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Adaptive Double-Threshold Based Energy and Matched Filter Detector in Cognitive Radio Networks

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***Abstract*—In this paper we propose a new cooperative spectrum sensing method using adaptive double threshold energy and matched filter detector in cognitive radio networks. The energy detector (ED) performance is highly degraded under noise uncertainty condition. Also, ED cannot well differentiate between the signal and noise, if the detected observational value of the primary user (PU) lies in the confused region i.e., between signal and noise. We propose a scheme based on adaptive double threshold that uses matched filter (MF) detector for the reliable detection in the confused region and energy efficient ED for the clear region where the detector can easily differentiate between signal and noise and makes its own local decision. The fusion center collects the local decisions and observational values of the secondary users and then makes the final decision to ascertain whether the primary user is present or not. Simulation results shows that our proposed method has higher detection performance as compared to other spectrum sensing methods.**

I. Introduction

In a survey conducted by the Federal Communications Commission (FCC) on spectrum utilization has indicated that the actual licensed spectrum is largely under-utilized in vast geographical dimensions [1]. Cognitive Radio (CR) provides opportunistic access to unused licensed bands [2][3]. CR allows secondary users (SU) to utilize the free portions of licensed spectrum while ensuring no interference to primary users (PU) transmissions. In the recent years, cooperative spectrum sensing scheme(CSS) has become a popular technique to solve the efficiency of spectrum usage and provide high level of protection to the PU from SU. In CR, sensing accuracy is important for avoiding interference to the primary users in CR technology. Reliable spectrum sensing is not always guaranteed due to multipath fading, shadowing and hidden terminal problem. Cooperative spectrum sensing has thus been introduced for quick and reliable detection [4][5][6][7]. The CSS has two successive stages, sensing and reporting. In sensing stage, spectrum sensing is done by several local SU. Then in next stage, PU sensing decisions or measurements are sent to fusion center (FC) to combine them and make a better overall decision.

Among several spectrum sensing techniques, energy detector (ED) is the most popular method employed for spectrum sensing. Measuring only the received signal power and comparing it with a pre-fixed threshold, the ED is a non-coherent detection device with low implementation complexity and is more power efficient. But ED performance is highly degraded under noise uncertainty condition [8]. Also, ED cannot well differentiate between the signal and noise, if the detected observational values lies in the confused region i.e., between signal and noise.

In [9], a censoring method using double threshold based on ED was proposed. If the detected observational energy values (O_i) by the SU lies in the confused region, they will not report to the fusion center. This method can reduce the sensing time and cause sensing failure problem. Paper [10] also proposed a method using double threshold based on ED to increase the detection performance as compared to the conventional ED. In this method, first SU will make the local decision by comparing their O_i of the clear region with the pre-defined threshold of ED. If the O_i lies in the confused region then the SU will forward it to the fusion center (FC). The FC will make overall decision by considering the local decision of SU of clear region and comparing the O_i of confused region with another threshold value of ED.

To overcome the noise uncertainty problem of ED and to increase the detection performance, we propose a new CSS technique using adaptive double threshold based on ED and matched filter (MF) detector. Our proposed scheme has higher detection performance as compared to other conventional methods and the method described in [10]. We take the advantages of energy efficient ED to make the local decision in the clear region and reliable MF to take the decision in the confused region. Simulation results shows that our proposed scheme has higher detection performance, lower miss-detection probability and it can perform well in low SNR as compared to other methods.

The rest of the paper is organized as follows: Section II presents the system description. Section III describes our proposed model. Simulation results are shown in Section IV. Finally conclusion is drawn in Section V.

II. System Description

The main aim of CR is to correctly identify the presence of PU and allows the SUs to utilize the unused spectrum if it is not used by licensed PUs. Under binary hypothesis testing, we consider the occurrence of two input events in observing signal x_i in some observation interval denoted by

$$\begin{aligned} H_0 &: x_i = n_i \\ H_1 &: x_i = s_i + n_i, \end{aligned} \tag{1}$$

where $i = 1, 2, 3, ...N$ is number of samples. H_0 represents the hypothesis that the observation vector consists of noise. H_1 represents the hypothesis that the observation vector consists of noise and signal. The noise component n_i is assumed to be Additive White Gaussian random variable which is independent and identically-distributed (i.i.d) with zero mean normal distribution with variance $\sigma^2 \sim \mathcal{N}(0, \sigma^2)$, and s_i is the signal.

A. Energy Detector

The ED is non-coherent detector and consumes less amount power. ED detects the presence of signals by simply squaring its energy and comparing that energy around the carrier frequency with certain threshold [11]. The ED is not so accurate as the detected signal can be affected by noise level. The performance of ED is highly degraded under noise uncertainty condition.

The ED consists of a quadrature receiver with y_I and y_Q representing samples from In-phase and Quadrature branch respectively. The samples after passing the squaring device, output of the integrator is denoted by

$$y_I = y_Q = (\frac{1}{N_0}) \int_0^T r^2(t)dt, \tag{2}$$

where $r(t)$ is input signal, N_0 is noise spectral density.

Within observed sensing period, test statistic ED can be approximated as $Y_{ED} = y_I + y_Q$. At the observation time t, decision variable Y_{ED} will be compared to a detection threshold of ED denoted by λ^{ED}. Threshold value is set to meet the target probability of false alarm p_f according to the noise power. The probability of detection p_d can be also identified. The expression for p_f and p_d can be given as [12]

$$p_{fa}^{ED} = 1 - F_\chi \left(\frac{\lambda^{ED}}{\sigma^2}, 2n \right), \tag{3}$$

where F_χ is cumulative distribution function (CDF) of standard chi-square random variable with k degree of freedom.

$$p_d^{ED} = \mathcal{Q} \left(\sqrt{n(SNR)}, \sqrt{\frac{\lambda^{ED}}{\sigma^2}} \right), \tag{4}$$

where $\mathcal{Q}$ is generalized Marcum-Q function.

B. Matched Filter

MF is a reliable detector but consumes high amount of power. MF works using receivers bank of L matched filters, which runs together to correlate the incoming signals [13]. At each sampling instant t, de-correlators process signal $x(t)$, the output on interval $(0, T)$ that contains two sample output from a module is given by

$$Y_{MF} = y_{I_i}^2 + y_{Q_i}^2, \quad i = 1, 2, ..., L \tag{5}$$

The Y_{MF} forms L de-correlators output in which we find the decision variable V from the maximum of Y_{MF} over M offset

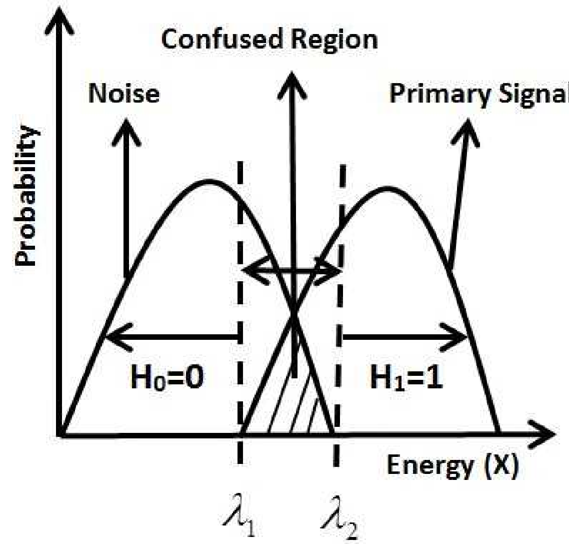

Fig. 1: Energy distribution of primary user signal and noise

bits. Variable V is compared to threshold λ^{MF} to decide the presence or absence of signal.

$$V = \max\{Y_{MF}^m\}, \quad m = 1...M \tag{6}$$

The acquisition process of MF will give probability of false alarm and probability of detection that can be calculated as [12]

$$p_{fa}^{MF} = 1 - F_\chi \left(\frac{\lambda^{MF}}{\sigma}, 2 \right), \tag{7}$$

$$p_d^{MF} = \mathcal{Q} \left(\sqrt{2n(SNR)}, \sqrt{\frac{\lambda^{MF}}{\sigma^2}} \right), \tag{8}$$

where λ^{MF} is the threshold setting for MF, the non-centrality parameter $s^2 = 2n(SNR)$ is the output of the filters in I and Q branches at the correct offset. The correlation process of MF has a central chi-square distribution with 2 degree of freedom with a variance $(\sigma = \sqrt{n})$.

III. Adaptive Double-Threshold Based Energy and Matched Filter Detector

In conventional ED, each SU makes their own local decision whether PU is present (H_1) or PU is absent (H_O) by comparing the O_i with single predefined threshold. Fig. 1 shows the energy distribution of the primary user signal and noise. [10] proposed a method using double threshold based on ED. In this method, cooperating SU will make the local decision by comparing their O_i of the clear region with the predefined threshold of ED i.e., λ_1 and λ_2. As shown in Fig. 1, if the O_i crosses the λ_2 then the local decision taken will be H_1 i.e., PU is present. Similarly, if the O_i is less than λ_1 then the local decision taken will be H_0 i.e., PU is absent. But if the O_i lies in the confused region i.e., between λ_1 and λ_2 then the SU will forward it to the FC along with the local decisions. In FC, the O_i of the confused region will be compared with another threshold value of ED λ and the overall decision will be taken by FC considering all the decisions.

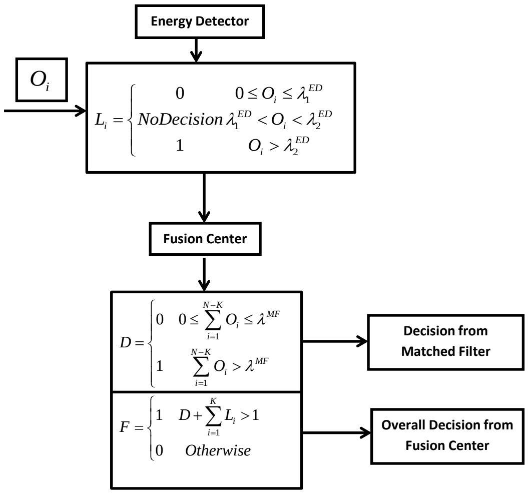

Fig. 2: Working model of proposed adaptive double-threshold based on energy and matched filter detector

The main idea of our proposed scheme is that we take the advantage of energy efficient ED to make decision in the clear region and reliable MF to make decision in the confused region. Our proposed scheme is based on adaptive double threshold of both ED and MF detector.

Fig. 2 shows the working model of our proposed method. Each SU of the CSS are equipped with ED and performs spectrum sensing individually. The observational value O_i of SU is checked with the threshold values λ_1^{ED} and λ_2^{ED} of ED and the decision will be taken accordingly. If O_i satisfies $\lambda_1^{ED} \le O_i < \lambda_2^{ED}$ then no decision will be taken and further the SU will forward its observational value O_i to the fusion center. The local decision L_i is given by

$$L_i = \begin{cases} 0 & 0 \le O_i \le \lambda_1^{ED} \\ \text{No Decision} & \lambda_1^{ED} \le O_i \le \lambda_2^{ED} \\ 1 & O_i \ge \lambda_2^{ED} \end{cases} \tag{9}$$

Without the loss of generality, we assume that fusion center FC receives K local decisions out of N SUs. Then $N - K$ observational values O_i will be reported to the FC to make the decision. The fusion center will now apply more reliable MF on those $N - K$ observational values of the signal for the decision process as $N - K$ secondary users could not distinguish between the presence or absence of the primary users. The threshold of MF λ^{MF} at the FC is chosen according to the appropriate false alarm probability of MF as given by Eq. 7. The decision D at the FC using the MF detector on $N - K$ O_i is as follows

$$D = \begin{cases} 0 & 0 \le \sum_{i=1}^{N-K} O_i \le \lambda^{MF} \\ 1 & \sum_{i=1}^{N-K} O_i > \lambda^{MF} \end{cases} \tag{10}$$

The FC has the local decision L_i of K SUs using ED and decision D of $N - K$ SUs using MF. Let us denote the total decision at FC by Z, i.e., $Z= D + \sum_{i=1}^{K} L_i$. The FC makes a final decision using a hard decision OR rule for deciding the presence or absence of PU. As per the hard decision OR rule, if total decision Z is greater or equal to 1 then signal is detected (H_1) and if Z is smaller than 1 then signal is not detected (H_0). The mathematical expression of hypothesis at the FC can be written as

$$FC = \begin{cases} \mathrm{Z} < 1, & H_0 \\ \mathrm{Z} \ge 1, & H_1 \end{cases} \tag{11}$$

1) Cooperative Detection and False Alarm Probabilities of Proposed Method: First each secondary user decides either '0' or '1' or "No Decision" on the basis of comparison of O_i with pre-defined threshold value of energy detector. Decision goes in favor of '0' if PU is absent. Similarly decision goes in favor of '1' if the PU is present. let us denote the probability of deciding '1', probability of "No Decision" and probability of deciding '0' under hypothesis H_1 is represented by p_{d1}^{ED}, $\triangle_{1,i}^{ED}$ and p_m^{ED} respectively. Similarly, Probability of deciding '1', probability of "No Decision" and probability of deciding '0' under hypothesis H_0 is denoted by p_{fa0}^{ED}, $\triangle_{0,i}^{ED}$ and p_{d0}^{ED} respectively. The expressions for different probabilities are given below considering the AWGN channel [9].

$$p_{d1}^{ED} = P\{O_i > \lambda_2^{ED}|H_1\} = \mathcal{Q}\left(\sqrt{n(SNR)}, \sqrt{\lambda_2^{ED}}\right), \tag{12}$$

$$p_{d0}^{ED} = P\{O_i < \lambda_1^{ED}|H_0\} = F_\chi\left(\lambda_1^{ED}, 2\right), \tag{13}$$

$$\triangle_{1,i}^{ED} = P\{\lambda_1^{ED} < O_i < \lambda_2^{ED}|H_1\} \tag{14}$$

$$\triangle_{0,i}^{ED} = P\{\lambda_1^{ED} < O_i < \lambda_2^{ED}|H_0\} \tag{15}$$

$$p_m^{ED} = P\{O_i \le \lambda_1^{ED}|H_1\} = 1 - \triangle_{1,i}^{ED} - p_{d1}^{ED}, \tag{16}$$

$$p_{fa0}^{ED} = P\{O_i > \lambda_2^{ED}|H_0\} = 1 - F_\chi\left(\lambda_2^{ED}, 2\right), \tag{17}$$

The cooperative probability of detection Q_d of the FC using OR rule as indicated in Eq. 11 can be expressed as

$$\begin{aligned} Q_d &= P\{Z \ge 1|H_1\} \\ Q_d &= P\{(\sum_{i=1}^{K} L_i + \sum_{i=1}^{N-K} D) \ge 1|H_1\} \\ Q_d &= 1 - \sum_{K=0}^{N-1} \binom{N}{K} \prod_{i=1}^{K} p_m^{ED}. \\ &\quad \prod_{i=K+1}^{N} \triangle_{1,i}^{ED}[1 - \mathcal{Q}_{(N-K)u}\left(\sqrt{2n(SNR)}, \sqrt{\lambda^{MF}}\right)] \\ &\quad + \prod_{i=1}^{N} p_m^{ED} \end{aligned} \tag{18}$$

where u is the time bandwidth product. The cooperative probability of miss-detection Q_m of the FC is given by

$$Q_m = 1 - Q_d \tag{19}$$

The cooperative probability of false alarm Q_f of the FC using OR rule as indicated in Eq. 11 can be expressed as

$$\begin{aligned}
Q_f &= P\{Z \geq 1 | H_0\} \\
Q_f &= P\{(\sum_{i=1}^{K} L_i + \sum_{i=1}^{N-K} D) \geq 1 | H_0\} \\
Q_f &= -\sum_{K=0}^{N-1} \binom{N}{K} \prod_{i=1}^{K} (1 - \triangle_{0,i}^{ED} - p_{fa0}^{ED}). \\
&\prod_{i=K+1}^{N} \triangle_{0,i}^{ED} [1 - F_{\chi(N-K)u} \left(\lambda^{MF}, 2\right)]
\end{aligned} \tag{20}$$

Algorithm 1 Adaptive Double-Threshold Based Energy and Matched Filter Detector Method

1: Given $\{x_1, x_2, ...x_N\}$
2: Given $\{SU_1, SU_2, ...SU_N\}$
3: Define the value for $\triangle_{0,i}^{ED}$ and $\triangle_{1,i}^{ED}$
4: Find threshold value λ_1^{ED} and λ_2^{ED} for Energy Detector for a given probability of false alarm p_{fa}^{ED} and using step 3
/* O_i is Observational Signal Value */
5: $If\ O_i \geq \lambda_2^{ED}$
  L_i=H_1;
$elseif\ O_i \leq \lambda_1^{ED}$
  L_i=H_0;
$else$
  L_i=$NoDecision$;
$endif$
/* Forward the Local Decision L_i of clear region sensed by K SUs and $N-K$ "No Decision" observational values O_i of confused region using Energy Detector to the fusion center to make overall decision by employing Matched Filter */
6: Set the threshold value for Matched Filter λ^{MF} by fixing the probability of false alarm p_{fa}^{ED} to a pre-defined threshold and setting the boundary value for λ_1^{ED} and λ_2^{ED} from step 4
7: $If \sum_{i=1}^{N-K} O_i \leq \lambda^{MF}$
  $D = 0$; /* PU is not present */
$else$
  $D = 1$; /* PU is present */
$endif$
8: Z= D + $\sum_{i=1}^{K} L_i$; /* Total Decision at fusion center */
9: $If\ Z < 1$
  $FC = H_0$; /* PU is not present */
$else$
  $FC = H_1$; /* PU is present */
$endif$

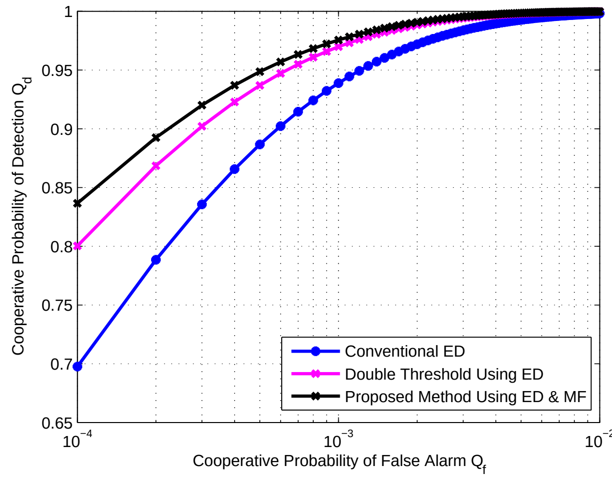

Fig. 3: ROC of our proposed scheme using adaptive double threshold energy and matched filter detector

IV. Simulation Results

Our simulation was conducted in MATLAB to investigate the performance of our proposed scheme. AWGN is imposed on the original signal x_i either for H_0 or H_1 condition. We assume that there is error free control channel available between the secondary users and the fusion center at the base station for sending local decisions and observational values O_i of the confused region.

The receiver operating characteristics (ROC) curves of our proposed scheme as compared to other schemes is shown in Fig. 3. The ROC curve is obtained with $SNR = 10dB$, Number of cooperative SUs=10, $\triangle_{0,i}^{ED}$=$\triangle_{1,i}^{ED}$=0.1, time bandwidth product u =5. Clearly our proposed scheme has the higher detection performance compared to other double threshold method using ED only and conventional ED. Our scheme takes the advantage of reliable MF detector in the confused region to take the decision.

Fig. 4 shows cooperative miss-detection probability curve of our proposed scheme as compared to other schemes. With the use of MF, our scheme is able to differentiate the signal and noise in the confused region and it can take decision accordingly. As expected our proposed scheme miss-detection probability is lower as compared to the previous schemes explained in the literature.

Fig. 5 shows the cooperative probability of detection curves against different SNR values. Fig. 5 is plotted using the probability of false alarm of energy detector is set at 0.01 i.e., $p_{fa}^{ED} = 0.01$, SNR values ranges from -10 dB to 10 dB, number of cooperative SUs= 10, $\triangle_{0,i}^{ED}$=$\triangle_{1,i}^{ED}$=0.01, time bandwidth product u =5. It is clear from Fig. 5 that our proposed scheme outperforms the other schemes at different SNR ranges. Even at -10 dB SNR value, our scheme is clearly able to detect the signal as compared to other schemes. The scheme using double threshold energy detector and conventional energy detector suffer greatly at low SNR region is due to the fact that the energy detector is highly susceptible to the noise uncertainty at the low SNR. The

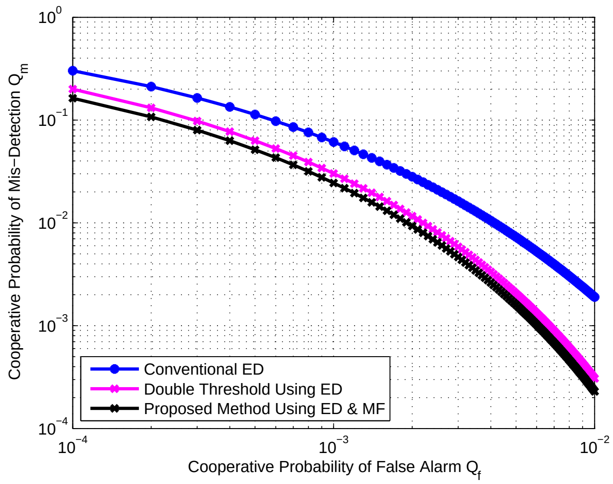

Fig. 4: Comparision of cooperative miss detection probability of our proposed scheme with other methods

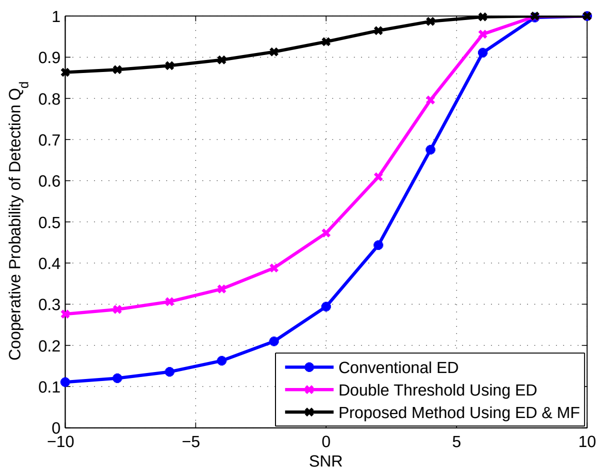

Fig. 5: Comparision of cooperative probability of detection of our proposed scheme with other methods at different SNR

decision in the confused region is clearly indicated by the MF in our scheme. Hence, our proposed scheme performance is superior to all other scheme.

V. Conclusion

In this paper, we have proposed a new adaptive double-threshold based energy and matched filter detector for cognitive radio networks. The proposed method gives significantly better detection performance compared to other methods. Also, the cooperative probability of miss-detection of our proposed scheme is lower than other scheme. At lower SNR region, energy detector cannot differentiate between signal and noise and is susceptible to noise uncertainty. Our proposed scheme takes the advantage of energy efficient energy detector to take decision in the clear region and reliable matched filter detector to take decision in the confused region. Hence our proposed scheme performance is better compared to other schemes.

Acknowledgment

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