Performance Analysis of Two-Stage Spectrum Sensing for Cognitive Radio Networks

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Abstract
Cognitive radio has emerged as a solution to the problem of low spectral occupancy and inefficient utilization of the licensed radio spectrum. Spectrum sensing is most important and basic operation of cognitive radio. In this paper we proposed a Two-stage spectrum sensing algorithm in order to increase the sensing performance of conventional single stage spectrum detection techniques. In the proposed scheme, Energy detection is used in the first stage to detect the existence of PU signal and if it is fail to detect the signal we used Maximum-Minimum Eigenvalue (MME) based detection in the second stage to find the presence of PU signal. The detection parameters are selected in such away to increase the probability of detection of PU signal. Also at the end performance comparison between Energy detection, MME detection and Two-stage i.e. combination of ED and MME techniques done for both Sinusoidal signal and Wireless Microphone FM signal over AWGN channel.

Keywords
Two-stage Spectrum Sensing, Cognitive Radios, Energy Detection, MME Detection, White Hole

I. Introduction

Communication networks, either it is wired and wirelesses, plays a very important role in each aspect of modern life: social, economic, healthcare, and others. During the last two decades, there has been a huge demand for wireless communication services, due to increase in consumer electronics applications and personal high-data-rate networks. Due to the ever-growing demand for the radio spectrum and the exclusive access to licensed bands, it has become challenge for the Federal Communications Commission (FCC) and regulators of many countries to allocate radio spectrum for new wireless services [1]. However, studies shows that allocated licensed band frequencies are largely underutilized in specific regions. It is observed that at any location at any given time around 85-90% of the licensed radio spectrum is not in use. Cognitive radio has emerged as a solution [14] to the problem of low spectral occupancy and inefficient utilization of the licensed radio spectrum. It enables the unlicensed users to access the licensed band without violating the exclusive usage facility for the licensed user. It identifies the unused portions of the licensed spectrum known as spectrum holes and makes them available for unlicensed or secondary users. Cognitive Radio cycle has the following function [4] as shown:

- Spectrum Sensing- it is the ability to detect unused frequencies in the licensed band.
- Spectrum Management-it is the analysis of the available frequency holes so as to select the one that satisfies certain quality-of service requirements.
- Spectrum Mobility or handoff- that guarantees that unlicensed users (SU) are able to coherently transit to use another frequency without connection loss once the licensed user (PU) is detected.
- Spectrum-Sharing-To coordinate access to this channel with other users.

The rest of the paper is organized as follows. Section II presents Spectrum Sensing techniques in detail.

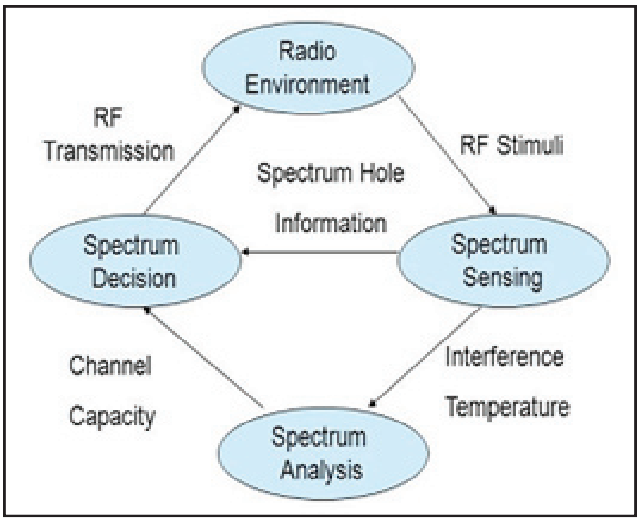

Fig. 1: Cognitive Radio Cycle

In Section III system model of two-stage spectrum sensing scheme and all the mathematical analysis carried out is given. In Section IV, results and simulation is presented in which performance of energy detection, MME detection and Two-stage i.e. Combination of ED and MME detection technique is analyzed for both Sinusoidal Signal and Wireless Microphone FM Signal over AWGN channel.. Finally conclusion and discussion is done in the last section V.

II. Spectrum Sensing Techniques

Sensing the radio environment and search for white spaces in it is one of the main tasks of Cognitive radio. Spectrum sensing is one of the important parts in cognitive radio cycle [2]. It enables the secondary user to observe its surrounding environment and to utilize the radio environment by determining spectrum holes, without any interference to the primary network. There are various primary user detection techniques used to detect PU signal, a brief description is given below [3, 15].

A. Energy Detection

It is the most widely used method for the detection of primary user signal since; it doesn't require any prior knowledge of primary use signal. In this method, the energy of the received signal is calculated which is then compared to some given threshold to determine whether primary user is present or absence.

B. Matched Filter Detection Method

In Matched filter method signal is detected by calculating the correlation between the received signal and a known copy of the signal. It is the optimal detection technique as it maximizes the SNR of the received signal in the presence of AWGN environment but it requires a priori knowledge about a PU's pilot signal, like modulation type, packet format, carrier frequency, and pulse shaping.

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C. Cyclostationary Feature Detection

In this technique, CR user uses the feature of periodic nature of the modulated signal in order to distinguish between PU signal and noise. It is a complex method among all techniques. Generally, the modulated signals contain the cyclostationary property due to sampling, cyclic prefix, sine wave carriers, etc. But since noise signal is a wide sense stationary signal with no correlation among its samples it doesn't exhibit cyclostationary property.

D. Maximum-Minimum Eigen Value (MME) Detection

In this method the received signal covariance matrix is generated and Eigenvalues of the covariance matrix is calculated. It has been observed that the ratio of maximum to minimum Eigenvalue of the received signal covariance matrix can be used to detect the signal. If the ratio of maximum to minimum Eigenvalue is greater than the threshold then the PU signal is considered to be present in the given band else considered to be empty.

III. System Model

A. Energy Detection

For the calculation of energy of the received signal, firstly the samples are squared and integrated over the observation interval and the output of the integrator is then compared against the threshold. If the output of the integrator greater than the threshold then it is assumed that the given radio spectrum is occupied otherwise it is considered as vacant.

The detection problem can be written as

$$T_{ED} = T(x) = \frac{1}{N}\sum_{n=1}^{N}|x[n]|^2$$

$$Y = \begin{cases} H_0 hypothesis; T(x) \le \lambda \\ H_1\ hypothesis; \mathrm{T(x)}\ > \lambda \end{cases}$$

Where x[n] is received signal and is the threshold which is used to decide whether the primary user is present or not. Denoting and as the respective probabilities of primary user presence and absence. The probability of false alarm can be calculated as

$$P_f = \Pr\{T(x) > \lambda | H_0\} = \int_{\lambda}^{\infty} P_{Ho}(x)\,dx$$

$$P_f = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}\right)$$

The Probability of detection can be calculated as

$$P_d = \Pr\{T > \lambda | H_1\} = \int_{\lambda}^{\infty} P(T: H_1)\,dx$$

$$P_d = Q\left(\frac{\lambda - N(\sigma_w^2 + \sigma_x^2)}{\sqrt{2N(\sigma_w^2 + \sigma_x^2)^2}}\right)$$

Where Q (a) is Q function, N number of sample taken in energy detection, σ_w^2 variance of the noise, σ_x^2 variance of the signal and λ is the threshold for energy detection.

B. MME Detection

In this method covariance matrix of received signal is generated and the ratio of maximum to minimum Eigen value of the received covariance method is than compared to the threshold . If the ratio is exceeding the threshold then the primary user signal (PU) is considered to be present else it considered to be absent. Based on some latest random matrix theories (RMT) [13] .we quantify the distributions of these ratios and obtain the detection thresholds for the MME detection algorithms [5-8].

The signal detection algorithm falls in two hypothetical decisions

H_0hypothesis : $\eta[n]$ And

H_1hypothesis : $x[n] + \eta[n]$

The H_0 hypothesis is for *"no signal exists"* and H_1 hypothesis is for *"Signal exists"*. Fig. 5.2. shows a simple MIMO system for two receivers and two transmitter scenario. The primary user signal S[n] is a superposition of signal from the two receivers, S_1 and S_2. The noises (η_1, η_2) at the receiver side (right side) are assumed to have zero correlation with the corresponding sent signals. Noise is assumed to i.i.d. Gaussian process. The channel responses are designated as h_{11}, h_{12},$h_{21}$and h_{22} for each of transmitter-receiver pairs. The matrix H[n] gives the channel property.

$$x[n] = \sum_{j=1}^{P}\sum_{k=0}^{N_{ij}} h_{ij}(k)S_j(n-k) + \eta(n)\ \ n=0,1 \qquad (1)$$

Where, P is the number of source signals, h_{ij} (k) is channel response from source signal j to receiver i and N_{ij} is the order of the channel. If we consider $N_j \stackrel{\text{def}}{=} \max_i N_{ij}$ be the number of sample of received signal. By considering to eq.(1) above and considering consecutive windows of length L, called smoothing factor we can write the received signal as

$$x(n) \stackrel{\text{def}}{=} [x^T(n), x^T(n-1), \dots, x^T(n-L+1)]^T \qquad (2)$$

$$(n) \stackrel{\text{def}}{=} [\eta^T(n), \eta^T(n-1), \dots, \eta^T(n-L+1)]^T \qquad (3)$$

$$s(n) \stackrel{\text{def}}{=} [s_1(n), s_1(n-1)\dots, s_1(n-N_1-L+1), \dots, s_P(n), s_P(n-1)\dots, s_P(n-N_1-L+1)]^T \qquad (4)$$

The received signal x(n) can be rewrite in term of channel model as

x(n) = Hs(n)+ η(n)

Where H is the channel model matrix

The statistical covariance of the received signal, transmitted signal and noise signal as,

$$R_x = E(x(n)x(n)^T) \qquad (5)$$

$$R_s = E(s(n)s(n)^T) \qquad (6)$$

$$R_\eta = E(\eta(n)\eta(n)^T) \qquad (7)$$

Let us consider by computing the covariance matrix of equation (5). β_{max} and β_{min} are the maximum and minimum Eigen value of covariance matrix of eq.(5)

Than the decision metric of MME stage is given as:

$$T_{MME} = \frac{\beta_{max}}{\beta_{min}}$$

$$Y = \begin{cases} H_0 hypothesis; T_{MME} \le \gamma \\ H_1\ hypothesis; T_{MME} > \gamma \end{cases}$$

Where γ is the threshold for MME detection. If the ratio T_{MME} is exceeding the threshold γ then the primary user signal (PU) is considered to be present else it considered to be absent.

The probability of false alarm for MME detection can be described as

$$P_f = \Pr\{T_{MME} > \gamma \,|\, H_0\}$$

$$P_f = 1 - F_1\left(\frac{\gamma(\sqrt{N}+\sqrt{ML})^2 - \mu}{v}\right)$$

Where $\mu = (\sqrt{N-1} + \sqrt{ML})^2$

$$v = (\sqrt{N-1} + \sqrt{ML})\left(\frac{1}{\sqrt{N-1}} + \frac{1}{\sqrt{ML}}\right)^{1/3}$$

Where N is the number of samples considered, L is the smoothing factor, P is the number of transmitter, and M is the number of receiver.

Here $F_1(t)$ is Tracy-Widom distribution function of order 1. It is generally difficult to evaluate it. Fortunately, there have been tables for the functions [20].

Table 1: Tracy-Widom Distribution Function

t	-3.90	-3.18	-2.78	-1.91	-1.27	-0.59	0.45	0.98	2.02
$F_1(t)$	0.01	0.05	0.10	0.30	0.50	0.70	0.90	0.95	0.99

Therefore the expression of threshold can be written as

$$\gamma = \frac{(\sqrt{N-1}+\sqrt{ML})^2}{(\sqrt{N-1}-\sqrt{ML})^2} \cdot \left(1 + \frac{(\sqrt{N-1}+\sqrt{ML})^{-2/3}}{(NML)^{1/6}} F^{-1}(1 - P_f)\right)$$

C. Two-stage Spectrum Sensing Scheme

From the above discussion of two detection methods i.e. Energy detection and Maximum-Minimum Eigenvalue (MME) detection, it is clear that at low SNR the performance of energy detection method is poor whereas the performance of MME detection is better at low SNR but it required high sensing time. So to optimize the sensing performance at low SNR without any much increase in sensing time we proposed two stage spectrum sensing in which we combine the merits of both the detection of method in order to optimize the sensing performance at low SNR [9-12]. Fig. 4.3 shows the block diagram of proposed two stage spectrum sensing method as below.

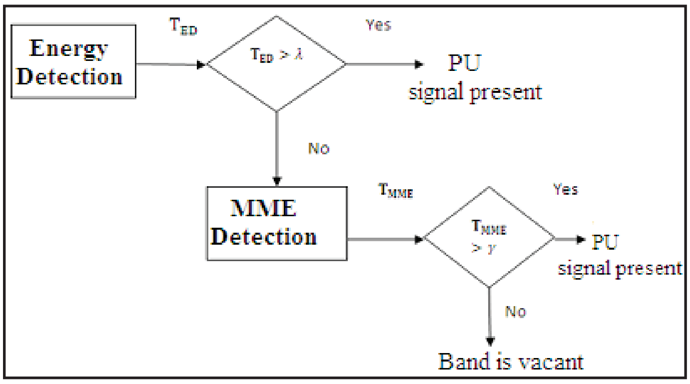

Fig. 2: Block Diagram of Two-stage spectrum sensing

In the proposed two-stage spectrum sensing we assume that there are L channels to be sensed and that channels are sensed serially. In the first sensing stage, the channel is sensed by using energy detection. If the decision metric is greater than that of the threshold λ, the channel is declared to be occupied. Else, the received signal is analyzed by second sensing stage consisting of MME detection. If the constituent detection metric is greater than a threshold γ, the channel is declared occupied, else it is declared to be empty.

IV. Simulation and Result

A. Performance Analysis of Energy Detection

In this section we analyze the performance of Energy Detection techniques over AWGN channel for two signals first is a Sinusoidal Signal and second one is a Wireless Microphone FM Signal operating on Silent Mode of receiver and noise is considered as independent identically distributed random Gaussian noise.

Fig. 3 is a ROC plot for probability of detection (P_d) vs. probability of false alarm (P_f) at constant value of signal to noise ratio SNR= -20dB by taking both Sinusoidal Signal and Wireless Microphone FM Signal over AWGN channel. In this number of samples taken is N=100000 and number of Number of Monte Carlo simulation is h=1000.from figure it is shown that at small value of P_f wireless signal have high value of probability of detection P_d to that of sinusoidal signal. Similarly Figure 4 is a ROC plot for probability of detection (P_d) vs. probability of false alarm (P_f) at constant value of signal to noise ratio SNR= -25dB.

From the figure 3 and 4 it is clearly shown that at low SNR i.e. -25 dB the probability of detection is less than that of at -20 dB in the same value of probability of false alarm.

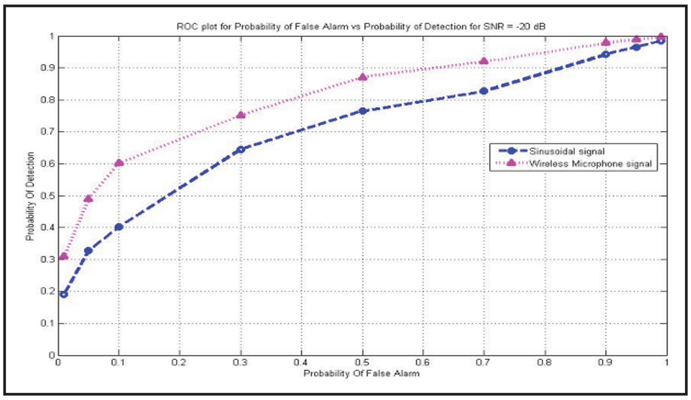

Fig. 3: ROC Plot for P_d Vs. P_f at SNR = -20 dB for Energy Detection

Similarly we plot P_d Vs. SNR at constant value of probability of false alarm. Figure 5 is a ROC plot for P_d Vs. SNR at P_f = 0.1 for both Sinusoidal and Wireless Microphone FM Signal (Silent Mode).

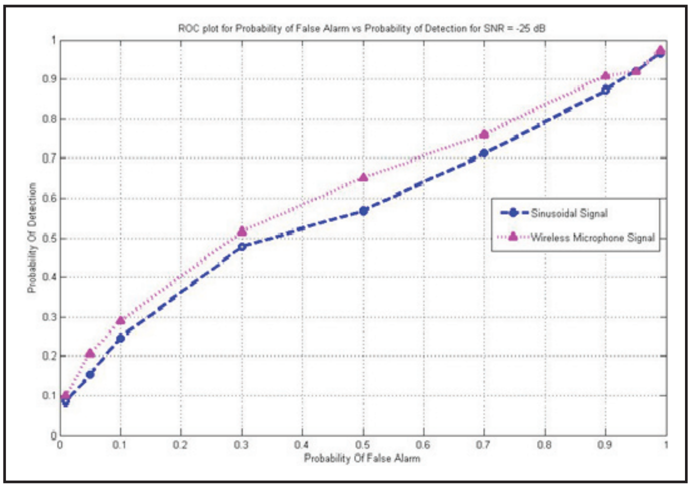

Fig. 4: ROC Plot for P_d Vs. P_f at SNR = -25 dB for Energy Detection

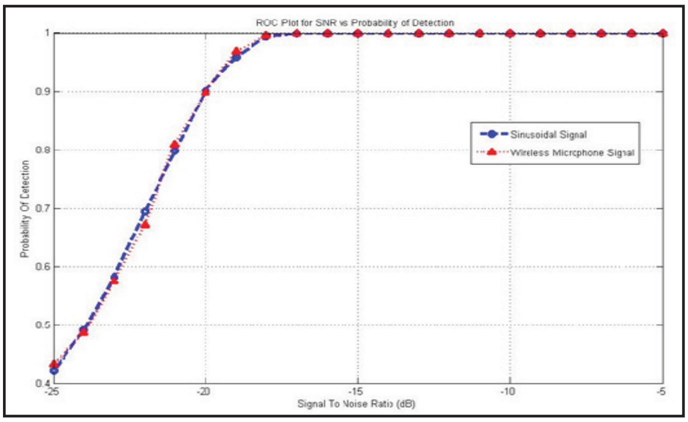

Fig. 5: ROC Plot for P_d Vs. SNR at P_f = 0.1 for Energy Detection

From fig. 5 it is clearly shown that at low SNR value i.e. from -25 to -20 dB, the probability of detection is small and its value increases as SNR value increases. Therefore we can say that the sensing performance of Energy Detection is poor at low SNR.

B. Performance analysis of MME Detection

In the simulation of MME Detection we consider Multiple Input Multiple Output (MIMO) system in which the number of transmitters are considered as P=2 and number of receivers are M=2. Also we taking smoothing factor L=8 and number of samples taken for simulation are N=100000. And number of Monte Carlo simulation are h=1000. Fig. 6 is a ROC plot for probability of detection (P_d) vs. probability of false alarm (P_f) at constant value of signal to noise ratio SNR= -20dB by taking both Sinusoidal Signal and Wireless Microphone FM Signal over AWGN channel. From figure it is shown that at small value of P_f wireless signal has low value of probability of detection P_d to that of sinusoidal signal. Similarly Fig. 7 is a ROC plot for probability of detection (P_d) Vs. probability of false alarm (P_f) at constant value of signal to noise ratio SNR= -25dB.

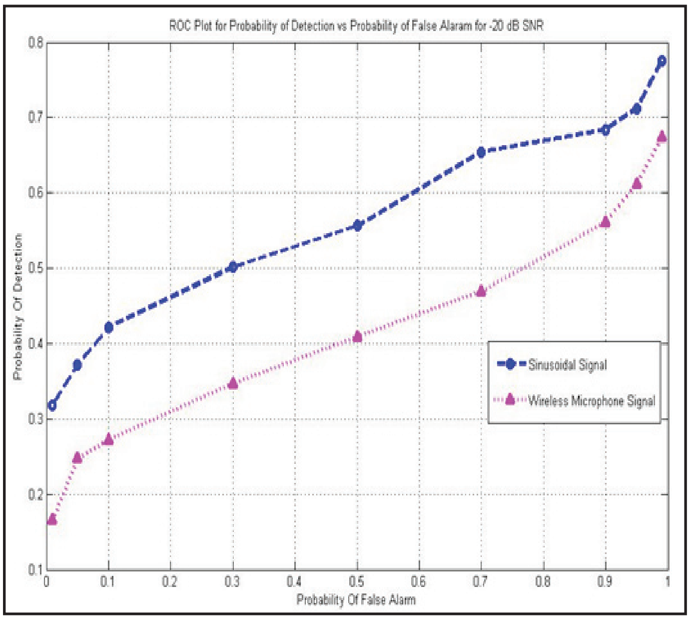

Fig. 6: ROC Plot for P_d Vs. P_f at SNR = -20 dB for MME Detection

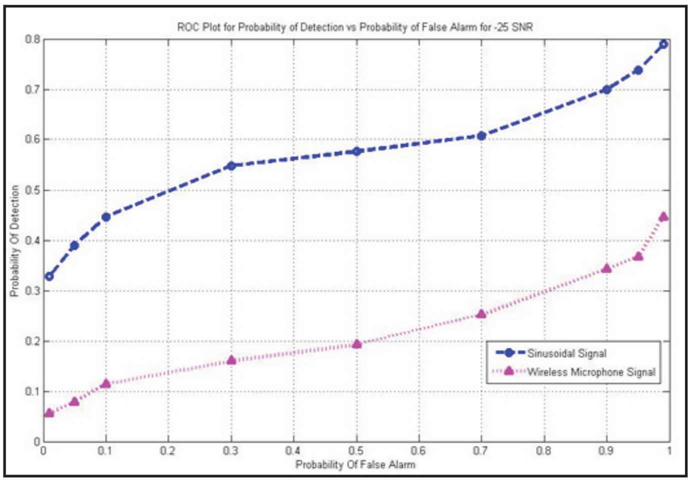

Fig. 7: ROC Plot for P_d Vs. P_f at SNR = -20 dB for MME Detection

Similarly we plot P_d Vs. SNR at constant value of probability of false alarm. Figure 8 is a ROC plot for P_d Vs. SNR at P_f = 0.1 for both Sinusoidal and Wireless Microphone FM Signal (Silent Mode). In fig. 8 it is shown that at low value of SNR, Probability of detection P_d has small value but greater than energy detection and it is increased as we increased the SNR value.

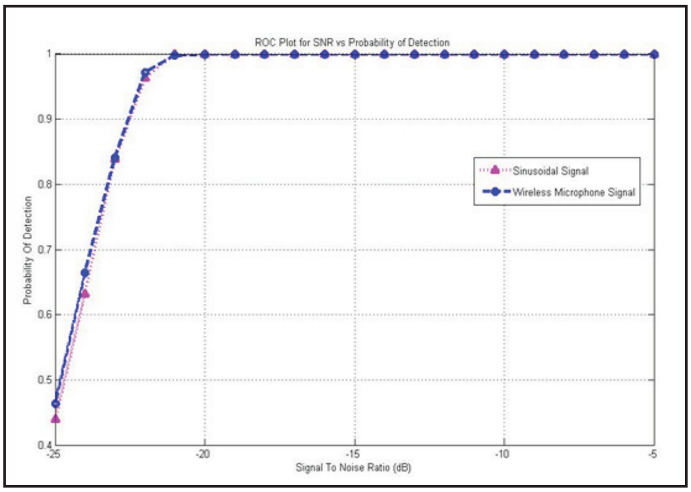

Fig. 8: ROC Plot for P_d Vs. SNR at P_f = 0.1 for MME Detection

C. Performance analysis of two-stage Spectrum Sensing (ED+MME)

For the simulation of proposed Two-stage spectrum sensing algorithm we first detect the PU signal at first stage i.e. Energy Detection stage and calculated probability of detection of PU signal at each SNR point and then compared it to the some fixed value of probability of detection which is the cutoff value for first stage. If the received signal probability is exceeding to the fixed value than PU signal is only detect by first stage otherwise it is passed to second stage i.e MME Detection for further detection.

The simulation result for two-stage method is given in figure 9 and figure 10 which are the ROC plot for probability of detection (P_d) vs. probability of false alarm (P_f) of both Energy detection and MME detection techniques at constant value of signal to noise ratio SNR= -20dB for both Sinusoidal Signal and Wireless Microphone FM Signal respectively.

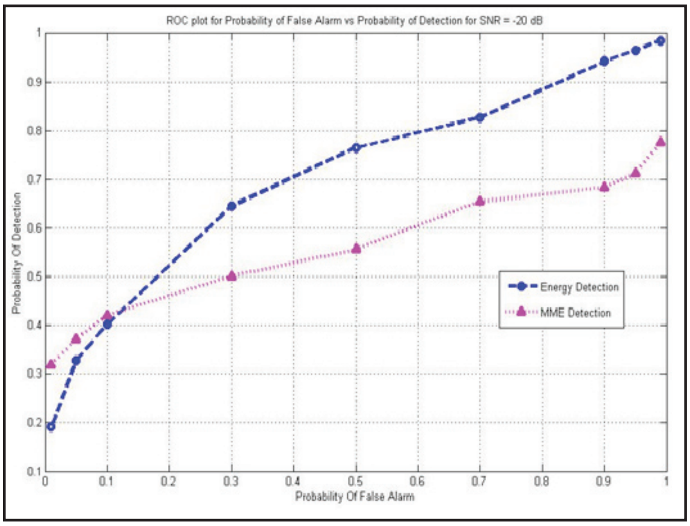

Fig. 9: ROC plot for P_d Vs. P_f at SNR = -20 dB for Sinusoidal Signal

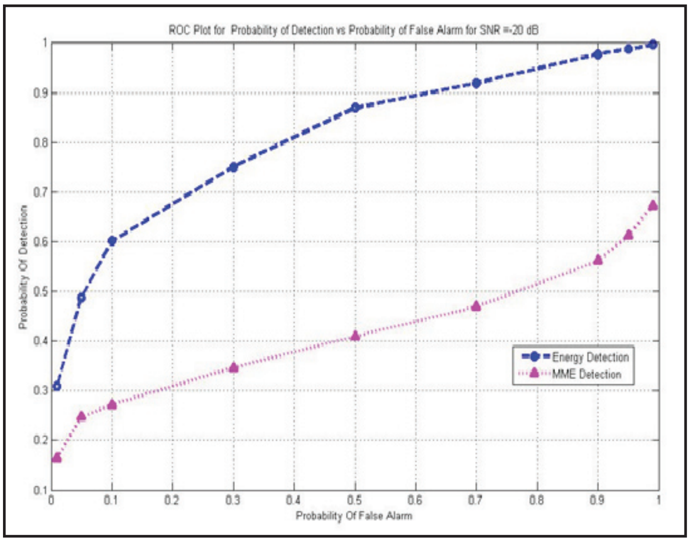

Fig. 10: ROC plot for P_d Vs. P_f at SNR = -20 dB for Wireless Microphone Signal

Figure 11 is a ROC plot for P_d Vs. SNR at P_f = 0.1 of both Energy detection and MME detection techniques for Sinusoidal Signal. Similarly, fig. 12 is a ROC plot for P_d Vs. SNR at P_f = 0.1 of both Energy detection and MME detection techniques for Wireless

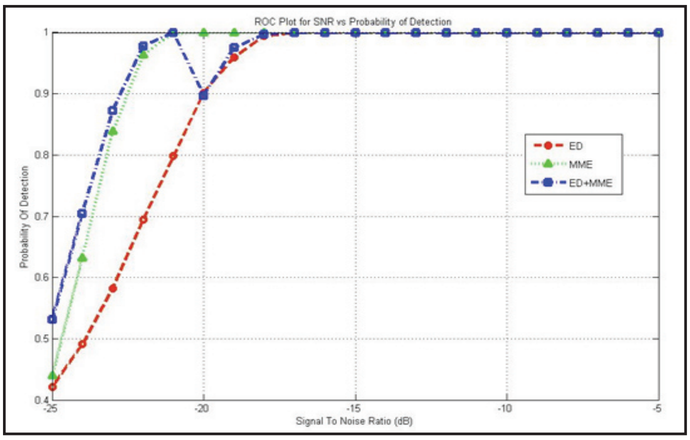

Fig. 11: ROC Plot for Vs. SNR at = 0.1 for Sinusoidal Signal

Microphone FM Signal (Silent Mode). From the simulation result obtained for both sinusoidal signal and wireless microphone signal it is clearly shown that at low SNR value two-stage (ED+MME) perform better with high value of probability of detection to that of individual Energy detection or MME detection techniques with fast sensing as compared to the MME detection.

The comparison of the result can be compute in tabular form as given in Table 2.

Table 2: Comparison of Prob. of Detection of Spectrum Sensing Techniques with SNR

SNR (dB)	P_d for ED	P_d for MME	P_d for ED+MME
-25	0.41	0.43	0.52
-23	0.7	0.97	0.98
-18	0.94	1.0	0.99

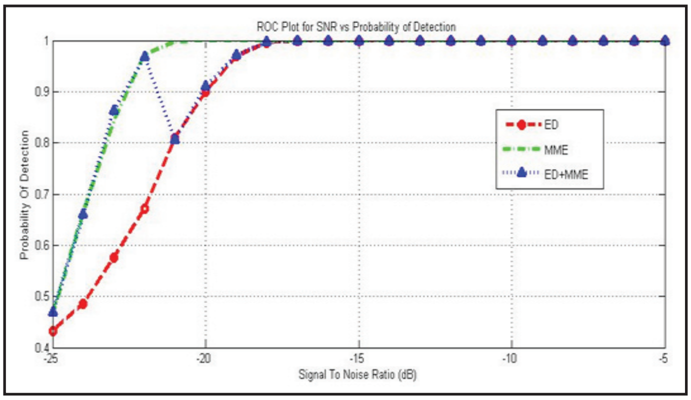

Fig. 12: ROC Plot for P_d Vs. SNR at P_f = 0.1 for Wireless Microphone Signal (Silent Mode)

V. Conclusion and Discussion

In this research, several spectrum sensing techniques have been reviewed and a comparison is made. But special attention has been given to Energy Detection and MME Detection because of its low computational complexity and it does not require any prior knowledge of PU signal and also the combination of these two methods as it improves the sensing performance. We analyzed the performance of Energy Detection, MME Detection and combination of Energy Detection and MME Detection (ED+MME) algorithm for spectrum sensing in cognitive radio by drawing the ROC plot between probability of detection P_d and probability of false alarm P_f at different value of SNR and probability of detection P_d Vs. SNR plot at constant value of probability of false alarm P_f for both Sinusoidal Signal and Wireless Microphone Signal operating in Silent mode over AWGN channel.

We conclude on the result after analyzing each of the above techniques that Two-stage (ED+MME) sensing algorithm perform better to that of Energy detection or MME Detection at low SNR value specially from -25 dB to -20 dB and also the sensing time requirement of two-stage algorithm is less as compared to the MME Detection.

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