Cooperative Spectrum Sensing Over Hyper-Rayleigh Fading Channels in Multiple Antenna Based Cognitive Radio Networks

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In

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DECLARATION

I **Rajeev Kumar**, hereby, declare that the work presented in the thesis entitled ***"Cooperative Spectrum Sensing Over Hyper-Rayleigh Fading Channels in Multiple Antenna Based Cognitive Radio Networks"*** by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Wireless Communication from Thapar University, Patiala, is an authentic record of my own work under the supervision of **Dr. Surbhi Sharma**, Assistant Professor, Electronics and Communication Engineering Department. The matter presented in this thesis has not been submitted in any other University/Institute for the award of any other degree.

Date: 06/07/2016

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This is to certify that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

Wireless communication systems have opened new dimensions in communications. People can be reached at any time and at any place. In today's world one of the most widely used forms of communication is wireless communication. But the demand of wireless applications are increasing and the number of unlicensed users are increasing which makes the problem of development for the wireless communication and the problem is known as spectrum scarcity. So to overcome the problem of spectrum scarcity, A tool known as the cognitive radio has been proposed. Primary users will not use the spectrum all the time. So to make the efficient utilization of the spectrum, cognitive radio helps the Secondary users which are known as the licensed users or the cognitive users to make use of the licensed spectrum band when the primary user is not using the licensed spectrum band. Cognitive radio (CR) is a very intelligent tool which sense the spectrum very intelligently and helps in making the efficient utilization of the available spectrum band.

Spectrum sensing is the important function of CR system and is very crucial. The various techniques of spectrum sensing has been studied and the various detectors has been used. Energy detector, matched filter, cyclostationary detectors has been studied. Energy detector is easy to implement since it is less complex and cyclostationary detector is complex to implement but the accuracy of cyclostationary detector is much better than the energy detector.

In this thesis, performance analysis of cooperative spectrum sensing employing improved energy detector over TWDP channel is evaluated and compared with threshold optimization and CFAR methods. In cooperative sensing, at each cognitive radio multiple receiving antennas has been used. Detection performance of the proposed schemes is analyzed in terms of error detection probability w.r.t. SNR. Simulation results shows that by using cooperative sensing, error detection probability can be reduced or in other words SNR gains of 14 dB and 3 dB can be achieved in comparison to CFAR and optimum threshold method respectively.

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LIST OF ACRONYMS

CR	Cognitive Radio
SS	Spectrum Sensing
PU	Primary User
SU	Secondary User
ED	Energy Detector
MF	Matched Filter
A/D	Analog to Digital
AWGN	Additive White Gaussian Noise
FFT	Fast Fourier Transform
SNR	Signal to Noise Ratio
AM	Amplitude Modulation
OFDM	Orthogonal Frequency Division Multiplexing
QPSK	Quadrature Phase Shift Keying
BPSK	Binary Phase Shift Keying
ROC	Receiver Operating Curves
EMA	Exponential Moving Average
EWMA	Exponential Weighted Moving Average
ADC	Analog to Digital Converter
GLRT	Generalized Likelihood Radio Test
CSI	Channel State Information
TFT	Tit For Tat
SINR	Signal to Noise plus Interference Ratio
MGF	Moment Generating Function
TWDP	Two Wave with Diffuse Power
CFAR	Constant False Alarm Rate
CSS	Cooperative Spectrum Sensing
MIMO	Multiple Input Multiple Output
ISI	Inter Symbol Interference
CAV	Covariance Absolute Value
CFN	Covariance Frobenius Norm
CWT	Continuous Wavelet Transform
DWT	Discrete Wavelet Transform

LOS	Line Of Sight
Vs	Versus
dB	decibel
FCC	Federal Communications Commission
LQ	Linear Quadratic
M2M	Machine-to-Machine

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CHAPTER 1

INTRODUCTION

In human's life, communication technologies have become a very important part. People can be reached at any place and at any time In today's world, wireless communication systems [1] have opened new dimensions and it has become one of the most widely used forms of communication. Due to increase in demand of wireless applications spectrum scarcity has become a major issue. Wireless communication has grown rapidly in last few days. If number of users which wants to access the spectrum will increases, then there will [2] be an increase in spectral traffic thereby causing congestion of spectrum. Spectrum can be precisely and effectively exploited for providing opportunistic access to cognitive users in licensed bands.

1.1 Cognitive Radio

J. Mitola [3] was the first person who anticipated cognitive radio's idea in 1998. Cognitive radios can examine and discover the atmosphere of their operational location. C.R. can dynamically change features for the best examination. Cognitive radio is known as a secondary user. CR can be categorized as:

- ***Full Cognitive Radio*****:** In this radio, Each feasible factor observable by wireless network is considered.
- ***Spectrum-Sensing Cognitive Radio*****:** In this radio, only radio frequency spectrum is considered.

The other types are:

- ***Licensed-Band Cognitive Radio*****:** In this only those users can use the spectrum which has license.
- ***Unlicensed-Band Cognitive Radio*****:** In this the spectrum is used by those users which do not have the license.

1.2 Cognitive Vs Conventional Radio

Conventional radio makes sure that spectrum band is free from interference in which they operate without any change in their parameters. When the cognitive radio is compared with the traditional one, CR exhibits the feature to sense the surrounding and consequently, CR changes their constraints and can access the spectrum freely.

Cognitive radio is a radio that senses its surrounding and can change its operating parameters according to surrounding. The primary users [4] have authority to use the spectrum band. Secondary users must monitor the empty spectrum band continuously to use the spectrum. But it is mandatory that secondary users must use the vacant bands in order to avoid interference to primary users.

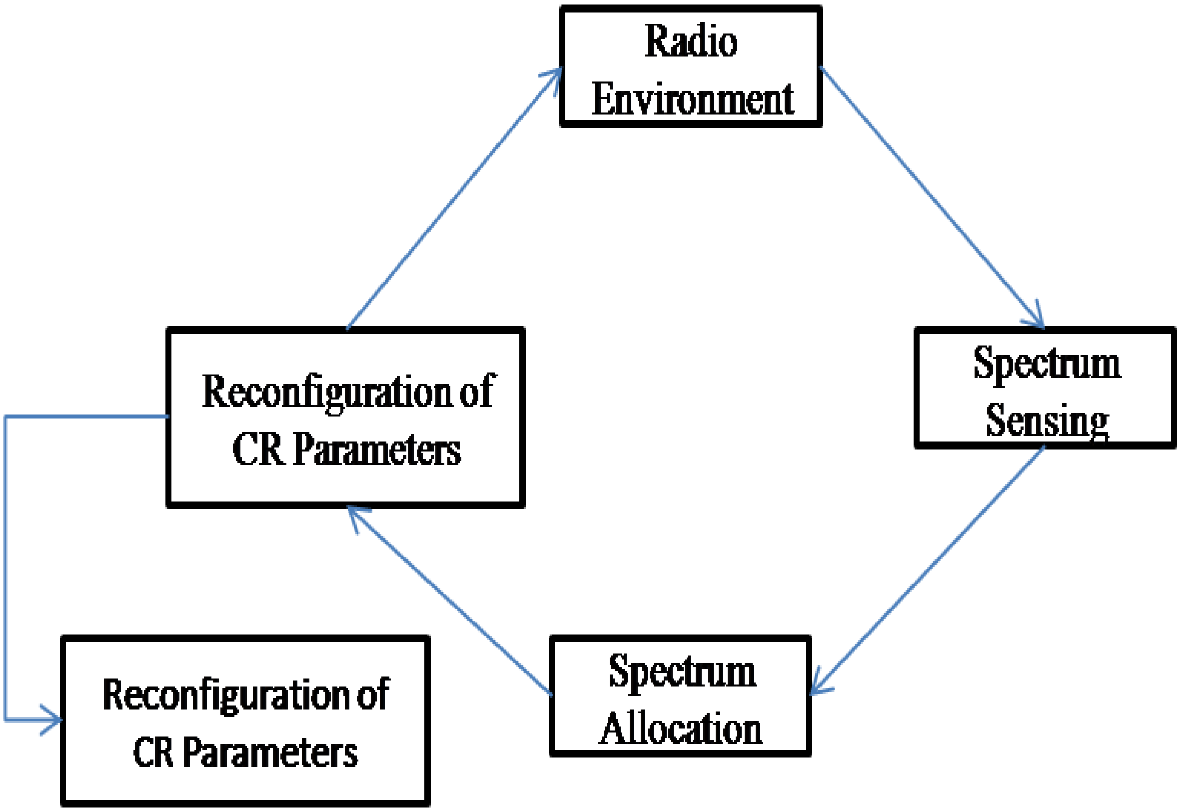

Fig. 1.1. Cognitive Radio Cycle [8]

To spot the presence of primary user in spectrum band spectrum sensing is used. Numerous techniques are there to spot the presence of primary user in the spectrum band like Cyclostationary feature detection, matched filter, energy detection, distributive and central cooperative sensing.

1.3 Cognitive Radio Architecture

The cognitive radio network consists of primary network and a secondary network. The primary network has one or more PUs. It also has one or more primary base stations. The PUs has the license and they can use the spectrum which is allocated to them. The PUs are synchronized [5] via the primary base stations. The base station is the only medium via which PUs can communicate with everyone. Usually, the properties of the cognitive radio are not exhibited by PUs. Also the base stations do not exhibit the properties of the cognitive radio.

In comparison to the primary network, the secondary network has one or more secondary users. The secondary network can or cannot have the secondary base station. For SUs, the usage of spectrum is controlled by the secondary base station. For PUs, the usage of spectrum is controlled by primary base station. Secondary users can communicate among themselves via secondary base station. If spectrum is shared by more than one secondary base stations then their spectrum usage is managed by central broker system. Secondary users can also communicate among themselves without base station and such type of networks are known as ad-hoc networks. The vehicular network is the one example of such network.

When the primary signal is transmitted, then there should not be any interference to primary signal by the secondary user's signal. All secondary users exhibits the features of CR. The base station also exhibit the features of CR. While using the spectrum, if secondary user senses the presence of primary user then secondary user has to leave that spectrum immediately. Then secondary user must shift to other vacant spectrum. In this way there will be no interference to primary user.

In spectrum band both certified/authorized and the unauthorized bands exists. Primary users are given license to use the licensed bands. Secondary users can access the spectrum when primary user is not using the spectrum. The base station provides the knowledge of all vacant and engaged bands to the secondary users. In the secondary network, the bands are distributed by the base station to the secondary users. Cognitive radio is the one who senses the primary user all the time. Then this information regarding the presence of primary user is delivered to secondary base station and to the secondary users. After that secondary base station request all secondary users to leave that band. Secondary users can exhibit ad-hoc network in which there is no base station.

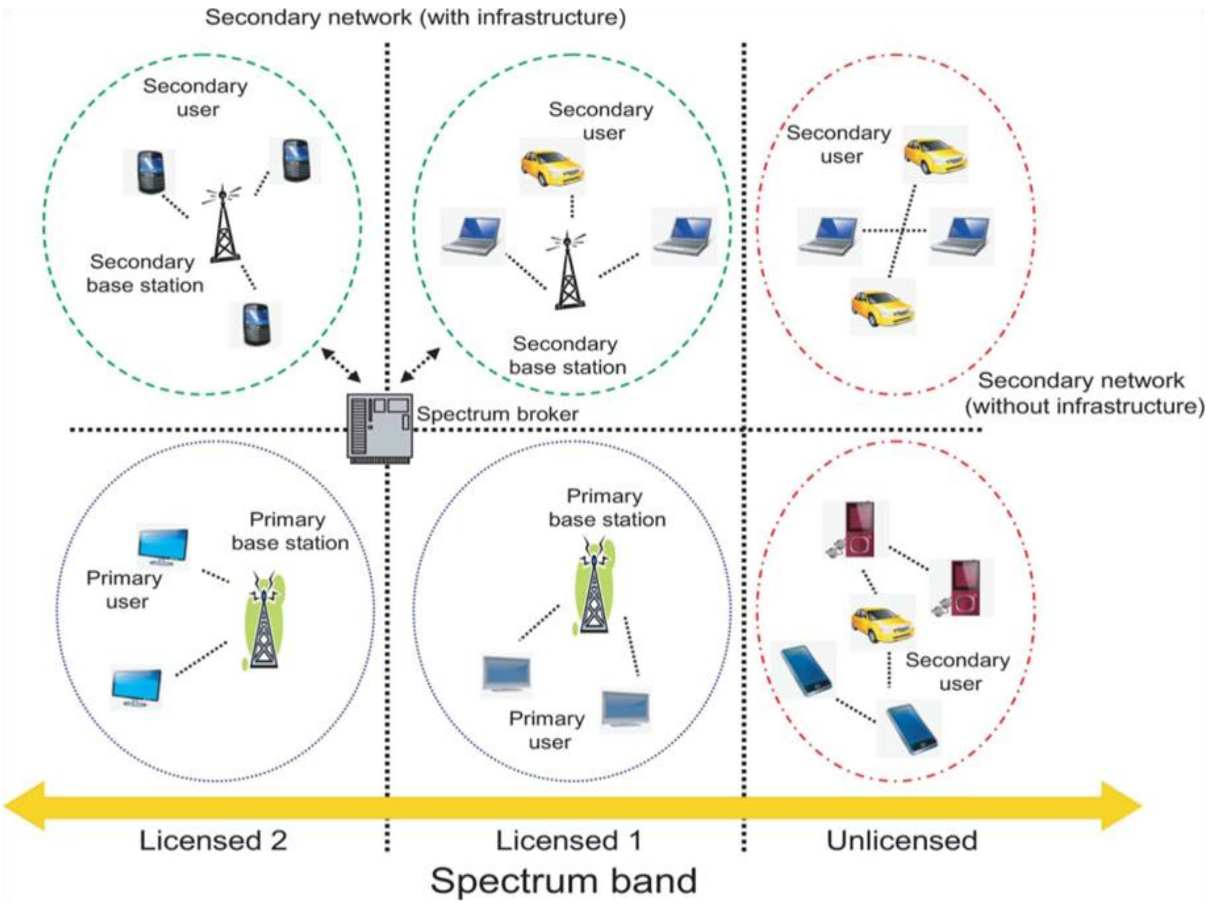

Fig. 1.2. Cognitive Radio Architecture [8]

1.4 Cognitive Radio Characteristics

- ***Operating environment sensing***: The surrounding in which CR operates is very vast. These surroundings can supports the work of the CRs or they may not be in the favour of the functionality of the CRs. The CRs are having the characteristics which make the sensing of the spectrum [6] bands very easy. For the perfect functionality of the CRs, they must change their parameters according to the surroundings. The surroundings can be of numerous types.
- ***Operational state languages***: Operational state languages are used for information sharing in a CR network. It is mandatory that states and observations of cognitive radio must be known to all nodes in the network. Language used for this purpose is operational state language. The awareness that CR sends may be the list of those emitters that it recently sensed.
- ***Distributed resource management***: Radio spectrum is a distributed resource. Consequently, use of spectrum at one location makes is unavailable at other

location. Therefore, spectrum resources must be allocated in a balanced manner. Numerous numbers of solutions are there to solve this problem.

1.5 Cognitive Radio Functions

- ***Spectrum sensing*****:** If the secondary user uses the spectrum then in that band there must not be any primary user. Otherwise, there will be interference between them. The vacant bands have to be sensed by the secondary users for their transmission. Different sensing methods are there for the detection of primary user like transmitter detection, cooperative detection and the interference based detection.
- ***Spectrum management*****:** To meet the requirements of the user, cognitive radio have to capture the best suitable band. CR is responsible for getting all possible information of the surroundings and after getting information of surroundings, CR senses a perfect band among all the bands according to the user's requirements. This type of provision done by the CR to fulfil the needs of the client comes underneath the examination and recognition of the spectrum.
- ***Spectrum mobility*****:** It is the uttermost operation of cognitive radio. In this function, cognitive radio user exchanges the frequency of operation. The clients of the CR exploit spectrum band in such a way so that there will not be any interference between secondary and primary users. So cognitive radio users uses the spectrum in dynamic manner to fulfil the user requirements.
- ***Spectrum sharing*****:** The sharing of spectrum band must be done precisely so that all the users can use the spectrum. It is mandatory to provide access of spectrum to all users. This is not an easy task. The spectrum must be distributed in a flexible manner, only then all the clients can get access to the spectrum.

1.6 Spectrum Sensing

Various numbers of parameters are there to sense the spectrum. These parameters include power consumption, how much spectrum is vacant, noise level, interference level etc. Spectrum sensing [7] is done particularly in two areas viz. frequency and time. But it is not mandatory that spectrum sensing is done only in these two areas.

There are numerous numbers of areas like code domain and the area of the phase where coding and angles come into existence. Cognitive radio is the best tool to sense whether primary user is present or not. To sense the presence or absence of primary user is main task in spectrum sensing. Secondary users waits for the vacant band for their transmission and spectrum bands can be vacant only when primary users are idle. When secondary users are using spectrum band and during that time cognitive radio senses the presence of primary user then secondary user must have to leave that band in order to avoid interference.

Spectrum sensing is the crucial issue in the technology of cognitive radio. Cognitive radio reduce the interference problems. The shadowing, fading etc. are numerous numbers of interferences and cognitive radio is best to reduce these interferences.

In the operation of cognitive radio network, spectrum sensing and sharing the sensing results is one of the most important tasks. In a multi-hop cognitive radio network, this becomes more crucial task. In a multi-hop cognitive radio network, no Omni-present central authority is present.

Spectrum sensing is done with numerous detectors:

- ***Energy detection***
- ***Matched filter detection***
- ***Cyclostationary detection***
- ***Covariance detection***
- ***Wavelet detection***
- ***Interference based detection***

Spectrum sensing can be done by various methods. The technique that executes the best outcome is matched filter. It provides the highest accuracy but it is difficult to implement. As it is shown in the figure 1.3, the technique of the energy detection is simple and consequently easy to implement but the accuracy is poor. Other methods are in the middle of these two.

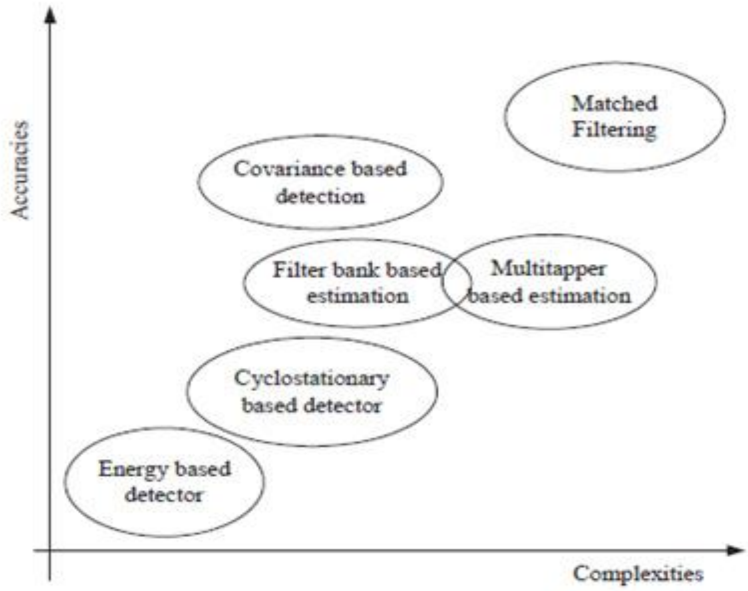

Fig. 1.3. Sensing accuracy and complexity of various sensing methods[21]

1.7 Issues and Challenges in Spectrum Sensing

- ***Channel uncertainty*:** In the wireless communication network, when the signal is transmitted, it is not mandatory that the received signal is identical due to the presence of interferences [8] like shadowing or fading. And due to these interferences uncertainties in received signal strength arises. Hence, it is mandatory that CR must have the capability to identify the faded signals. Any uncertainty in the received power of primary signal translates into a higher detection sensitivity requirement.
- ***Noise uncertainty*:** If The CR senses the primary user at minimum SNR, it is termed as the detection sensitivity.
- ***Aggregate interference uncertainty*:** In future, due to the widespread deployment of secondary networks, there is the chance that various CRs systems will function over the same band. Consequently, spectrum sensing will be affected by uncertainty in aggregate interference. This interference may result in wrong detection. So sensitive detector is required so that secondary user may not cause any interference to primary user.

- ***Sensing interference limit*****:** In spectrum sensing, the main motive is to detect the status of spectrum i.e. whether it is idle or interference measurement at the licensed receiver caused by transmissions from unlicensed users.

CHAPTER 2

LITERATURE SURVEY

J. Unnikrishnan *et al.* [9]: In this letter, cooperation of cognitive user's has been considered. It is assumed that all cooperating nodes use same energy detectors. On this basis, received signals are modelled as correlated log-normal random variables. A linear-quadratic fusion scheme has been designed in this paper. Simulations suggests that, LQ detector performs well when the observations are correlated.

S. H. Hwang *et al.* [10]: This letter represents the novel technique of energy detector to sense the spectrum band. Complementary receiver operating curves (ROC) has been exploited to sense the performance of the anticipated technique. In the anticipated technique, numerous antennas have been employed. The channel that has been considered is Suzuki channel.

This letter exploits the energy detection which is very simple to implement. To check the performance of the technique two scenarios has been considered. The parameter that has been taken into consideration is a threshold. If the primary user has to be present, then the threshold must have to be less than the received value of the energy. If this is more than the outcome, then primary user will be absent Simulations recommends that by exploiting the anticipated scheme, the detection performance can be increased with the help of multiple antennas.

Lin *et al.* [11]: This paper exploits the new technique named as Exponential Moving Average (EMA). The technique that has been exploited in this letter increases the energy detection.

The technique that has been used is based on spotting the bands of the spectrum. The anticipated technique can predict the strength of the energy in the frequency bands. The EMA technique also known as EWMA (Exponentially Weighted Moving Average). This technique does not need the awareness of the primary user's parameters since this technique already knows the strength of the energy. Consequently, if the strength of the energy is more as compared to the already known

threshold, then the key user is present. If the power of the energy is not up to the threshold, then the primary user is absent.
When the anticipated technique is compared with the traditional energy detection method, the anticipated technique outperforms the traditional one. By employing the anticipated technique, the time to sense the primary user in spectrum band decreases. The anticipated technique uses the parameters of weight which decreases exponentially. The anticipated technique uses the estimate of EMA and that of the energy detection to boost the detection performance The anticipated technique can enhance the time to sense the primary user but the false rate increases. The anticipated technique is valid only to sense the energy only.

R. Ramanathan *et al.* [12]: This paper employs the energy detection approach to sense the spectrum. The CR that has been deployed is depending on the OFDM. Numerous scenarios of signals and the noise are considered. The anticipated procedure is the uncomplicated and the most valuable one. Since the anticipated technique does not demand any awareness of the parameters of the primary user, this technique is easy to use. The technique that has been deployed in the letter to evaluate the threshold is Divide and Conquer.
The CR in a dynamic manner allocates the spectrum bands. The effect caused by the SNR also has been discussed. CR that depends on OFDM signals has been discussed in the letter. CR exploits the OFDM modulation technique having numerous carriers. The CR that is based on OFDM has numerous benefits. The anticipated technique of modulation has so many benefits like it can diminish the intrusions caused due to inter-carrier, due to inter-symbol etc. The anticipated technique has the FFT in the structure. This takes care of the information about the spectrum bands in the limited spectrum and shares this information with the secondary users. Consequently, the secondary users can use the vacant spectrum.
To spot the vacant bands numerous techniques are there. To determine the variance of the intrusion, the eigen value examination is done. At the transmitter side, numerous values of the SNR has been taken and for that particular values of the SNR, the threshold has been evaluated. The value of the threshold that has been evaluated corresponding to the specific values of the high SNR provides the valuable outcomes.

K. Kim *et al.* [13]: This letter exploits the software radio and understands how to sense the spectrum bu employing energy detection method. The anticipated technique has been deployed in the real atmosphere. The propose technique is based on the histogram which is used to find the value of threshold. On the basis of threshold, presence or absence of the primary user is determined. In the real surrounding, the power of the intrusion varies. A GNU radio module system has been developed to perform the desired task in the letter. is there. Radio frequency has been used. The ADC (Analog to digital converter) also has been used.

In the technique of the energy detector, two scenarios are considered. One spots the awareness of the primary user and the other scenario does not spot the awareness of the primary user. The sensing of the spectrum has been accomplished practically. Also, the importance of the histogram approach has been investigated in the real atmosphere.

H. B. Li *et al.* [14]: This letter accomplishes sensing of primary user by exploiting the numerous antennas at the receiver side of the cognitive radio. The generalized likelihood radio test (GLRT) approach has been exploited. The main issue in spotting the spectrum band is time to sense. The anticipated technique has been compared with other techniques The licensed frequency bands that have been allocated can only be used by primary users and they can be exploited by them at any time. Secondary users can use the spectrum only when the primary users are not transmitting their signals. Energy detection, cyclostationary detection are numerous techniques to sense the spectrum.

This letter considers the situation in which numerous antennas at the receiver side of the cognitive radio are there and only one crucial user has to be spotted. The energy detector demands the awareness of the variance of the intrusion. In this letter, GLRT approach has been exploited and the concept of the maximum likelihood also has been examined. Numerous detectors are there to spot the primary user. MME is the one detector to spot the primary user in the spectrum. The proposed technique has been compared with the energy detection technique.

L. Zhang *et al.* [15]: This letter accomplishes the spectrum sensing performance. The scenarios that have been considered to accomplish the performance of the anticipated sensing are Rayleigh an AWGN (Additive White Gaussian Noise). There is some trouble that is out of sight. To solve such kind of problem, cooperative spectrum sensing is used. Consequently by exploiting the cooperative spectrum sensing, the outcome of the sensing has been boosted. The detector that has been exploited in the anticipated spectrum sensing is energy detector. The numerous scenarios have been taken into consideration to accomplish the performance.

In this letter, the system consists of only one primary user and some finite numbers of the secondary users. The energy detector method is the uncomplicated and the most common used method to spot the presence of the primary signal. If one does not have any awareness about the parameters of the primary signal, then the most valuable detector is the energy detector. The modulation technique that has been exploited on the major signal is the BPSK. The Rayleigh fading channel is flat. In the simulation, the curves of the sensing are plotted. To plot the curves, different values of the SNR are provided. The curves are plotted underneath Rayleigh fading channel that is flat and the AWGN channel.

E. G. Larsson *et al.* [16]: This paper anticipates the numerous methods of the spectrum sensing in the cognitive radio. Numerous detectors have been taken into consideration and the performance of them has been discussed. Different detectors like Energy detector, GLRT detector, cyclostationary, matched filter can be used to sense or to detect the primary user in the spectrum.

The data fusion principles has been used. The two scenarios of Soft and hard combining have been considered in this paper. The concept of the cooperation also has been exploited in the letter. The Neyman- Pearson test has been done. The Neyman-Pearson test is most favorable one. The model has been considered in which the received signal is the sum of the intrusion plus noise.

Energy detector is the simple method to detect the primary user. This detector is much not interested in the awareness of the signal. It assumes the key signal only as an intrusion and then after seeing the experimental signal's energy, it tells about the awareness of the key signal whether it is present or not.

R. Fan *et al.* [17]: This letter examines the approach of cooperative spectrum sensing. The anticipated technique uses the concept of cooperation which is the optimal solution. The set-up of the cognitive radio has been considered. To spot the awareness of the primary user in the spectrum, it is divided into the sub bands. Consequently, the time to sense the primary user in the spectrum band consist of numerous mini-slots. The secondary users senses the channel by using the concept of cooperation. The problem of the optimization is evaluated. By evaluating the problem of optimization, the performance of secondary users has been increased. An algorithm has been exploited to solve the problem of the optimization.

To sense the spectrum, a time-slotted structure has been considered. If the time to sense the primary user is more, then the probability of detection is high and therefore the false alarm rate degrades. Numerous slotted frequencies have been considered in the structure. In the letter, the two sensing approaches have been evaluated and those modes are the continuous-time and the slotted-time.

P. D. Phong *et al.* [18]: In this paper, a new technique has been developed to sense the spectrum. The anticipated technique does not demand any awareness accurate information of the variance of interference, signal and the channel state information (CSI). The traditional technique that senses the primary user has two issues. Firstly, they demand the awareness of the channel state information (CSI) and secondly they demand awareness of the accurate information of the variance of the interference and the signal. The anticipated technique has been compared with traditional technique.

In the model where numerous antennas are present at each antenna, one signal is received. The three techniques of sensing have been considered and their performance has been accomplished. Four antennas have been considered. Quantization weights have been exploited. In the anticipated techniques, the missed detection probability has been kept constant and correspondingly the threshold and the false alarm has been calculated. When false alarm has been kept constant, then correspondingly the missed detection and threshold has been formulated. The practical technique of sensing the spectrum has been developed in the letter and performance has been established.

T. Cui *et al.* [19]: In this letter, cooperative spectrum sensing has been considered. Two sensing schemes has been investigated. In first scheme, all the information by secondary users is exchanged locally. In the second scheme, there is one central controller to which all the information by secondary users is relayed. Second scheme is the optimized scheme. Results recommend that the proposed scheme performs well in comparison to the existing techniques.

S. Nallagonda *et al.* [20]: This letter accomplished the performance of the tool named as cognitive radio. The spectrum sensing uses the concept of energy detection method. The performance has been executed underneath numerous fading channels like AWGN, log-normal shadowing, Nakagami, Rayleigh, Wiebull.

To accomplish the performance, numerous probabilities has been evaluated. Receiver operating curves (ROC) has been plotted. The parameters that have been evaluated to see the performance are false alarm and missed detection. ROC are the curves that have been plotted between missed and false alarm. Different SNR has been considered. The only scenario in which the spectrum can be exploited by CR is that it should not cause any intrusion to the primary user.

In this letter, The technique of the energy detector has been employed. In some scenarios the intrusions affected by the fading, shadowing may be high. In such scenarios, the CR cannot spot the primary user.

Simulation has been done in various scenarios. The matrices of the numerous parameters viz. missed detection, false alarm probabilities has been evaluated. The main motive to do simulation is to study the effect of intrusions caused by fading or shadowing. It has been accomplished that this technique gives better performance in Nakagami or Weibull fading when compared to other fading scenarios.

S. Atapattu *et al.* [21]: This paper examines the performance of the cooperative sensing. The concept of energy detection method has been employed. The effect of shadowing and the effect of the fading has been considered. The tool that provides the right to use the spectrum to secondary users is cognitive radio. The anticipated technique spotlights the two techniques of the fusion namely data fusion and the decision fusion.

In the data fusion, the secondary user increase the strength of primary signal and forwards to fusion point. When the concept of cooperation is used in sensing the presence or absence of the primary user in the spectrum band with the help of energy detector, then the secondary users sends their outcomes to the fusion centre by exploiting one of the two techniques employed in the fusion. At the point of fusion, numerous methods like Square law combining, maximal ratio etc. can be considered.

In the decision fusion algorithm, the secondary users makes an judgement on the activities of the primary users and sends their information to the point of fusion. In the first algorithm, the data of the medium is required from the secondary user to the point of the fusion only if the amplification parameter is constant. If the amplification parameter is not fixed, then the data of the medium is required by both sides viz. from the primary user to secondary user and from secondary user to the point of the fusion.

D. R. Joshi *et al.* [22]: This paper accomplished the detection of threshold. This has been done in various scenarios. The different scenarios have been taken in which different parameters have been changed and simulations have been carried out. In different cases, a new technique is also assumed which is based on the gradient for the optimization of the threshold. The detector which has been well thought-out is energy detector. ADC scheme has been carried out as well. Energy is calculated of numerous numbers of signals which are then averaged and then there are two scenarios on which tests are carried out and by testing, presence or absence of the signal is evaluated. After averaging the energy of the numerous numbers of the signals, approximation is done which is unbiased of the autocorrelation coefficients. Then variance has been evaluated and after that gradient has been evaluated and after that threshold has been evaluated and then optimization has been done.

E. Axell *et al.* [23]: This letter considers the OFDM signals and then employs the concept of sensing in AWGN fading. The detector that has been employed in this paper is optimal. This detector correlates the OFDM signals. Cyclic prefix concept has come into use. The optimal detector is Neyman-Pearson and this has been employed in the case of deterministic noise. The comparison of the optimal detector has been carried out with that of the uncomplicated one known as energy detector. GLRT (generalized likelihood radio test) approach has been exploited, if the signal's awareness is not known. Then afterward the GLRT detector has been compared to that detector that has been employed to access the performance of the OFDM signals. The GLRT method is precise one in comparison to others, if the awareness of the noise is unknown.

In this paper, the Neyman-Pearson detector is first derivative for OFDM signals. This detector can also be implemented directly. After the optimal detector, the GLRT method come into existence. The model that has been employed is a complex, discrete-time baseband model. One second-order statistics detection has also been evaluated. The detector that is based on the statistics of the second-order is complicated. Monte-Carlo simulation has been carried out to accomplish the results.

Y. Kondareddy *et al.* [24]: The most significant task in the functionality of the cognitive radio network is the sensing of the spectrum band and sharing the outcomes of the sensing. In the multi-hop cognitive radio network, there is no authority available at all the positions. In such scenarios, the function of the cognitive radio set-up is more significant. To share the outcomes between the users, it is mandatory to use significant techniques since in exchanging the awareness of the key signals among the secondary users uses the energy which is wasted most of the time. So to conserve the energy of the secondary users, significant techniques must be employed. TFT (Tit-For-Tat) algorithm cannot be exploited to accomplish the cooperative sensing of vacant bands.
Distributed and the centralized are the types of sensing. If there is non-cooperation, then the spectrum band cannot be utilized completely. In multi-hop case, the sensing outcomes that has been established by the nodes, are communicated among all the nodes. A multi-hop network of cognitive radio has been considered. In the network, all the nodes must have to cooperate. The first segment is the sensing and the sharing. This is the significant stage of the network. The anticipated technique has been exploited at the physical layer. Packets are forwarded. The network of the cognitive radio is the most significant network in this paper. To support the cooperation, classic TFT cannot be deployed. The technique that accomplishes the most significant cooperation is the cross-layered structure.

M. Subhedar *et al.* [25]: This letter examines the different techniques of spectrum sensing. In the real surrounding, the numerous numbers of techniques have been exploited in sensing the spectrum band. Energy detection technique is uncomplicated and the valuable procedure. This technique is not aware of the signal and it does not demand any awareness regarding the signal. It assumes the primary signal only as an intrusion and then after seeing the experimental signal's energy, It tells about the awareness of the primary signal whether it is present or not. There is integrator in the energy detector and whatever the result comes out of this integrator is the energy of the filtered received signal over the specific time interval. On the basis of this result two scenarios are assumed. The first scenario tell about that it has not spotted any primary signal and it has spotted only the noise. And the other one scenario tells about that both the signal and noise has been spotted.

The matched filter detection is the perfect only if the awareness of the key signals is known. The information can include parameters viz. how much rate of modulation is used, how much rate of coding is used, which modulation technique has been used, which technique of coding has been used etc. If all this awareness about the primary signal is known, then this method is best available to sense the primary user and to reduce the SNR at the receiver side. This method decreases SNR and executes the perfect functionality of the detection.

Cyclostationary-feature detection method is mainly discovered because most of the man-made signals like AM, BPSK, OFDM, QPSK have the feature of cyclostationary. Signals that are noisy in nature does not exhibit the feature of cyclostationary. The detectors of such kind are very robust against the variance of the intrusion. The main motive of such detectors is to exploit the feature of cyclostationary in the man-made signals.

S. Bokharaiee *et al.* [26]: In this paper, cooperative spectrum sensing has been proposed for cognitive radio networks and then performance has been analyzed. The signals of the cognitive radio are prevented by the channel impairments so that they cannot reach at the destination perfectly.

In this paper, non-coherent schemes like BFSK are used to transmit decisions to fusion centre in the binary form. Energy and decoding fusion principals has been developed and for these rules, optimum sensing parameters are obtained.

X. Ling *et al.* [27]: This letter examines the spectrum sensing based on energy detection method. The wireless channels experience the varying nature in time. Also the primary users have the varying character. Therefore, at the receiving side of the secondary users, the SINR (signal to noise plus interference) varies. The main motive is to keep the intensity of the intrusion in the limit so that the average rate of the secondary user can be increased. To determine the threshold, the linear concept has been formulated. This paper accomplishes the maximum rate of transmission of the secondary. The threshold is adjusted dynamically as a linear function of the secondary users.

A time-slotted model has been considered. Both the primary and the secondary users are present in the model. Along with the AWGN, Rayleigh fading has been considered. The one issue in solving MAR is to find the closed form expression of threshold. The concept of adaptive control for threshold has been exploited. The anticipated technique has performed better and achieves higher outcome when contrasted to energy detector.

V. R. S. Banjade *et al.* [28]: In this paper, the performance of spectrum sensing has been discussed using energy detector method. Numerous correlated antennas have been employed. The scenario of the fading is Nakagami-*m*. The main motive why the numerous antenna has been exploited is enhance the detection performance in the low SNR regions.

The technique that has been employed to find the probability is Moment Generating function (MGF). The square law combining has been exploited in this technique. CRs spot the vacant area of the spectrum and allocates them to the secondary users. Spatial diversity algorithm has been exploited. Numerous numbers of parameters like time-bandwidth product, degree of correlation have been employed in the detection performance.

E. Alsusa *et al.* [29]: This paper discusses the sensing performance using the Barlett's estimate. To sense the spectrum band, numerous techniques has been developed. This paper uses the concept of the energy detection method. The scenarios of fading that has been exploited are Rayleigh and Rician. Monte Carlo simulation has also been use to confirm the accuracy of the desired technique.

In the Barlett's estimate, firstly the quadratic outline has been evaluated. Then numerous probabilities like missed and false alarm also have been evaluated. These have been evaluated to check the performance that how precisely the above-exploited scheme has been accurate in sensing the spectrum band. One function that is named as the cumulative distribution has also been derived after formulating the quadratic expression of the estimate. The above scheme provides better performance to spot the gamut of the pop group in comparison to the raw periodogram.

R. K. Mallik *et al.* [30]: This paper represents the accomplishment of cooperative spectrum sensing. Numerous cognitive radios have been considered and at each cognitive radio, numerous antennas have been taken. The improved energy detector has been considered. At each CR, selection combining has been used. This scheme at each CR detects that primary signal is there or not. At each CR, this scheme takes the highest output among all the antennas. After evaluating the highest output among all the antennas, the output has been fed into the detector and if the output of the detector is binary 1 then this accomplish that primary signal is there and if the detector results in binary 0 then this accomplish that primary user is not there. Some sample's amplitude also have been taken into consideration by the detector. Different probabilities named as a false alarm and missed detection has been evaluated. Improved energy detector increases the performance of the network which consists of various CRs. Numerous antennas at different CRs increases the reliability of sensing the spectrum.

Y. Eghbali *et al.* [31]: In this letter, the technique of cooperation has been considered. In the anticipated technique of cooperation, each cognitive radio sense the common frequency. Simulation has revealed that by exploiting the concept of the cooperation, the performance of detection has been increased. The concept of cooperation has been considered to increase the detection performance. A model has been considered to perform the simulation. In model, a primary user and some secondary users has been considered. The techniques to sense the spectrum band has significant consequence as they have the potential to reduce the interferences caused by secondary users to the primary users. OR, AND rules at the point of fusion has been applied to get the final outcome. The one with the OR principal provides better performance in comparison to the AND principal.

O. S. Vaidya *et al.* [32]: This paper accomplishes the receiver operating curves (ROC) of different fading channels. The numerous scenarios has been compared after plotting the ROC. Nakagami-m, Rayleigh, AWGN are the numerous fading scenarios. The numbers of the users that demand to exploit the spectrum are increasing in the limited spectrum, so cognitive radio is the tool that provide access to all these secondary users in the limited spectrum. The performance of the detection is measured in terms of ROC. Numerous probabilities like missed and false alarm have been evaluated. The techniques that exploit the concept of dynamic allocation translate the limited spectrum band.

The energy detection method has been used in this letter. The performance of sensing is examined by receiver operating curves. Different ROCs has been plotted. When the Nakagami-m is contrasted to Rayleigh and AWGN, it outperforms. That means better exploitation of the gamut in Nakagami-m fading channel.

E. Chatziantoniou *et al.* [33]: In this paper, the expression for the average probability of detection over TWDP (two-wave with diffuse power) fading channel in a closed form is derived which is based on the energy detection spectrum sensing. In cognitive radio system, the key function is spectrum sensing. In this paper, the detection threshold is optimized using the closed form expression. TWDP model can characterize a small scaling fading channel which is known as Hyper-Rayleigh Fading Channel.

In this paper, the performance of energy detection based spectrum sensing is discussed over Hyper- Rayleigh Fading Channel. However in this fading channel, performance severely degrades. So the concept of threshold optimization comes into existence and the performance is increased under this fading channel. By minimizing the error probability which is expressed in terms of false alarm errors and missed detection, threshold optimization is achieved. The performance of optimal threshold approach is analyzed in terms of required SNR for different fading scenarios. This paper analyzes the detection performance of energy detection based spectrum sensing with respect to the required SNR in terms of detection error probability which is expressed as a linear combination of probability of missed detection and probability of false alarm with the corresponding primary occupancy statistics as weights for the conventional Constant False Alarm Rate (CFAR) and for the optimum threshold approach.

I. Sobron *et al.* [34]: This letter intended a new technique to spot the empty spectrum band adaptively. This letter exploits the energy detection technique. The one important parameter that has been exploited is the cost function. This utility depends on a single parameter that has all the important awareness. The energy detection procedure exploits the adaptive sensing of the spectrum instead of the soft combining. In the model, the secondary users are scattered spatially. Deflection coefficient has been taken into consideration.

The anticipated technique has outperformed well when compared with the conventional one. The anticipated technique has enhanced the detection performance in the spectrum band.

Y. Liu *et al.* [35]: This letter intended to exploit the concept of the cyclostationary in the cognitive radio network to sense the spectrum. The cooperation of the sensing has been evaluated. In the cooperative technique, one point of fusion and numerous nodes are present. The anticipated technique has precise and reliable performance in the low SNRs regions.

The energy detection, matched filter, and the anticipated one are various techniques to sense the primary user in the spectrum band. In addition to the exploitation of the cyclostationary, the concept of cooperation also has been employed. This increases the performance to sense the primary user.

CHAPTER 3

PROBLEM STATEMENT

3.1 Gaps

Based on the literature survey, it has been found that researchers worked on spectrum sensing with the help of cognitive radio. They used different detectors namely energy detector, matched filter detector, cyclostationary detector. But there were some gaps in which they worked and those gaps are as follows:

1. In case of different detectors, the change in threshold value has been considered but the concept of optimization of threshold has not been taken into account for different detectors.
2. The concept of co-operation has not been considered over two wave with diffuse power fading.
3. The concept of threshold optimization has not been considered in co-operation mode.
4. The concept of optimization of co-operation has not been considered over two wave with diffuse power fading.

Based on these research gaps, following objectives has been formulated.

3.2 Objectives

1. Performance evaluation of above-proposed scheme using the threshold optimization approach employing the spectrum sensing based on the energy detector method over TWDP fading.
2. Performance evaluation of above-proposed scheme using the constant false alarm rate (CFAR) approach employing the energy detector based spectrum sensing method over TWDP fading.
3. Performance evaluation of above-proposed scheme using cooperative spectrum sensing employing improved energy detector over TWDP fading.
4. Comparison of performance of all three schemes in terms of probability of error detection.

CHAPTER 4

SPECTRUM SENSING TCHNIQUES AND FADING CHANNELS

4.1 Cooperative Spectrum Sensing

Secondary users are present in cognitive radio network. Secondary users communicate among each other about the prior information of the primary users. Secondary users uses the spectrum band for their transmission only if the primary users are not using the spectrum band. If secondary users senses the presence of the primary user in the spectrum band [36] then all this information is communicated among all secondary users. This is known as cooperative spectrum sensing (CSS). By using cooperative spectrum sensing, spectrum can be fully utilized.

This sensing depends on the strength of signal which have properties of deviation. If secondary users are using cooperative spectrum sensing among themselves then the performance to sense the presence of primary users increases. Interference decrease the detection performance.

Interference can also be among secondary users if all the secondary users are using the same spectrum band. To solve this problem, cooperative and non-cooperative are the approaches.. In non-cooperative spectrum sensing all the secondary users do not communicate among themselves about the presence of the primary user.

In cooperative spectrum sensing, all the secondary users shares the information about the presence of the primary user among themselves. Interference due to shadowing and multipath fading can be controlled by cooperative spectrum sensing. Cooperative spectrum sensing is used mainly to reduce interference so that detection performance can be increased.

Cooperative spectrum sensing can be done in two ways: centralized and distributed. In the centralized cooperative spectrum sensing, a central unit collects sensing information from cognitive devices, identifies the available spectrum and then broadcasts this information to all other devices or directly controls the cognitive radio traffic. The main motive is to mitigate the fading effects so that detection performance can be increased. In the distributed technique, exchange of observations among cognitive radios is required. The distributed cooperative spectrum sensing is more significant in comparison to centralized cooperative spectrum sensing.

The non-cooperative sensing is more suitable for unlicensed spectrum where all users can be expected to tolerate a small amount of interference. This sensing is precise for uncertified spectrum. In the cooperative spectrum sensing, secondary users have cooperation among themselves and consequently, the false alarm and missed detection probabilities decreases. Hence, secondary users can use the maximum spectrum efficiently. This will increase the detection performance and the spectrum can be utilized. Analytically and numerically it has been shown that the cooperative spectrum sensing gives higher capacity gains.

4.1.1 Operation of Cooperative Spectrum Sensing

The operation of cooperative spectrum sensing can be performed as :

- By using channel, each cognitive radio calculates specifications of their own local spectrum sensing independently and senses the primary user in the spectrum band by making a binary decision.
- Through reporting channels, the binary decisions are forwarded to the receiver.
- By using fusion principals, the common receiver uses the outcomes of the cognitive radios and finally decision is made on the presence of primary user in the spectrum band.

4.1.2 Types of Cooperative Spectrum Sensing

- ***Centralized approach***
- ***Distributed approach***
- ***Cluster-based cooperative spectrum sensing***
- ***Collaborative spectrum sensing***
- ***Transmit and relay diversity in cooperation technique***

***Centralized*:** In this approach, there is a master node within the network that collects the sensing information from all the sense nodes or radios within the network. It analyses [37] which bands of the frequencies are vacant and which are engaged. It collects the prior information of the primary user and then forward to all the nodes. The governing node can also give the right to another node to collect the information about the primary user. Consequently, the secondary users will cause less interference to primary users and secondary users can use the spectrum more efficiently.

Distributed**:** In this approach, no governing node is there. Consequently, no node takes the control. All users communicate among themselves about the prior information of the primary user in the spectrum band. In the distributed technique, communication exists between different nodes and they are able to share the sense information. The distributed spectrum sensing is more significant in comparison to the centralized cooperative sensing.

Cluster-based cooperative spectrum sensing**:** In this sensing, cognitive users collaborate with each other to perform spectrum sensing. There are numerous clusters of secondary users [38] which cooperate with each other within a cluster. In this instead of the single cognitive radio, there is a cluster of the secondary users. The system has secondary user, primary user and common receiver. Between two users channel in the same cluster is perfect since they are close to each other. One governing node is present that collects all the information. The governing node on the basis of the information decides on the presence or absence of the primary user. This decision is made by some principals of fusion and then the decision is fed over the reporting path to the receiver. Selection diversity is used at each cluster. From each cluster maximum output is taken and then applied to the detector and in this way the proposed technique work.

***Collaborative spectrum* sensing:** The set up must identify and sense the signals precisely in order to work properly. If the number of inspections increases then variance of estimated parameters decreases.. The problem of hidden is improved by this sensing.

Transmit and relay diversity in cooperation**:** In the transmit sensing and the relay, there is the difference. Suppose the two secondary users are there in the system. Both the radios make their decisions and thus forward their result to the receiver then transmit diversity is done . In the relay diversity, the secondary user which is at larger distance from the common receivers can transmit its decision to another secondary user which is nearer to the common receiver. Consequently, the secondary user which is nearer to the common receiver sends its information along with the secondary user which is far from the common receiver.

4.1.3 System Requirements for Cooperative Spectrum Sensing

- ***Control channel*****:** A control channel is required to communicate in cooperative spectrum sensing. The overall system banwidth is managed by this control channel.
- ***System synchronisation*****:** In the cognitive radio cooperative spectrum sensing, it is necessary to provide synchronisation among all the nodes. This is required to keep channel free from transmissions from cognitive network during sensing. If synchronisation is not done then the secondary users will start transmitting during the sensing of primary users. This will cause interference to primary users and thus detection performance will decrease. Hence, system synchronisation is mandatory.
- ***The suitable geographical spread of cooperative nodes*****:** In the cognitive radio network, to gain optimal sensing from the cooperative points, it is mandatory to obtain the best geographical spread. Consequently, the hidden problem decreases.

Advantages of cooperative spectrum sensing:

The cooperative spectrum sensing spectrum is complex in comparison to non-cooperative sensing. But it has various advantages that overcome the complexity. Where this technique can be used exploited, significant gain has been accomplished.

- *Hidden node problem is significantly reduced*: In the non-cooperative sensing, the hidden problem was the main aspect. In that case, sometimes the CR could not sense the primary user and due to this spectrum cannot be fully utilized and thus the detection performance decreases. But in the cooperative spectrum sensing, the hidden problem are reduced since the secondary users shares the prior information about the primary user due to cooperation. In this way, spectrum can be fully utilized and the detection performance increases.
- *Increase in agility*: Since in the cooperative spectrum sensing, sensing performance is increased and hence the agility is increased.
- *Reduced false alarms*: Since this technique overcome the hidden problem, the secondary users can use the spectrum in a precise manner and thus the spectrum can be fully utilized. Therefore, false alarm rate decreases. Consequently, the detection performance increases.

- *More accurate signal detection*: By using the cooperative spectrum sensing, system become reliable and therefore detection is more accurate.

Disadvantages:

- *Control channel*
- *System Synchronisation*
- *Suitable geographical spread of cooperative nodes*

4.2 Sensing In MIMO Systems

This sensing is a new idea in cognitive radio technology. By using multiple antennas at primary [39] and secondary user's side, detection probability can be increased. Optimal detector is considered which have information of the parameters like variance of noise, path gains and the variance of the primary user. It is assumed that samples of the primary users are independent and secondary users have some finite antennas at the receiver side. In MIMO, capacity is compared to a minimum number of receiver and transmitter antennas. Two approaches are available of this technique:

For independent channel: Optimal detector is exploited in MIMO set up. The approximation has been done that the detector has the information of the variance of primary user, path gains and variance of the noise.

For correlated channel: In this sensing, secondary user has multiple antennas and primary user has single antenna. The channel is independent. But if numerous antennas are present at secondary side path cannot be fully independent. Channels are correlated in that scenario. The intensity of the correlation depends on the parameters like polarization of the antenna components and how far are they from each other and the propagation environment. If two different antennas generate two different electromagnetic waves and they got reflected by identical object, then between the propagation coefficients of these waves there will be a correlation. Fading correlation has two independent components:

- *Receive correlation*
- *Transmit correlation*

Advantages of MIMO Systems with Sensing:

Interference detection, array gain, multiplexing gain, diversity gain are numerous aspects for the benefits of the MIMO with spectrum sensing and these benefits are:

- *Increased coverage*
- *Higher capacity*
- *Improved user position estimation*
- *Better transmission quality*
- *Low false alarm rate*

4.3 Detection Techniques In Spectrum Sensing

- ***Energy detection***
- ***Matched filter detection***
- ***Cyclostationary detection***
- ***Covariance detection***
- ***Wavelet detection***
- ***Interference based detection***

***Energy detection technique*:** It is simple and valuable procedure. This technique does not require any prior information [32] about the primary signal. That is the main reason why this technique is the most popular spectrum sensing method.

It assumes the primary signal as noise and on the basis of energy of observed signal decides the presence or absence of the primary signal. There is an integrator in the block diagram and whatever the result comes out of this integrator is the energy of filtered received signal over the specific time interval . On the basis of this result two scenarios are considered viz. H_0 and H_1. The first scenario H_0 corresponds to the absence of signal and presence of noise only and the other one scenario H_1 corresponds to the presence of both noise and signal.

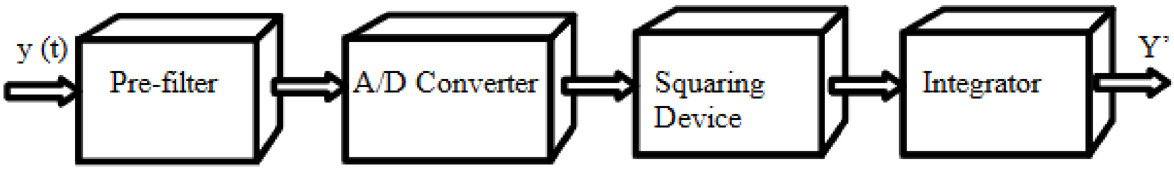

Fig. 4.1. Block Diagram Of Energy detection Based Spectrum Sensing[12]

Since no prior information of primary signal is required this technique is also known as Blind detector technique. After receiving the energy of all the signals the detector compares that energy with predetermined threshold. Threshold has been derived from all the information of noise. The two scenarios can be formulated analytically as:

$H_0: y(n) = w(n)$: Primary user absent

$H_1: y(n) = s(n) + w(n)$: Primary user present

Where $w(n)$ is Additive White Gaussian noise (AWGN), $s(n)$ is the signal transmitted by primary user, $y(n)$ is the signal that has been captured by the Cognitive radio. The matrix is evaluated from the energy of all filtered received signals. The energy of all these filtered received signals is compared with a known threshold. Then afterward numerous probabilities like missed detection, false alarm and detection probabilities are evaluated.

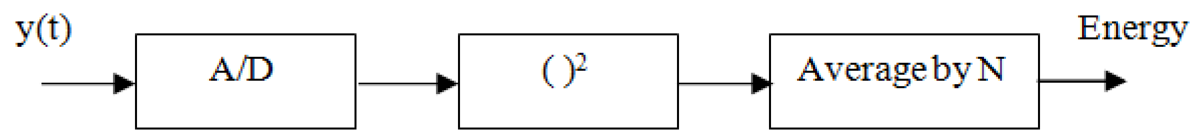

Fig. 4.2. Implementation of Energy detector with square law device[24]

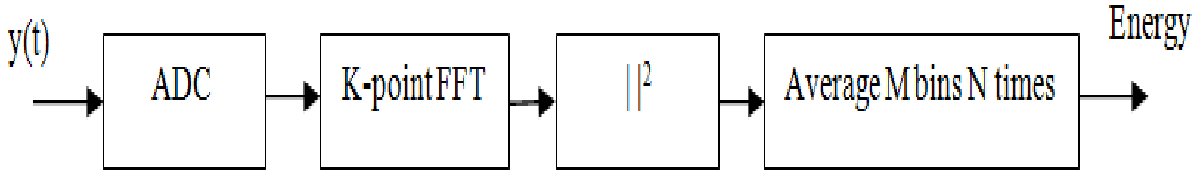

Fig. 4.3. Implementation of Energy detector using FFT [24]

Along with some *advantages* discussed above, it also has some *disadvantages*.

Disadvantages:

1. To achieve a given probability of detection, sensing time is high.

2. ED cannot distinguish primary signals from the CR user signals. As a result CR users need to be tightly synchronized and refrained from the transmissions during an interval called Quiet Period in cooperative sensing.
3. Detection performance is subject to the uncertainty of noise power.
4. ED cannot detect spread spectrum signals.

Matched filter based detection**:** It is very complex. This procedure demands prior information of primary user which is very [25] difficult to get. Matched filter is the ideal method to sense the presence of the primary signal if modulation rate, coding technique etc. of primary user are known. If all this awareness about the primary signal is known then this method is best available to sense the presence of the primary signal. This method correlates received signal with the already known primary signal and thus reduces the SNR. Consequently, this technique executes the perfect functionality of the detection.

To achieve a given probability of detection, sensing time is less since it requires less received samples due to prior information of primary signal.

Matched filter (MF) is a linear filter. The main task of this filter is to maximize SNR at the receiver side when the input is given. This technique is applied when secondary user knows the information of the primary user.

Advantages:

1. The time required by this filter to detect the primary user is less.
2. This detection is optimal in stationary Gaussian noise if cognitive radio have information of primary user.

Disadvantages:

1. This method demands prior information of primary signal which is difficult to get.
2. One most considerable limitation of this method is that for different primary signals, CR would need a dedicated receiver.
3. If all the information about the primary signal is not accurate then this technique will perform poorly.

Cyclostationary-feature detection**:** This method of detection is mainly discovered since most of man-made communication signals like AM, BPSK, OFDM, QPSK exhibit cyclostationary behaviour. Signals that are noisy in nature does not exhibit the feature of Cyclostationary. The detectors of such kind are very forceful against the variance of the noise. The main motive of such detectors is to exploit cyclostationary nature of man-made communication [40] signals buried in noise. The detectors that exploit the characteristics of the Cyclostationary can be single or multi cycle.

- ***Single Cycle detectors*****:** The detectors of such kind just takes into consideration one cyclic frequency.
- ***Multi-cycle detectors*****:** In this detector, to detect whether primary signal is present or not multiple cyclic frequencies are examined. The scenarios in which such kind of detectors are employed gives better but the multi ones are very complex.

This procedure exploits the concept of the periodicity in received signals to sense the presence of primary user. Generally in pulse trains, spreading code, sinusoidal carriers, hopping sequences of the primary signals periodicity is employed. Properties of periodic statistics and spectral correlation are exhibited by these signals due to periodicity. This kind of detector also demands the awareness of the primary signal's data. Such kind of detectors are robust to noise and this detector executes the better outcome when it is compared to the energy detector. This technique can distinguish the cognitive radio transmissions from various primary signals. This eliminates synchronization requirement of energy detection in cooperative sensing. Hence, the minor users will not cause any intrusions to the crucial ones and this increases the performance of the detector.

However this method executes the high outcome but some shortcomings are also exhibited by this method. This technique is very complex. The time of sensing of this detector is high. Consequently, this method of detection is less employed when it is compared to that energy detector in cooperative sensing.

Covariance detection**:** If two random are present in nature, the link must be among them. This is the measure of [41] strength of the link between two random variables. The two scenarios can be there generally. First is the case in which value of the single variable is known and does not specifies the second variable's value. In that case, both variables are independent. Second is the case where some relation is among both variables. If in between relation has to be defined then covariance is the technique. Covariance technique does not demand the awareness of the values to be determined.

It quantifies the link among variables by exploiting the distributions. Types of this method are:

1. *Covariance absolute value (CAV) detection*
2. *Covariance frobenius norm (CFN) detection*

The false alarm probability is formulated. Threshold and missed detection probability are also formulated. This technique can be exploited if the awareness of the signal, intrusion, channel etc. is not known.

***Wavelet detection*:** To diminish constraints of the Fourier transforms wavelet analysis is the most latest solution. A wave is an oscillating function of time. In this technique, the problem of window cutting is deciphered by exploiting fully scalable modulated window. Alongside message window is shifted formation of the spectrum at every point. Then for every new cycle, this process is repeated in which the size of the window is smaller or larger. In the end the result will be a collection of time-frequency representations of the signal, all with different resolutions. Types of this method are:

1. *Continuous wavelet transform (CWT)*
2. *Discrete wavelet transform (DWT)*

Continuous wavelet transform (CWT): The functions of wavelets that are exploited in transformations are evaluated by employing shifting and scaling principals on governing wavelet. In CWT simple rules or functions are employed to analyze the signal.

Discrete wavelet transform (DWT): It exploits sub-band coding. It yield a fast computation of Wavelet Transform. It is uncomplicated and the valuable technique since the resources these demands are less and it reduces the computation time. In DWT, digital filter techniques are exploited to execute the time-scale concert of signal that is a digital signal.

In this technique, signals are analyzed using a basic set of functions which relate to each other by simple scaling and translation. Numerous numbers of functions are available that can be deployed as governing wavelet. Since the spectrum band is limited so to provide access to all users in the spectrum band wideband techniques has been developed. It is based on correlations signal patterns that are known. In such patterns generally spread sequences, preambles, pilot patterns that are transmitted recurrently are there. For the synchronization in wireless systems, these known patterns are used. The reliability of this technique is greater when compared to the energy detection. As the known patterns increases in length, the performance of detection increases.

***Interference based detection*:** Interference is generally maintained in a transmitter-centric way, which means interference can be controlled at transmitter side through radiated power To control the intrusion [42] at the transmitter side radiated power. Interference temperature is the model to measure the interference that has been developed. At the receiver side, temperature limitation concept has been exploited in this approach. The noise floor is the one aspect up to which the intensity of the intrusion is nil. But if the level of the noise floor is enhanced then there is an interference. To measure the interference temperature, some limitations exists. If secondary users do not have any information about primary users then this technique can be used. Antennas, types of modulation of secondary users, power control, activity to spot the licensed channels, activity intensity of the secondary and the primary users are various parameters of this technique.

The FCC has made some commendations. These commendations deem a shift in the interference. This shift is away from the fixed transmitter. It measures the bandwidth of used spectrum and also measure the intensity of intrusion. If secondary users demands to transmit their signals then they must make sure that level of interference should not exceed by them. If noise floor's intensity is enhancing by transmitting signal then that signal is considered as harmful. Since cognitive radio does not has any information of primary users in the spectrum and also do not know the distance between primary and secondary user, the cognitive radio will not what emission level will raise the interference temperature of primary receiver. So cognitive radio is exploited only to sense the primary user in the spectrum band. When signal is detected then the cognitive radio system can respond in numerous ways:

- *Avoidance*: The set up of cognitive radio will choose a frequency band which will not overlap with the detected signal. So, cognitive radio is intended to detect the radio signal only.
- *Transmit power control or spectrum spreading*: The range and the capacity will degrade if the intensity of transmission degrades. If the spreading parameter is increasing then capacity will decrease. If cognitive radio do not know the strength of primary user, then secondary user will not know that how

much PSD can be reduced. So the only aspect is to degrade the intensity of transmission.

4.4 Fading

Fading describes the rapid fluctuations of phases, amplitudes, or multipath delays of a radio signal over a short time period. The fading experiences by the specific channel is known as fading channel. Fading is random in nature. The fading [43] is introduced due to numerous factors like geographical region, radio frequency etc. The factors that are accountable for the fading can be multipath or the shadowing. To transmit the signal there is need of one receiver and one transmitter. The signal while traversing from the transmitter side to the receiver side, it is not mandatory that original signal has been received. This is due to various interferences in the channel.

Types of fading:

- ***Large scale shadowing***
- ***Small scale fading***

***Large scale* shadowing:** This type of fading occurs on a large scale. This fading corresponds to conditions that may vary as one turns a corner. The log-normal is an example of this shadowing.

***Small scale fading*:** The fading that occurs on a small scale is small scale fading. It is basically termed as fading. This interference occurs among the transmitted signals. These reach the destination at different times. The aspects of the fading are the swift changeability of the radio signal over the shorter period. The fluctuations that are rapid can be of the phases, delays of the multipath and the amplitudes. Since all these variations are occurring over the period that is small, the fading that occurs on large scale ignored.

4.4.1 Types of Small Scale Fading

To categorize the small scale fading, Doppler spread and the multiple time delay spread are the two parameters.

Fading effects due to multipath time delay spread

- ***Flat fading***
- ***Frequency selective fading***

***Flat fading*:** In this fading, spectrum bandwidth of the channel is greater than the bandwidth of transmitted signal. The signal's strength of the received signal does not remain same. In this fading, the strength of the received signal varies if the gain of the channel changes.

This fading results in deep fading. This fading is also known as amplitude varying channel. Narrowband channels are characterised by the flat fading. To design the radio link, the distribution of the instantaneous gain is significant. In this delay spread is higher in comparison to symbol period.

***Frequency selective* fading:** In this fading, spectrum bandwidth of the channel is greater than the bandwidth of transmitted signal. Frequency selective fading occurs because of the time dispersion in the bandwidth of the transmitted samples.

In this scenario, the impulse response of the channel exhibit delay spread and it is higher in comparison to the reciprocal bandwidth of the transmitted signal. The intersymbol interference is provoked in the channel due to this fading. For this fading, The transmitted signal's has higher bandwidth in comparison to coherence bandwidth of the channel. This fading is complicated to model in comparison to the flat fading. Multiple path delays are accountable for frequency selective fading. Wideband channels are also differentiated by the frequency selective fading. The symbol period is higher in comparison to delay spread. Fading effects due to Doppler spread are:

- ***Fast fading***
- ***Slow fading***

***Fast fading*:** The transmitted baseband signal. In this fading, the impulse response of path revolutionizes swiftly. Frequency dispersion is exhibited by this fading. The signal distortion boosts due to this fading, when the Doppler spread increases. This fading is exhibited by only low data rates.

In fast fading, Doppler spread is higher when compared with slow fading. The variations in the message are slow when compared to the variations of the channel. Coherence time is smaller when compared to the symbol period. The bandwidth of transmitted signal increases slowly with increase in Doppler spread in comparison to signal distortion in fast fading.

***Slow* fading:** In slow fading, Doppler spread is smaller. The variations in the baseband signal are greater than the variations in the channel. The symbol period is greater when compared to the coherence time.

4.4.2 Fading Distributions

- ***Rayleigh fading***
- ***Rician***
- ***Nakagami-m***
- ***Gaussian***
- ***Log-normal***
- ***Weibull***
- ***TWDP fading channels***

Rayleigh fading**:** Multipath propagation of the signal is accountable for this fading. This phenomenon finds purpose in hindered propagation paths. The received power actually becomes random.

This signifies most unpleasant case of fading. The most common fading [44] in communication is Rayleigh fading. The intensity of this fading is exponentially distributed. The phase does not depend on amplitude. The distribution of phase is unvarying. Theoretically, the channels that are exploited widely are Rayleigh fading channels. They have no line of sight (LOS) which is direct. If noise spectral density is Gaussian and one-sided, the distribution of SNR is exponential.

This fading is exploited to illustrate the behaviour of the envelope that has been received in the time domain of flat fading channel. If there are two quadrature noise signals and they are Gaussian then their envelope obeys Rayleigh fading.

Rician fading**:** The distribution of the small-scale fading is Ricean, if the LOS is present. In this fading, various components of the multiple paths arrives at numerous angles at the stationary signal. If the governing component fades away, then Ricean distribution becomes Rayleigh fading. The dc components are added to random multipath due to this fading.

If one governing component is there and numerous weaker signals are traversing along the governing signal, then this will give rise to Ricean fading. In this case, one is the governing signal and the remaining are weaker ones. The field in the Ricean fading is spotted moderately.

Nakagami-m**:** This fading exhibits various features that are discussed below.

- The received power is Gamma distributed.
- It was basically developed empirically based on measurements.

- The intensity of the received signal is described by this fading after maximum ratio diversity combining.
- The multiple signals that are independent and identically distributed Rayleigh faded exhibit Nakagami distribution.

The functionality of the Ricean and Nakagami is almost equivalent near their mean value. The empirical data [45] granted by this fading are better than other fading. In a cellular system, this model is appropriate to model interference. The time delay spread is high and occurs for multiple scattered ways. It is universal distribution. One sided Gaussian and Rayleigh are typical scenarios of this fading. It is very flexible. The accuracy is high when compared to other scenarios of fading. It is a universal way to mould small scale fading. To mould intensity, this is sufficient in urban areas. It is better when compared to Rayleigh fading.

***Gaussian*:** This fading has some characteristics that has been discussed below.

- Normal and Gaussian distributions are equivalent.
- It is a continuous probability distribution.
- Bell curve is also regarded as Normal distribution.
- It is symmetric about its mean.
- It is family of stable distributions.

***Log*-normal:** The scenarios where the fading arises at the large scale follows the log-normal distribution. In such fading, the signal that has been transmitted hardly receives at the receiver side since in such scenario the intrusions are numerous that put a stop to over the signal. Consequently, the signal cannot get to the destination and the signal goes to deep phase. So the fading is the kind of intrusion that become an obstacle in the gamut of the signal that has been transmitted so that the signal cannot reach destination.

***TWDP fading channels*:** Devices communicate independently in Machine-To-machine (M2M) wireless communication. Number of smart devices are present in typical M2M network that can perform different functions like processing of data and sensing without the human need. Intelligent transportation, healthcare monitoring, automated manufacturing, home multimedia sharing are different where M2M communication can be used. In such networks, thousands of interconnected [46] devices are present to access the spectrum. So, congestion problem is there. Hence, cognitive radio based M2M networks [47] has been proposed to solve the spectrum congestion problem.

In comparison to conventional system, M2M networks are new wireless technologies since the operational scenarios are supposed to contain enclosed structures like vehicles, aircraft etc. These operating environments [48] have fading conditions that the existing fading models do not exhibits. For example, wireless sensor nodes that has been used in metallic enclosed structures exhibit spatially-dependent and frequency-dependent fading are more severe than predicted by Rayleigh fading model, which is the worst-case fading case in wireless communication. This type of small scale fading cases are known as Hyper-Rayleigh fading channels. These were Characterized by Two-Wave with Diffuse Power (TWDP) model. Different propagation environments and small scale fading environments like directional antennas, narrow-band receiver operation and wideband signals can be characterized by this fading model. Relating to wireless channel, a TWDP fading channel is characterized by two parameters. First parameter is denoted as S and is defined as ratio between average specular and diffused power. S is expressed as:

$$S = p_1^2 + p_2^2/2\sigma^2 \tag{4.1}$$

where σ^2 is average power of diffused waves and p_1 and $p_2$are voltage magnitudes of two specular waves. Second parameter is denoted as L and is defined as relative strength of two specular waves and is expressed as:

$$L = 2p_1p_2/(p_1^2 + p_2^2) \tag{4.2}$$

Over the TWDP channel, the PDF (probability density function) of SNR (signal-to-noise ratio) is given as

$$f_\gamma(\gamma) = \frac{S+1}{2\bar{\gamma}}\exp(-S)\sum_{i=1}^{V} r_i\left[\exp(r_iS)\exp\left(-\frac{(S+1)\gamma}{\bar{\gamma}}\right)C + \exp(-r_iS)\exp\left(-\frac{(S+1)\gamma}{\bar{\gamma}}\right)D\right] \tag{4.3}$$

Where, $C = I_0\left(2\sqrt{\frac{S(S+1)(1-r_i)\gamma}{\bar{\gamma}}}\right)$ (4.4)

$$D = I_0\left(2\sqrt{\frac{S(S+1)(1+r_i)\gamma}{\bar{\gamma}}}\right) \tag{4.5}$$

Where γ is instantaneous SNR and $\bar{\gamma}$ is average SNR and $I_0(.)$ is modified Bessel function of first kind of order zero. r_i is approximation coefficient and is expressed as:

$$r_i = \Delta \cos(\pi(i-1)/2V-1) \quad (4.6)$$

where V denotes order of approximation of TWDP PDF.

CHAPTER 5
PROPOSED METHODOLOGY, RESULTS AND DISCUSSION

5.1 System Model

In this thesis, a cognitive radio network is considered with N cognitive radios and one primary user. All cognitive radios have T receiving antennas and primary user contains a single transmitting antenna. To sense/detect the primary signal in the spectrum, two hypotheses U_0 and U_1 are considered. U_0 corresponds to the absence of primary signal and U_1 corresponds to the presence of primary user in the spectrum. Mathematically, these hypotheses can be described as:

$$U_0: y_l(t) = w_l(t) \tag{5.1}$$

$$U_1: y_l(t) = h_l(t)a(t) + w_l(t) \tag{5.2}$$

where $l = (1,2, \dots, T)$, $w_l(t)$ is Additive White Gaussian Noise that is circularly symmetrical with Zero mean and variance of σ^2, $a(t)$ denotes transmission of key signal, $h_l(t)$ are path gains and these path gains are independent and identically distributed. Improved energy detector has been used at cognitive radios.

5.2 Proposed Methodology

In today's world, secondary users are increasing every day and consequently, congestion is key factor in the spectrum. To conquer this problem, a tool named as cognitive radio has been established. Spectrum has been sensed over Hyper-Rayleigh fading using cooperative spectrum sensing. In the cooperation mode, spectrum has been sensed by using improved energy detector at cognitive radios. Then, Output of the proposed scheme is compared with threshold optimization method and Constant False Alarm Rate method.

Simulation has been performed over AWGN fading channel with the help of Receiver Operating Curves (ROC). Receiver Operating Curves are basically a plot of P_d versus P_f or P_m versus P_f, where P_d, P_f and P_m are detection, false alarm and missed detection probabilities. Detection probability is the probability that the spectrum has been sensed correctly. In false alarm, it is sensed that the primary user is using the spectrum but in actual, the spectrum is vacant. This results in inefficient spectrum utilization. In missed detection, it is sensed that the spectrum is vacant but in actual, primary user is present and this leads to interference between the primary and the secondary user.

Receiver Operating Curves (ROC) has been plotted over AWGN fading channel using the following equations [32]:

$$P_f = \frac{\Gamma(g, \lambda/2)}{\Gamma(g)} \tag{5.3}$$

$$P_{d,AWGN} = Q_v\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \tag{5.4}$$

where $Q_v(c,d) = (1/c^{(v-1)}) \int_d^{\infty} p^v e^{-\left(p^{2+c^2}/2\right)} I_{(v-1)}(cp)dp$ is the generalised Marcum Q-function, $\Gamma(P,z) = \int_z^{\infty} H^{(P-H)} exp^{-H} dH$ is upper incomplete gamma function and γ is received SNR. Detection probability over Rayleigh fading is given by:

$$\begin{aligned} P_{d,Rayleigh} = {} & exp^{(-\lambda/2)} \sum_{t=0}^{g-2} \frac{1}{t!}\left(\frac{\lambda}{2}\right)^t \\ & + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)\left[e^{\left(-\frac{\lambda}{2(1+\bar{\gamma})}\right)} \right. \\ & \left. - e^{(-\lambda/2)} \sum_{t=0}^{g-2} \frac{1}{t!}\left(\frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})}\right)^t\right] \end{aligned} \tag{5.5}$$

where $\bar{\gamma}$ is the average SNR.

Then detection performance has been analyzed over numerous fading scenarios viz. AWGN, Rayleigh and TWDP (two wave with diffuse power) fading in terms of error probability of detection with respect to threshold. TWDP fading is also distinguished by Hyper-Rayleigh fading.

Average detection probability over fading is obtained by averaging (5.4) over corresponding SNR fading statistics. For TWDP channel [33] average detection probability is expressed as:

$$\overline{P_{d_{TWDP}}} = \sum_{i=}^{V} \frac{1}{2} s_i \left[Q\left(\sqrt{\frac{2S\bar{\gamma}(1-s_i)}{S+\bar{\gamma}+1}}, \sqrt{\frac{\lambda(S+1)}{S+\bar{\gamma}+1}} \right) + Q\left(\sqrt{\frac{2S\bar{\gamma}(1+s_i)}{S+\bar{\gamma}+1}}, \sqrt{\frac{\lambda(S+1)}{S+\bar{\gamma}+1}} \right) \right] \quad (5.6)$$

Then detection performance has been analyzed by using cooperative spectrum sensing.

False and missed probabilities in [30] cooperative spectrum sensing are given as:

$$Q_f = 1 - \left[(1-P_f)(1-k) + kP_f \right]^N \quad (5.7)$$

$$Q_m = \left[P_m(1-k) + k(1-P_m) \right]^N \quad (5.8)$$

Then in terms of detection error probability P_e, performance of the proposed scheme is analyzed with respect to SNR over TWDP by evaluating $P_e = P(H_0)\, Q_f + P(H_1)P_{md}$.

$$P_e = 0.5\left(1 - \left[(1-P_f)(1-k) + kP_f\right]^N + 0.5\,(1-P_d)\right)$$

where

$$P_f = \frac{1}{T} - \frac{1}{T}\left[1 - exp\left(-\frac{\lambda^{\frac{2}{u}}}{\sigma_n^2}\right)\right]^T$$

$$P_m = \frac{1}{T}\left[1 - exp\left(-\frac{\lambda^{\frac{2}{u}}}{\sigma_n^2(1+\gamma)}\right)\right]^T$$

Therefore,

$$P_e = 0.5\left(1 - \left[\left(1 - \frac{1}{T} - \frac{1}{T}\left[1 - exp\left(-\frac{\lambda^{\frac{2}{u}}}{\sigma_n^2}\right)\right]^T (1-k) + k\left(\frac{1}{T} - \frac{1}{T}\left[1 - exp\left(-\frac{\lambda^{\frac{2}{u}}}{\sigma_n^2}\right)\right]^T\right)\right)\right]\right)^N + 0.5\left(1 - \sum_{i=}^{V} \frac{1}{2} s_i \left[Q\left(\sqrt{\frac{2S\bar{\gamma}(1-s_i)}{S+\bar{\gamma}+1}}, \sqrt{\frac{\lambda(S+1)}{S+\bar{\gamma}+1}} \right) + Q\left(\sqrt{\frac{2S\bar{\gamma}(1+s_i)}{S+\bar{\gamma}+1}}, \sqrt{\frac{\lambda(S+1)}{S+\bar{\gamma}+1}} \right) \right] \right) \quad (5.9)$$

In the cooperative mode, selection combining has been used and total error rate has been established in terms of false and missed detection over binary symmetrical channel. Curves has been plotted in terms of total error rate in the cooperative mode with respect to amplitude's power (p) of samples of primary users and with respect to SNR. In the end, performance has been analyzed in terms of error detection probability over Hyper-Rayleigh fading with respect to SNR and is compared with threshold optimization and CFAR method in which energy detector is used using MATLAB.

5.3 Results

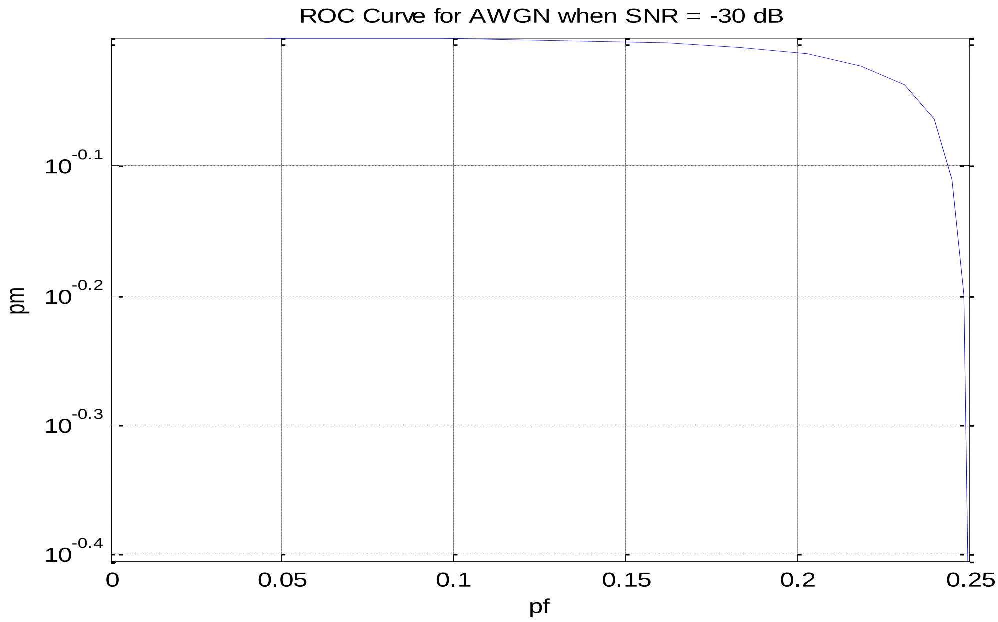

Fig. 5.1. ROC Curve for AWGN Fading Channel

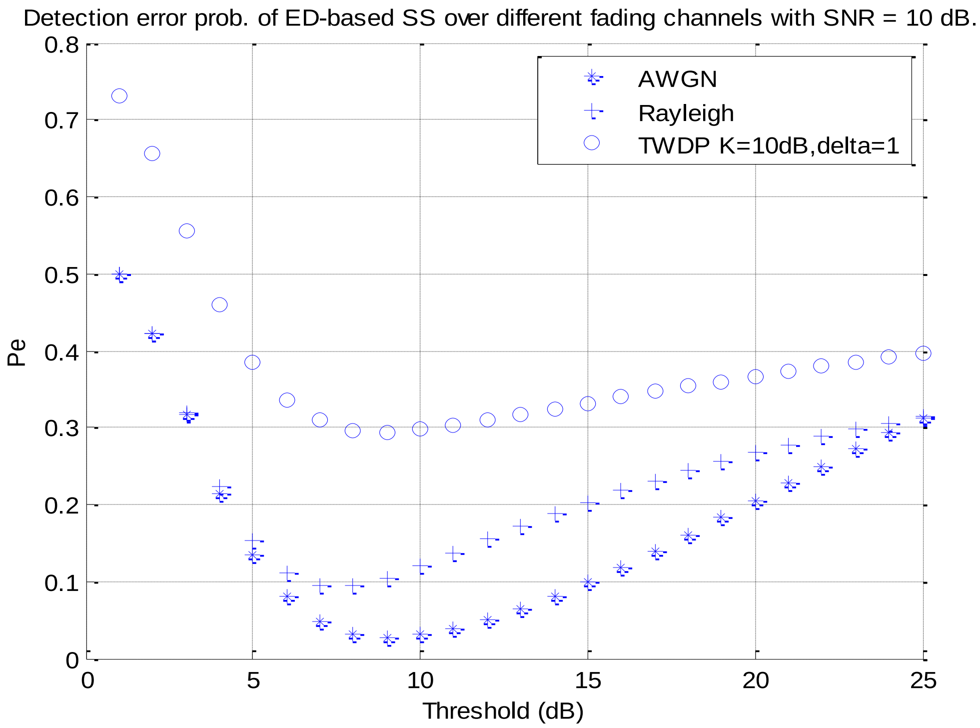

Fig. 5.2. Detection Error Prob. of ED-SS Over Diff. Fading Channels

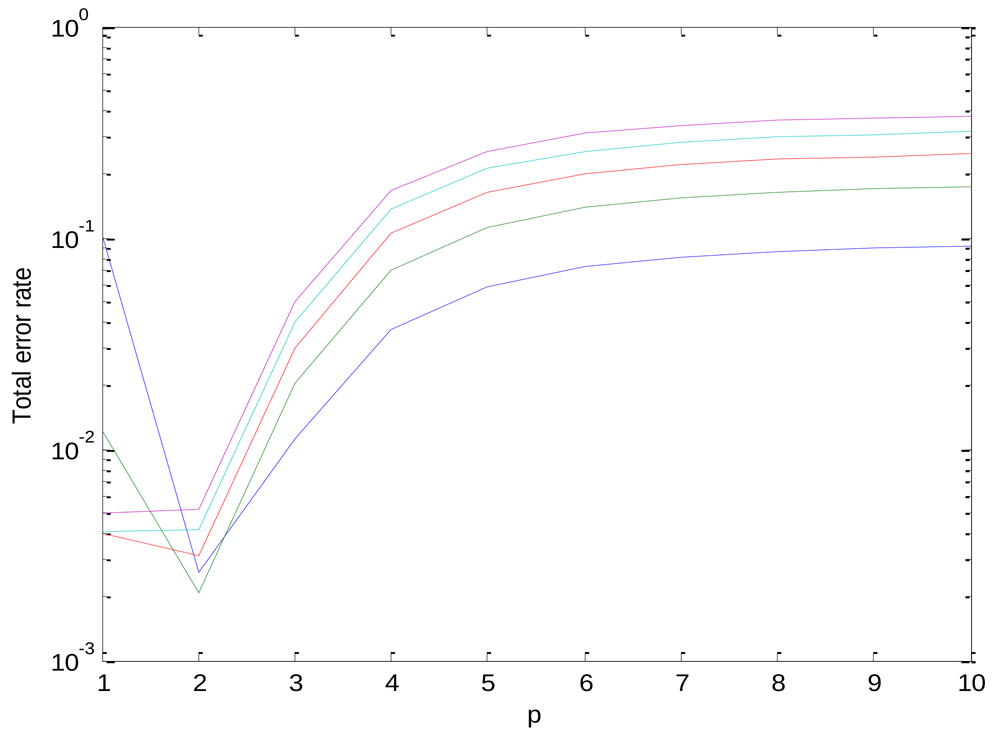

Fig. 5.3. Total Error Rate Vs p Plot in Cooperative Spectrum sensing

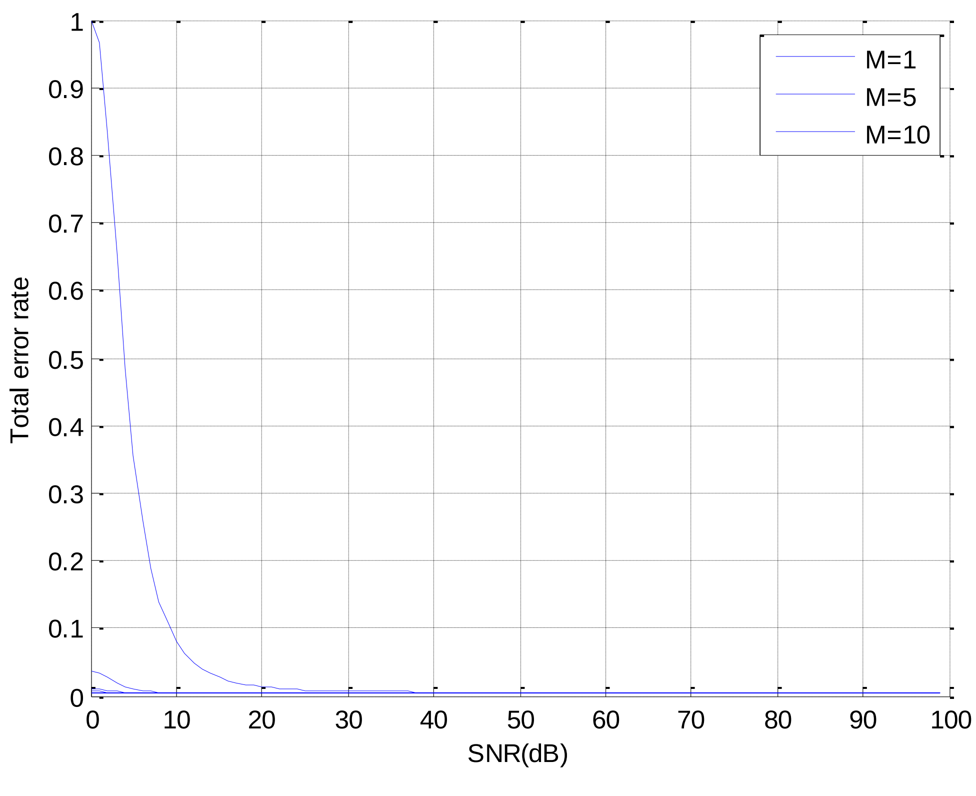

Fig. 5.4. Total error rate Vs SNR Plot in Cooperative Spectrum Sensing

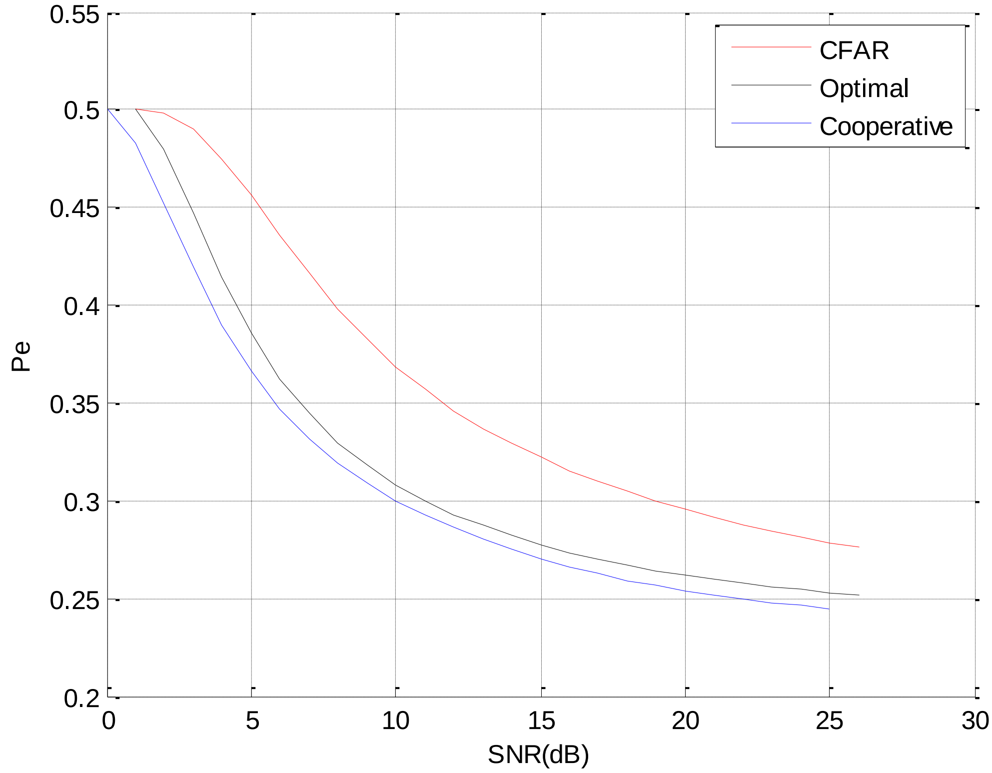

Fig. 5.5. Detection Error Probability Vs SNR Plot Over TWDP for Cooperative Spectrum Sensing, CFAR and Optimal Threshold

TABLE 5.1. Comparison of P_e Vs SNR in Different Sensing Techniques

SNR in dB	Value of P_e in Cooperative Spectrum Sensing	Value of P_e in Optimal Threshold method	Value of P_e in CFAR
0	0.50	0.50	0.50
5	0.37	0.39	0.45
10	0.30	0.31	0.37
15	0.27	0.28	0.32
20	0.25	0.27	0.29
25	0.24	0.26	0.28

5.4 Discussion

In this thesis, performance analysis of cooperative spectrum sensing employing improved energy detector over TWDP channel is evaluated and compared with threshold optimization and CFAR methods. Also, ROC curves for AWGN and Rayleigh fading channel has been simulated.

In cooperative spectrum sensing, at each cognitive radio different antennas has been used.. In CFAR, the performance curves are obtained by evaluating (5.6) w.r.t. SNR for optimized detection threshold of 17.5 (this value is calculated over various iterations). For optimum approach, curves are obtained by evaluating (5.6) w.r.t. SNR for optimized detection threshold of 9.5 (this values is calculated over various iterations). When cooperative spectrum sensing is used, then performance curves are obtained by evaluating (5.9) w.r.t. SNR for an optimum number of cognitive radios, antennas, and threshold. The optimum number of CRs, antennas and threshold are 5, 10 and 10 respectively.

Figure 5.6 shows that using CFAR, minimum P_e = 0.28 is achieved at 25 dB and for the same SNR, optimum threshold method achieves a minimum P_e = 0.26. But when cooperative spectrum sensing is used, the minimum P_e = 0.24 is achieved for the same SNR. Also, for optimum threshold method and cooperative method P_e = 0.28 is achieved at 14 dB and 11 dB respectively. Therefore, by using cooperative sensing error detection probability can be reduced or in other words SNR gains can be achieved.

In figure 5.1, receiver operating curve has been simulated for AWGN channel. These curves are the graph between false and missed probabilities.

In figure 5.2, simulation of energy detector based spectrum sensing has analyzed over different fading channels. This figure shows that how the probability of error detection is varying with respect to a threshold in different fading channels.

In figure 5.3, simulation of total error rate versus amplitude of primary user's samples has been analyzed. Results shows that in cooperation mode, the number of cognitive radios and value of *p* are exceptional for which minimum error rate exhibits.

In figure 5.4, Simulation of total error rate versus SNR has been analyzed. Results shows that in low SNR regions, less error rate is achieved if at each CR various antennas are used

In figure 5.5, the comparison of cooperative sensing technique using improved energy detector over TWDP has been done with CFAR and the threshold optimization approach. The comparison has been done through simulation. These results shows that by using cooperative sensing error detection probability can be reduced or in other words SNR gains can be achieved.

In table 6.1, Comparison of P_e versus SNR in Different Sensing Techniques has been done. Error detection probability over different techniques is calculated at different values of SNR and it is decreasing with increase in the SNR values. Cooperative spectrum sensing has outperformed the CFAR and optimum threshold methods. Thus by using cooperative spectrum sensing, SNR gains can be achieved.

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Simulation results of Complementary Receiver Operating Curves (ROC) have been evaluated for AWGN Channel and for Rayleigh Channel with the help of MATLAB. Also simulation results to sense vacant spectrum bands over the Hyper-Rayleigh Fading has been executed in terms of P_e with respect to threshold. In the cooperative spectrum sensing, simulation of total error rate versus amplitude of primary user's samples, and SNR has been analyzed. The comparison of cooperative sensing technique using improved energy detector over TWDP has been done with CFAR and the threshold optimization approach in terms of P_e with respect to SNR.

Closed-form expression is derived for average detection probability over TWDP. Missed and false alarm probabilities are derived in cooperative spectrum sensing. Results shows that detection probability is reduced when cooperative spectrum sensing is used in comparison to energy detection based spectrum sensing or in other words SNR gains can be achieved and hence efficiency can be enhanced of cognitive M2M wireless nodes.

6.2 Future Scope

Spectrum Sensing is very important in today's world. The number of secondary users are increasing day by day and this will create the problem of spectrum scarcity. To overcome this problem many people worked and they found a tool named cognitive radio which will sense the spectrum very intelligently. Secondary users can transmit their signals only when the primary users are not using the spectrum band. Cognitive radio will tell the secondary users which channel is available. There are many techniques on which people have worked and for the future scope people can work on other spectrum sensing techniques.

1. Cooperative spectrum sensing can be performed for different fading channels using different detectors .
2. Cooperative spectrum sensing for cognitive radio with the help of cyclostationary detector can be performed over TWDP.

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LIST OF PUBLICATIONS

1) Communicated:

"Cooperative Spectrum Sensing Over Hyper-Rayleigh Fading Channels in Multiple Antenna Based Cognitive Radio Networks," submitted in International Conference on Intelligent Circuits and Systems.

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