}\int_{-\Delta t/2}^{\Delta t/2} \frac{1}{T} X_T(t, f + \alpha/2) X_T^*(t, f - \alpha/2)\, dt \qquad (2.17)$$

where the finite time Fourier transform is given by:

$$X_T(t, v) = \int_{t-T/2}^{t+T/2} x(u)\, e^{-j2\pi vu}\, du \qquad (2.18)$$

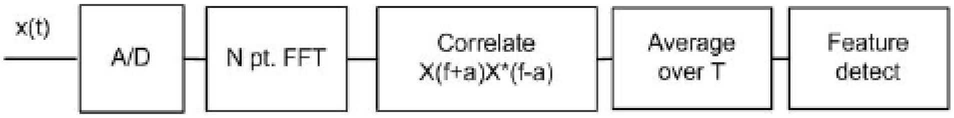


Figure 2.3 Implementation of Cyclostationary Feature Detector

Spectral correlation function is also known as cyclic spectrum. While power spectral density (PSD) is a real valued one dimensional transform, SCF is a complex valued two dimensional transform. The parameter α is called the cycle frequency. If α = 0 then SCF gives the PSD of the signal.

Because of the inherent spectral redundancy signal selectivity becomes possible. Analysis of signal in this domain retains its phase and frequency information related to timing parameters of modulated signals [11]. Due to this, overlapping features in power spectral density are non overlapping features in cyclic spectrum.Hence different types of modulated signals that have identical power spectral density can have different cyclic spectrum.

Because of all these properties cyclostationary feature detector can perform better than energy detector in discriminating against noise. However it is computationally complex and requires significantly large observation time. For more efficient detection, the enhanced feature detection scheme combined with cyclic spectrum analysis and pattern recognition based on neural networks is proposed in [12].

2.6 Cooperative Spectrum Sensing

Cooperative spectrum sensing exploits the broadcast nature and spatial diversity of the channel. Through cooperative sensing sets of wireless terminals benefit by relaying messages to each other to propogate redundant signals over multiple paths in the network.

This allows the receivers to estimate channel variations resulting from fading, noise, interference etc. Cooperative schemes with orthogonal transmission in a TDMA system has been studied in [15] and [16]. In [15] various cooperative protocols are demonstrated. A fixed relay protocol is also discussed in which the relay either amplifies or encodes-decodes and retransmits the signal. These are Amplify-and Forward and Decode-and-Forward respectively.

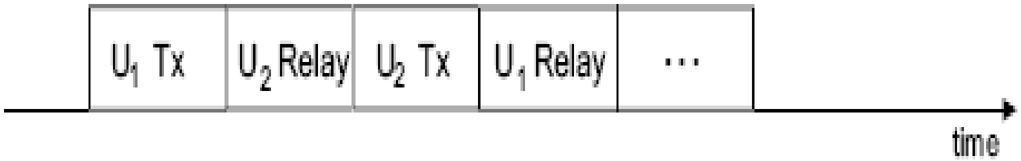


Figure 2.4 Cooperation in cognitive network

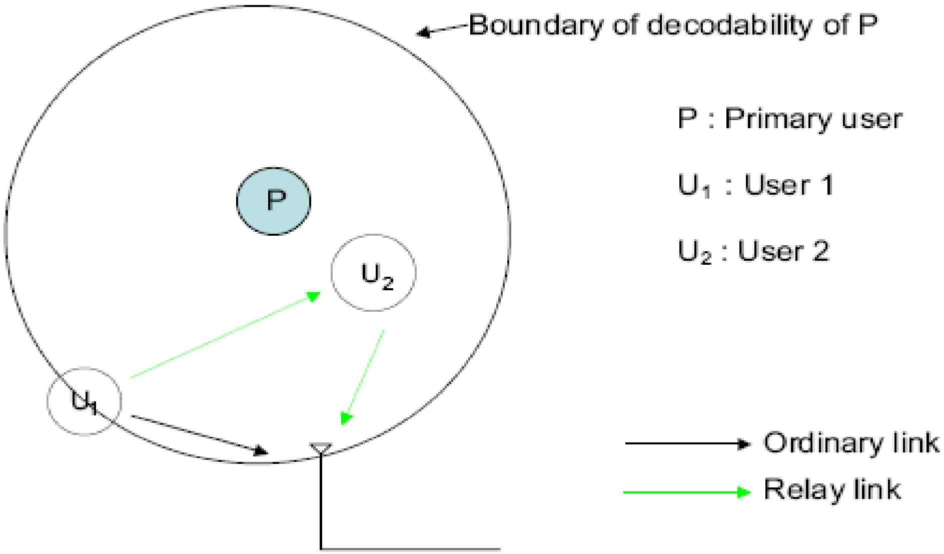


Figure 2.5 Relay Protocol

In cognitive network the presence of licensed user should be detected by the secondary user as quickly as possible so as to avoid interference to licensed user. For this reason continuous spectrum sensing is required. In [17] a two user cooperative sensing scenario is discussed. In a network with two cognitive radio users U_1 and U_2 operating in a fixed TDMA mode are sending data to a base station. Meanwhile if a primary user starts using the band then they have to vacate it as soon as possible.Now if say U_1 is in the boundary of decodablity as shown in Figure 2.5, then the signal received by the cognitive user U_1 is very weak and hence it takes more time to sense the primary.However if cooperation sensing scheme is applied the time taken to detect the weak signal is reduced. In Figure 2.4 user U_1 and U_2 transmits in successive slots as per amplify-and-forward protocol. In time slot T_1 U_1 transmits and U_2 listens and in time slot T_2 U_2 relays the information of the previous slot.

2.7 Hidden Node Problem

Before transmitting any signal, cognitive radio should estimate the power spectral density of the radio spectrum so as to check which bands are in use and which bands are not utilized. For the above requirement the cognitive radio should use a highly sensitive receiver which can measure the signals at the cell boundraies. In [17] a scenario is discussed in which digital TV station is present at the edge of a cell site. The signals coming from the TV station will be just suffecient to be sensed by the cell site. Now for the cognitive radio to detect this weak incoming signal, its receiver should be highly sensitive. If this is not the case then the cognitive radio will not be able to detect the signal and would start transmitting its own signal, causing interference to the TV receiver to decode the signals. This situation is an example of Hidden Node.

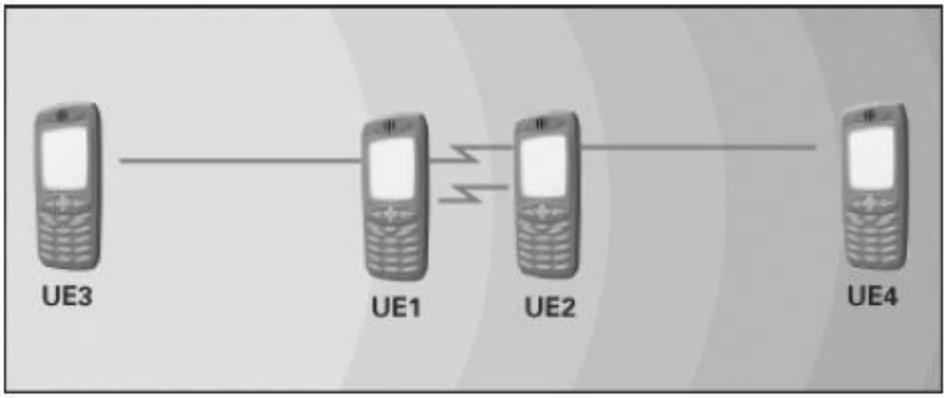


Figure 2.6 Hidden Node Problem

Another example of Hidden Node is shown in figure 2.6. In this example we can see that when UE1 and UE2 are communicating with each other, UE3 and UE4 would not know about the transmissions even though if it lies at the signalling distance. So thinking that the spectrum is unused UE3 and UE4 will start communicating causing interference to UE1 and UE2.

Chapter 3 Methodology

This chapter includes the methodology involved for the simulation of results.

3.1 Ideal Energy Detection

Before working on the detection method few definations are discussed required for ideal energy detection. The frequency channel is divided into three different states [19]:

3.1.1 Idle Channel:

When the secondary transmitter and receiver do not sense any signal then the channel is said to be idle and the secondary transmitters can transmit their signals. Let the probability of channel being idle be p_{id} .

3.1.2 Busy Channel:

When the secondary receivers senses the beacon signal coming from primary transmitter or the secondary transmitter senses the signal from primary receiver then it should not use the channel for its communication and the channel is said to be in a busy state. Let the probability that channel is busy be p_{bs} .

3.1.3 Fake Busy:

In this case either the secondary transmitter senses the signal from primary transmitter or the secondary receiver senses the signal from primary receiver. This state is termed as fake busy and either of the user can transmit their signals since there is no way to detect interference within the channel and its probability is p_{fbs}.

Also,

$$p_{id} + p_{bs} + p_{fbs} = 1 \tag{3.1}$$

The sensing probabilities are defined as,

P{no signal sensed | no signal existing} = P_{00}

P{signal sensed | signal existing} = P_{11}

P{no signal sensed | signal existing} = P_{01}

P{signal sensed | no signal existing} = P_{10}

Now the probability of correct descision P_{cd} is that the secondary user senses correctly the state of the channel.

P_{cd} = P{transmission blocked | channel busy}P{channel busy} +

P{transmission processed | channel fake/busy}P{channel fake/busy} (3.2)

For ideal energy detection both primary transmitter and receivers can transmit beacon signals to indicate that are communicating. For energy detection both secondary transmitter and secondary receiver must sense the environment and based on this a descision should be made weather the secondary transmission should occur or not.

Suppose S be a 2×2 matrix of the detection results

$$S = \begin{pmatrix} s_{r1} & s_{r2} \\ s_{t1} & s_{t2} \end{pmatrix} \tag{3.3}$$

where s_{r1} and s_{r2} are the detection results of secondary receiver that it senses from primary transmitter and primary receiver, correspondingly s_{t1} and s_{t2} are the detection results at secondary transmitter . The values of these detection results can be either 0 or 1 depending upon weather there is signal present or not. Based on this there could be 16 possible states as follows:

Channel State	**S**
Idle	$\begin{pmatrix}0 & 0\\0 & 0\end{pmatrix}$
Fake Busy	$\begin{pmatrix}0 & 0\\0 & 1\end{pmatrix}, \begin{pmatrix}1 & 0\\0 & 0\end{pmatrix}, \begin{pmatrix}1 & 0\\0 & 1\end{pmatrix}$
Busy	$\begin{pmatrix}0 & 0\\1 & 0\end{pmatrix}, \begin{pmatrix}0 & 0\\1 & 1\end{pmatrix}, \begin{pmatrix}0 & 1\\0 & 0\end{pmatrix}$ $\begin{pmatrix}0 & 1\\0 & 1\end{pmatrix}, \begin{pmatrix}0 & 1\\1 & 0\end{pmatrix}, \begin{pmatrix}0 & 1\\1 & 1\end{pmatrix}$ $\begin{pmatrix}1 & 0\\1 & 0\end{pmatrix}, \begin{pmatrix}1 & 0\\1 & 1\end{pmatrix}, \begin{pmatrix}1 & 1\\0 & 0\end{pmatrix}$ $\begin{pmatrix}1 & 1\\0 & 1\end{pmatrix}, \begin{pmatrix}1 & 1\\1 & 0\end{pmatrix}, \begin{pmatrix}1 & 1\\1 & 1\end{pmatrix}$

Table 3.1 State table for Ideal Energy Detection scheme

Based on 3.2 we can define the probability of correct detection for the generic case as follows:

$$P_{\text{cd}} = \begin{array}{l}(p_{id} + p_{fbs})p_{00}(\gamma_{r2})p_{00}(\gamma_{t1}) + \frac{1}{9} p_{fbs}[p_{01}(\gamma_{t1}) + p_{00}(\gamma_{r2}) + p_{10}(\gamma_{r2})p_{11}(\gamma_{t1}) + \\ p_{11}(\gamma_{r2})p_{10}(\gamma_{t1}) + 3p_{11}(\gamma_{r2})p_{00}(\gamma_{t1}) + 3p_{11}(\gamma_{r2})p_{11}(\gamma_{t1}) + 3p_{00}(\gamma_{r2})p_{11}(\gamma_{t1})]\end{array} \quad (3.4)$$

However the detection probability for correct detection for identical environment, where $p_{fbs} = 0$ and the signal sensed by secondary transmitter or secondary receiver is same i.e. $p(\gamma_{r2}) = p(\gamma_2)$ and $p(\gamma_{t1}) = p(\gamma_1)$. Hence detection probability is as follows:

$$P_{cd} = p_{00}(\gamma_1)p_{00}(\gamma_2) + \frac{1}{3}p_{bs}[p_{01}(\gamma_1) + p_{11}(\gamma_1) + p_{01}(\gamma_2) + p_{00}(\gamma_1)p_{11}(\gamma_2) + p_{10}(\gamma_1)p_{11}(\gamma_2) + p_{11}(\gamma_1)p_{00}(\gamma_2)] \tag{3.5}$$

3.2 Amplify-and-Forward Algorithm for cooperation scheme

3.2.1 Cooperation scheme

In this scheme as shown in Figure 2.4above, two users U_1 and U_2 transmits data to some common receiver. A slotted transmission is assumed in which U_1 and U_2 transmits successively. In time slot T_1, U_1 transmits its data and in time slot U_2 relays the information passed by U_2. Meanwhile if the primary user starts transmitting its data, then both U_1 and U_2 should vacate the frequency band as soon as possible. Now at time T_1 signal received by U_2 is

$$y_2 = \theta h_{p2} + a h_{12} + w_1 \tag{3.6}$$

h_{pi} = channel gain between primary user and user U_i

h_{ij} = channel gain between user U_i and U_j

θ = indicates the presence of primary user, either 0 or 1

In cooperation scheme, user U_1 also listens during time T_2 . So, the signal received by U_1 from U_2 during relay slot is given by

$$y_1 = \sqrt{\beta}\, h_{12}(y_2) + \theta h_{p2} + w_2 \tag{3.7}$$

$\beta = \frac{1}{E\{|h_{12}|^2\}}$ used as a scaling factor chosen by U_2 for power constraint.

In the above equations the channel is assumed to be reciprocal i.e. $h_{ij} = h_{ji}$

We can write the above equations in a generic form as

$$Y = \theta H + W \tag{3.8}$$

$H = h_{p1} + \sqrt{\beta} h_{p2} h_{12}$ and $W = w_1 + \sqrt{\beta}\, h_{12} w_2$. So, the signal is said to be detected if $\theta = 1$.

In this both H and W are Rayleigh distributed random variables with zero mean and variances,

$$\sigma_H^2 = P_1 + P_2 h \tag{3.9}$$

$$\sigma_W^2 = 1 + h \tag{3.10}$$

$$h = \frac{|h_{12}|^2}{E\{|h_{12}|^2\}}$$

Since h_{12} is complex Gaussian so h is exponentially distributed with unit mean and variance.

For energy detecter we can write

$$T(Y) = Y^2 \tag{3.11}$$

We compare this statistics with some threshold which is calculated using some predefined false alarm probability α. Let for any positive t,a,b

$$\varphi(t; a, b) = \int_0^\infty e^{-h - \frac{t}{a+bh}}\, dh \tag{3.12}$$

Let the cumulative density function $F_i(t)$ for the random variable T when no primary signal is present is given by

$$F_0(t) = P(T(Y) > t \mid H_0)$$

$$= \int_0^\infty P(T(Y) > t \mid H_0, h)\, f(h) dh$$

$$= \int_0^\infty e^{-h-\frac{t}{1+h}}\, dh \; = \varphi(t; 1,1)$$

Similarly,

$$F_1(t) = P(t, P_1 + 1, P_2 + \;1)$$

Thus for a given probability of false alarm α we need to find the threshold λ such that,

$$\varphi(\lambda; 1,1) = \;\alpha \tag{3.13}$$

And similarly the probability of detection for by U_1 with cooperation from U_2 is given by,

$$p_c^{(1)} = \; P(\lambda, P_1 + 1, P_2 + \;1) \tag{3.14}$$

There is an increase in average SNR in cooperation scheme when compared to non cooperation scheme if $P_2 > P_1$, the instantaneous SNR is given by

$$E\{\gamma_c \mid h\} = \frac{P_1 + P_2 h}{1+h} \tag{3.15}$$

and average SNR is given by,

$$\overline{\gamma_c} = \int_0^\infty E\{\gamma_c \mid h\} f(h)\; dh \tag{3.16}$$

For the non cooperative case the average SNR is given by

$$\bar{\gamma}_{nc} = P_1 \tag{3.17}$$

So the average SNR gain is given by

$$\bar{\gamma} = \frac{\overline{\gamma_c}}{\overline{\gamma_{nc}}} = \frac{P_2}{P_1}(1-F) + F \tag{3.18}$$

Where, F = $\int_0^{\infty}(1+h)^{-1}e^{-h}\,dh < 1$

F-1 is the actual SNR gain and is positive.

3.2.2 Agility gain in two user cognitive network

The reduction in average detection time by the cognitive user to detect the primary signal defines the increase in agility of the cognitive user.

Suppose the number of slots used by user U_1 to detect the primary user be k and the time taken be τ_n,then,

$$P_r\{\tau_n = k\} = \left(1 - p_n^{(1)}\right)^{k-1} p_n^{(1)} \tag{3.19}$$

where $p_n^{(i)}$ is the probability of detection by the user U_i in a single slot in non cooperation scheme. We can show that,

$$p_n^{(1)} = \alpha^{\frac{1}{P_1+1}} \quad \text{and} \quad p_n^{(2)} = \alpha^{\frac{1}{P_2+1}}$$

So, the total time taken by the cognitive users to vacate the band in cooperative and non cooperative scheme is given by

$$T_n = 2\left(\frac{1}{p_n^{(1)}} + \frac{1}{p_n^{(2)}} - \frac{1}{p_n^{(1)} + p_n^{(2)} - p_n^{(1)} p_n^{(2)}}\right) \quad \text{for non cooperation scheme.} \tag{3.20}$$

$$T_c = \frac{2 - \frac{p_c^{(1)} + p_n^{(2)}}{2}}{p_c^{(1)} + p_n^{(2)} - p_c^{(1)} p_n^{(2)}} \quad \text{for cooperation scheme.} \tag{3.21}$$

So, the agility gain for a two user scenario, in cooperation scheme over non cooperation scheme is given by,

$$\mu_{n/c}(2) = \frac{T_n}{T_c} \tag{3.22}$$

3.3 Power scaling for cognitive radios

In this we discuss the power constraints that could be imposed to cognitive users so as to avoid interference to the licensed users in the same operating frequency. This could be applied by using the received SNR and as a function of distance to the primary receivers. The cognitive users can then alters its transmitting power accordingly so as to avoid interference.We can examine the average interference caused by all the cognitive users and set a noise floor accordingly, now if the SNR is less than the noise floor the cognitive radio can transmit their signal [20].

Assuming a band has already been assigned to a high powered single transmitter system and all transmissions omnidirectional. In this scenario, within a protected region all primary users should receive signals without interference even in the presence of cognitive users.

All these primary systems have a minimum SINR (signal to interference noise ratio) to successfully decode the signal at a given rate R.

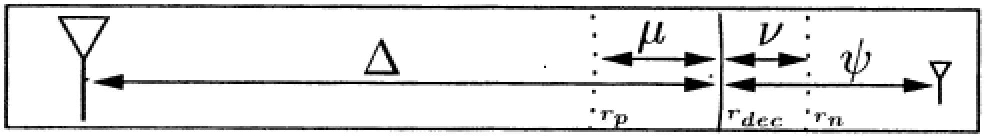


Figure 3.1 SNR margins

If there is no interference from the cognitive users the minimum SINR at some decodable radius

r_{dec} from the transmitter is γ_{dec}. To guarantee interference free zone there is an additional radius (r_p) is provided called protected radius. There is a no-talk radius (r_n) defined where unlicensed users should not transmit their signals and at distances greator than this radius from the primary transmitter, cognitive users can freely tarnsmit their signals. SNR at protected and decodable region (γ_p, γ_{dec}) is measured by primary receiver, while at no talk region SNR (γ_n) is measured by secondary transmitters.

Suppose the power at primary transmitter is P_2 and noise power at primary receiver is σ^2, then,

$$\Delta = 10log\left(\frac{P_2}{\sigma^2}\right) - \gamma_{dec} \tag{3.23}$$

$$\mu = \gamma_p - \gamma_{dec} \tag{3.24}$$

$$\vartheta = \gamma_{dec} - \gamma_n \tag{3.25}$$

The propagation related gain betwwen two users at a distance r apart is given by a function $g(r)$, continuous in the interval [0,∞] [20]. We define,

$$g_{11}(r) = g_{12}(r) = r^{-\alpha_1} \tag{3.26}$$

$$g_{21}(r) = r^{-\alpha_2} \tag{3.27}$$

$g_{11}(r)$ is the path loss gain function between primary transmitter and receiver.

$g_{12}(r)$ is the path loss gain function between primary transmitter and secondary receiver.

$g_{21}(r)$ path loss gain function between primary receiver and secondary transmitter.

3.3.1 Out of system interference.

As the primary user comes closer to the boundaries where secondary user is allowed to transmit freely, it faces maximum amount of interference from the cognitive users.So to maintain a minimum level of SINR at the boundaries so as to decode the signal at primary receiver, maximum allowable power from the secondary devices is examined.

Suppose q_1 and q_2 denote the primary and combined secondary transmitted power as sensed by primary receiver.Then,

$$q_1 = Pg_{11}(r_p) \tag{3.28}$$

Reception at primary receiver is guaranteed if ,

$$\frac{q_1}{q_2 + \sigma^2} \geq 10^{\frac{\gamma_{dec}}{10}} \tag{3.29}$$

Therefore,

$$q_2 \leq q_1 10^{\frac{-\gamma_{dec}}{10}} - \sigma^2 \tag{3.30}$$

and primary transmitter power at primary receiver at boundary of decodability in terms of SNR is given as,

$$log\left(\frac{q_1}{\sigma^2}\right) = \gamma_{dec} + \mu$$

Therefore,

$$q_1 = \sigma^2 10^{\frac{\gamma_{dec} + \mu}{10}} \tag{3.31}$$

From (3.30) and (3.31) the power constraint on secondary transmitter is given by,

$$q_2 \leq \sigma^2 (10^{\frac{\mu}{10}} - 1) \tag{3.32}$$

3.3.2 Single secondary transmitter

Suppose there is only one secondary transmitter at the edge of the no talk zone and the primary receiver at the boundary of protected zone.Then,

$$p_2 g_{21}(r_n - r_p) \leq \sigma^2 (10^{\frac{\mu}{10}} - 1)$$

or, $$p_2 \leq \sigma^2 (10^{\frac{\mu}{10}} - 1)\left(g_{21}(r_n - r_p)\right)^{-1} \tag{3.33}$$

Now suppose if the secondary transmitter is allowed to vary its power depending upon its distance to the protected region. If the distance of secondary transmitter is changed from no talk region to the actual distance from primary transmitter r. We calculate this distance as the worst case scenario in terms SNR.

The protected radius in terms of SNR can be calculated as follows,

$$10log\left(\frac{p_1}{\sigma^2}\right) - 10log\left(\frac{p_1 g_{11}(r_p)}{\sigma^2}\right) = \Delta - \mu$$

Thus,

$$r_p = g_{11}^{-1}\left(10^{\frac{-\Delta+\mu}{10}}\right) \tag{3.34}$$

Similarly,

$$r_2 = g_{12}^{-1}\left(10^{\frac{-\Delta-\psi}{10}}\right) \tag{3.35}$$

Using equation (3.26), (3.27), (3.34) and (3.35) we can write equation (3.33) in terms of SNR.

$$\begin{aligned} 10log\left(\frac{P_2}{\sigma^2}\right) \le\ & \alpha_1\alpha_2\Delta + 10\log\left(10^{\frac{\mu}{10}} - 1\right) \\ & + 10\alpha_2\, log\left(\left(10^{\frac{\psi}{10}}\right)^{\alpha_1} - \left(\left(10^{\frac{-\mu}{10}}\right)^{\alpha_1}\right)\right) \end{aligned} \tag{3.36}$$

The first term shows the distance in terms of power, about the primary user can move from the primary transmitter and still decode the signal.The second term gives the tolerance of primary receivers towards secondary interference within the protected zone. The third term describes the distance of primary receivers from secondary transmitters.

3.4 Summary

In this chapter we discussed various methods that could be applied to sense and detect primary signals by cognitive users. Energy detection in ideal and generic environment are discussed for the correct probability of detection are formulated. An algorithm for cooperation and non cooperation between various cognitive users is also discussed which shows that the agility of cognitive users could be increased using this scheme.At last power scaling method is discussed in which SNR is used as a proxy for distance is used to constraint the transmit power for cognitive users is calculated. This guarantees a minimum decodability of signal by primary users in a given radius inspite of the number of unlicensed users. The simulation results based on these calculations is shown in next chapter.

Chapter 4 Results and Discussions

4.1 Introduction

In this chapter simulation results and discussions of the techniques discussed in the previous chapter has been conducted with different parameters.

4.2 Agility Improvement

The detection probability in cooperative scheme and non cooperative scheme with respect to false alarm probability is given by,

$$p = p_c^{(1)} + p_n^{(2)} - p_c^{(1)} p_n^{(2)}$$

While in non cooperation scheme it is

$$p' = p_c^{(1)} + p_n^{(2)} - p_c^{(1)} p_n^{(2)}$$

These probabilities depend on P_1 and P_2 and in the previous discussion. In this case U_2 acts as a relay for U_1 while its opposite is not. So $p > p'$ is obvious and is shown in the performance curve plot of energy detector. In the simulation we have kept $P_1 = 1$ and $P_2 = 2.7$, where P_1 and P_2 are average power in non cooperation and cooperation mode respectively. Both P_1 and P_2 are in decibel. We can see in Figure 4.1 that there is a considerable increase in detection probability if the cognitive users operate cooperatively.

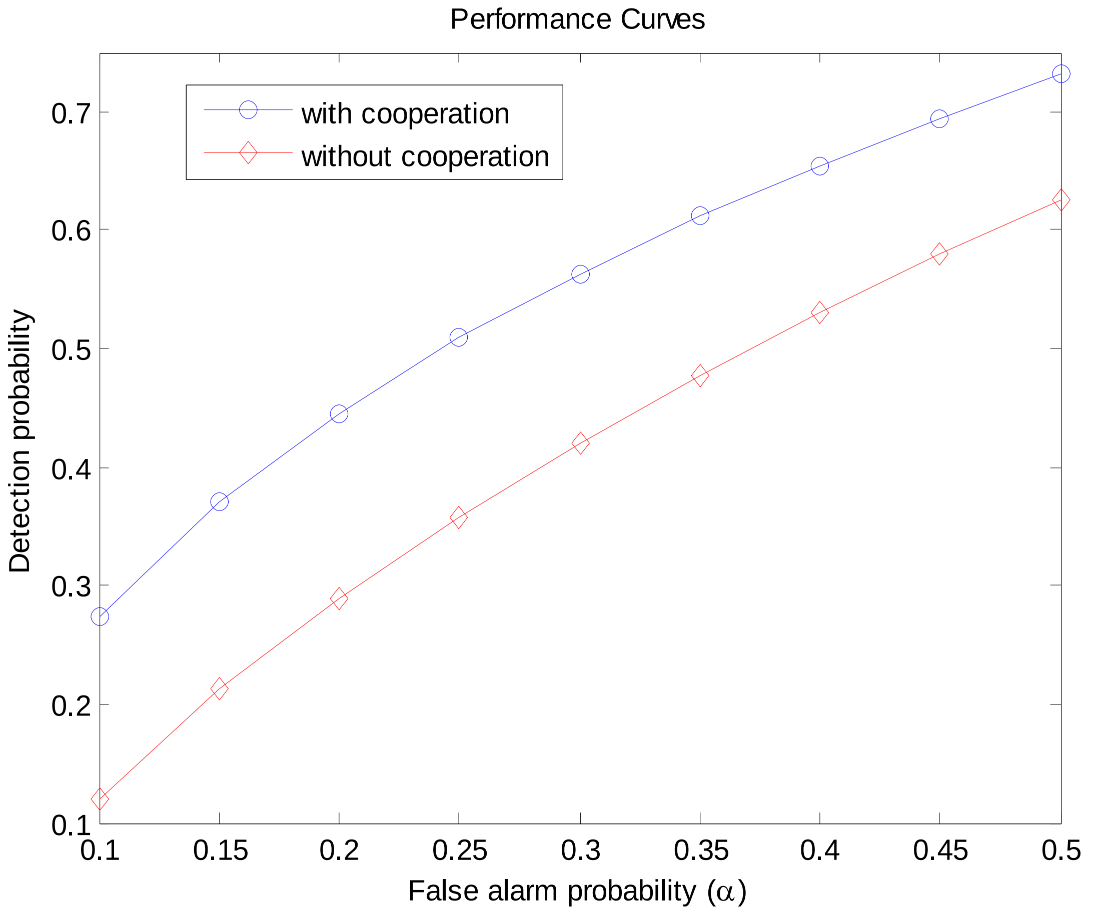


Figure 4.1 False alarm probability vs Detection probability

If there are 2n cognitive users then the total bandwidth is equally divided in n sub bands among those users. So if two users are working on a single band in cooperation scheme then the average noise and variance in that sub band will also reduce by a factor n along with the threshold for a given probability of false alarm. So even in the multiuser case the detection probability will remain the same.

In Figure 4.2 we plotted a curve for agility gain which is given by the ratio of time taken to detect the primary user in non cooperative to cooperative scheme for different values of false alarm probabilities in a multi user multi carrier scenario.

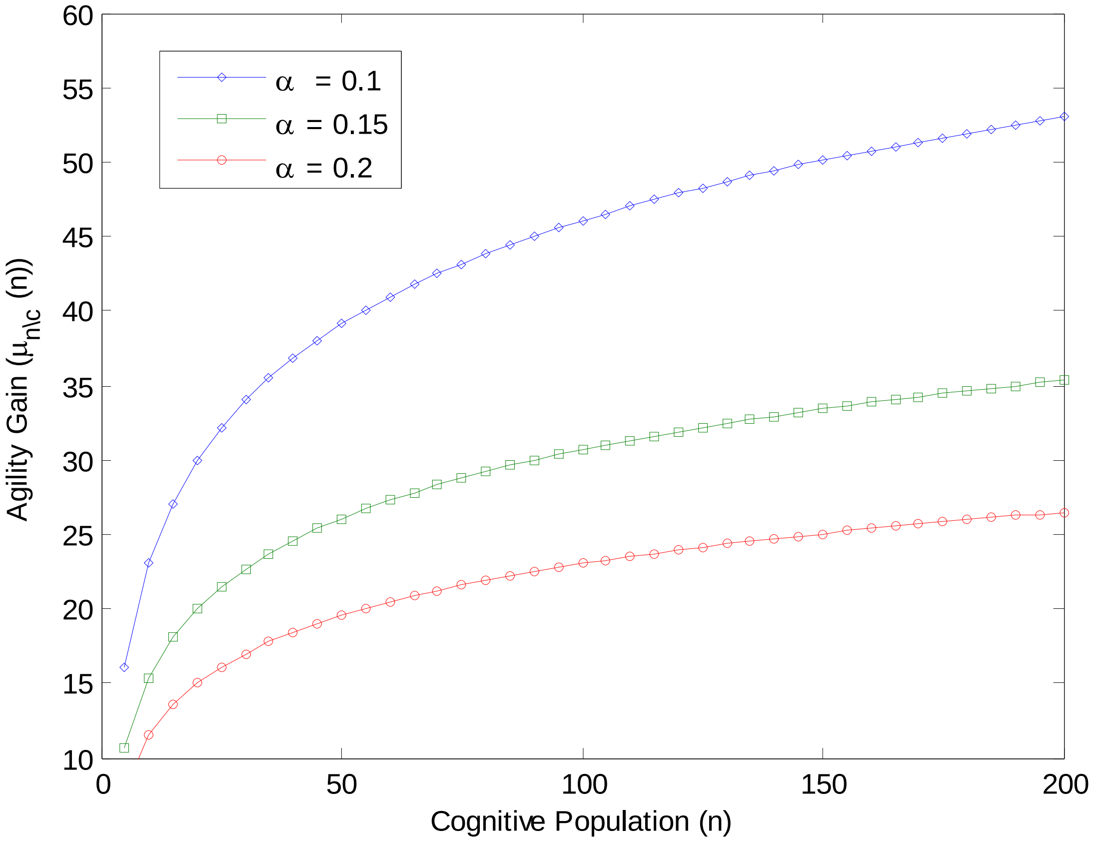


Figure 4.2 Cognitive Population vs Agility Gain

The above figure shows that the agility gain increases logarithmically with increasing number of cooperative cognitive users, however this gain doesn't has much improvement if the number of users are increased infinitely which depends on P_1 and P_2.

4.3 Probability of correct detection

Figure 4.3 and Figure 4.4 below shows the detection probabilities P_{cd} for ideal energy detection method for generic environment and ideal environment for secondary transmitter/receiver scenario for different values of p_{bs} .

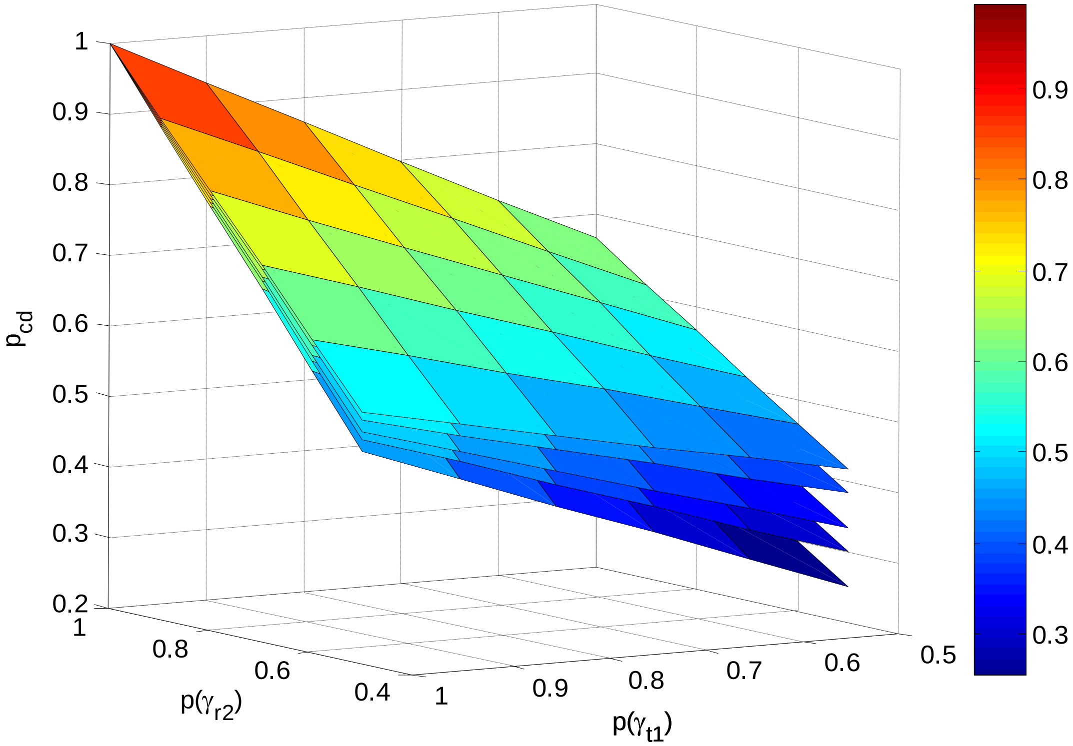


Figure 4.3 Detection probability Pcd for ideal energy detection method for generic transmitter/receiver case

P_{bs}	Maximum P_{cd}	Minimum P_{cd}
0	1	0.25
0.3	1	0.3
0.5	1	0.3333
0.8	1	0.3833
1	1	0.4167

Table 4.1 Minimum and maximum value of correct probability of detection for generic environment

Table 4.1 shows the minimum and maximum value of correct probability of detection.

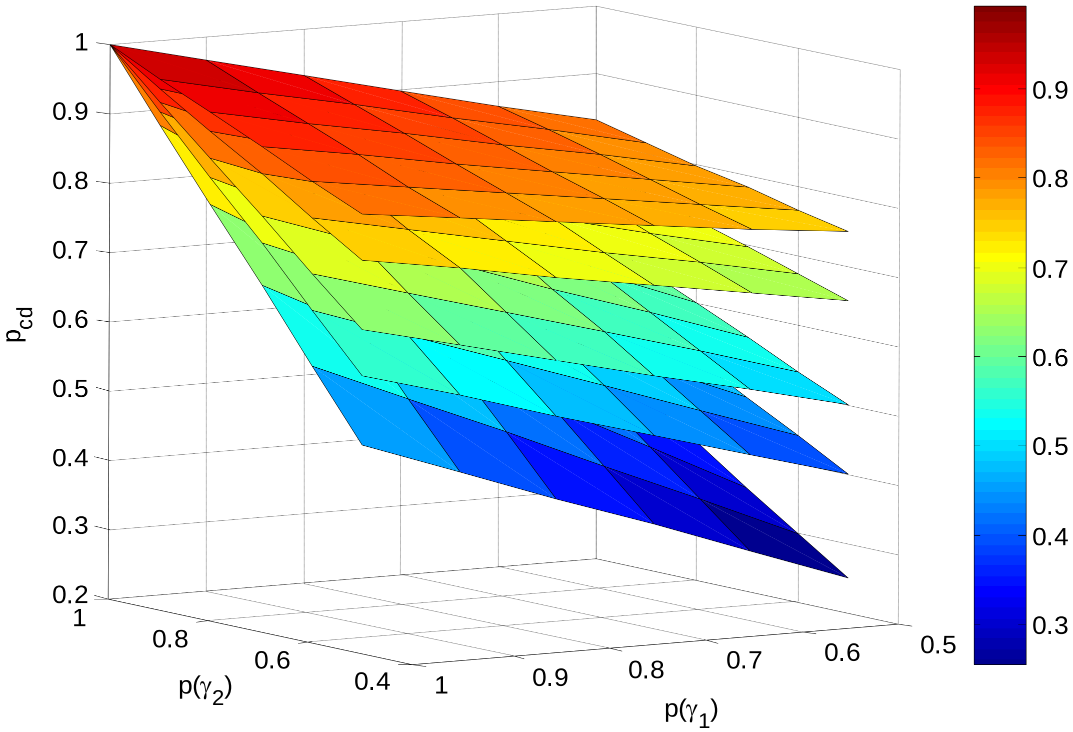


Figure 4.4 Detection probability Pcd for ideal energy detection method for identical environment transmitter/receiver case

Figure 4.4 and Table 4.2 below shows the detection probabilities P_{cd} for ideal energy detection method for identical environment for secondary transmitter/receiver scenario.

P_{bs}	Maximum P_{cd}	Minimum P_{cd}
0	1	0.25
0.3	1	0.4
0.5	1	0.5
0.8	1	0.65
1	1	0.75

Table 4.2 Minimum and maximum value of correct probability of detection for identical environment

Discussion:

If we fix the traffic coming from primary users with increasing detection capability for secondary users shows that there is higher chance to make correct decision and hence less interference to primary devices. And for the identical environment case where there is no chance for channel being fake busy is the results are much better than the generic environment case.

4.4 Power scaling

The figure below shows that the interference from secondary transmitters increases at the boundary of protected region. We can see the interference becomes infinite at border.

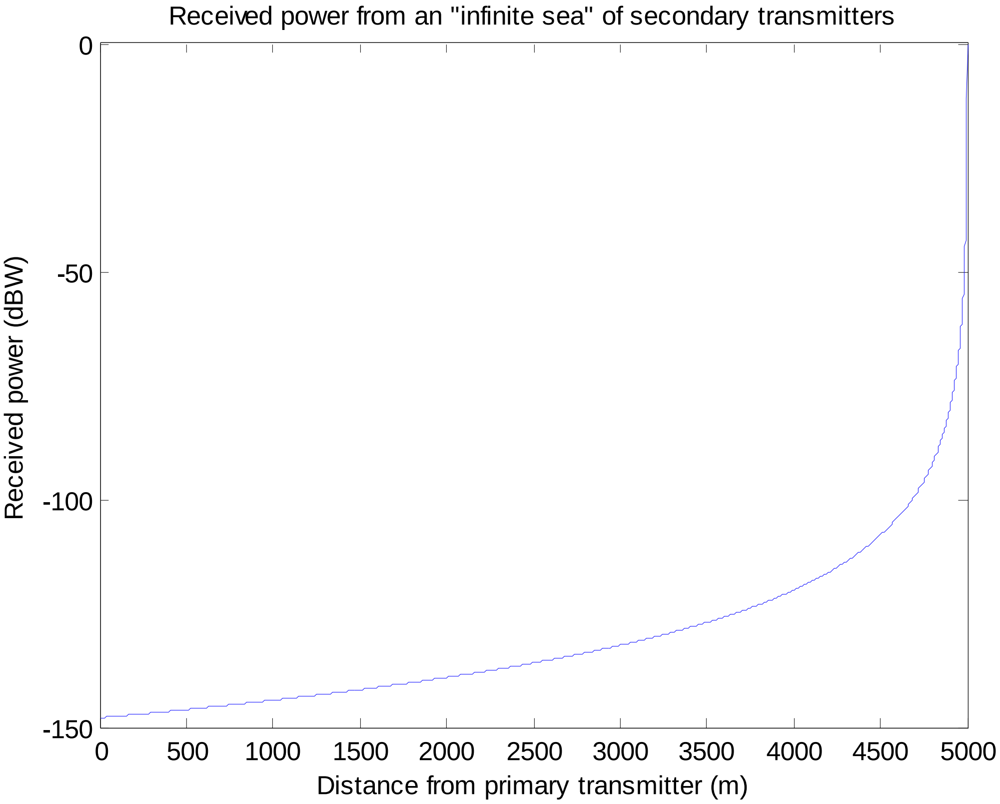


Figure 4.5 Plot of received power (dBW) vs distance from primary transmitter (m)

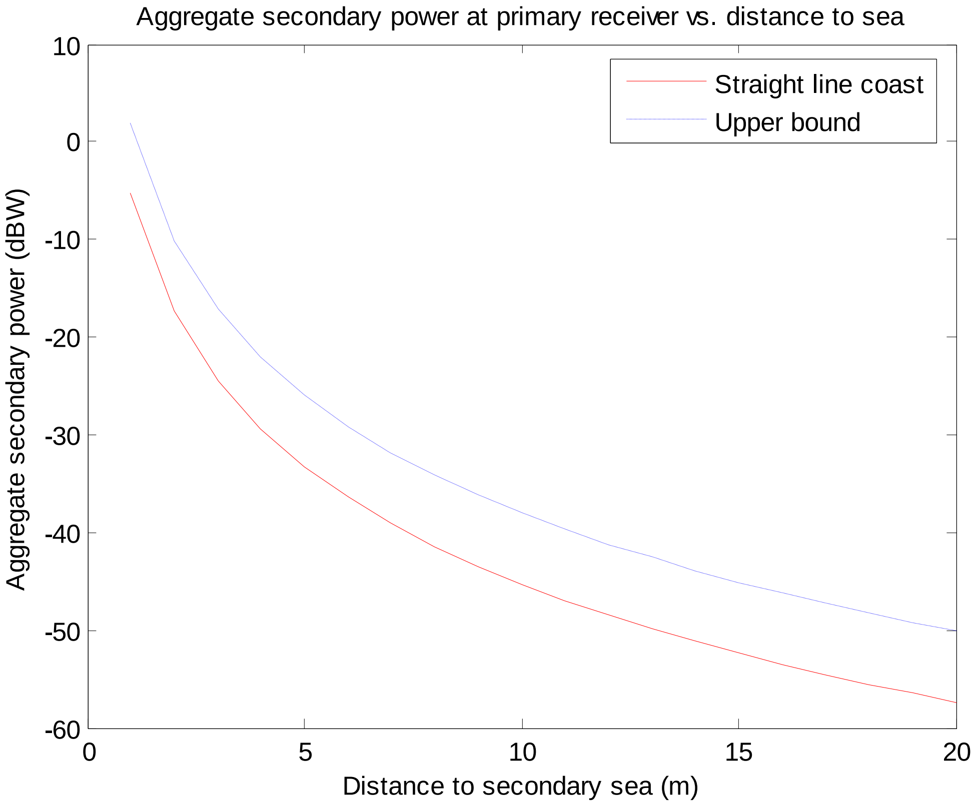


Figure 4.6 Plot of Aggregate secondary power at primary receiver vs distance from protected zone

Figure 4.6 shows the path loss decay exponents upper and lower bounds with increase in distance from the coast i.e. the boundary of secondary transmitters.

The other figures from 4.7 to 4.10 show the maximum power that can be transmitted by the secondary transmitters. These figures show the effect of margin Δ between primary transmitter and decodable radius. We can see from these figures that when this margin is less, secondary users have to be more sensitive then primary users. However if Δ is increased then the maximum allowable transmit power increases heavily. So as long as the secondary transmitter is outside the decodable radius there is no problem of sensitivity.

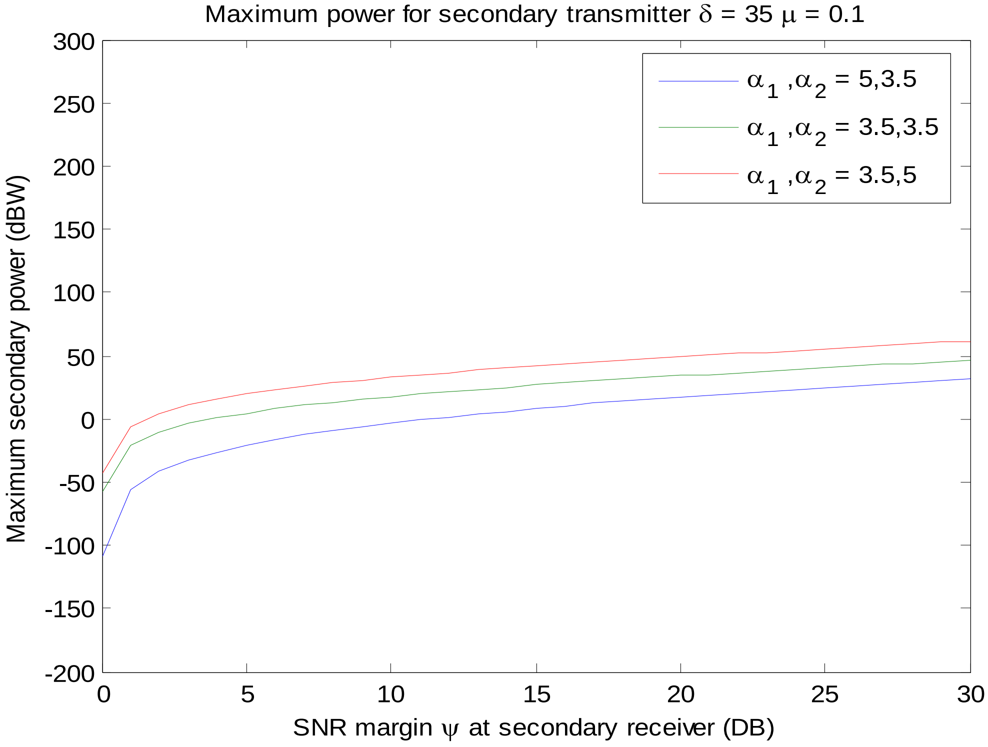


Figure 4.7 Maximum secondary power vs SNR margin ψ at secondary receiver for Δ = 35, μ =0.1

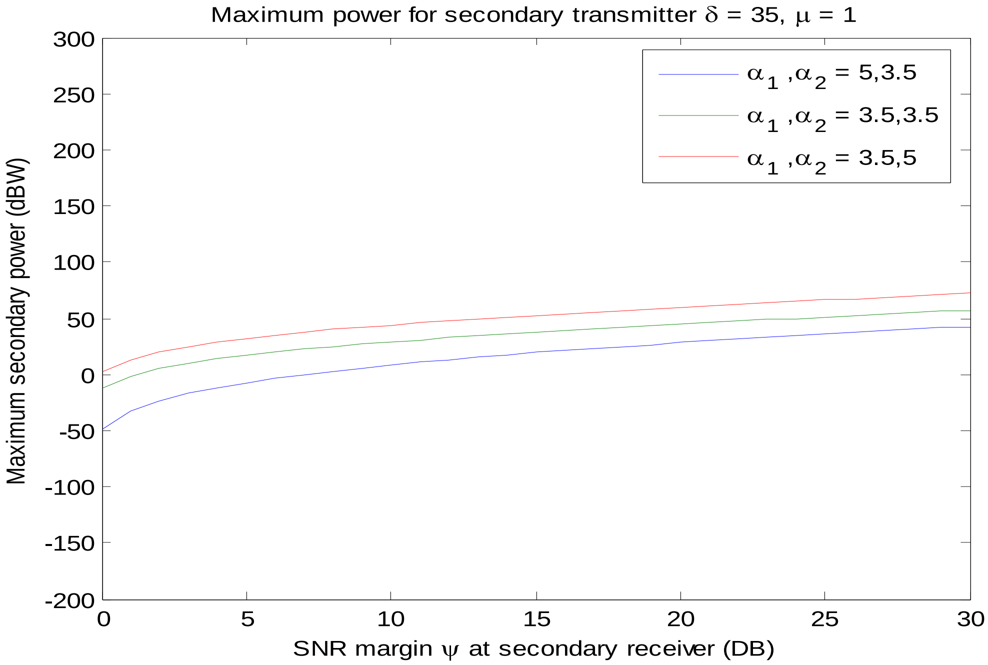


Figure 4.8 Maximum secondary power vs SNR margin ψ at secondary receiver for Δ = 35, μ =1

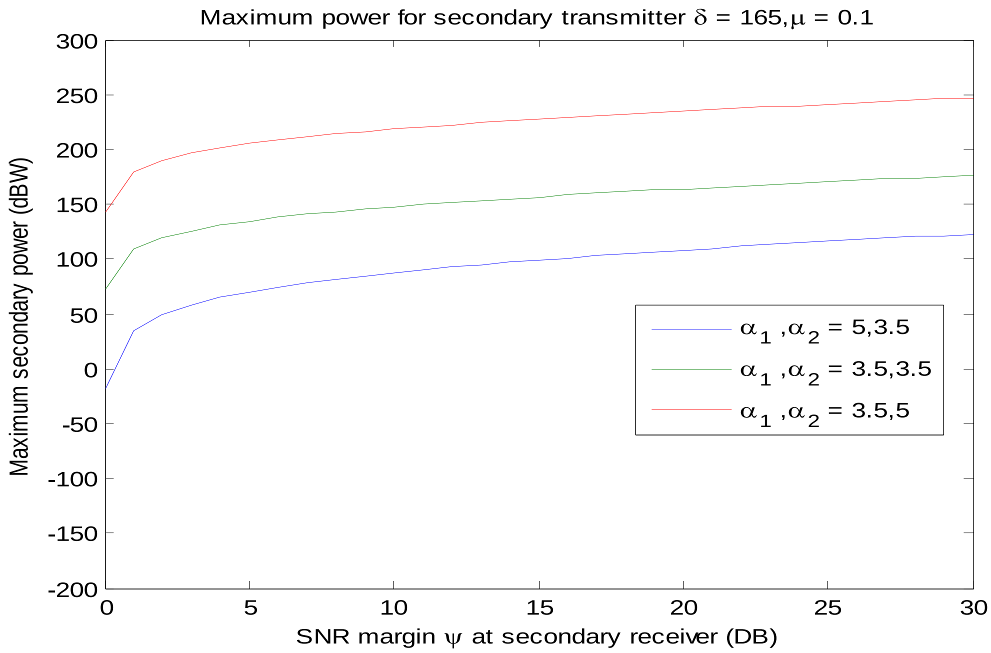


Figure 4.9 Maximum secondary power vs SNR margin ψ at secondary receiver for Δ = 165, μ =0.1

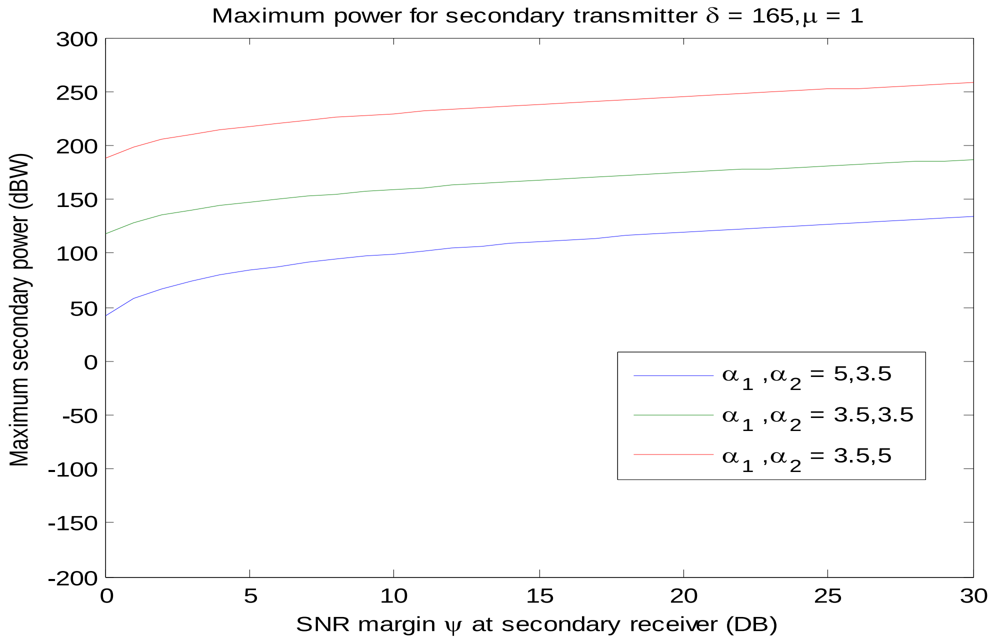


Figure 4.10 Maximum secondary power vs SNR margin ψ at secondary receiver for Δ = 165, μ =1

4.5 Summary

In this chapter we simulated the results discussed in previous chapters. After looking at the results we can say that cooperative sensing is a better option for signal detection method in a multiuser cognitive environment. Also applying power scaling to secondary users we can guarantee no or little interference to primary users within some protected region. We have also shown that how increasing the probability of correct detection of channel being busy or idle lowers interference to the cognitive users.

Chapter 5 Conclusion

5.1 Conclusion

In this thesis we have discussed about cognitive radio and the issues in spectrum sensing that may cause interference to primary users. We have shown some results which can mitigate these issues. The cognitive radios must adjust their power according to their distance from primary receiver protected zone. To detect the signals cognitive receiver must be highly sensitive. Agility improvement by cooperative spectrum sensing helps in vacating the frequency band faster as compared to non cooperative in which one user relays its message to other user there by reducing the detection time. The agility gain is a function of log (n) where n is the number of sub bands. Energy detection has been extensively studied in the past, however hidden terminal and exposed node problem is ignored, which assumes same environment for transmitters and receivers. The results take care of this situation and surface plots for different traffic intensities the probability of correct detection is calculated. An increase in detection probability reduces the chances of interference with primary users.

Hence, if we employ all these techniques to sense the signal in cognitive environment, better results could be achieved, thereby making a way towards efficient spectrum utilization.

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