DESIGN OF A NOVEL TWO-STAGE SPECTRUM SENSING MODEL FOR COGNITIVE RADIO NETWORK

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CERTIFICATE

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I hereby certify that this thesis entitled, **“Design of a Novel Two-stage Spectrum Sensing Model for Cognitive Radio Network”-**

a. Is original and has been done by me under the guidance of my supervisor.

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LIST OF ABBREVIATION

CRN	:	Cognitive Radio Network
IED	:	Improved Energy Detection
CED	:	Conventional Energy Detection
CD	:	Cyclostationary Detection
AWGN	:	Additive White Gaussian Noise
MFD	:	Matched Filtering Detection
CR	:	Cognitive Radio
CSD	:	Cyclostationary Spectrum Density
SNR	:	Signal to Noise Ratio
FFT	:	Fast Fourier Transform
PSD	:	Power Spectral Density

ABSTRACT

Cognitive radio (CR) is the most efficient technology ever to meet the requirement of radio spectrum, which is a very scarce resource now days. CR allows secondary or unlicensed users to access the spectrum dynamically and opportunistically without interfering the services of primary or licensed users. The design of a “Cognitive Radio Network” requires an efficient method of “spectrum sensing”. As only efficient sensing allows the secondary users to access the spectrum opportunistically. Many potential researchers have been working all over the world on this topic. Different “spectrum sensing” techniques have been developed in recent years. Some of the researches focus on enhancing the efficiency of the method, some provides better robustness against noise uncertainty and some reduces the time of sensing as well as complexity. “Energy Detection” technique of spectrum sensing is the foremost and simplest method. Motivated by this method, a novel Two-stage Model of “Spectrum Sensing” has been proposed in this work. Furthermore, to reduce the complexity and enhance the robustness against noise two different stages have been described in this model. Firstly, the SNR value of the incoming signal is evaluated. Next, a hybrid method associated with “Improved Energy Detection” and “Cyclostationary Feature Detection” is established to sense the spectrum in low SNR regime. Some digital filtering techniques are used to reduce the effect of noise. It allows the sensing technique to perform effectively when weak primary signal is transmitted. Next, an SNR wall is implemented. According to the SNR value of the incoming signal the dedicated stages of the algorithm will be executed. Subsequently, a “Binary Hypothesis Test” is formulated to perceive the resultant detection performance. Some other spectrum sensing technique is also implemented for comparison purpose with the proposed model. Simulation results reflect that the proposed architecture outperforms existing techniques in varying SNR regime, thus establishing the superiority of the proposed model over the others.

Chapter 1

Introduction

1.1 Overview

In recent years, the “Cognitive Radio Network” is considered as one of the major contribution in wireless communication field. It is the only effective solution for the problem of spectrum scarcity [1]. The effectiveness of this network is directly linked to the efficient “spectrum sensing” techniques. Various sensing techniques have been proposed by several researchers over the year such as “Energy Detection”, “Matched Filter Detection”, “Cyclostationary Detection” etc [2]. To obtain the best possible performance of the network the sensing techniques should be very efficient. Enhanced detection performance, reduced complexity, reduced sensing time ensures the effectiveness of the “Cognitive Radio Network”.

1.2 Motivation

After introducing by Joseph Mitola [3] the term ‘Cognitive Radio Network’ received a considerable amount of interest in the wireless communication field.

Limited network coordination and static spectrum allocation limits the functionalities of a wireless system. Radio spectrum is considered as the most valuable resource. Cognitive Radio system offers to use the available spectrum dynamically in an opportunistic manner. It helps the unlicensed users to adapt with the available local spectrum and prevent interference with the licensed user [4]. In “Cognitive Radio Network”, the unlicensed users sense the spectrum and in the case of its availability, they start communicating with other unlicensed users without interfering the licensed users. Otherwise, they wait for a predetermined amount of time and sense the spectrum again.

Form the time of evolution the “Cognitive Radio Network” is considered as the most effective solution of spectrum scarcity [5]. A good sensing algorithm ensures the proper functionality of this network. Since then, various research papers have been published showing different sensing algorithm with some pros and cons. The motivation for reduced complexity and enhanced detection performance drive us towards designing of this sensing model. In this work, we have used “Improved Energy Detection” model as it offers less computational complexity. To enhance the detection performance “Cyclostationary Detection” model have been used here in conjunction with “Improved Energy Detection” model.

1.3 Thesis Objective

Designing a spectrum sensing technique with reduced complexity and high detection performance is much needed for the effectiveness of the “Cognitive Radio Network”. In recent time, some potential researches have been published to reduce the complexity and enhancing the detection probability of the sensing techniques. In this regard, different techniques, algorithms are emerged. Among different sensing algorithms, “Energy Detection” is the most useful due to its low computational complexity [6] and “Cyclostationary Detection” is useful for its considerably high detection performance [7]. Getting motivated by this research trends, a novel approach has been taken to design an efficient “spectrum sensing” model. The main objective of this thesis is to find an effective “spectrum sensing” technique with reduced complexity and enhanced detection probability. Another objective of this thesis is to estimate a comparative analysis in between the existing and proposed sensing models and suggest the best possible option among them. The objective of any research work is to modify the existing work to obtain the better result. In this work also, an attempt has been made to modify the existing models to achieve further improvement. In order to achieve this, a two-stage hybrid model associated with "Improved Energy Detection" and "Cyclostationary Detection" is proposed here. The final simulation result reflect that the proposed model outperform the existing models.

1.4 Contribution of the Thesis

In this thesis, the design of a two-stage hybrid spectrum sensing model is presented. The pertinent contributions are as follows:

- The mathematical equations necessary for designing the proposed model is derived from the conventional spectrum sensing techniques.
- The algorithm is designed for the proposed model based on the mathematical derivations in MATLAB 2016a platform.
- The design of the "Conventional Energy Detection Technique", "Improved Energy Detection Technique" and "Cyclostationary Detection Technique" has also been developed in the same platform for the purpose of comparison.
- Finally, the afore mentioned sensing techniques is compared with the proposed model to estimate the superiority of the later one.

1.5 Thesis Outline

The rest of the thesis has been structured in the following way:

- In chapter 2, the detailed literature survey on "spectrum sensing" methods in "Cognitive Radio Network" is presented.

- An overview of the "Cognitive Radio Network" and "Spectrum Sensing" methods are discussed in chapter 3.

- Chapter 4 includes the detailed description of the proposed two-stage hybrid spectrum sensing model.

- Simulation results of the corresponding work, its critical analysis and its comparison with existing models are summarized in chapter 5.

- Finally, the concluding remarks are put in chapter 6. Some of the scopes for future relevant works are also discussed in this chapter.

Chapter 2

Literature Review

2.1 Overview

In this chapter, the potential contribution of several researchers across the world in the field of "Cognitive Radio Network (CRN)" is thoroughly reviewed. "Spectrum Sensing" is the fundamental requirement of CRN. So, in this chapter various spectrum sensing methods have been reviewed to understand different evolutionary techniques and technologies to improve the overall performance of a CRN.

2.2 Review of the Related Work

The "Cognitive Radio Network" is the most powerful solution to the problem of spectrum scarcity. As most of the spectrum is assigned already in a fixed manner, spectrum is getting scarce day by day. That is why CRN technique had been adopted to allow the underutilized spectrum to be reused in an opportunistic manner [8]. In order to make this technique efficient proper spectrum sensing is the mostly needed thing. Some of the important factors based on which the performance of a sensing technique is judged are efficiency, complexity and power consumption. In recent times, a number of research article have been published to reduce the complexity and increase the efficiency. Our proposed work is mainly focused on "Energy

Detection Techniques", "Cyclostationary Detection Technique" and some hybrid models. So, these methods are reviewed elaborately in subsequent sections. Some other spectrum sensing methods also exists. That has been also reviewed later on.

For better understanding of the literature review the total portion is sub divided categorically.

2.2.1 Review of the Energy Detection Technique

A paper published in 2007 [9] proposed the fundamental tradeoff in between the achievable throughput and the sensing efficiency by employing a form of Energy Detection method. In this work, the sensing slot duration is studied and designed to maximize the throughput. The throughput of the secondary users has been maximized under the constraints of the sufficient protection of the primary users. It has been shown here that the Energy Detection scheme provides the best trade off with an optimal sensing time. This work focused on cooperative sensing based on this sensing- throughput tradeoff.

To overcome the issue of susceptibility to noise uncertainty of energy detection method a new method was proposed in [10] which focus on the combination of the received signal. The received sampled signals are optimally combined in space and time under the condition of maximizing the signal to noise ratio. Energy Detection scheme is used after combination. But, this process requires the information of the signal and channel which is usually unknown. To resolve this issue "Blind Combination" is suggested in this paper. This proposed method does not require any prior information just as in case of simple Energy Detection. This method works better for correlated signals. Even it does not require perfect synchronization.

In 2009 [11], a paper was published which focuses on the performance of the energy detection while employed in cooperative spectrum sensing. In cooperative spectrum sensing multiple CRN works simultaneously and their collaborative results are interpreted in a fusion center. Several CRN searches the spectrum simultaneously to detect the white space. In this work, the optimality of the cooperative sensing has been tested with an aim to maximize the detection probability. The optimal voting rule is derived also in this work. The threshold was also determined in that scenario when energy detection was applied. Finally, a fast sensing algorithm was proposed for a large network which needed few no of CRN units in cooperative sensing within a fixed error bound.

The detection performance of energy detector employed in a cooperative sensing was investigated for the channel with both multipath effect and shadowing. The result had been discussed in [12]. The analysis was focused on decision fusion and data fusion strategy. In decision fusion the exact probability of false alarm and probability of detection was derived. This model works on multi hop network. The performance of this model has also been tested for lognormal shadowing and Rayleigh fading channel.

Energy detection technique can be limited severely at times for the effect of noise uncertainty. It affects the detection performance badly. The estimated noise power is employed in energy detection and the threshold is determined for a specifically designed SNR wall in the proposition [13]. This method is suitable for fast sensing applications. It has been shown in this work that SNR wall can be avoided by the noise estimation if the consistency is maintained in estimation process with the interval of observation.

Adaptive Double Threshold technique was employed in energy detection for better detection performance and minimizing the miss detection probability. This scheme was described in [14].In this technique a lower bound and upper bound of threshold is determined. The actual threshold holds in between this two level. Numerical results show that this method performs well than conventional type. Also it enhances the detection probability and also demise the false alarm probability. It performs better than even single threshold technique. The double threshold is adaptive in nature, i.e. the value of the threshold will get changed according to the received signal.

A paper was published in 2014 [15], which focus on the multiple energy detectors. The performance of that technique is evaluated on the basis of double threshold mechanism. In this proposition each energy detector unit is equipped with single antenna and each CR node has multiple energy detector units. This method was also employed on cooperative spectrum sensing. Results shows that this method gives better result in low SNR region. This method improves the system reliability as well as accuracy and also minimizes the complexity.

A double threshold scheme associated with adaptive power allocation scheme is proposed in [16]. Double threshold enhances the accuracy. At the same time, adaptive power allocation scheme reduced the power consumption. Both this scheme is employed with energy detection technique under the constraints of limited interference. The whole method was implemented for cooperative spectrum sensing and detection probability was evaluated. Results prove that, this method increases the detection performance.

The performance of energy detection technique was analyzed for an inverse Gaussian channel in [17]. The selection combining diversity scheme also employed. The detection performance of the method is analyzed for a single channel and multi channel scheme. The threshold is determined over several diversity branches. Shadowing effect on this scheme is also analyzed. The miss detection is less in this technique. It is proved in this work, that optimized threshold performs better than fixed threshold.

To deal with the random signal with Gaussian noise a new proposition was presented in [18]. CED performs well for deterministic signal with Gaussian noise and also its performance is poor in low SNR regime. To overcome this issue a new method “Improved Energy Detection” was proposed. Here, the squaring operation on the signal amplitude is replaced by a positive arbitrary integer. In a special case i.e. when the improved parameter is equal to 2, it resembles conventional energy detection technique. Simulation results prove that, it works well in noise uncertainty.

An energy detection technique using estimated noise variance is proposed in [19]. In this work, the noise variance is not the available information. It is estimated and used for threshold calculation. The statistical performance of this method is evaluated. Numerical result of this work proves that this method accurately calculate the threshold value and appropriate for cooperative spectrum sensing technique.

An energy detection method comprising of adaptive threshold is elaborated in [20]. Here, two types of threshold are determined. One is local threshold and another is global threshold. The different value of threshold is calculated and using those values the performance of the sensing technique is evaluated. It has been proved in this work that the local threshold may reduce the value of false alarm, but provides probability of detection. Hence, it is proved here, that global threshold provides better result than local threshold technique.

2.2.2 Review of the Cyclostationary Detection Technique

In 2007, a paper was published [21] which focuses on the evaluation of cyclostationary spectrum density (CSD). The main advantage of this method is its robustness against noise uncertainty. So, it provides better result in fluctuating noise scenario. But, as CSD estimation is a two dimensional method, it makes the proposition more complex. The proposition again offers to convert the process from two dimensional to one dimensional to make it more feasible. This method provides good result in noise uncertainty.

Using the noise rejection property of the cyclostationary spectrum a new method was proposed in [22]. This works well in very low SNR value (>-20 dB). In this method, the cyclic spectrum of the received signal is measured. The measurement is done for a white Gaussian noise affected channel. The total scheme is analyzed for three different measurement methods of cyclic spectrum. This method effectively reduces the probability of false alarm.

To reduce the complexity of cyclostationary feature detection a new method was proposed in [23]. In this work, performance of some cyclic frequency and some other frequency has been analyzed according to the primary user, which in turns reduces the complexity. Second order cyclic feature is used here. To obtain better result multiple detection point is used here. The detection points are determined by simulation. Finally, the combination detection method is employed.

Multiple antennas were employed in cyclostationary detection method to obtain better performance. This method also reduces the complexity. This proposition is described in [24]. While most of the ratio combination method performs well in high SNR value, it performs well even in low SNR. This method enhances the detection performance better than the methods employing single antenna.

In the paper [25], a collaborative cyclostationary spectrum sensing method is described. It is the multi dimensional process. The static hypothesis test used for detecting the signal is transformed to multiple cyclic frequency testing. In this scheme, a collaborative test statistics is defined. This consists of local test statistic and a censoring technique. Among these, only informative test statistic is fed to the fusion center. This method is more suitable for mobile communication.

A novel method was proposed in [26], which employ the smart antennas to locate the primary user. Transmit beam forming is used to avoid spatial diversity. The objective is to establish an adaptive cyclostationary sensing with smart antennas. “Adaptive Cross Self Coherent Restoral” algorithm is proposed here. The complexity of this algorithm is higher than ED, but lower than the existing cyclostationary detection.

To apply the cyclostationary detection scheme in non cooperative sensing a new proposal was given in [27]. This scheme is suitable for detection and avoidance scheme. Using this method the co existence between Wimax and UWB-MB is ensured. Where fast sensing is a primary choice then this method can be used in conjunction with ED to obtain better result.

A cyclostationary feature extraction method is discussed in [28] to sense the vacant spectrum. This work proposes the detection of IEEE 802.11a signals. The pilot subcarriers in the IEEE 802.11 a signals are detected. When detected the pilot carriers the scheme will compare the cyclic frequency values with the pre defined threshold. This confirms the availability of the spectrum. In low SNR value this scheme performs well.

A method was discussed in [29], where each SU performs the single cycle detection process to detect the spectrum. The collaborative decision of the SUs will sent to the fusion center. As, each SU is performing the detection process, a sufficient number of cycle frequency is searched. This enhances the reliability of the system. The performance evaluated in this paper in terms of deflection coefficients.

A wideband spectrum sensing algorithm is proposed in [30], which in turns reduce the complexity also. For wide band sensing high sampling rates are required. The sampling rates are limited by the functionalities of the A/D converter. This method uses the compressed sample via a closed form solution. This closed form solution is very useful in case of compressed sensing. A tradeoff in between the sensing time and compression ratio is established here.

The sensing method targeted for the receivers which has multiple antennas is described in [31]. The eigen value is calculated of the cyclic co variance matrix of the signal. That eigen value is used to determine the presence of the signal in channel. This method can be used for spatially co related signals. This method also shows better robustness to noise uncertainty and better detection probability. This proposed method is tested for quasi-static Rayleigh fading channel.

Usually the signal properties like data rate, modulation, carrier frequency is unknown to cognitive users. This uncertainty produces difficulties in searching the white space in a range of spectrum. To resolve this issue a blind cyclostationary spectrum sensing method is proposed in [32]. In low SNR value it is difficult to sense the presence of the primary user without the knowledge of cyclic frequency. This method allows the cognitive user to sense the spectrum in this condition.

The sensing technique comprising of cyclostationary detection for SC-FDMA signals in “Cognitive Radio Network” is presented in [33]. SC-FDMA is a multiple access technique and it has reasonable complexity. The cyclostationary property of SC-FDMA signal is used for detection purpose. The incoming signal is compared to a predefined threshold, which is calculated by bayesian detection. In this paper is has been shown that bayesian detection outperforms the Neyman-Pearson detector and it minimize the posterior cost.

In the paper [34], a spectrum sensing technique is presented which is associated with auto correlation property and euclidean distance of the signal. The Euclidean distance is calculated from the incoming signal and using that derivation the auto correlation property of the received sample is calculated. Numerical results show that the detection performance of this method is very high.

A cyclostationary detection technique for multiple receivers is presented in [35]. In this work, the maximal ratio combining technique is used. The cyclostationary detection technique is designed based on maximal ratio combining. It shows better result in low SNR value. In this proposition it has been shown that it outperforms the method which comprises with single receiver.

A cyclostationary detection based sensing method for complicated electromagnetic environment is shown in [36]. Some other detection method cannot be applied for this kind of signal as it needs detail information about the noise power. Hilbert transformation is also applied in this work. This method is less complex with compared to the conventional cyclostationary detection as the computational complexity can be controlled according to the sampling time and the step size of the cyclic frequency.

The paper [37] focused on the method associated with entropy estimation using the cyclostationary features of a signal. The entropy estimation of autocorrelation is estimated for different cyclic frequencies. This method is compared to conventional energy detection and conventional cyclostationary detection based on spectral coherence function and it proves its supremacy over the others.

2.2.3 Review of the Hybrid Detection Technique

A hybrid spectrum sensing technique associated with ED and CD is proposed in [38] to enhance the capability of ED in noise uncertainty. In a constant nature of noise, this method provides very high detection performance. Two thresholds are calculated in this method form different parameters. The rule is when the ED is not working reliably then CD invokes. If the priori information of the received signal is available then the parameters of ED can be modified according to CD.

A proper channelization is maintained in between ED, CD and matched filter by constituting a hybrid method proposed in [39]. This method works well in non cooperative spectrum sensing and its reliability is high. Three techniques senses the spectrum at a simultaneously and according to the channel condition the final decision is taken.

A hybrid method is proposed in [40] associated with energy detection and co variance based detection. ED is simple but its performance degrades in low SNR regime. But co variance based method performs well for co related signals. So, by using the hybrid the detection performance is enhanced. When the signal is highly correlated the co variance method invokes else ED takes place.

In the proposition [41], a hybrid model of ED and eigen value based spectrum sensing is presented. To improve the efficiency and enhance the reliability this method is implemented. No priori information is needed for this method. In this method, when ED fails to detect, Eigen value based method invoked.

A two stage hybrid method associated with ED and co variance absolute value method is described in [42]. The time taken for sensing is reduced in this method. The method adaptively decides the sensing method according to the correlation level of the signal. Depending on the level of correlation the corresponding sensing method is invoked.

A hybrid detection technique comprising of Improved Energy Detection (IED) and First Order Cyclostationary Detection (FOCD) is described in [43]. When the IED fails to detect the signal the FOCD invoked. IED has less complexity with respect to FOCD, in contrast the FOCD has better robustness against noise than IED. Finally, all the secondary user decision is summed up in fusion center and final decision is taken there. This method performs well in low SNR regime.

2.2.4 Review of the Matched Filtering Detection Technique

A spectrum sensing technique based on matched filter is discussed on [44]. This method can be employed only if the prior information of the channel and the signal is available. This method requires the detail information regarding the different parameters of PHY and MAC layer of a primary signal. The detector is Gaussian in nature and in order to work properly the received SNR value is to be maximized. The main advantage of this method is that it reduces complexity; perform well in low SNR value. But, if the prior information is not accurate the performance of this method degrades.

In 2013, a research work [45] has been published which emphasized on the matched filtering based spectrum sensing for OFDM WLANs. In this method, the unused spectrum of OFDM WLANs can be detected in minimum time. The accuracy of this method is very good. It is also capable of interference reduction. This technique is mainly implemented to focus on IEEE 802.11a signals.

Another matched filtering based spectrum sensing technique is described in [46]. Here, a closed form equation is derived to find the decision region and several performance matrices. When the primary user is capable of working in different power levels then this method can be employed. This method works well when the primary user transmits different power level.

As the noise is dynamic in nature, so using the static threshold may decrease the quality of performance of the sensing technique. To resolve this issue, dynamic threshold selection is suggested in matched filtering technique in this work [47]. In this method, the threshold keeps changing according to the different parameters of the received signal. So, it works well in noise uncertainty. Results show that, this method works more efficiently than the methods using static threshold.

2.2.5 Review of the Eigen Value Based Detection Technique

A novel method of spectrum sensing was proposed in [48]. In this method, the co variance matrix of the received signal is calculated. The proposition is based on the eigen value of the co variance matrix. In this work, it has been shown that the ratio of maximum to minimum eigen value of the co variance matrix can be used for the spectrum sensing. The threshold can be calculated using “Random Matrix Theory” (RMT). The probability of false alarm also can be determined from the RMT. This method overcomes the problems of noise uncertainty but at the same time it does not require any prior channel information. Hence, reduces the complexity. This method is useful for various signal detection application where prior signal information is not available.

In continuation of the above mentioned proposition another model is described in [49]. The exact decision threshold of a maximum-minimum eigen value detector can be calculated by using the eigen values of a complex wishart matrix. Here, finite number of samples and cooperative receivers are considered to obtain the exact value of threshold and probability of false alarm. In this proposition if equal number of antenna and data samples are used then an approximate closed form formula is to be used to decide the exact threshold. This method outperforms the existing methods of the asymptotic decision threshold.

Another method based on eigen value is proposed in [50]. This method can be used to detect the correlated signals. The co variance matrix of the received signal is generated. The maximum eigen value of that matrix is used to detect the spectrum. Using RMT, the threshold can be determined. As the co variance matrix associated with the co related signals, so this method is best suited for identification of correlated signals. This method does not require any prior information and proper synchronization as well.

To overcome the noise uncertainty problem, an eigen value based spectrum sensing technique is used where double threshold is employed [51]. Selecting double threshold confirms the better performance in low SNR regime. It performs better than the technique which uses single threshold. The RMT is used here also to determine the threshold as well as the probability of false alarm. By employing this technique the detection performance can be enhanced and at the same time the reliability can be increased.

A method of blind spectrum sensing is incorporated with “eigen value based spectrum sensing” technique. In this work [52], the blind spectrum sensing for multi antenna system is investigated. Most of the work uses maximum likelihood ratio. Here, in contrast the eigenvalue moment ratio is calculated using random matrix theory. By employing this method the absence of signal can be detected and the theoretical value of the threshold can be calculated precisely. The eigen value moment ratio is calculated by matrix trace operations. Numerical results show it provides good detection probability.

A decentralized “eigen value based detection” is mentioned in [53]. This kind of sensing technique may work blindly for specific types of signals. In this work, mostly two types of cooperative sensing is discussed. They are batch and centralized type. This work considers the generation of adaptive cooperative technique associated with “eigen value based sensing” in decentralized manner. Firstly, basic “eigen value based sensing techniques” are developed. Next, “distributed subspace tracking” method is executed. This method reduces the problems associated with the centralized approaches.

A comparative study associated with complexity and accuracy in between “eigen value based sensing” and “energy detection” proposed in [54]. The impact of observation bandwidth and signal bandwidth is evaluated here. The “probability of detection” is proportional to signal bandwidth in case of energy detection. The ratio of signal bandwidth to observation bandwidth is 0.5 for “eigen value based sensing”. Based on this evaluation a new strategy of detector is proposed here. The proposed model provides better accuracy than others.

2.3 Outcome of the Review

From the above literature review, it is found that the spectrum sensing plays an important role in CRN. Performance optimization of the sensing techniques can be done in different ways: (i) by reducing the complexity, (ii) by enhancing the detection probability, (iii) by decreasing the probability of false alarm as well as miss detection, (iv) by enhancing the robustness against noise uncertainty. Over the years, researchers have developed or modified different sensing techniques to achieve the best possible result. While reviewing different sensing techniques it is found that the ED is the simplest form of spectrum sensing. It has low computational and implementation complexity. But, robustness in noise uncertainty is very poor. This problem is partially resolved by IED. Matched filtering technique provides good result but only if the prior information is accurate. The CD performs well in low SNR value. But, the complexity is very high. Form the review, it has been seen that ED is less complex as compared to where as CD may resolve the disadvantage of ED. So, in this thesis, an attempt has been made to design a less complex and more efficient spectrum sensing technique suitable for “Cognitive Radio Network”.

Chapter 3

Theoretical Background of Spectrum Sensing Technique In Cognitive Radio Network

3.1 Overview

The recent boom in the wireless communication field creates the spectrum scarcity problem. To resolve the issue the concept of "Cognitive Radio Network (CRN)" was evolved. From then, the CRN is considered as the most useful method for spectrum reuse. Spectrum sensing is the basic requirement of a CRN. To reuse the spectrum opportunistically it is obvious to sense the spectrum in an effective manner. As, efficient spectrum sensing allows the CRN to work in a proper way. This chapter covers a general overview of spectrum sensing methods in CRN.

3.2 Evolution of Cognitive Radio Network

With the rapid development of the wireless communication field the spectrum is getting congested. At the same time, high data rate is the fundamental requirement of the wireless services. High data rate needs more spectrum availability [55]. But, the spectrum is mostly allocated in a static manner for fixed services in most of the countries. So, the spectrum scarcity problem occurs. But, potential studies on spectrum usage pattern shows that most of the spectrum is underutilized [56]. That creates the "Spectrum Hole". This invokes the concept of "spectrum reuse", where the unutilized spectrum or spectrum hole is opportunistically used by the secondary user (SU). There are two types of users in CRN, i.e. Primary User (PU) and Secondary User (SU).Primary user is the licensed user, which has the dedicated spectrum to use. Secondary user is allowed to use the spectrum if and only if the primary user is not availing the spectrum. Secondary user is not supposed to disrupt the service of the primary user.This constitutes the concept of "Cognitive Radio Network" [57]. CRN allows the spectrum to be allocated dynamically, which enables the proper utilization of the spectrum.

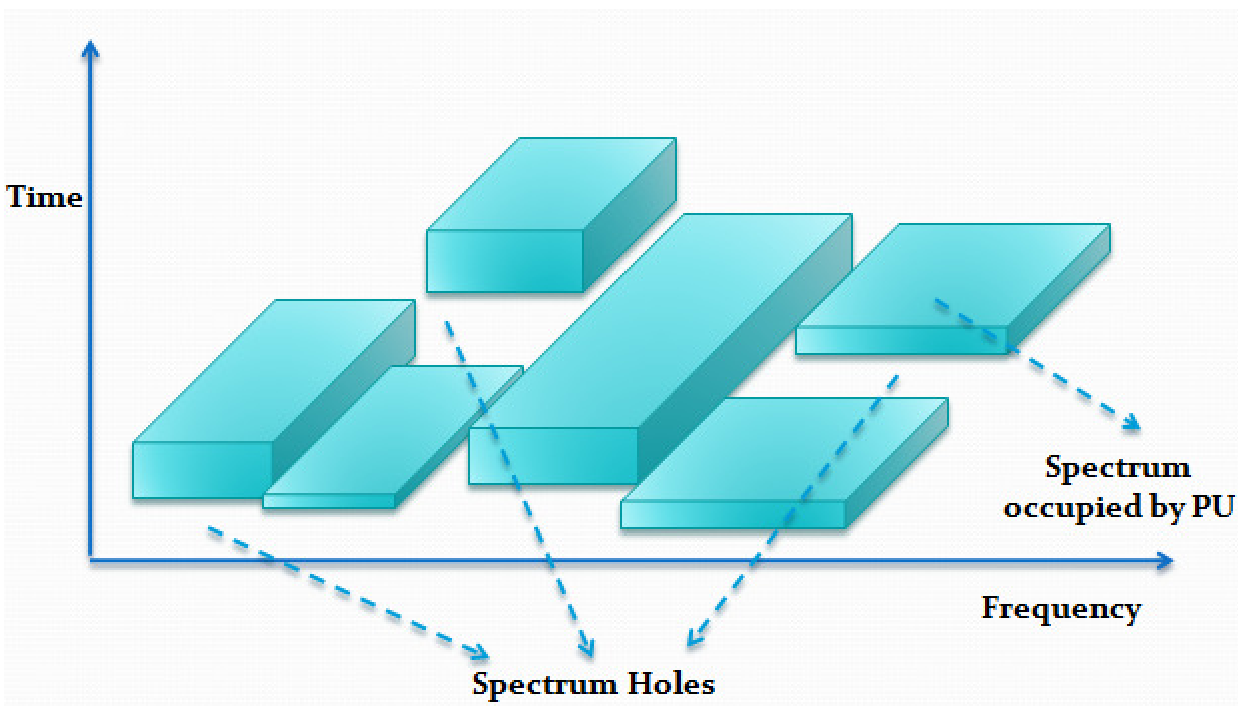

Fig 3.1 Concept of Spectrum Hole [58]

3.2.1 Functions of Cognitive Radio Network

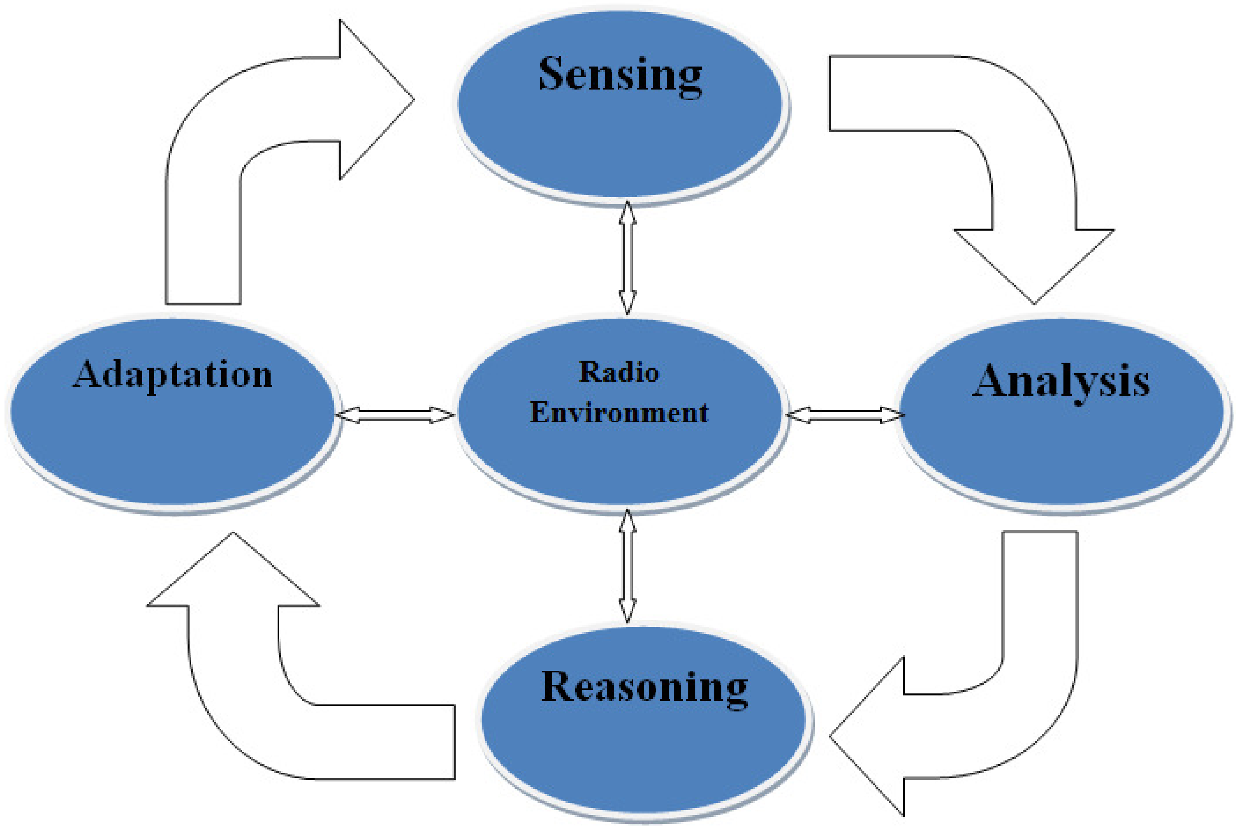

Fig 3.2 Cognitive Cycle

An illustrative cognitive cycle is presented in Fig 3.2 [58]. Firstly, the channel is sensed to locate the "white space" or "spectrum hole". The sensing method should be very efficient so that it can detect the frequency band that is not occupied by the primary user. Besides that, the CRN should be capable enough to sense the channel further, when the primary user starts their communication, so that no harmful disruption is caused by the secondary user. After detecting the spectrum hole the CRN is supposed to select the best frequency band for communication of the secondary users by doing proper analysis. It also enables the secondary user to hop in between available frequency bands in accordance with the time varying channel characteristics. So that, when the PUs return to their dedicated channel for further communication, the SU can hop from the present frequency band to other available frequency band. The CRN also enables the secondary user to be adaptive in nature. So that, when it hop from one frequency band to another it may adapt the new operating parameters.

3.3 Spectrum sensing

Cognitive Radio Network is associated with some fundamental essential components [59], i.e. (a) spectrum sensing, (b) dynamic spectrum allocation and (c) adaptive communication technique. Among these, spectrum sensing is the most important factor. As the basic requirement of a CRN is setting up communication in between the secondary users without affecting the services of the primary user. The SU uses several methods to sense the spectrum whether the primary user is occupying the channel or not. If the SU senses the channel is busy, the communication in between the SU's will not be generated.Several useful methods have been implemented to sense the spectrum, they are categorized below:

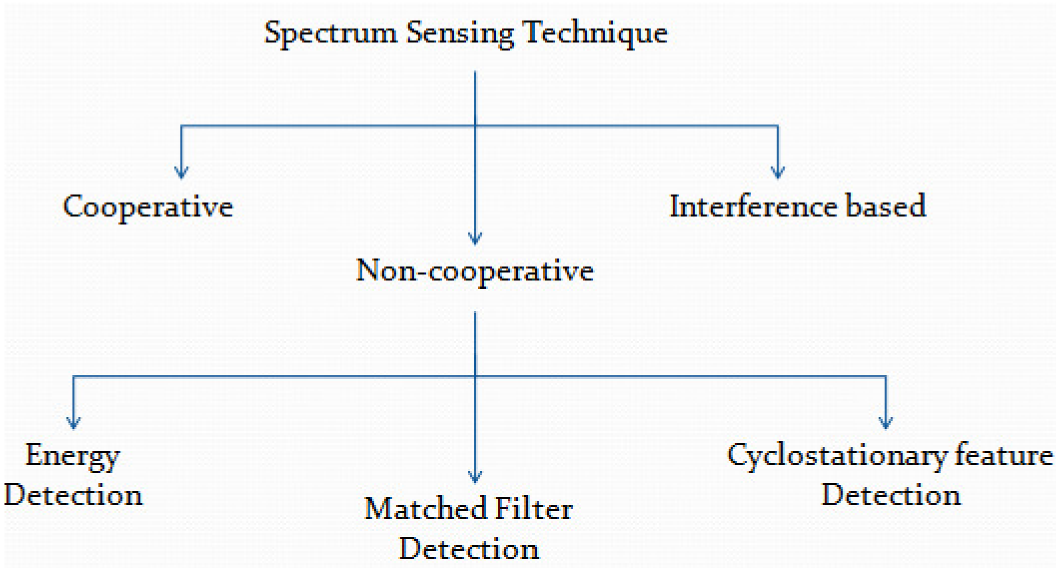

Fig 3.3 Classification of Spectrum Sensing Technique [59]

Among all the above mentioned technique the design of "Energy Detection technique" and "Cyclostationary Detection" technique are discussed later. As, both of them are needed further for the development of the proposed method.

3.4 Design of Energy Detection Technique

The Energy Detection technique is the simplest method of spectrum sensing. It has very low computational complexity [10]. It performs considerably well in high SNR region. In order to make this method more efficient, so that it can even perform well in low SNR region the improved version of this method was proposed. The "Conventional Energy Detection" method and "Improved Energy Detection" method is discussed later.

3.4.1 Design of Conventional Energy Detection Technique

In this method, the energy of the received signal is evaluated at first. The evaluation is done over a range of signal. Next, it is compared with a threshold value which is pre defined. Then, using binary hypothesis test the final decision is made about the channel availability. Based on the test results the "Detection Probability" and "False Alarm Probability" are defined. This defines the efficiency of the sensing method. The detailed description of this method is given below:

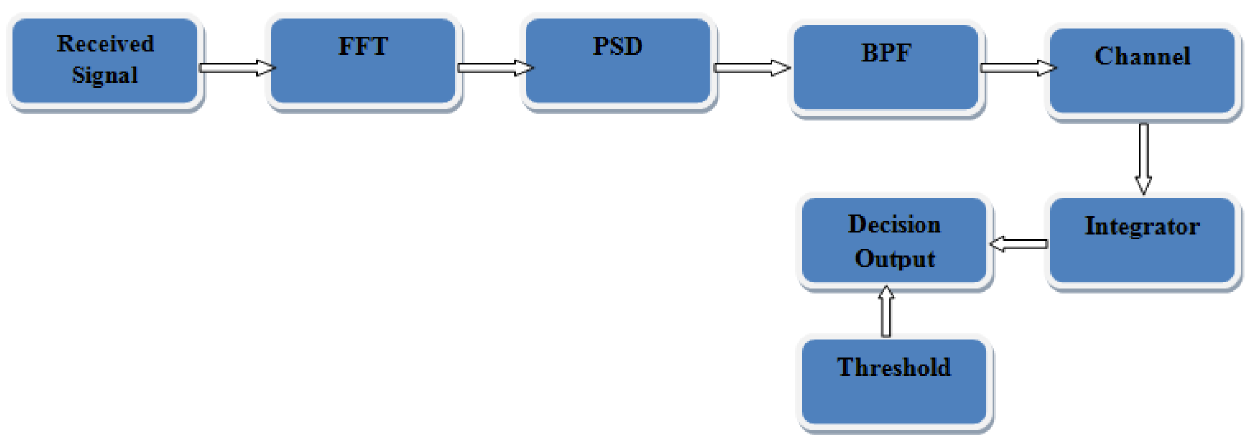

Fig 3.4 Block Diagram of Conventional Energy Detection Technique[5]

It is the simplest method in terms of implementation complexity. It is a non-coherent spectrum sensing technique [12]. At first, the received signal is shifted to frequency domain by employing Fast Fourier Transform (FFT). Next, the Power Spectral Density (PSD) of the signal is evaluated. It passes through a band pass filter then and integrated over a range of signal. The channel is selected by the band pass filter. By the binary hypothesis test the decision output is taken. Where, a pre defined threshold is already faded. The integrator output is compared with the pre defined threshold and the final decision is taken after that.

This method has some pros and cons as well. It is very well known method for its simplicity. Also, it does not require any prior information of the signal. It simply receives the signal and process that. On the other hand, it is incapable of discriminating the PU's signal from SU's signal [6]. It has a very poor performance at low SNR value. It is also incapable of detecting spread spectrum signals.

3.4.2 Design of Improved Energy Detection Technique

The "Conventional Energy Detection" Technique was suitable for unknown deterministic signal with Gaussian noise. Whereas, the "Improved Energy Detection (IED) Technique" is more suitable for random signal with Gaussian noise. A simple modification was done in CED, which constitutes IED. In CED, a squaring operation was done on signal amplitude. In IED, that squaring operation was replaced by a positive arbitrary number. So, it can be stated that in a special case the IED constitutes CED. When the improved detector parameter is equal to 2, it resembles CED [18]. The detailed description of this method is given below:

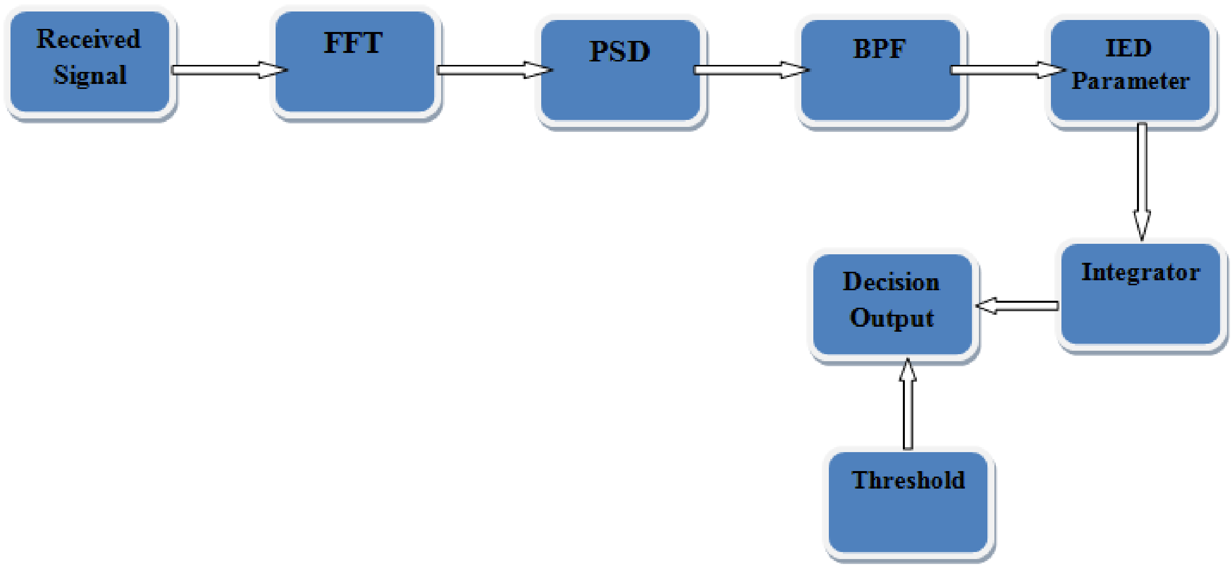

Fig 3.5 Block Diagram of Improved Energy Detection Technique [18]

Firstly, a received signal which is random in nature and corrupted by Gaussian noise is passed through a "Fast Fourier Transform (FFT)" unit. There, the signal is shifted to frequency domain from time domain. Next, the "Power Spectral Density (PSD)" of the signal is calculated and fed it to the band pass filtering unit. In this unit, the channel is selected and the improved detector parameter is imposed. The squaring operation of the signal amplitude is replaced by the improved parameter. Next, it is integrated over a range of signal. Finally, using "binary hypothesis test" the signal is compared with a pre determined threshold and the final decision output is taken.

The performance of CED is improved partially by constituting the IED technique.

3.5 Design of Cyclostationary Detection Technique

This technique is processed by sampling the signal followed by the modulation technique along the cyclic redundancy. This method can be exploited when some statistical property of the signal exists, i.e. the mean and the auto correlation of the signal vary periodically with time. If the auto correlation function of a continuous signal is periodic as well as time varying in nature and it has zero mean then it is called as second order wide sense cyclostationary signal [23].

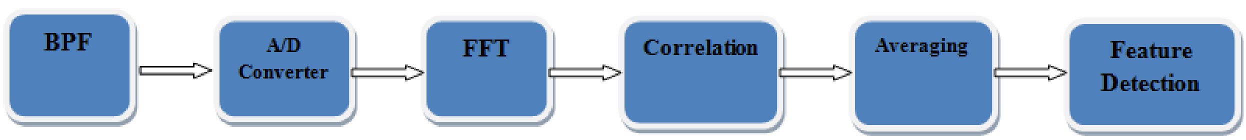

Fig 3.6 Block Diagram of Cyclostationary Detection Technique [5]

The periodicity of a signal is basically exploited for this method. Firstly, the received signal is passed through a band pass filter. Then it is sampled and modulated. Next, the "Fast Fourier Transform (FFT)" of the signal is calculated and by exploiting the correlation property of the signal it is averaged over the range of a signal. Then, by comparing with the pre defined threshold value the binary hypothesis test is done and the final decision is taken.

Some advantages and disadvantages for this method also exist [25, 7]. It performs well in low SNR regime and is capable of discriminating the primary user from secondary user. Prior information regarding primary user is needed for this method. Without exact knowledge it cannot function properly. It has high computational complexity and also it cannot be used in high speed sensing.

3.6 Conclusion

Based on above mentioned information, we can say that CED is the simplest form of spectrum sensing among all. But it does not perform well in certain conditions i.e. in low SNR regime. To resolve this issue partially IED has been proposed. CD has very high computational complexity. But, it provides better result. So, it can be said that there is a trade-off in between performance and complexity for all afore mentioned methods.

Chapter 4

Proposed Model of Spectrum Sensing Technique for Cognitive Radio Network

4.1 Overview

In this chapter, the proposed model of spectrum sensing technique for "cognitive radio network" is presented. The proposed model is divided into different segments for better understanding. Detailed discussion of each segment is also been presented here.In this section, the detailed discussion of the sensing algorithms i.e. "Conventional Energy Detection", "Improved Energy Detection", "Cyclostationary Detection"are presented, as they are entitled for the further development of the proposed model.

4.2 Design of System Model

Our objective is to sense the channel to check whether it is free or not. If it is free i.e. not occupied by the primary user then it can be used by the secondary user opportunistically. Else, the secondary user is not allowed to use the channel. Firstly, a random signal has to be considered along with "Additive White Gaussian Noise (AWGN)". The noise have zero mean and variance one. A "binary hypothesis testing" problem considered for the received signal is expressed as [13, 15]:

H_0:   y (t) = n (t)………. (4.1)

H_1:   y (t) = x (t) + n (t)………. (4.2)

Where, hypothesis H_0 represent that only noise is present i.e. the spectrum is vacant; H_1 represent that primary user is occupying the spectrum i.e. signal is present along with the noise in the spectrum; n(t) represent Additive White Gaussian Noise (AWGN)with zero mean and variance 1;x (t) is the fading signal and y (t) is the received signal.

4.3 Mathematical Model of Conventional Energy Detection Technique

The implementation of “Conventional Energy Detection (CED)” technique is very simple. It has very less complexity. In this method, the energy of the received signal is evaluated and compared to a pre-determined value of threshold to detect the presence of signal in the spectrum.

The value of “probability of false alarm” is to be set to a fixed value at first. Then the “threshold” is calculated depending on the value of “probability of false alarm”. Next, the value “probability of detection” is derived with the help of the value of “probability of false alarm” and “threshold”.

The test statistics for “CED” is expressed as [17]:

Test statistic = $\frac{1}{N}\sum_{t=1}^{N}|y(t)|^2$………. (4.3)

Where, N represents the number of samples.

The probability density function of the test statistic is calculated and based on that value the "probability of detection" can be expressed as [9]:

$$P_{\text{detect | CED}} = Q\left(\left(\frac{\lambda}{\sigma_u^2} - \frac{s}{n} - 1\right)\sqrt{\frac{\tau f_s}{2\frac{s}{n}+1}}\right) \text{.........} (4.4)$$

Where, "Q is the marcum Q-function"; λ represents the value of threshold; $\sigma_u^2$is themeanvalue; $\frac{s}{n}$represents the signal to noise ratio and τ is the sensing time.

The relation between "probability of false alarm" and "threshold" for this method can be expressed as [9]:

$$Q^{-1}(P_{\text{false alarm | CED}}) = \left(\frac{\lambda}{\sigma_u^2} - 1\right)\sqrt{\tau f_s} \text{ ....} (4.5)$$

Where, "Q^{-1} is the inverse Marcum Q-function" and "λ represents the value of threshold".

4.4 Mathematical Model of Improved Energy Detection Technique

The "Improved Energy Detection (IED)" method is the modified version of "CED". The squaring operation of the "CED" is replaced by a positive integer value. Hence, it can be said that when the improved parameter is equal to 2, it resembles "CED".

The test statistics for "IED" is expressed as [18]:

$$\text{Test statistic} = \frac{1}{N}\sum_{t=1}^{N} |y(t)|^{\eta} \text{……….} \quad (4.6)$$

Where, N represents the number of samples and η represent the improved detector parameter, which can be of any positive integer value.

The "probability of detection" for this method can be expressed as [18]:

$$P_{\text{detect | IED}} = \frac{1}{\sqrt{\pi}}\Gamma\left(\frac{1}{2}, \frac{\lambda^{\frac{2}{\eta}}}{2\,(\sigma_s^2+\sigma_u^2)}\right) \text{……….} \quad (4.7)$$

Where, "Γ is the gamma function"; η represent the improved detector parameter and "λ represents the value of threshold".

The "probability of false alarm" for this method can be expressed as [18]:

$$P_{\text{false alarm | IED}} = \frac{1}{\sqrt{\pi}}\Gamma\left(\frac{1}{2}, \frac{\lambda^{\frac{2}{\eta}}}{2\sigma_u^2}\right) \text{……….} \quad (4.8)$$

Where, "Γ is the gamma function"; "η representing the improved detector parameter" and "λ represents the value of threshold".

4.5 Mathematical Model of Cyclostationary Detection Technique

In this method, any cyclostationary property of a signal is used to determine the test statistics [24]. This method is complex with respect to "IED" and "CED".

It is known that the mean of a cyclostationary signal is periodic with period T_1 with respect to time. As the period of the signal is known, with the help of the synchronized averaging we can calculate the periodicity of the signal.

So, the mean can be represented of the signal y (t) as [43]:

$$M(\mathrm{t})_{\mathrm{T}} \triangleq \frac{1}{2\mathrm{I}+1}\sum_{\mathrm{k}=-\mathrm{I}}^{\mathrm{I}} \mathrm{y}\ (\mathrm{t}+\mathrm{kT}_1) \ \ldots\ldots\ldots\ (4.9)$$

Where, $T \triangleq (2I+1)\ T_1$ represents the observation time and the number of collected cyclic prefix is represented by I. The sampled values are taken of y (t) for sampling interval of $t-kT_{1,\ldots\ldots}t,\ldots.t+T_1,\ldots.t+kT_1$. Where, k is the integer and t represents time.

The "probability of detection" for this method can be expressed as [43]:

$$P_{\text{detect | CYCLO}} = Q\ \left(\frac{\sqrt{2\frac{s}{n}}}{\sigma}, \frac{\lambda}{\sigma_a}\right) \ \ldots\ldots\ldots\ (4.10)$$

Where, "Q is the marcum Q-function"; "λ represents the value of threshold" and $\frac{s}{n}$ represents the signal to noise ratio.

The "probability of false alarm" for this method can be expressed as [43]:

$$P_{\text{false alarm | CYCLO}} = \exp\left(-\frac{\lambda^2}{2\sigma_a^2}\right) \ \ldots\ldots\ldots\ (4.11)$$

Where, "λ indicates the value of threshold".

4.6 Description of the Proposed Sensing Technique

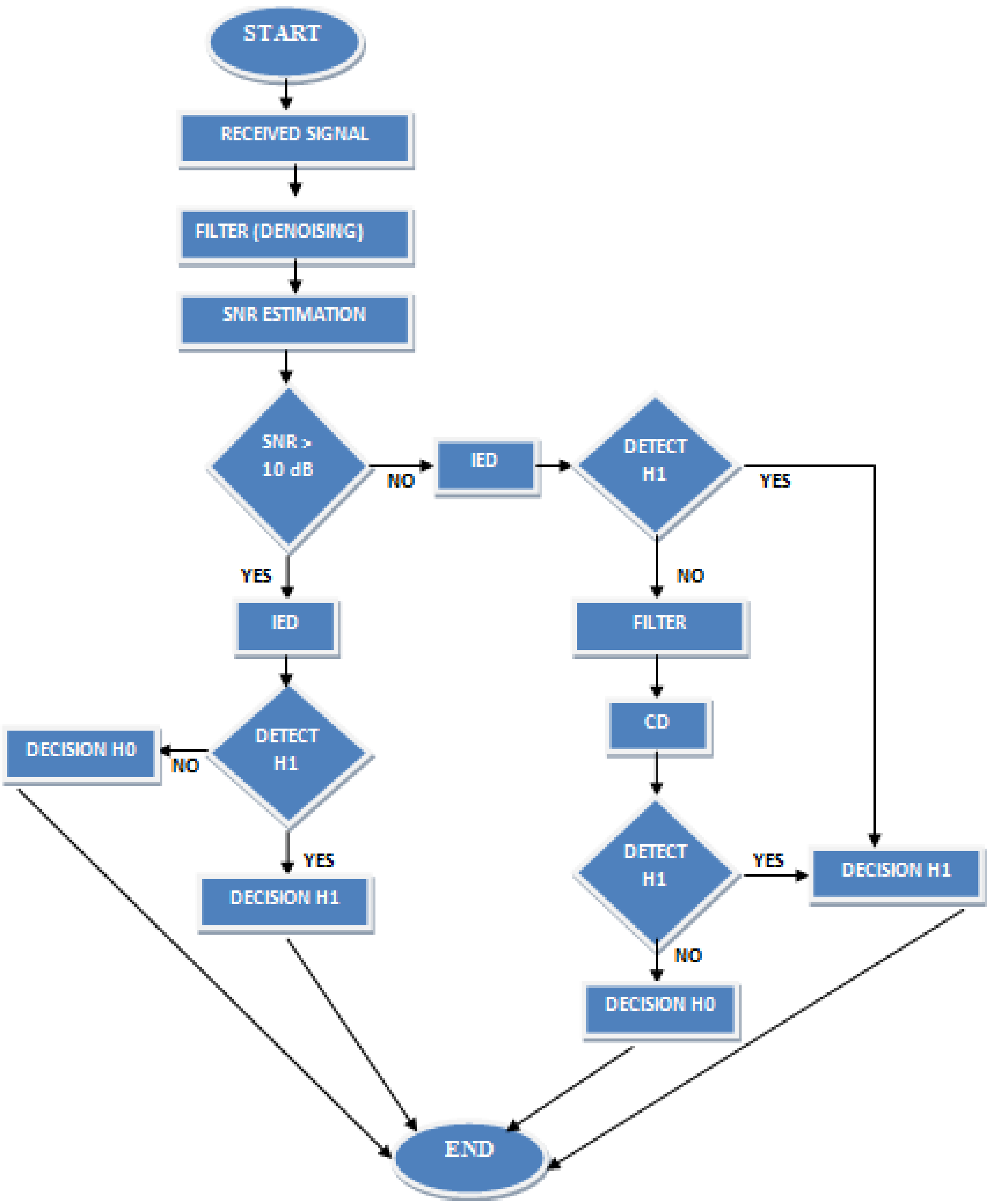

Fig. 4.1 Flowchart of the Proposed Sensing Technique

In this model, our main target is to minimize the false alarm as well as the miss detection and maximize the detection. In CD, the probability of miss detection is lower but implementation of this scheme is complex and also the power consumption is high. At the same time, implementation of IED is simple but it does not perform well in low SNR, while CD gives better performance in low SNR. So, to maximize the efficiency and minimize the complexity we propose a two step hybrid model for spectrum sensing.

The process of sensing is as follows. Firstly, the signal is received and goes through a digital filter to minimize the effect of noise. Then the SNR is estimated. Depending on the estimated SNR, the path of the algorithm is decided. If the estimated SNR is greater than or equal to 10 dB then it follows only IED. If it detects the primary user, the secondary is not allowed to communicate and vice versa. If the estimated SNR is less than 10 dB then, it passed through IED followed by CD, which is preceded by a median filter. If CD detects the signal, the final decision is considered as primary user is present, if it fails the final decision is primary user is not present. The flowchart of the scheme is presented in Fig.4.1. If SNR is greater than or equal to 10 dB it will follow step 1(left part of the flowchart) else step 2(right part of the flowchart) would be followed.

4.7 Algorithm of the Proposed Sensing Technique

The algorithm for the proposed sensing model is described below:

Step 1: Initialization of the network.

Step 2: Filtering technique is to be used to reduce the effect of the noise from the received signal.

Step 3: The signal to noise ratio is calculated of the incoming signal.

Step 4: If the value of the SNR is greater than 10 dB, then “IED” will be initialized else go to Step 6.

Step 5: Whatever the “IED” will detect, it will be the final decision (either spectrum is ‘busy’ or ‘idle’) and go to Step 10.

Step 6: The “hybrid” method will be executed.

Step 7: Firstly, the “IED” will be initiated.

Step 8: If “IED” detects the signal then go to Step 10, else another filtering technique is to be initiated and “CD” will be invoked.

Step 9: Consider the “CD” s decision as the final decision and go to Step 10.

Step 10: End.

4.8 Analysis of the Proposed Sensing Technique

In this section, the mathematical background of the proposed sensing technique has been presented. The calculation of “Probability of Detection”, “Probability of False Alarm” and “Probability of Miss Detection” of the proposed sensing technique has been presented here.

4.8.1 Cooperative Spectrum Sensing

The decision from each secondary user is sent to the “Fusion Center (FC)”. The final decision for the hybrid part is taken in the FC. In our proposed model, we use ‘OR’ rule in FC. According to ‘OR’ rule the FC declares the presence of PU if 1 out of ‘N’ SU detect a PU. The “probability of false alarm” and “probability of miss detection” of ‘OR’ rule is defined as [43]:

$$P_{md,t} = P_{md}{}^{N}$$

$$P_{fa,t} = 1\text{-}\,(1\text{-}P_{fa})^{N} \quad \text{........... (4.12)}$$

In ‘OR’ rule the probability of miss detection is very low as the final decision will confirm the presence of PU if and only if any single SU confirms the presence of PU.

In our proposed model, in case of high SNR, we will rely on only “IED”. But, as “IED” doesn’t perform well in low SNR, we have used hybrid scheme for that part. In hybrid part, if “IED” fails to detect PU then “CD” is invoked.

4.8.2 Calculation of P_{detect} and $P_{false\ alarm}$

The total number of “Cognitive Radio Unit (CRU)” that invokes CD can be expressed as [43]:

P_{cyclo}= missed detection probability of IED ……….. (4.13)

$= 1-P_{detect\ |\ IED}$

$=P_{miss\ detect\ |\ IED}$

In “cooperative spectrum sensing” if we consider the decision from more number of CRU, then the decision will be exact. Each decision of each CRU is gathered at the “Fusion Center” and final decision is made according to ‘OR’ rule.

- The “probability of detection” for our proposed model can be expressed as [43]:

$$P_{detect\ |\ proposed} = 1 - (1 - P_{detect\ |\ IED})\ (1 - P_{detect\ |\ CD}) \ldots\ldots\ldots \quad (4.14)$$

- The “probability of false alarm” for our proposed model can be written as [43]:

$$P_{false\ alarm\ |\ proposed} = 1 - (1 - P_{false\ alarm\ |\ IED})\ (1 - P_{false\ alarm\ |\ CD}) \ldots\ldots\ldots \quad (4.15)$$

- The “probability of miss detection” for our proposed model can be formulated as [43]:

$$P_{miss\ detect\ |\ proposed} = (1 - P_{detect\ |\ proposed}) \ldots\ldots\ldots \quad (4.16)$$

Chapter 5

Simulation Results and Analysis

5.1 Overview

Simulation results of the proposed work and their detailed analysis are summarized in this chapter. MATLAB R2016a platform has been used for all simulation purpose. At first, the "Improved Energy Detection (IED)" technique and "Cyclostationary Detection (CD)" technique of spectrum sensing have been implemented. Next, a novel two-stage hybrid model is proposed to reduce the complexity and enhance the efficiency. Performance of the proposed sensing method is compared with the result obtained from the existing spectrum sensing methods.

In the first section, the performance of the "Energy Detection (ED)" technique is presented, which is the classic spectrum sensing method. In next section, "Improved Energy Detection (IED)" technique and "Cyclostationary Detection (CD)" is presented, which are used as the basic building blocks of the proposed method.

After that, the detailed simulation results of the proposed sensing method are presented.

In the last section, the comparative analysis of the proposed sensing method with respect to the conventional spectrum sensing method is shown.

5.2 Simulation Parameters

MATLAB R2016a has been used as the simulation tool for this present work. The setting of different parameters has been made according to Table 5.1.

TABLE 5.1 Various Simulation Parameters

Parameter	Values
Detection Probability	0 - 1
False alarm Probability	0.01 - 0.2
Smoothing Factor (L)	16
No. of tests done in Monte-Carlo Simulations	5000
range of SNR	-20 dB to 20 dB
No. of samples Used	40000
Simulation Software	MATLAB (R2016a)

Here, "probability of detection" varies from 0 to 1 and "probability of false alarm" also varies from 0 to 1. Since our motive is to minimize the value of false alarm as much as possible, it has been set at a value of 0.01-0.2 in most of the cases. All the simulations are done for the SNR ranges from -20 dB to 20 dB [48, 50]. The smoothing factor is kept 16 [48, 50], as lower value of smoothing factor minimizes the complexity. The number of samples used here are around 40000. The number of iterations for Monte-Carlo simulation is kept as 5000 as higher no. of iterations would provide better result.

5.3 Simulation Results of Conventional Energy Detection (CED) Technique

"Conventional Energy Detection (CED)" technique is the classic method of spectrum sensing. As proposed in [12], some random signal is generated and then an Additive White Gaussian Noise (AWGN) with zero mean and variance one is added to the signal. Then, the threshold is determined according to the formula equation (4.5) as referred in Chapter 4. Next, using "binary hypothesis test", the final result has been drawn. Analysis of various parameters and simulation results of this method are shown below. The brief comparison of this method with other methodologies is discussed in the subsequent sections.

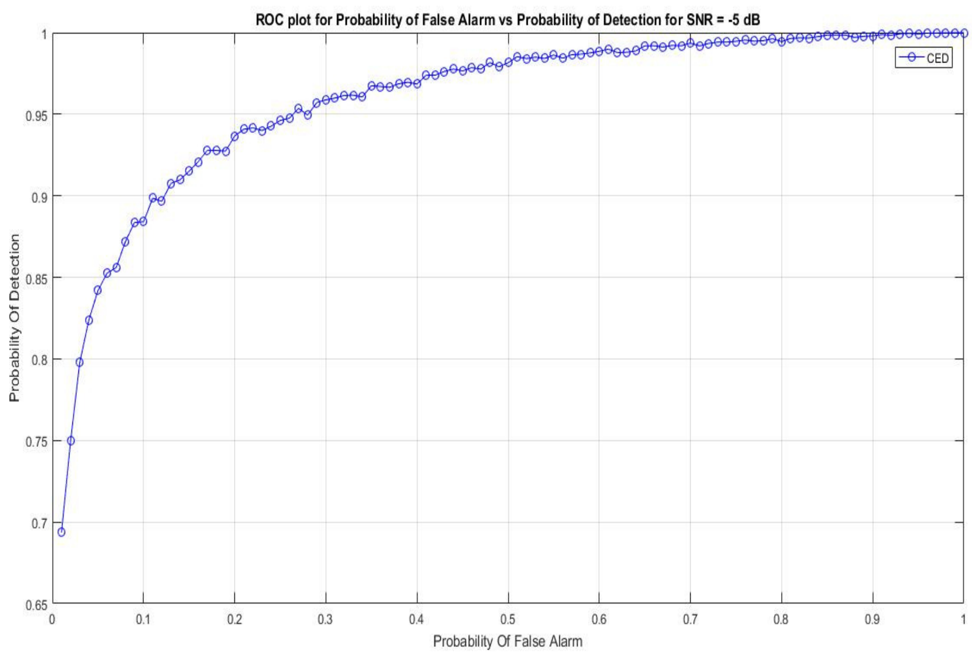

Fig 5.1 ROC plot for Probability of Detection versus Probability of false alarm for Conventional Energy Detection Technique

The above figure depicts the "Receiver Operating Characteristics (ROC)" of the "CED" with "Probability of detection" versus "Probability of false alarm" at SNR= -5 dB. It seems that the "probability of detection" is around 0.7 when the "probability of false alarm" is almost zero. The "probability of detection" approaches one when "probability of false alarm" is almost 0.8.

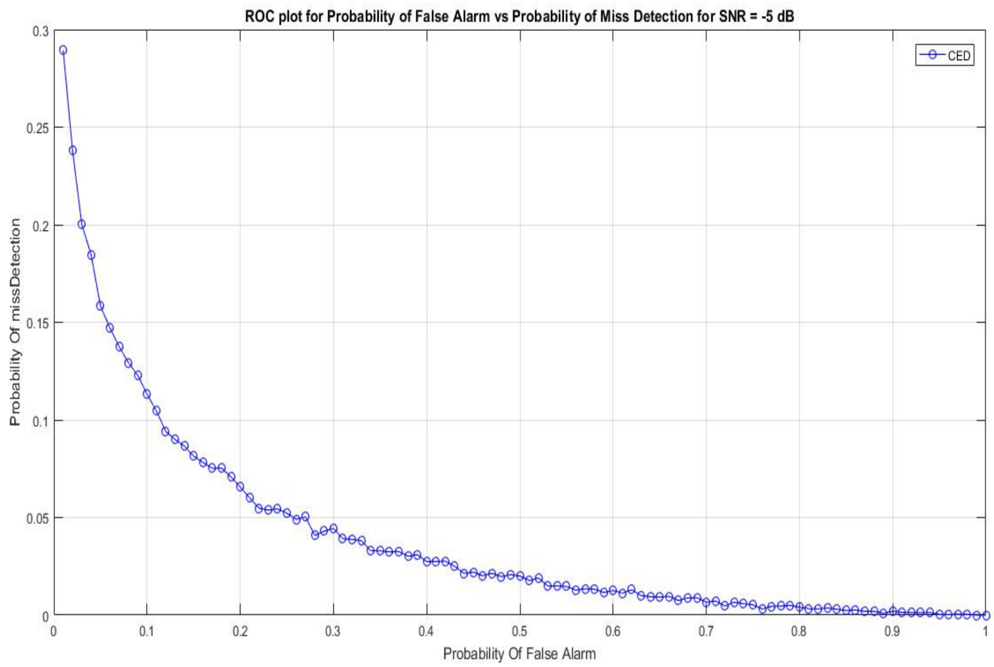

Fig 5.2 ROC plot for Probability of Miss Detection versus Probability of false alarm for Conventional Energy Detection Technique

The above figure depicts the "Receiver Operating Characteristics (ROC)" of the "CED" with "Probability of Miss detection" versus "Probability of false alarm" at SNR= -5 dB. It can be seen from the plot that the "Probability of miss detection" is less than 0.3 when the false alarm probability is around zero. The miss detection is minimum when the probability of false alarm approaches 0.8.

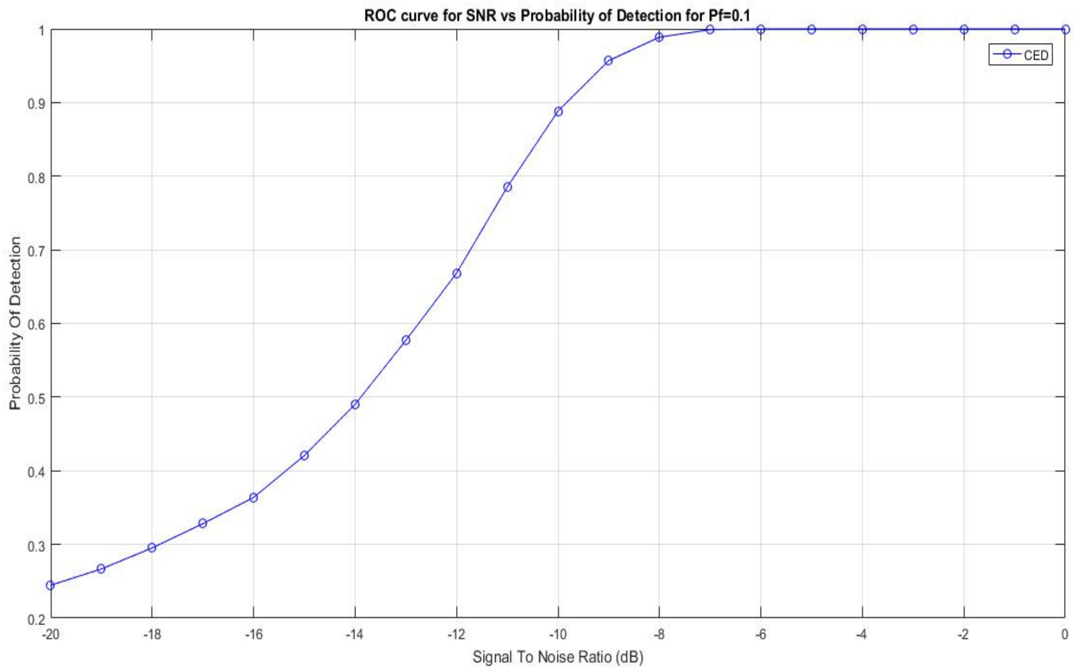

Fig 5.3 ROC plot for Probability of Detection versus Signal to Noise Ratio for Conventional Energy Detection Technique

The above figure depicts the “Receiver Operating Characteristics (ROC)” of the “CED” with “Probability of detection” versus SNR when “probability of false alarm” is 0.1. It can be seen from the graph that the “probability of detection” increases gradually when the SNR approaches the higher values.

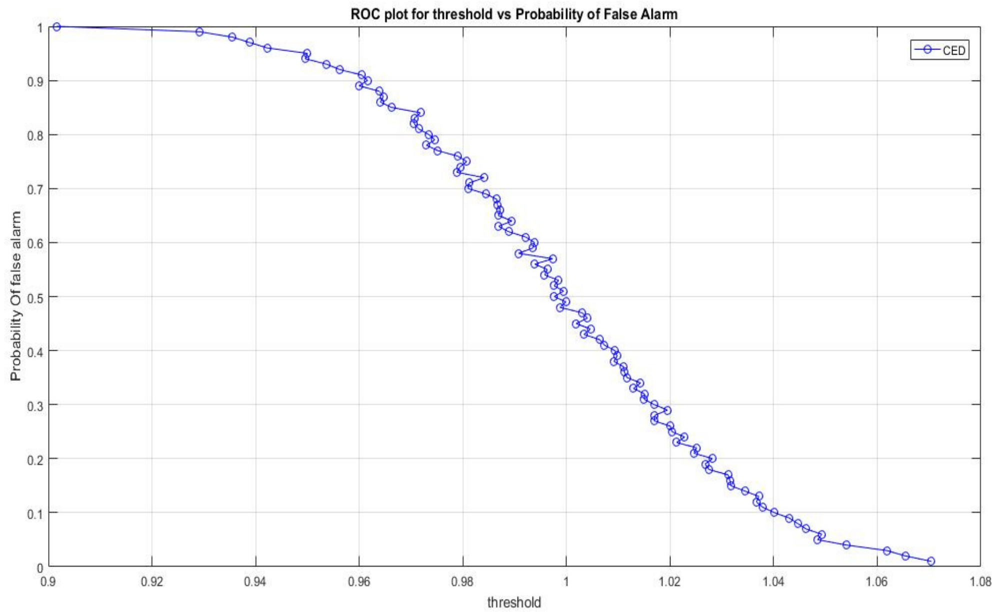

Fig 5.4 ROC plot for Probability of False Alarm versus Threshold for Conventional Energy Detection Technique

The above figure depicts the "Receiver Operating Characteristics (ROC)" of the "CED" with "Probability of false alarm" versus threshold. The values of threshold can be determined from the formula (4.5) as described in chapter 4.

- At first, the value of "probability of false alarm" has to be set. Then according to the formula the threshold can be calculated. Next, the value of the "probability of detection" is derived. The values of threshold are calculated according to the following setting:

Case I –

For "Probability of false alarm"= 0.1

"Probability of detection"= 0.4210

The value of "Threshold" is calculated as= 1.0405

From figure 5.4 the observed result is found to be, "Threshold" =1.04

Hence, it seems that both the theoretical and graphical result resembles each other.

Case II –

For "Probability of false alarm"= 0.7

"Probability of detection"= 0.8650

The value of "Threshold" is calculated as= 0.9834

From figure 5.4 the observed result is found to be, "Threshold" =0.98

Hence, it seems that both the theoretical and graphical result resembles each other.

5.4 Simulation Results of Improved Energy Detection (IED) Technique

The "Improved Energy Detection (IED)" technique is nothing but the improved version of "Conventional Energy Detection" technique. When the "improved energy detector" parameter is equal to 2, then "IED" corresponds to "CED". This is the basic building block of the proposed model. As referred in [18], some random signal with Additive White Gaussian Noise is generated. Then the threshold is determined according to the formula (4.8) presented in chapter 4. Finally, using binary hypothesis test, the final result has been drawn. Analysis of various parameters and simulation results of this method are shown below. The brief comparison of this method with other methodologies is discussed in the subsequent sections.

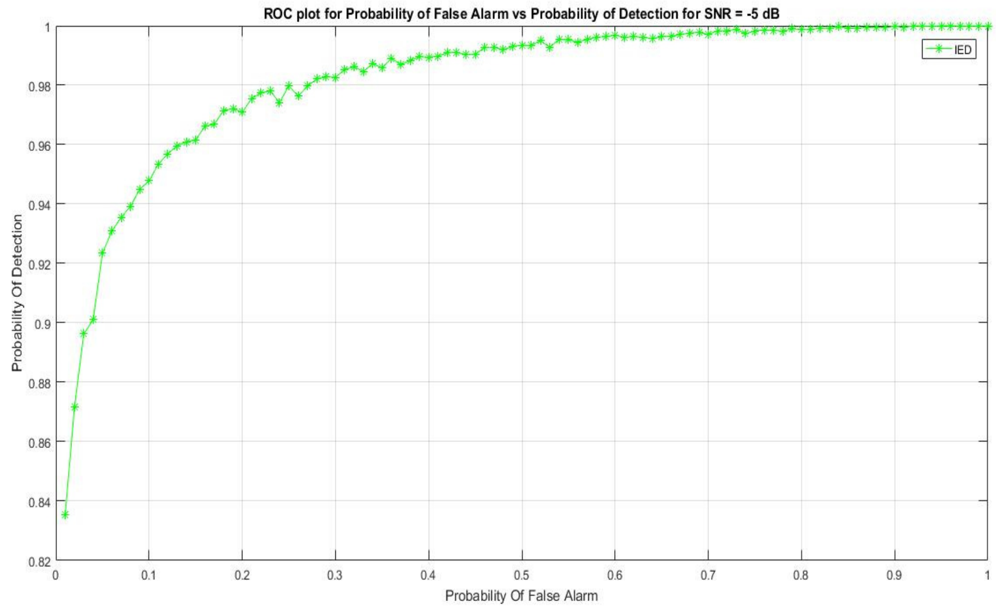

Fig 5.5 ROC plot for Probability of Detection versus Probability of false alarm for Improved Energy Detection Technique

The above figure represents the "Receiver Operating Characteristics (ROC)" of the "IED" with "Probability of detection" versus "Probability of false alarm" at SNR= -5 dB. It seems from the graph that the "probability of detection" reaches almost 0.84 when the false alarm probability is around zero. The detection probability is maximum when the false alarm probability approaches 0.7.

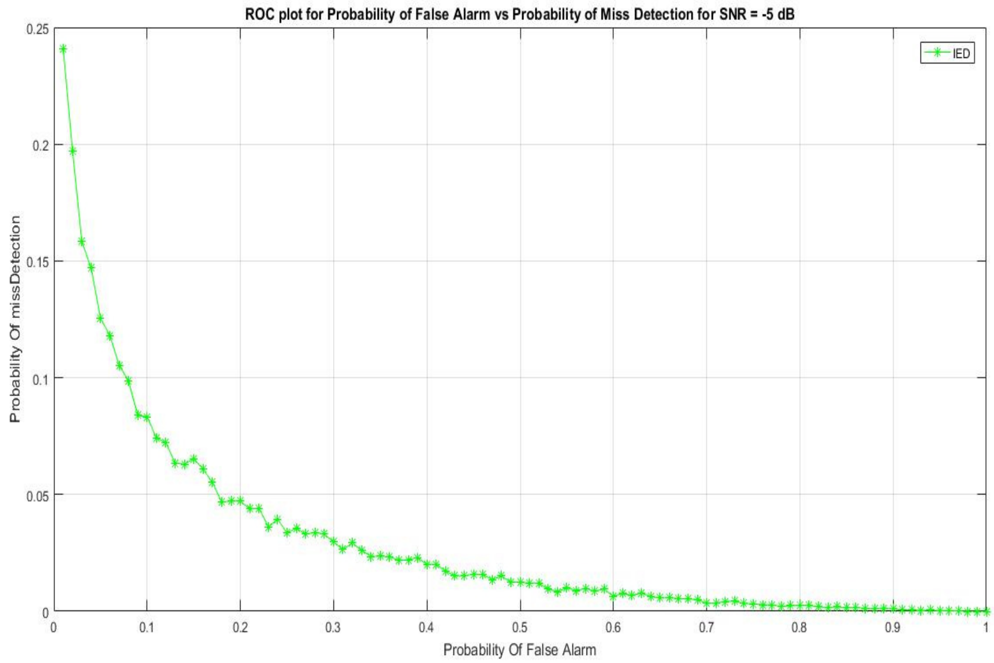

Fig 5.6 ROC plot for Probability of Miss Detection versus Probability of false alarm for Improved Energy Detection Technique

The figure 5.6 is representing the "Receiver Operating Characteristics (ROC)" of the "IED" with "Probability of miss detection" versus "Probability of false alarm" at SNR= -5 dB. In this scenario, the "miss detection probability" is even less than 0.25 when the false alarm probability is zero. The "miss detection probability" reaches the minimum value when "false alarm probability" is around 0.7.

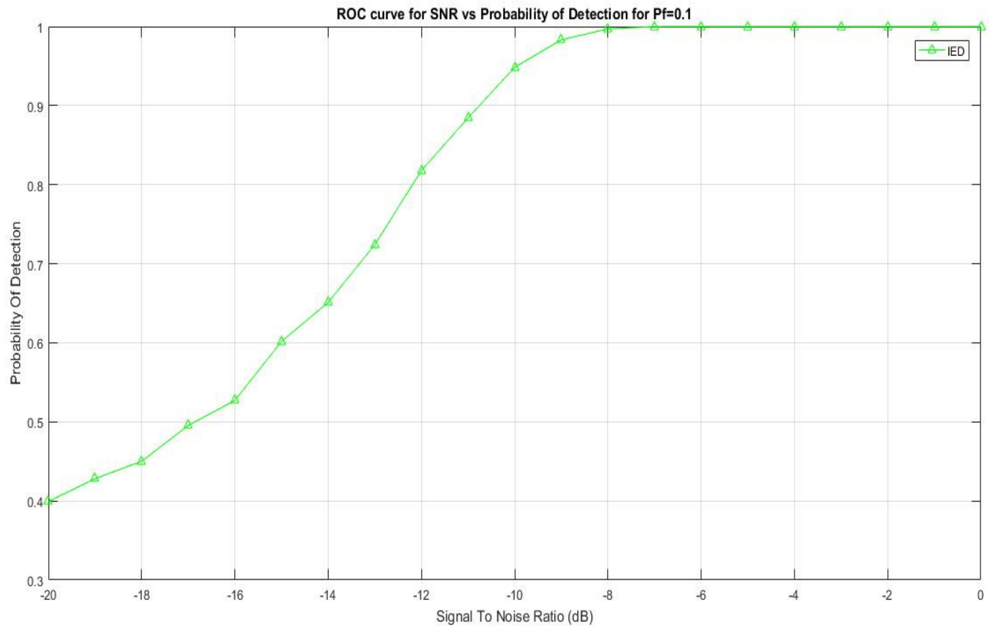

Fig 5.7 ROC plot for Probability of Detection versus Signal to Noise Ratio for Improved Energy Detection Technique

The graph demonstrates the "Receiver Operating Characteristic (ROC)" for "probability of detection" versus SNR at "false alarm probability" 0.1. It can be seen from the graph that the "probability of detection" follows an increasing order with the increasing nature of SNR.

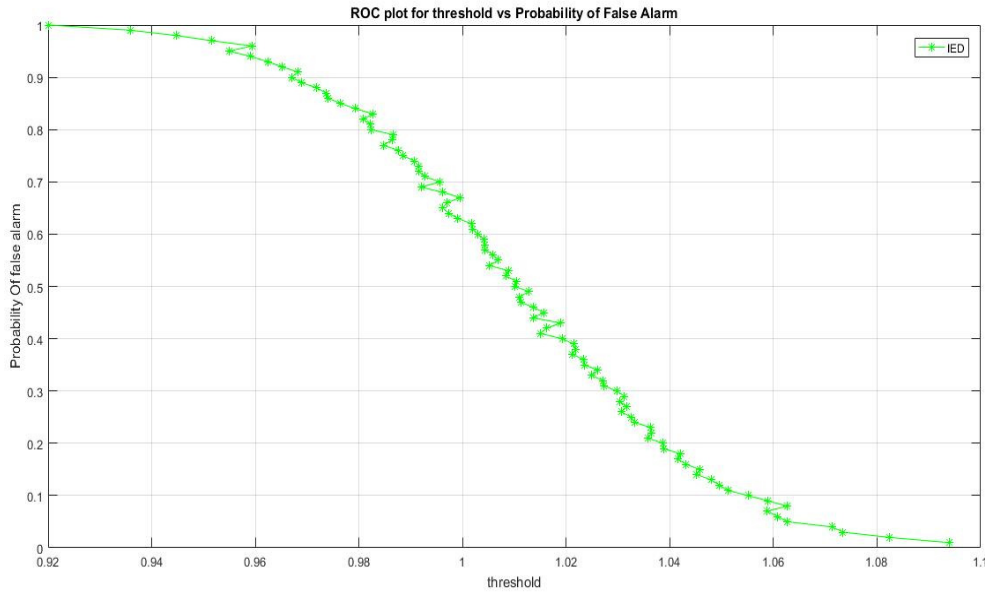

Fig 5.8 ROC plot for Probability of False Alarm versus Threshold for Improved Energy Detection Technique

The above figure reflects the "Receiver Operating Characteristics (ROC)" of the "IED" with "Probability of false alarm" versus threshold. The values of threshold can be determined from the formula (4.8) described in chapter 4.

- Similar to "CED" at first, the value of "probability of false alarm" has to be set. Then according to the formula the threshold can be calculated. Next, the value of the "probability of detection" is derived. The values of threshold are calculated according to the following setting:

Case I –

For "Probability of false alarm"= 0.4

"Probability of detection"= 0.8180

The value of "Threshold" is calculated as= 1.0080

From figure 5.4 the observed result is found to be, "Threshold" =1.02

Hence, it seems that both the theoretical and graphical result resembles each other.

Case II –

For “Probability of false alarm”= 0.7

“Probability of detection”= 0.9340

The value of “Threshold” is calculated as= 0.9834

From figure 5.4 the observed result is found to be, “Threshold” =0.9802

Hence, it seems that both the theoretical and graphical result resembles each other.

5.5 Simulation Results of Cyclostationary Detection (CD) Technique

The “Cyclostationary Detection (CD)” technique is the basic building block of the proposed model. After generating the signal and noise, the threshold is determined according to the formula equation (4.11) as presented in Chapter 4. Then, using “binary hypothesis test” the final result has been drawn. Analysis of various parameters and simulation results of this method are shown below. The brief comparison of this method with other methodologies is discussed in the subsequent sections.

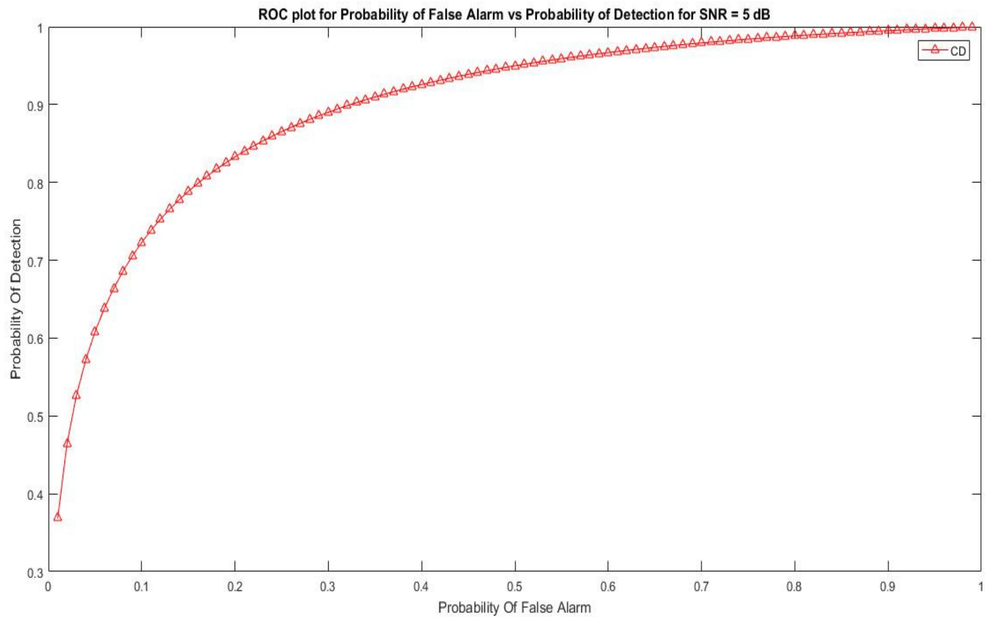

Fig 5.9 ROC plot for Probability of Detection versus Probability of false alarm for Cyclostationary Detection Technique

The above figure represents the "Receiver Operating Characteristics (ROC)" of the "CD" with "Probability of detection" versus "Probability of false alarm" at SNR= 5 dB. It is seen from the graph that the detection probability approaches almost one when the false alarm probability is 0.7. In fact, the "probability of detection" is almost 90% when the false alarm probability is only 0.3.

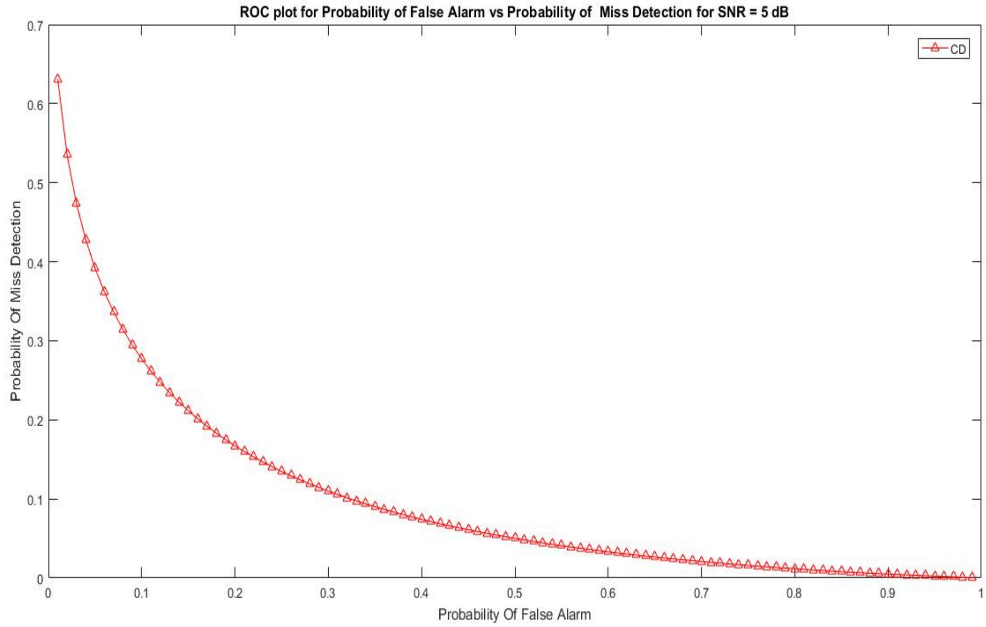

Fig 5.10 ROC plot for Probability of Miss Detection versus Probability of false alarm for Cyclostationary Detection Technique

In the figure 5.10, the “ROC” plot of “miss detection probability” versus “false alarm probability” for “CD” is represented at SNR= 5 dB. The “miss detection probability” is gradually decreasing with increasing order of “false alarm probability”.

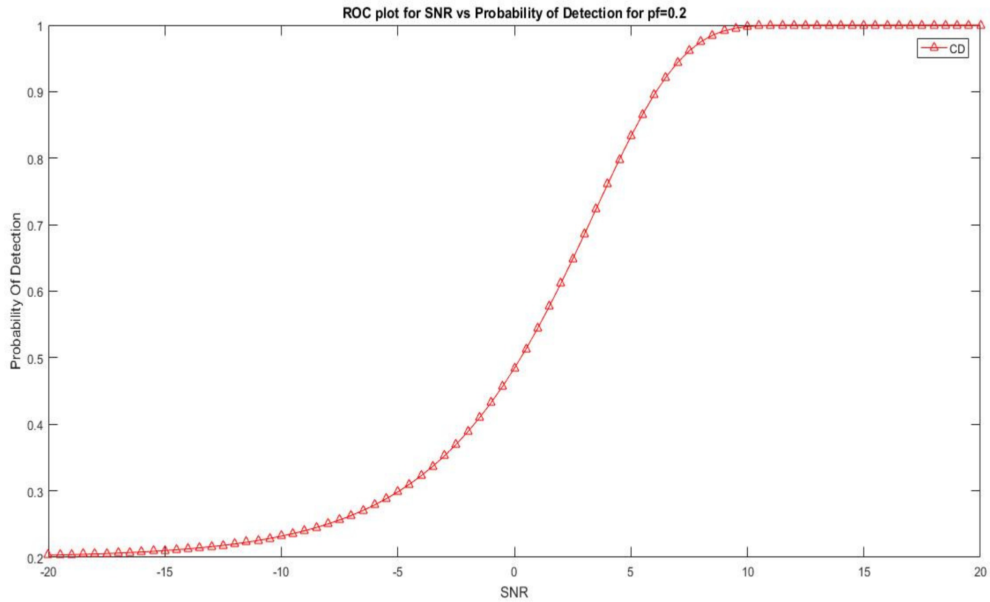

Fig 5.11 ROC plot for Probability of Detection versus Signal to Noise Ratio for Cyclostationary Detection Technique

The above graph depicts the nature of "probability of detection" for varying SNR for "CD" when the "false alarm probability" is 0.2. It is shown in the graph that the detection probability increases sharply when the SNR approaches positive value. For negative values of SNR the detection probability gradually increases with increasing SNR.

5.6 Simulation Results of Proposed Technique

As discussed in chapter 4, the proposed model combines "Improved Energy Detection" technique and "Cyclostationary Detection" technique. From the literature review it is evident that "CD" is more complex than "IED", but it gives better results in certain conditions. The objective behind this work is to reduce the complexity and increase the efficiency. Here, initially, a signal with Additive White Gaussian Noise (AWGN) is generated. Then, the signal is passed through a filter before entering in the decision making section. Next, according to the value of SNR, the algorithm is followed. Analysis of various parameters and simulation results of this method are shown below. The brief comparison of this method with other methodologies is discussed in the subsequent sections.

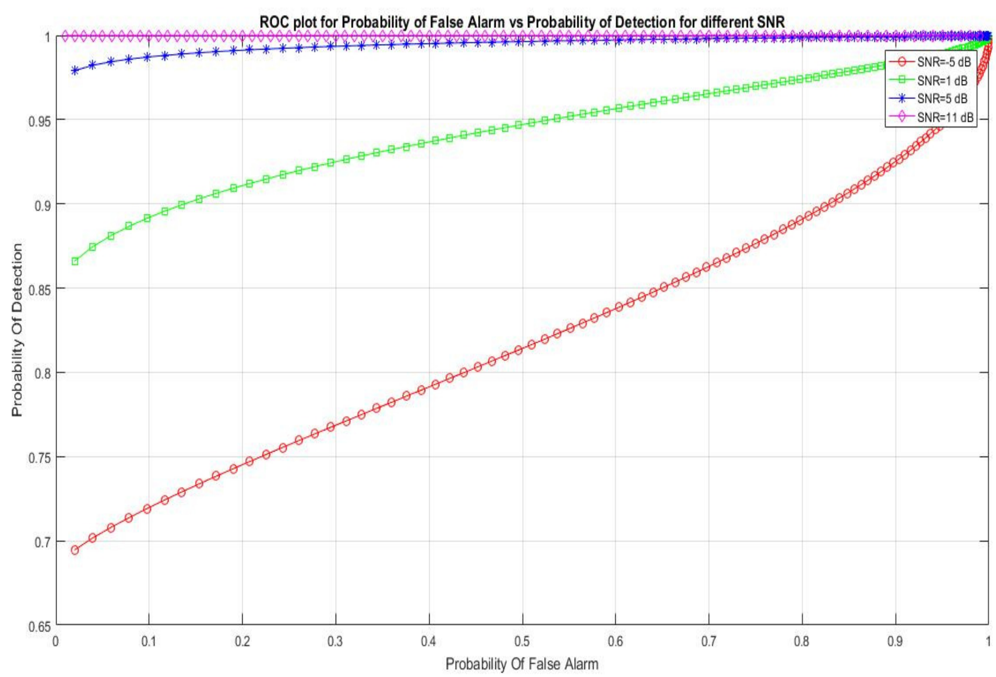

Fig 5.12 ROC plot for Probability of Detection versus Probability of false alarm for Proposed Technique

The above figure depicts the "Receiver Operating Characteristics (ROC)" of the proposed sensing method with "Probability of detection" versus "Probability of false alarm" at different values of SNR such as -5 dB, 1 dB, 5 dB, and 11 dB. It is evident from the graph that even at low SNR (SNR=-5 dB), the "Probability of detection" for the proposed method reaches approximately 0.7. This proves that this method performs very well even at low SNR value. When SNR is 5 dB, Probability of detection reaches almost 0.9. At high SNR, the "probability of detection" of the proposed method approaches 1.

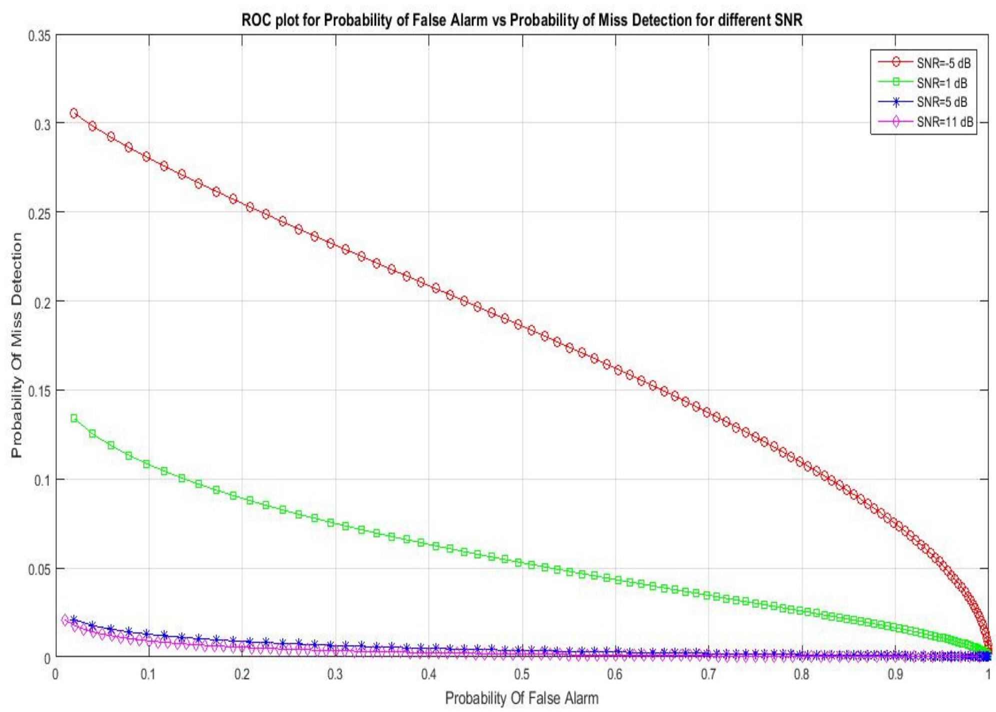

Fig 5.13 ROC plot for Probability of Miss Detection versus Probability of false alarm for Proposed Technique

Figure 5.13 shows the "Receiver Operating Characteristics (ROC)" of the proposed sensing method with "Probability of miss detection" versus "Probability of false alarm" at different value of SNR (SNR=-5 dB, SNR=1 dB, SNR=5 dB, SNR=11 dB). The "probability of miss detection" is 0.3 (approx.) when SNR is -5 dB. As the SNR is gradually increasing the "probability of miss detection" follows the decreasing order. This proves that the chances of miss detection in this method are very low even in varying SNR conditions.

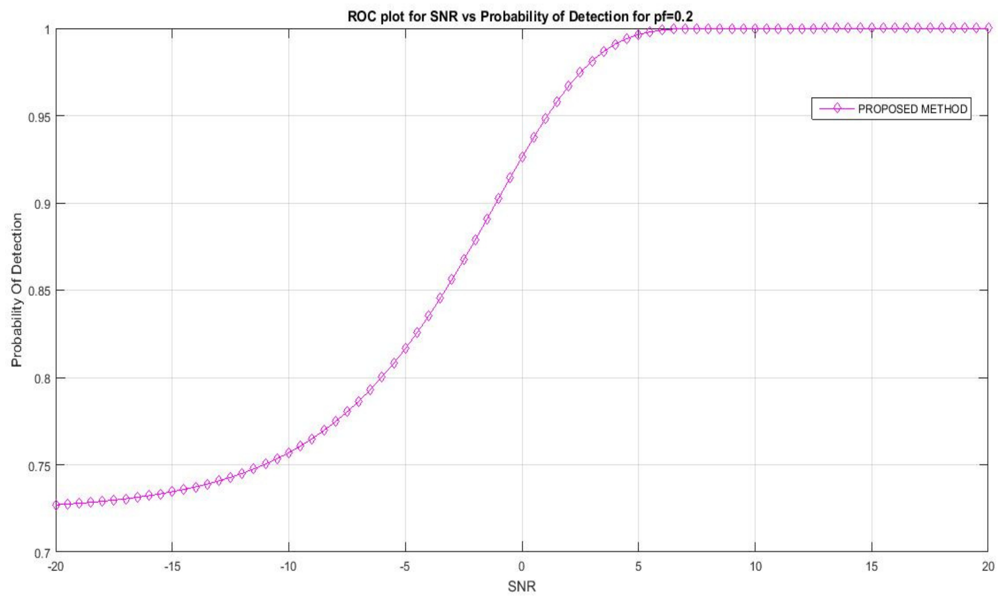

Fig 5.14 ROC plot for Probability of Detection versus Signal to Noise Ratio for Proposed Technique

The above figure depicts the "Receiver Operating Characteristics (ROC)" of the proposed method with "Probability of detection" versus SNR when "probability of false alarm" is set to 0.2. The SNR is used here in the range of-20 dB to 20 dB. As it seems from the graph that at an SNR level of -20 dB, the "Probability of detection" of the proposed method reaches almost at 0.8. Again, if we consider 0 dB SNR, the "probability of detection" for the proposed model reaches at 0.95 (approx.).

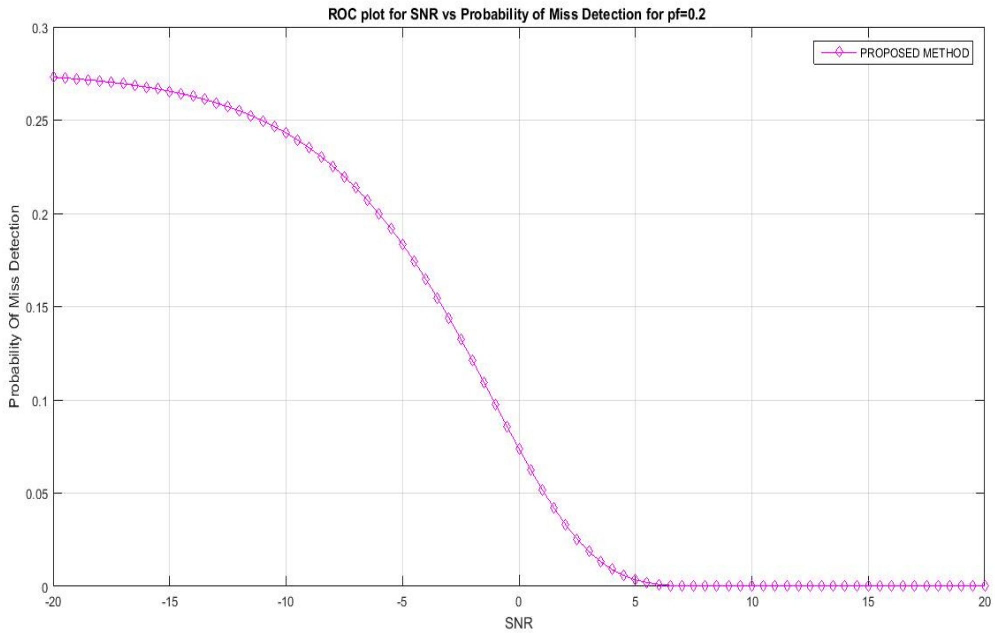

Fig 5.15 ROC plot for Probability of Miss Detection versus Signal to Noise Ratio for Proposed Technique

Figure 5.15 shows the "Receiver Operating Characteristics (ROC)" of the proposed method with "Probability of Miss detection" versus SNR when "probability of false alarm" is 0.2. The value of SNR ranges from -20 dB to 20 dB. From the figure, it seems that the "probability of miss detection" is gradually decreasing when the SNR ranges from -20 dB to 5 dB. For higher SNR value, the "probability of miss detection" almost reaches to zero. This proves that the proposed method performs very well at high SNR.

5.7 Comparison of Simulation Results of the Proposed Model with Existing Models

The comparative performance analysis of the proposed model with IED, CD and hybrid of IED and CD is presented in this section. Here, comparison has been carried out in terms of "probability of detection", "probability of miss detection" and "signal to noise ratio". The comparison in terms of computational complexity is also presented here.

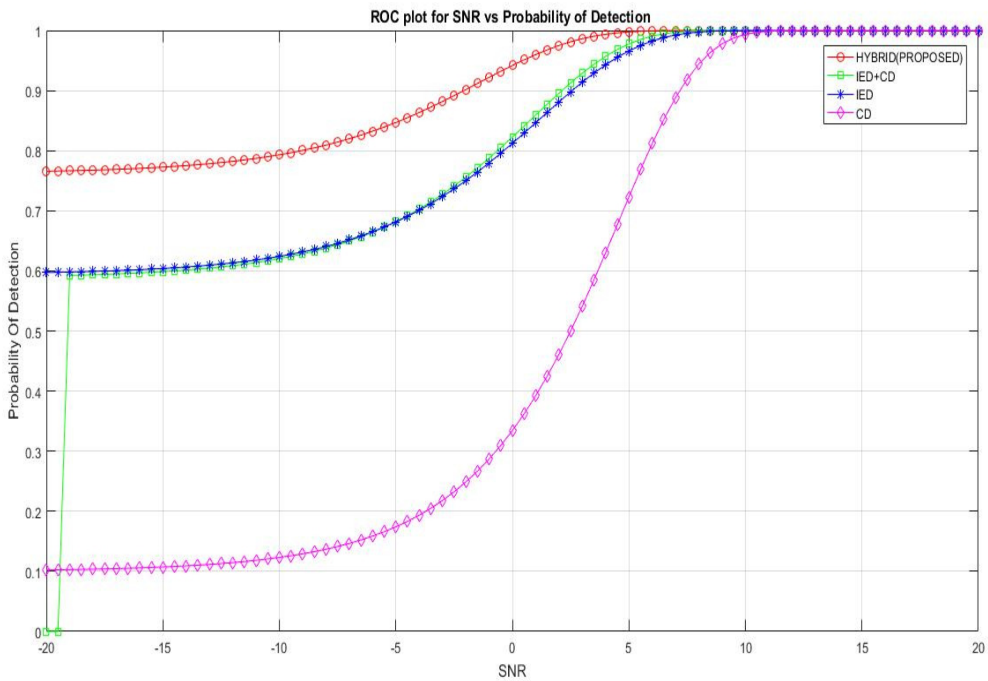

Fig 5.16 ROC plot for Probability of Detection versus Signal to Noise Ratio for different methods

The above figure depicts the "Receiver Operating Characteristics (ROC)" of different spectrum sensing methods along with our proposed method with "Probability of detection" versus SNR when "probability of false alarm" is set to a value of 0.2. The range of SNR value is taken as-20 dB to 20 dB. In the above figure, the performance of the proposed method is analyzed and compared with some existing methods, i.e. “Improved energy detection method (IED)”, “Cyclostationary method (CD)” and hybrid of “IED and CD”. As it seems from the graph that, at -20 dB value of SNR, the Probability of detection of the proposed method reaches almost at 0.8.While “IED”, “CD”, and hybrid of “IED” and “CD” offer the value of 0.6, 0.1 and 0 respectively. So, at this value of SNR, the percentage improvement for the proposed model is approximately 17% over “IED”, which offers the best value among all. Again, if we consider the value of SNR is 0 dB, then the “probability of detection” for the proposed model reaches at 0.95 (approx.). While, the other methods are lagging behind this value. At this point, the percentage improvement is around 15% over “IED”. All methods converge at 10 dB value of SNR.

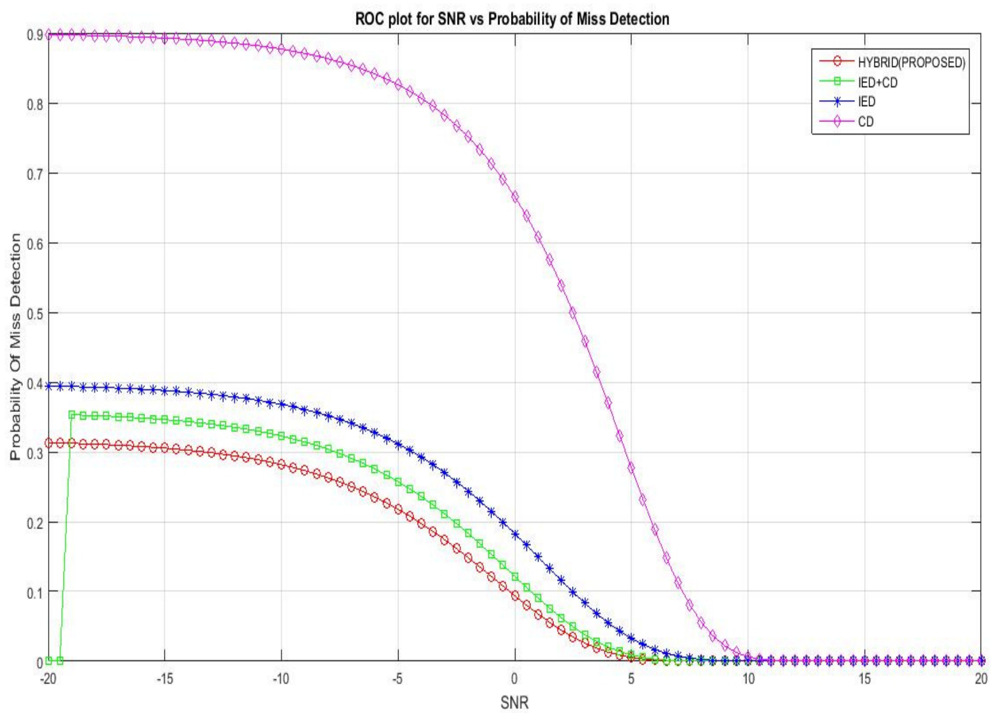

Fig 5.17 ROC plot for Probability of Miss Detection versus Signal to Noise Ratio for different methods

Figure 5.17 exhibits the "Receiver Operating Characteristics (ROC)" of different spectrum sensing methods along with our proposed method with "Probability of Miss detection" versus SNR when "probability of false alarm" is 0.2. The value of SNR ranges from -20 dB to 20 dB. The above figure shows that the "probability of miss detection" of the proposed model is less than the existing methods, when the SNR ranges from -20 dB to 5 dB. For higher SNR, the "probability of miss detection" almost reaches zero. This proves that, the proposed method performs very well at high SNR. Another important observation is that the proposed method provides better performance than the others in low SNR.

5.7.1 Comparison in terms of Computational Complexity

Let us consider, the computational complexity for "IED" is equal to C_1 (worst case). For different number of samples, the loop will be executed according to the number of samples. Say, the loop will be executed for 'n' times. So, the complexity will be nC_1.

Similarly, the computational complexity for "CD" is equal to C_2 (worst case). So, for n time execution, the complexity will be nC_2.

Now, according to the old hybrid method comprising of "IED" and "CD" it has been stated that whenever "IED" fails to detect the signal, "CD" will be invoked. So, if the loop is executed for 'n' times the complexity will be ($nC_1 + nC_2$).

In the proposed method, the concept of "SNR Wall" has been implemented. That means, for a specific range of value of SNR only "IED" will be executed and for a specific range of SNR the hybrid of "IED" and "CD" will be executed. So, if we consider only "IED" is executed for 'n' times, then the complexity will be 'nC_1'. Else, if the hybrid method is invoked then the complexity will be "($nC_1 + nC_2$)".

Hence, it can be said that the complexity of the proposed model is greater than "IED" and "CD" but either 'equal' or 'lower' than the existing hybrid method with better detection performance.

5.7.2 Outcome of Comparison

From the analysis of the simulation results we can draw a comparative study of the proposed method over the existing ones.

- The detection and accuracy is good for "Energy detection technique" only in high SNR. "Cyclostationary method" performs well in low SNR also. Proposed method provides satisfactory results in varying SNR conditions i.e. low as well as high SNR regions.
- The computational and implementation complexity is low for IED, but high for CD. The existing hybrid method offers a complexity higher than the aforementioned methods. In contrast, the proposed method offers a computational complexity higher than ED and CD both but lower or equal to the existing hybrid method.

5.8 Critical Analysis

The corresponding percentage improvements of the proposed model over the existing techniques in terms of "probability of detection" and "SNR" are shown in table 5.2, 5.3 and 5.4.

TABLE 5.2 Comparison of Simulation Result of the Proposed Model with Improved Energy Detection Technique

SNR (dB)	Probability of detection		Percentage Improvement (%)
	IED	Proposed	
-20	0.6	0.77	28.33
-15	0.6	0.79	31.66
-10	0.62	0.8	29.03
-5	0.68	0.85	25
0	0.71	0.95	33.80
5	0.95	1	5.26
10	1	1	-

TABLE 5.3 Comparison of Simulation Result of the Proposed Model with Cyclostationary Detection Technique

SNR (dB)	Probability of detection		Percentage Improvement (%)
	CD	Proposed	
-20	0.1	0.77	67
-15	0.12	0.79	55.80
-10	0.14	0.8	47.14
-5	0.18	0.85	37.22
0	0.34	0.95	17.94
5	0.72	1	38.88
10	1	1	-

TABLE 5.4 Comparison of Simulation Result of the Proposed Model with Hybrid of IED and CD Technique

SNR (dB)	Probability of detection		Percentage Improvement (%)
	IED+CD	Proposed	
-20	0	0.77	77
-15	0.6	0.79	31.66
-10	0.62	0.8	29.03
-5	0.68	0.85	25
0	0.82	0.95	15.85
5	0.98	1	2.04
10	1	1	-

The above critical analysis of results establishes the supremacy of the proposed method over the other existing methods.

Chapter 6

Conclusion

6.1 Concluding Remarks

In wireless communication field, many researchers have recognized the need for "Cognitive Radio Network". Since evolution, the motivation of researchers had been to develop an efficient "spectrum sensing" technique to design an effective "Cognitive Radio Network". In this regard, it has been found that the "Energy Detection" model is the potential one in terms of its simplicity. Furthermore, "Cyclostationary Detection" is the efficient one in terms of its detection performance.

In this work, the design of a two stage hybrid sensing model associated with "Improved Energy Detection" and "Cyclostationary Detection" has been presented. The detection performance is enhanced to an extent by employing this method. Firstly, the detection models are designed. Next, based on the value of SNR the corresponding algorithm is designed. Some filtering technique has been used to reduce the effect of noise in the received signal. Then, a "Binary Hypothesis Test" is designed to generate the decision output. In the hypothesis test, the incoming signal is compared to a pre defined value i.e. "Threshold Value". On the basis of the result of comparison the final decision is taken. Finally, some conventional spectrum sensing model is simulated for the comparison purpose. The simulation result reflects that the detection probability is enhanced by almost 33% with respect to "Improved Energy Detection" technique.

The proposed method offers a computational complexity higher than IED and CD both but lower or equal to the existing hybrid method. So, we can conclude that the proposed design offers a potential sensing model with reduced complexity and enhanced detection performance.

6.2 Future Scope

In this thesis, an attempt has been made to maximize the detection performance and minimize the complexity of a sensing model. The other important parameters such as sensing time, power consumption can also be considered. These parameters can also be optimized by employing different techniques. It is clearly understood that, the proposed model concentrates only on detection performance and complexity. The parameters like sensing time and power consumption can also be controlled by establishing some efficient modifications. This work could further be extended by formulating "Double Threshold" technique to meet more accuracy. Incorporating the "Blind Combination" method in the proposed model may be considered as another potential research direction.

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