A Comprehensive Analysis of Spectrum Sensing Methods in Cognitive Radio Networks

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Abstract

Optimum use of the spectrum is based on the observation of primary signal present in the spectrum. Various methods are defined in the literature for signal detection. The work presented in this paper is about the performance of different spectrum sensing methods. A comparative analysis the performance of energy detection, matched filter detection, co-variance detection and cyclo-stationary feature detection is done using MATLAB simulations. These methods have their own pros and cons. Computer simulations show that matched filter detection gives the maximum value of detection probability, thus proving the best method to sense the channel for the presence of primary signal. It is observed and verified that matched filter detection is the most efficient type of spectrum sensing method in terms of detection probability.

Keywords: Energy Detection, Matched Filter Detection, Co-variance Detection, Cyclo-stationary Feature Detection. Cognitive Radio Network

1. Introduction

Spectrum is a finite resource; hence it should be optimally allotted to the requesting users. In current scenario, we need an almost infinite spectrum to cater the needs of the young generation [1]. The available bandwidth should be distributed in such a way, that every user gets a time to access the channel. However, when the channels are statically assigned to a fixed number of licensed users, it is observed that these channels never remain busy at all times [2]. Sometimes the channel is free and can be accessed by the non-licensed users of the network. This fact is exploited by a cognitive radio to give service to more number of users, thereby increasingthe overall system capacity. A cognitive radio intelligently senses the free slots in the band and uses to transmit their signals. But the main problem is to keep a track on the free time of the channel. For this purpose, the users continuously sense the intended channel and report whenever there are blank spaces in the usage of the channel [3]. The need to sense the channel gives rise to a vast research in the field of spectrum sensing. A lot of methods are available to sense the channel. The problem lies in finding the ideal method to use for spectrum sensing. This paper gives an insight into the advantages, disadvantages and applications of different spectrum sensing methods.Spectrum sensing is limited by a number of factors [4]. Some of them are random nature of noise, shadowing (especially in urban areas), multipath fading etc.

Concepts of Cognitive Radio Networks

Cognitive Radio: The radio device which is capable of adjusting its own operating features like operating frequency, modulation format etc. depending on the current traffic conditions.

Cognitive users: The users which are accessing the wireless channel. They are of two types- primary and secondary. Primary user is the sole owner of the spectrum, also known as the licensed user. Secondary user is the non-licensed users which uses the spectrum allotted to the primary user, when primary user is not transmitting [5].

Spectrum Sensing: the cognitive radio identifies unused parts of the time frequency plane. The sensing is done in the presence of noise and fading. Sensing makes it possible to determine the spectrum holes. Spectrum sensing can be done by multiple users simultaneously to improve the sensing accuracy [6].

Spectrum Management: the cognitive radio decides in which part of the spectrum it should transmit and at what time instant. Since the SU have only the causal knowledge of the spectrum, it uses Markov's Model that says that a channel can be either in the occupied state or unoccupied state and has a transition probability to switch from one state to other. The CR takes care of the operating parameters such as to maintain the required QoS.

Spectrum Mobility: it involves maintaining smooth and continuous connection during transition and handoff across the spectrum. In order to minimize the interference for licensed user real time sensing is important for as to continuous searching for the spectrum holes and free channels. The exploration of free channels is a continuous process.

Spectrum Sharing: after sensing decision is made, the decision on distribution of the available spectrum is taken. The CRs use a mathematical tool named Game Theory is used for the analysis of the spectrum-sharing. The parameters used for a game includes the number of players, each player's strategy and a utility function named payoff. Player adjusts their strategies in a way to maximize their individual payoff. It defines fair spectrum scheduling methods.

Therefore, the most popular research area when it comes to cognitive radios is spectrum sensing.

2. Detection Techniques

Spectrum sensing is the preliminary processes performed by cognitive radio. It permits the secondary users to gain information about the radio traffic. This is done by SUs by recognizing the primary user transmission in the concerned channel of interest using one or more techniques. Based on this recognition it decides whether to transmit or not. Various techniques to detect the voids in spectrum have been defined in literature. Depending on whether the primary user is accessing the channel or not can be done with the help of many techniques.

Some of the widely used spectrum detectors are asfollows:

2.1 Energy Detector

Energy detector which is also known as *Radiometer* is the simplest and easiest method to sense the spectrum. The receiver need not have advance knowledge of the primary user signal so it is called a non-coherent technique. Samples of the received signal areused to calculate the received signal's energy. This energy is compared with a predefined threshold value. When the signal energy is more than the threshold than it is assumed that the PU is accessing the channel. While if the signal energy falls below the threshold than it is assumed that the PU is not accessing the desired channel.The input signal is made band limited by passing it across a band pass filter to get the required frequency. The band-limited signal is then squared and its energy is calculated by integrating it over N time instances.The integrator output is used for decision making by comparing it with a predefined threshold.Energy detector is simple for implementation.SU need not know anything about the transmitted waveform. The computational cost is low. However there are some major disadvantages of Energy detection. The performance is poor at low SNRs due to the unpredictable nature of noise.It is not capable of distinguishing between the interference caused due to the secondary user or the primary user.

2.2 Matched Filter Detector

Matched filtering is the optimum method for detection of primary users if the characteristics of the transmitted signal are known. It takes very little time to achieve a certain probability of false alarm or probability of miss-detection. Matched filtering is the best way to improve SNR of the detection process. It is referred as the optimal method for spectrum sensing because even in the presence of AWGN noise it can maximize the output SNR. It is called a coherent detection technique as advance knowledge of the primary signal is required for detection. It is referred as a linear filter in where an unknown signal is correlated with a known signal to track the presence or absence of primary signal. It quickly attains high processing gain and error probabilities.It has low computational cost. It requires deliberately dedicated sensors. However getting advance information of the signal characteristics of the primary user is difficult for SUs. The main limitations of matched filter are large power consumption and large execution time.

2.3 Cyclo-stationary Feature Detector

In this method cyclo-stationary features of the signal received are extracted to detect the presence of primary signal. Cyclo-stationary features occur due to the periodicity in a signal or its statistics viz. mean, standard deviation, autocorrelation etc. It is possible to intentionally induce these features in a signal of interest. These features can be used to for signal detection even at very low SNR values. It is called a coherent detection technique where a advance knowledge of the transmitted signal is mandatory. If a PU's signal is cyclo-stationary then its auto-correlation function should be a periodic function with time period T. This ACF is compared to a threshold. If the ACF is more than the threshold level it is assumed that the PU signal has seized the channel otherwise the channel is free.Cyclo-stationary Feature detection shows good results at very low values of SNR also. It shows high sensing accuracy as noise and interference does not correlate.No need of synchronization.It attains huge processing gain. The major limitations are that they are applicable to sensors with signals with strong cyclo-stationary property.Performance is worse when noise is stationary.Computational complexity is high. Sensing time is long and high computational cost.

2.4 Covariance Detection

When no information regarding the primary signal and noise is known to the sensor it uses covariance detection method. In this method the statistical covariance matrix or autocorrelation functions of the primary signal and noise signal are different. The covariance matrix between the noise and transmitted signal is computed. If the diagonal elements in the covariance matrix obtained from the received signal have all non-zero elements it is assumed that PU is using the channel. If the diagonal elements are all zero it is assumed that PU is not present. It is also known as Maximum Minimum Eigen value detection.It is robust at small SNR. However detection is based on the units used to express the two signals.It requires more sensing time.It is susceptible to synchronization errors.

2.5 Wavelet Detection:

If the power spectral density(PSD) of the primary user signal is smooth within a frequency band, wavelet transform may be used to detect a primary user signal. In this technique wavelet transform is used which is a multi-resolution analysis system where an input signal is decomposed into different frequency component and analyzed using the set of basic function which relate to each other by simple scaling and translation.It is a non-coherent detection technique.It has flexibility in adapting to the dynamic spectrum.High computation cost.Not applicable for spread spectrum signals and CDMA.High sampling rates are required.

3. Simulation Details

Before performing the actual computer simulations the analytical design of various spectrum sensing methods is done by solving a hypothesis that is been tested for different algorithms.

H_0: only noise present

H_1: signal plus noise present

Hypothesis H_0 corresponds to false alarms while H_1 indicates detection.H_0 is known as the null hypothesis indicating that the PUis not transmitting through that channel andH_1 is known as the alternate hypothesis indicating that the PU is transmitting through that channel.It is possible to define four cases associated with the detected signal:

1. H_1validunder H_1 hypothesis contributing to a Probability of Detection(P_D).
2. H_1validunderH_0hypothesis contributing to a Probability of False Alarm (P_F).
3. H_0validunderH_1hypothesis contributing to a Probability of Missed detection(P_{MD}).
4. H_0valid underH_0hypothesis.

Numerous sets of simulations have been performed using MATLAB tool. The performance evaluation of energy detection spectrum sensing is analyzed under the effect of AWGN channel. The result is obtained in terms of probability of detection, the reverse probability of miss detection and probability of false alarm at different values of SNR in different channels.

A set of metrics is used to assess the performance of the spectrum sharing system in a CR network. In addition to its impact on the primary user's network, these metrics comprise level of interference to primary users and spectral utilization efficiency within the network. These metrics are defined below:

1. Probability of Detection (P_D): It specifies the probability that a SU verifies the existence of a PUwhen the spectrum is actually occupied by the PU. For better performance it should have a high value.
2. Probability for False Alarm (P_F): It specifies the probability of aSU that verifies the existence of a PU misleading that the spectrum is occupied when it is actually free. It should have a low value for better performance of a CRN.
3. Probability of Miss-detection (P_{MD}): It specifies the probability of a SU stating the absence of a PU again misleading that the spectrum is free in contrast to the occupancy of the spectrum by a PU. It creates interference to the PU. It should have a low value for better performance of a CRN.
4. Total Error Probability/ Probability of Error (P_E): It denotes the error caused due to false alarms and missed detections in the sensing process. In fusion rules this is simply the sum of P_F and P_D. For better performance it should be low.

A number of assumptions and initializations have been done for simulation.The number of samples use for simulation are1000 and the simulations are done for 10000 iterations. The targeted SNR is from -25 dB to 25 dB.Above detection techniques are simulated and obtained results are plotted in the form of Receiver's Operating Characteristics and Complementary Receiver's Operating Characteristicscurves.

4. Results and Analysis

All non-cooperative sensing methods (ED, MFD, CFD, MME) are simulated and the results are presented in this section. To start with, the graphs regarding the performance of energy detection are presented.

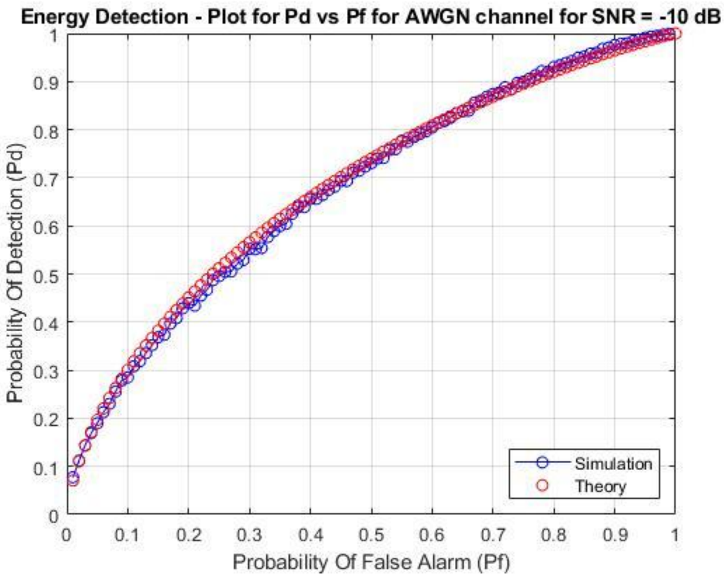

Figure 1: ROC for Energy Detector

The curve in figure 1 shows that P_D increases with the increasing value of P_F. For the sake of analysis SNR = -10 dB and PF = 0.1 is selected. At $P_F = 0.1$, it is observed that P_D attains a value of 0.3. This value increases linearly till it reaches 1 at $P_F = 1$. This happens due to the fact that as the number of sensing attempts increase, the number of detections increases and correspondingly false alarms also increase.

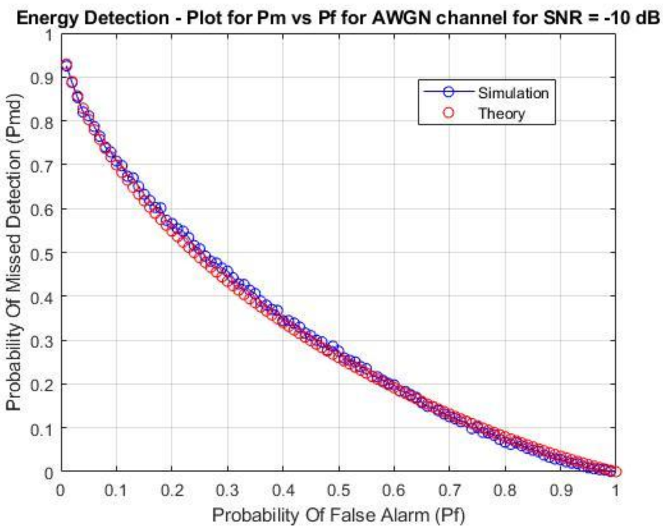

Figure 2: CROC for Energy Detector

The complementary curve for the figure 2 is shown here. It shows the reverse pattern. As P_F increases P_{MD} decreases till becoming zero at $P_F = 1$.The curve verifies the fact that $P_{MD} = 1 - P_D$It is obvious that when false alarms are less, the sensor will not create alarms regarding presence of PU and the possibility of missing the detection increases. This increases the probability of missed detections.

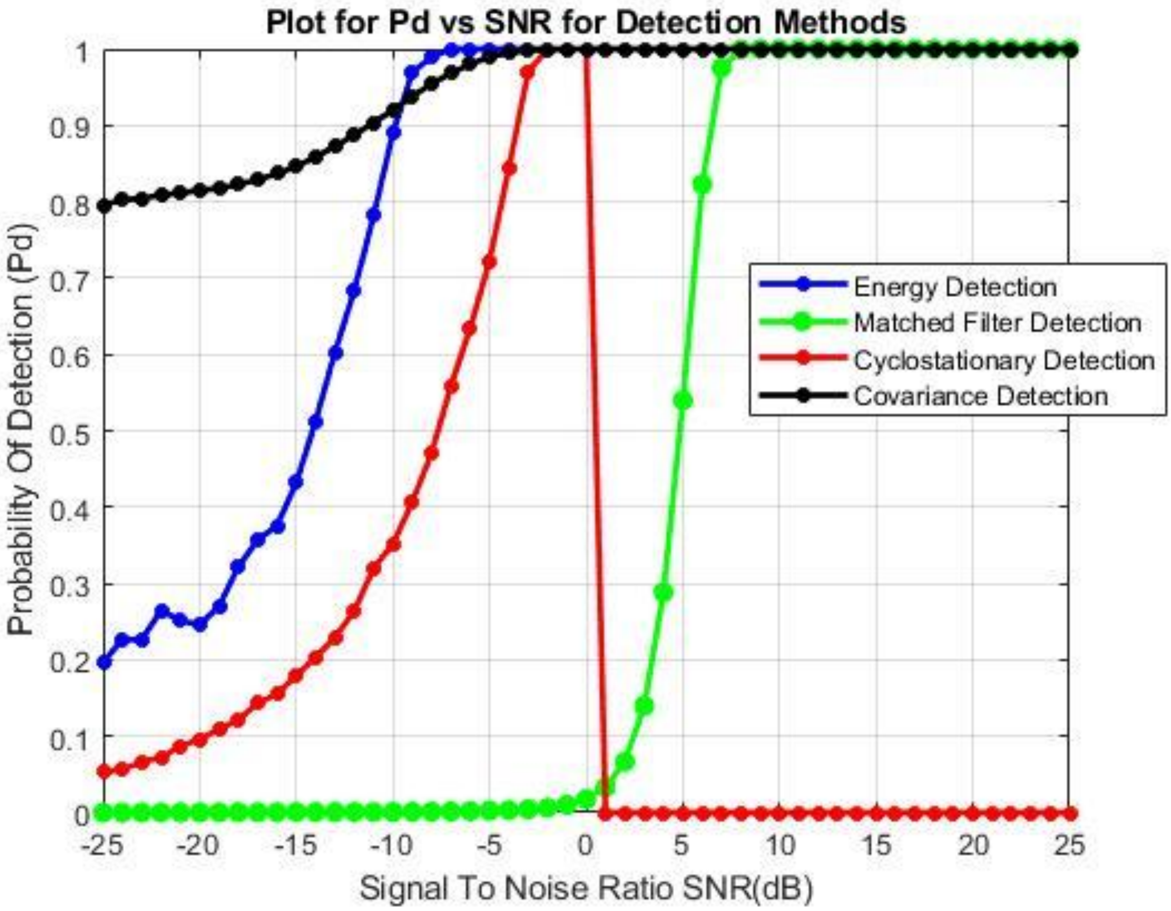

Figure 3: SNR vs P_D for Non-cooperative Detection methods in AWGN channel

Different detection methods are simulated under the influence of AWGN channel. The performance of Energy Detection (ED) is already discussed in the above figures. Matched filter detection (MFD) performs excellent at higher values of SNR while cyclo-stationary feature detection (CFD) works well at lower SNRs. Covariance detection (MME) show excellent performance at all values of SNR. Even at -25dB it achieves a P_D of 0.8. At around -8 dB it P_D attains 1 and remains flat for higher SNRs. All detection methods show fairly good performance with their own pros and cons. However energy detection is the most popular and versatile detection technique. In the further work energy detection is ben used for individual sensing by each of the SU. ED is the foundation of cooperative spectrum sensing.

5. Conclusion

Spectrum is a very valuable resource in wireless communication systems and it has been a focal point for research and development efforts over the last several decades. Cognitive Radio is a novel technology that can potentially improve the utilization efficiency of the radio spectrum.In this research several spectrum sensing techniques have been implemented using MATALB software and the results are plotted as ROC and CROC curves. The work commenced from the analysis of simple energy detector and is used as the reference to study the results of all other detection methods. The value of P_D attained is 0.38. Other non-cooperative sensing methods were also simulated and their relative performance with energy detection was studied. It is observed that all non-cooperative detection techniques perform well at low SNR values also. The optimum results are obtained for Matched filter detection. Each sensing method hasits own pros and cons.

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