

ORIGINAL PAPER

Cooperative spectrum sensing based on adaptive activation of energy and preamble detector for cognitive radio networks

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In this paper, we propose a new cooperative spectrum sensing method based on adaptive activation of energy detector (ED) and preamble detector (PD) for cognitive radio networks. The ED performance is highly degraded under low signal to noise ratio and noise uncertainty condition. To alleviate the problem of ED and increase the sensing performance, we have used adaptive activation of energy efficient ED and reliable PD. As the first step of our proposed method, we have used ED to take a decision in the clear region where the detector can easily make its own local decision. There are two thresholds for the measured energy in the first step. If the sensed energy in the first step is between these two thresholds, the second step which involves the activation of cooperative PD is triggered to make an appropriate decision on the presence or absence of primary users's signal. Otherwise, the second step detector PD is not activated. In this way, we can enhance the detection performance and energy efficiency by taking the collaborative advantages of ED and PD at the same time. Simulation results validate the effectiveness of our proposed method as compared with conventional schemes.

Keywords: Spectrum sensing, Cognitive radio networks, Energy detector, Preamble detector, Adaptive activation

Received 4 November 2016; Revised 3 February 2018

I. INTRODUCTION

A survey carried out by the Federal Communications Commission (FCC) on spectrum utilization has indicated that the actual licensed spectrum whose sole owner is primary user (PU) is largely under-utilized in vast geographical dimensions [1]. Cognitive radio (CR) provides opportunistic access to unused bands to the secondary users (SUs) [2, 3]. Sensing accuracy is important for avoiding interference to the PU in CR technology. Reliable spectrum sensing is not always guaranteed due to multipath fading, shadowing, and hidden terminal problem. In the recent years, cooperative spectrum sensing scheme (CSS) has thus become a popular technique to solve the efficiency of spectrum usage and provide a high level of protection to the PU from SUs. CSS has been widely studied in [4–8]. The CSS has two successive stages; sensing and reporting. In sensing stage, spectrum sensing is done by several local SUs. Then in next stage, sensing decisions of the SUs is sent to the fusion center (FC) where it is combined by using some fusion rule to make an overall decision regarding the presence or absence of PU. Among several spectrum sensing

techniques, energy detector (ED) is one of the most popular detectors employed for spectrum sensing. Measuring only the received signal power and comparing it with a pre-defined threshold, the ED is a non-coherent detection device with low-implementation complexity and is more energy efficient. It is to be noted that ED performance is highly degraded under low signal to noise ratio (SNR) and noise uncertainty condition [9]. Also, ED cannot well differentiate between the signal and noise, if the detected observational values lie in the confused region i.e., between signal and noise. Another detector, preamble detector (PD) [10] is quite reliable as it takes advantage of the processing gain inherent in the preamble. Its power consumption, however, may be usurious.

A censoring scheme using double threshold based on ED was proposed in [11]. If the detected observational energy values (O_i) by the SUs lie in the confused region, they will not report their decision to the FC. The authors showed that their proposed method can reduce the sensing time. However, at the same time, it also created sensing failure problem. An adaptive double threshold energy detection based on Markov model (ADEMM) for CR was proposed in [12]. Time-varying characteristic of the channel was taken into consideration to overcome the issue of confused region of the occupied channel. A hybrid double-threshold-based CSS over fading channels using ED was proposed in [13]. The authors also proposed an optimal SU

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selection algorithm for forwarding local decisions to the FC. Another method using double threshold based on ED to increase the detection performance as compared with the conventional ED, proposed in [14]. In this method, SU will make the local decision by comparing their O_i of the clear region with the two pre-fixed thresholds of ED. If the O_i lies in the confused region i.e. between these two pre-fixed thresholds then the SU will forward it to the FC. The FC will make an overall decision by considering the local decision of SU of clear region and comparing the O_i of confused region with another final threshold value of ED. We have considered ref. [14] as a baseline approach for our proposed method and have compared it in Section IV. A two-step fast-and-fine sensing has been proposed in [15] where the second step of fine sensing is triggered when it is difficult to decide on the presence of PUs in the first step of energy detection. Also, a two step selectively triggered CSS in CRNs is proposed in [16] to alleviate the problems of ED. Here, as a first step, non-cooperative ED is used and as a second step, again ED is used for CSS to arrive at a final decision. There have also been similar approaches such as two-step hard and soft combination techniques, proposed in [17], where the second step of the soft combination is initiated when it is difficult to arrive at a decision in the first step of the hard combination. However, it uses only one detector i.e. ED for decision-making process which is completely different from our proposed approach. Further, a novel cascaded-clear channel assessment (CCA) method: cascaded ED matched filter (CEM) for wireless network was proposed in [18]. CEM cartel the advantages of two CCA mechanisms, energy efficient ED, and reliable matched filter (MF) to devise a new approach of CCA in wireless network. However, CEM scheme considers multi-stage detection through ED and MF detector. In CEM scheme, the second step detector MF is only triggered when the probability of false alarm of ED is set as 10, 20, 30, and 40%.

To overcome the noise uncertainty problem of ED and to increase the detection performance, we propose a CSS technique using adaptive activation of energy efficient ED and reliable PD. As the first step of our proposed method, we have used ED to take decision in the clear region where the detector can easily differentiate between signal and noise and makes its own local decision. There are two thresholds for the measured energy in the first step and ED is used in the first step. If the sensed energy in the first step is between these two thresholds, the second step which involves the activation of PD is activated in a cooperative way. Otherwise, the second step detector PD is not activated at all. In this way, we can enhance the detection performance and energy efficiency at the same time by using the collaborative advantages of ED and PD.

The rest of the paper is organized as follows: Section II presents system brief working and explanation of ED and PD. Section III describes our proposed model. Numerical results are shown in Section IV. Finally, conclusion is drawn in Section V.

II. STRUCTURES OF ENERGY DETECTOR AND PREAMBLE DETECTOR

The main goal of CR is to correctly identify the presence and absence of PU and allows the SUs to utilize the unused spectrum if it is not used by PUs. Under binary hypothesis testing, we consider the occurrence of two input events in observing signal x_i in some observation interval denoted by [19]

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

where $i = 1, 2, 3, \dots, N$ 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 $n_i \sim \mathcal{N}(0, \sigma^2)$, and s_i is the signal.

A) Energy detector

ED is non-coherent detector which detects the presence of signals by simply squaring its energy and comparing that energy around the carrier frequency with a certain threshold. 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

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

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 with a detection threshold of ED denoted by λ^{ED} . Threshold value is set to meet the target probability of false alarm p_{fa} according to the noise power. In the case of p_{fa} , the detector classifies the channel as busy when the actual channel is free. Probability of detection (p_d) is the probability of correctly detecting the presence of PU when the actual channel is in busy state. The expression for p_{fa} and p_d can be given as [9]

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

where F_χ is cumulative distribution function (CDF) of standard chi-square random variable with k degree of freedom, n_T is the number of bits during the observation interval T ,

and has a variance $\sigma = 1$,

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

where Q is generalized Marcum-Q function with non-central chi-square distribution of non-centrality parameter $s^2 = \psi_{ED} = n_T(SNR)$.

ED is a robust, universal detector which can be deployed in all systems without requiring any prior knowledge of the type of underlying modulation scheme employed. Also, ED is more energy efficient in terms of energy consumption and ED's computational complexity is lower than the most of the detectors. However, ED is inherently less reliable at low SNR and noise uncertainty condition.

B) Preamble detector

For coherent detection of signals, the sensing node has to attain time synchronism with the ongoing transmission. In packet-based systems, the process of acquiring time synchronism is facilitated by the transmission of a preamble in front of every packet, typically consisting of repetitions of a sequence of known symbols. The receiver performs a correlation of the known sequence with the received signal with varying time offsets. At the offset corresponding to time synchronism, the correlation is high due to the processing gain resulting from the repetition of the known symbols. This high correlation is both indicative of the signal presence and provides an estimate of the time offset. This carrier-sense based CCA using the correlation of the known preamble with the received signal is called PD [10].

In simple terms, PD [10, 20] performs correlation of the known signal, thus the high processing gain due to correct offset gives higher reliability than ED. However, for the successful operation of PD, it consumes a high amount of power. Hence, PD is also considered as power hungry detector. Also, the computational complexity of PD is much higher than ED.

The expression for p_{fa} and p_d of a PD can be given as [10]

$$p_{fa}^{PD} = 1 - F_\chi\left(\frac{\lambda^{PD}}{\sigma}, 2\right), \tag{5}$$

$$p_d^{PD} = Q\left(\sqrt{\psi_{PD}}, \sqrt{\frac{\lambda^{PD}}{\sigma^2}}\right), \tag{6}$$

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

III. PROPOSED SCHEME

Our proposed scheme is based on adaptive activation of energy efficient ED and reliable PD. As the first step of our

proposed method, ED is used where it can easily make its own local decision. There are two thresholds λ_1^{ED} and λ_2^{ED} for the measured energy in the first step. If the sensed energy in the first step is between these two thresholds, the second step which involves the activation of PD is triggered to make an appropriate decision on the presence or absence of PU signal. Otherwise, the second step detector PD is not activated. In this way, we can enhance the detection performance and energy efficiency at the same time.

In our proposed scheme, when an SU confirms the presence or absence of the signal of PU, the second step PD detector is not activated at all; only the first step ED detector is sufficient to take the decision and increase the energy efficiency of our proposed scheme. The determination of double threshold values for ED is discussed in paper [14, 21]. For threshold setting, first, the boundary values Δ_0 and Δ_1 is defined according to the chosen false alarm probability of ED to determine the region of uncertainty. Based on Δ_0 and Δ_1 , the two threshold value λ_1^{ED} and λ_2^{ED} of ED is set accordingly. It should be noted that the region of uncertainty depends on the value of Δ_0 and Δ_1 chosen. If we choose the higher values for Δ_0 and Δ_1 , there is a greater region of uncertainty i.e. sensed energy is in between two thresholds values λ_1^{ED} and λ_2^{ED} . Hence, there is a higher chance of activation of second step detector PD and vice versa. The threshold setting λ_3^{PD} for PD is set according to the chosen false alarm probability which is the same false alarm probability of first step detector ED.

In step 1, if the sensed energy level by the SU is above threshold λ_2^{ED} , then decision D_i '11' will be taken and it indicates the presence of a PU's signal i.e. condition H_{11} and if it is below threshold λ_1^{ED} , then decision D_i '00' will be taken and it indicates the absence of a PU's signal i.e. condition H_{00} . When the received energy of the PU's signal at the SU is between these two thresholds i.e. in the confused region then ED cannot take any decision D_i and further reports either '01' or '10' to FC to report uncertainty of the decision. For simplicity, it should be noted that '01' or '10' represents the same uncertainty of decision in our scheme. Now, the second step PD detector is activated. In the second step, the FC orders all the SUs to sense. The SUs sensing in the second step only need to report a one-bit decision; that is, '1' means the presence of PU and '0' means the absence of PU. Also, it should be noted that, in our proposed scheme, if SU is uncertain about the decision, it triggers the activation of second step PD to arrive at a concrete decision; the sensing result from the first step ED is no more considered and FC instructs all the SUs for sensing in the second step using reliable PD where the threshold is pre-defined for PD. Finally, the FC makes a decision by using a given hard decision fusion rule such as Majority, AND, or OR rule.

The decision D_i in the first step when ED is active is given as:

$$D_i = \text{if} \begin{cases} O_i < \lambda_1^{ED}, & H_{00} \\ \lambda_1^{ED} \leq O_i \leq \lambda_2^{ED}, & H_{10} \text{ or } H_{01} \\ O_i \geq \lambda_2^{ED}, & H_{11} \end{cases} \tag{7}$$

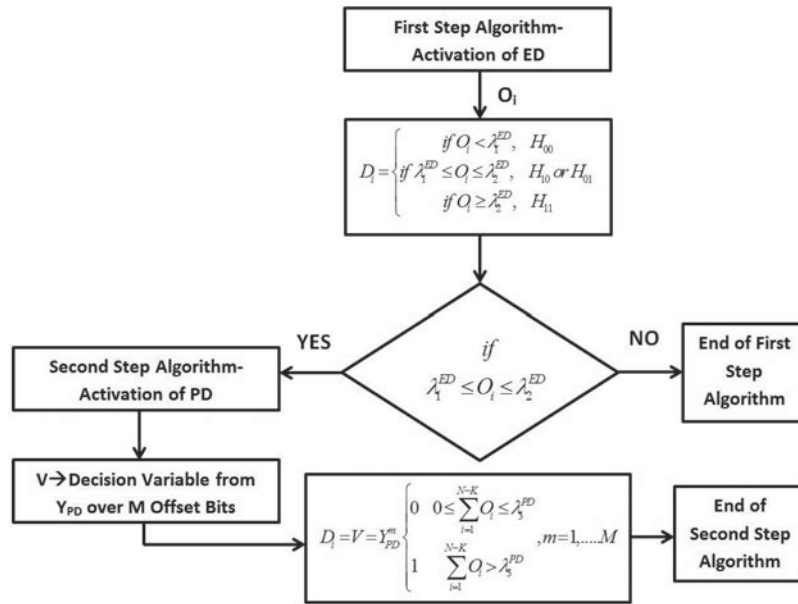


Fig. 1. Procedural flow of proposed scheme.

In the second step, when the PD is activated, we find the decision variable V from Y_{PD} over M offset bits. Y_{PD} is the output from the PD receiver. Variable V is compared with PD threshold λ_3^{PD} to decide the presence or absence of PU signal.

The decision D_i in the second step when PD is active is given as:

$$D_i = V = Y_{PD}^m \begin{cases} 0 & 0 \leq \sum_{i=1}^{N-K} O_i \leq \lambda_3^{PD} \\ 1 & \sum_{i=1}^{N-K} O_i > \lambda_3^{PD} \end{cases}, \quad m = 1, \dots, M, \tag{8}$$

where $m = 1, \dots, M$ is the varying time offset bits where the PD receiver performs a correlation of the known sequence with the received signal.

The FC makes a final decision based on a voting rule. In this paper, we have considered widely used hard decision voting rule, ‘K out of N rule’. In this rule, the presence of PU is declared, if K SUs out of total N SUs declare the presence of PU. Similarly, the absence of PU is declared if K SUs out of total N SUs declare the absence of PU. The procedural flow of our proposed scheme block diagram is shown in Fig. 1.

Based on above discussion, we can say that our proposed scheme is energy efficient than PD as in our scheme the second step PD is only triggered when the O_i of first step ED lies in the confused region. The detection performance of our proposed scheme is higher as compared with ED due to the involvement of reliable PD. Since the involvement of cooperative PD is only triggered if the O_i values lies in confused region, we can say that the computational complexity of our proposed scheme is higher than ED and lower than PD i.e. in between ED and PD. Thus, making our proposed scheme as both energy efficient than PD and reliable than ED.

Algorithm 1 First Step Algorithm-Activation of Non-cooperative ED

- 1: Input Double Threshold for ED: $\lambda_1^{ED}, \lambda_2^{ED}$
 - 2: Output: D_i
 - 3: Activate ED
 - 4: *for* each PU channel
 - 5: Sense $O_i \rightarrow$ Observational Energy Value
 - 6: *if* $O_i \geq \lambda_2^{ED}$
 $D_i = H_{11}$
 - 7: *elseif* $O_i \leq \lambda_1^{ED}$ Then
 $D_i = H_{00}$
 - 8: *else*
 Activate Algorithm 2 (Second Step Algorithm-Activation of Cooperative PD)
 - 9: *end for*
 - 10: End of Algorithm 1
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Algorithm 2 Second Step Algorithm-Activation of Cooperative PD

- 1: Input Threshold for PD: λ_3^{PD}
 - 2: Output: D_i
 - 3: Activate PD
 - 4: *for* 1 to N SUs
 - 5: $V \rightarrow$ Decision Variable From Y_{PD} over M Offset Bits
 - 6: *if* $V \geq \lambda_3^{PD}$
 $D_i = H_1$
 - 7: *else*
 $D_i = H_0$
 - 8: *End for*
 - 9: Use K out of N Rule for Final Decision
 - 10: End of Algorithm 2
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A) False alarm and detection probabilities of proposed adaptive method

The use of double thresholds for ED allow the probabilities of false alarm and miss detection to be set arbitrarily low at the expense of an increased uncertainty region. This means that when the region of uncertainty increases, there is a involvement of reliable PD which keeps the low probabilities of false alarm and miss detection in the system. When the ED detector is active in first step, the false alarm probability $p_{fa,Step1}^{ED}$, probability of no false alarm $p_{No-fa,Step1}^{ED}$, probability of detection $p_{d,Step1}^{ED}$, and miss detection probability $p_{m,Step1}^{ED}$ concerned with double thresholds of ED are given as follows:

$$p_{fa,Step1}^{ED} = P\{O_i > \lambda_2^{ED} | H_{00}\} = 1 - F_\chi\left(\frac{\lambda_2^{ED}}{\sigma^2}, 2n_T\right), \tag{9}$$

$$p_{No-fa,Step1}^{ED} = P\{O_i \leq \lambda_1^{ED} | H_{00}\} = 1 - \left(1 - F_\chi\left(\frac{\lambda_1^{ED}}{\sigma^2}, 2n_T\right)\right), \tag{10}$$

$$p_{d,Step1}^{ED} = P\{O_i > \lambda_2^{ED} | H_{11}\} = Q\left(\sqrt{\psi_{ED}}, \sqrt{\frac{\lambda_2^{ED}}{\sigma^2}}\right), \tag{11}$$

$$p_{m,Step1}^{ED} = P\{O_i \leq \lambda_1^{ED} | H_{11}\} = 1 - \left(Q\left(\sqrt{\psi_{ED}}, \sqrt{\frac{\lambda_2^{ED}}{\sigma^2}}\right)\right). \tag{12}$$

The probabilities of uncertainty under H_0 and H_1 are denoted by Δ_0 and Δ_1 , respectively, and are given by

$$\Delta_0 = P\{\lambda_1^{ED} < O_i \leq \lambda_2^{ED} | H_{00}\} = 1 - p_{fa,Step1}^{ED} - p_{No-fa,Step1}^{ED}, \tag{13}$$

$$\Delta_1 = P\{\lambda_1^{ED} < O_i \leq \lambda_2^{ED} | H_{11}\} = 1 - p_{d,Step1}^{ED} - p_{m,Step1}^{ED}. \tag{14}$$

As we know in our proposed scheme, when the ED in first step is uncertain about the decision, it will trigger the activation of cooperative PD in second step. When the PD detector is active in second step, the false alarm probability $p_{fa,Step2}^{PD}$, probability of no false alarm $p_{No-fa,Step2}^{PD}$, probability of detection $p_{d,Step2}^{PD}$, and miss detection probability $p_{m,Step2}^{PD}$ concerned with PD are given as follows:

$$p_{fa,Step2}^{PD} = P\{V > \lambda_3^{PD} | H_0\} = 1 - F_\chi\left(\frac{\lambda_3^{PD}}{\sigma}, 2\right), \tag{15}$$

$$p_{No-fa,Step2}^{PD} = P\{V \leq \lambda_3^{PD} | H_0\} = 1 - \left(1 - F_\chi\left(\frac{\lambda_3^{PD}}{\sigma}, 2\right)\right), \tag{16}$$

$$p_{d,Step2}^{PD} = P\{V > \lambda_3^{PD} | H_1\} = Q\left(\sqrt{\psi_{PD}}, \sqrt{\frac{\lambda_3^{PD}}{\sigma^2}}\right), \tag{17}$$

$$p_{m,Step2}^{PD} = P\{V \leq \lambda_3^{PD} | H_1\} = 1 - \left(Q\left(\sqrt{\psi_{PD}}, \sqrt{\frac{\lambda_3^{PD}}{\sigma^2}}\right)\right), \tag{18}$$

since we have used K out of N rule for the second step i.e. when the PD is active, the cooperative probabilities of false alarm $p_{Coop-fa,Step2}^{PD}$ and cooperative detection probabilities $p_{Coop-d,Step2}^{PD}$ can be respectively obtained as follows:

$$p_{Coop-fa,Step2}^{PD} = \sum_K^N \binom{N}{K} (1 - p_{fa,Step2}^{PD})^{N-K} (p_{fa,Step2}^{PD})^K, \tag{19}$$

$$p_{Coop-d,Step2}^{PD} = \sum_K^N \binom{N}{K} (1 - p_{d,Step2}^{PD})^{N-K} (p_{d,Step2}^{PD})^K. \tag{20}$$

The overall probability of detection for our adaptive activation of ED and PD scheme can be given as

$$p_d^{ov} = p_{d,Step1}^{ED} + \Delta_1 p_{coop-fa,Step2}^{PD}. \tag{21}$$

Similarly, the overall probability of no false alarm and false alarm for our scheme can be respectively given as

$$p_{No-fa}^{ov} = p_{No-fa,Step1}^{ED} + \Delta_0 p_{No-fa,Step2}^{PD} \tag{22}$$

$$p_{fa}^{ov} = 1 - p_{No-fa}^{ov} = p_{fa,Step1}^{ED} - \Delta_0 (1 - p_{fa,Step2}^{PD}). \tag{23}$$

IV. NUMERICAL RESULTS

Our simulation was conducted in MATLAB to investigate the performance of our proposed scheme. Additive White Gaussian Noise is imposed on the original signal x_i either for H_0 or H_1 condition. We assumed that there exists an error-free control channel available between the SUs and the FC for sending local decisions and observational values O_i of the confused region. For a fair comparison of our proposed scheme, we compared our scheme with conventional ED where only a single threshold based on the probability of false alarm of ED is defined for decision making process and double threshold using ED method of [14].

The receiver operating characteristics (ROC) curves of our proposed scheme as compared with other schemes is shown in Fig. 2. The ROC curve is obtained with SNR = 5 dB, Number of cooperative SUs=6, $\Delta_0 = \Delta_1 = 0.1$, time bandwidth product $u = 5$. As we can clearly see from Fig. 2, our proposed scheme has the higher detection performance compared with double threshold method using ED and conventional ED methods. Our scheme takes the advantage of

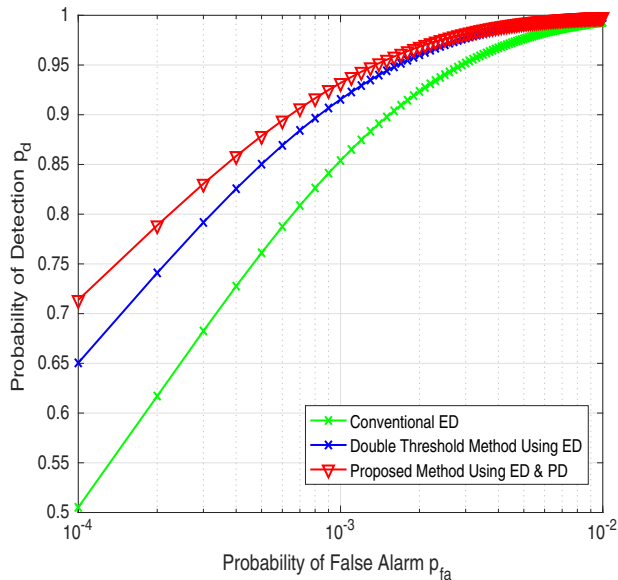


Fig. 2. ROC of proposed adaptive activation of ED and PD detector scheme.

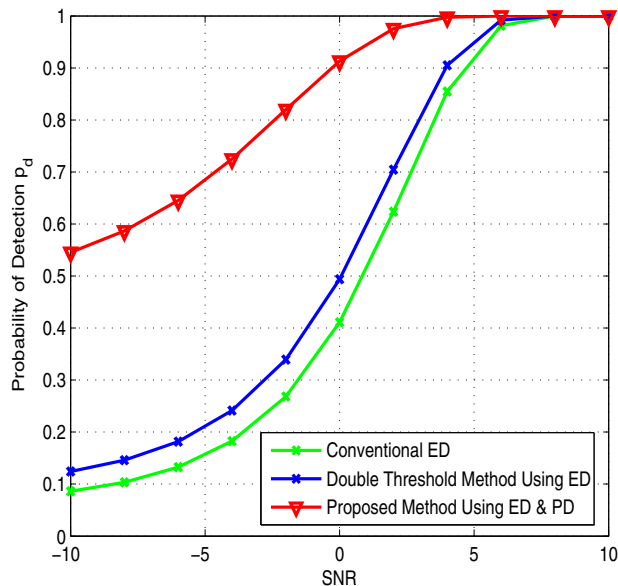


Fig. 3. Comparison of probability of detection of our proposed scheme with other methods at different SNR when $\Delta_0 = \Delta_1 = 0.01$.

reliable activation of PD at the second step if the decision from first step using ED is uncertain.

Figure 3 shows the cooperative probability of detection curves against different SNR values when $\Delta_0 = \Delta_1 = 0.01$. Figure 3 is plotted using $\Delta_0 = \Delta_1 = 0.01$, SNR values ranges from -10 dB to 10 dB, number of cooperative SUs= 6, p_{fa} is set at 0.1, time bandwidth product $u = 5$. It is clear from Fig. 3 that our proposed adaptive activation of ED and PD scheme is better in detecting PU signal than the other schemes at different SNR ranges. Even at -10 dB SNR value, our scheme is clearly able to detect the PU signal. The scheme using double threshold ED and conventional ED suffer greatly at low SNR region due to the fact that

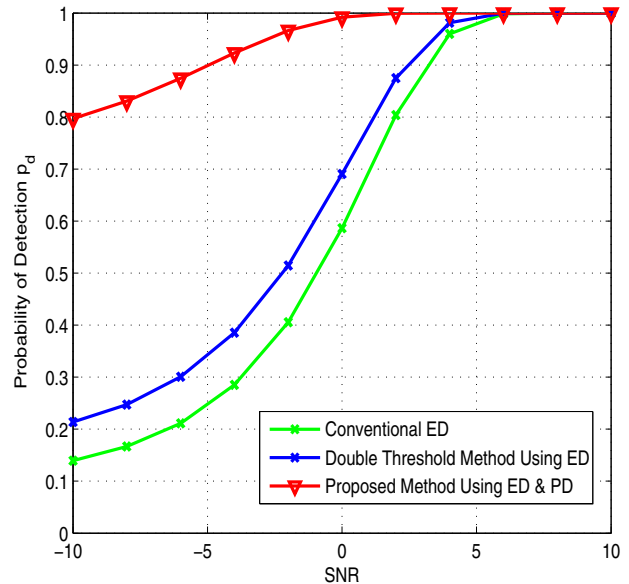


Fig. 4. Comparison of probability of detection of our proposed scheme with other methods at different SNR when $\Delta_0 = \Delta_1 = 0.1$.

the energy detector is highly susceptible to the noise uncertainty at the low SNR. The uncertainty of the decision in the confused region by first step ED detector activates the second step which is back-off by reliable PD detector in our scheme. Hence, our proposed scheme performance is superior to all other schemes. It should be noted that detection performance of PD is obviously higher and is almost equal to “1” as shown by the reference [10], hence it is not shown in our simulation results.

Figure 4 shows the cooperative probability of detection curves against different SNR values when $\Delta_0 = \Delta_1 = 0.1$. Figure 4 is plotted using $\Delta_0 = \Delta_1 = 0.1$, SNR values ranges from -10 dB to 10 dB, number of cooperative SUs= 6, p_{fa} is set at 0.1, time bandwidth product $u = 5$. As we increase the uncertainty region, the second step detector PD is triggered to make the reliable detection. Hence it is clear from Fig. 4, that in our proposed adaptive activation of ED and PD scheme, PD is activated most of the time. so, the detection probability is higher for our scheme over all ranges of SNR as compared with other schemes.

V. CONCLUSION

In this paper, we have proposed a cooperative spectrum sensing based on adaptive activation of ED and PD for CR networks. The ED performance is highly degraded under low SNR and noise uncertainty condition. To alleviate the problem of ED, as the first step in our proposed method, ED was used to take a decision in clear region where it can easily make its own local decision. Two thresholds were pre-defined for the measured energy in the first step for ED. If the sensed energy in the first step is between these two thresholds, the second step which involves the activation of cooperative PD is triggered to make an appropriate decision on the presence or absence of the PU’s signal. Otherwise, the

second step cooperative PD detector is not activated. In this way, we enhanced the detection performance and energy efficiency at the same time by taking the collaborative advantage of energy efficient ED and reliable PD detector. The effectiveness of our proposed method as compared with conventional schemes was validated through MATLAB simulations. Our proposed method gives significantly better detection performance compared with other conventional methods.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGEMENTS

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ITRC(Information Technology Research Center) support program(IITP-2017-2014-0-00639) supervised by the IITP(Institute for Information & Communications Technology Promotion).

REFERENCES

- [1] Force, S.P.T.: Spectrum policy task force report et docket no. 02-135. 2002.
- [2] Mitola, J. III; Maguire, G.Q. Jr.: Cognitive radio: making software radios more personal. *IEEE Personal Communications*, **6**(4) (1991), 13–18.
- [3] Haykin, S.: Cognitive radio: brain-empowered wireless communications. *IEEE J. Selected Areas Commun.*, **23**(2) (2005), 201–220.
- [4] Ganesan, G.; Ye, L.: Cooperative spectrum sensing in cognitive radio, part II: Multiuser networks. *IEEE Trans. Wireless Commun.*, **6**(6) (2007), 2214–2222.
- [5] Fan, R.; Jiang, H.: Optimal multi-channel cooperative sensing in cognitive radio networks. *IEEE Trans. Wireless Commun.*, **9**(3) (2010), 1128–1138.
- [6] Zhang, W.; Mallik, R.K.; Letaief, K.: Optimization of cooperative spectrum sensing with energy detection in cognitive radio networks. *IEEE Trans. Wireless Commun.*, **8**(12) (2009), 5761–5766.
- [7] Mishra, S.M.; Sahai, A.; Brodersen, R.W.: Cooperative sensing among cognitive radios. in *IEEE Int. Conf. Commun., Istanbul, Turkey, 2006. ICC'06*, vol. 4, 2006, 1658–1663.
- [8] Lu, J.; Wei, P.: Improved cooperative spectrum sensing based on the reputation in cognitive radio networks. *Int. J. Electron.*, **102**(5) (2015), 855–863.
- [9] Park, K.Y.: Performance evaluation of energy detectors. *IEEE Trans. Aerospace Electron. Syst.*, **AES-14**(2) (1978), 237–241.
- [10] Shin, S.Y.; Ramachandran, I.; Roy, S.: New energy efficient clear channel assessment for wireless network. *KSII Transactions on Internet and Information Systems (TIIS)*, **5**(8) (2011), 1404–1422.
- [11] Sun, C.; Zhang, W.; Letaief, K.B.: Cooperative spectrum sensing for cognitive radios under bandwidth constraints. in *IEEE Wireless Communications and Networking Conf., WCNC Kowloon, China, 2007*, 1–5.
- [12] Liu, Y. *et al.*: Adaptive double threshold energy detection based on markov model for cognitive radio. *PloS ONE*, **12**(5) (2017), e0177625.
- [13] Vien, Q.-T.; Nguyen, H.X.; Trestian, R.; Shah, P.; Gemikonakli, O.: A hybrid double-threshold based cooperative spectrum sensing over fading channels. *IEEE Trans. Wireless Commun.*, **15**(3) (2016), 1821–1834.
- [14] Zhu, J.; Xu, Z.; Wang, F.; Huang, B.; Zhang, B.: Double threshold energy detection of cooperative spectrum sensing in cognitive radio. in *3rd Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom 2008*, Singapore, Singapore, 2008, 1–5.
- [15] Choi, Y.-J.; Xin, Y.; Rangarajan, S.: Overhead-throughput tradeoff in cooperative cognitive radio networks. in *IEEE Wireless Commun. Networking Conf., WCNC 2009*, Budapest, Hungary, 2009, 1–6.
- [16] Paul, R.; Pak, W.; Choi, Y.-J.: Selectively triggered cooperative sensing in cognitive radio networks. *IET Communications*, **8**(15) (2014), 2720–2728.
- [17] Alemseged, Y.; Sun, C.; Tran, H.; Harada, H.: Distributed spectrum sensing with two-stage detection for cognitive radio. in *IEEE 70th Vehicular Technology Conf. Fall (VTC 2009-Fall)*, Anchorage, AK, USA, 2009, 1–5.
- [18] Triwicaksono, D.; Rauniyar, A.; Shin, S.Y.: Cascaded energy detector and matched filter-clear channel assessment for wireless network. *Wireless Personal Communications*, **84**(4) (2015), 2427–2443.
- [19] Lehtomäki, J.J.; Vartiainen, J.; Vuohtoniemi, R.; Saarnisaari, H.: Adaptive fcm-based threshold setting for energy detectors. in *Proc. 4th Int. Conf. on Cognitive Radio and Advanced Spectrum Management*. ACM, Barcelona, Spain, 2011, 33–37.
- [20] Nagaraj, S.; Khan, S.; Schlegel, C.; Burnashev, M.V.: Differential preamble detection in packet-based wireless networks. *IEEE Trans. Wireless Commun.*, **8**(2) (2009), 599–607.
- [21] Peh, E.C.; Liang, Y.-C.; Guan, Y.L.; Zeng, Y.: Cooperative spectrum sensing in cognitive radio networks with weighted decision fusion schemes. *IEEE Trans. Wireless Commun.*, **9**(12) (2010), 3838–3847.

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