Research Article

Multiple Antenna-Aided Cascaded Energy and Matched Filter Detector for Cognitive Radio Networks

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A new multiple antenna-aided cascaded energy and matched filter detector (MCEM) for cognitive radio networks is proposed. Our proposed scheme is equipped with multiple receive antennas employing energy efficient energy detector (ED) and reliable matched filter (MF) to mitigate the channel fading and increase the detection performance of the secondary users (SUs). Partial decisions are first made by using cascaded energy and matched filter detector (CEM) at each antenna and then the final collaborative decision is made based on those partial decisions. The probability of detection/false alarm of the proposed scheme is presented in terms of the complementary receiver operating characteristics (ROCs). The performance of MCEM scheme is explored via MATLAB simulations that implement the clear channel assessment (CCA) modules for IEEE 802.15.4. Simulation results showed that our proposed MCEM scheme improves the detection performance and is more energy efficient as compared to CEM scheme employing single antenna and other conventional schemes.

1. Introduction

The explosive growth of the wireless devices over the past few years has led to the spectral congestion and an apparent scarcity in radio spectrum is felt for quite some time. The densely spaced wireless devices have resulted in spectrum overcrowded, whilst licensed band occupied with primary user (PU) is often underutilized. A survey conducted by Federal Communication Commission (FCC) has revealed that hardly 25% of the spectrum gets utilized [1]. A scheme to exploit the underutilized spectrum opportunistically, better known as cognitive radio (CR) technology, uses clear channel assessment (CCA) to determine the spectrum holes [2, 3]. In wireless communication, CR has become a promising technique to solve the conflicts and enable spectrum sharing. In CR systems, the unlicensed or secondary users (SUs) can utilize the licensed frequencies while the PU is absent. The precise detection is a prerequisite so that PU does not face any excessive interference from the contending SU. This can only be achieved through accurate spectrum/channel sensing by the SU during CCA. Different algorithms for spectrum sensing such as energy detector (ED) [4], matched filter detector (MF) [5], and Cyclostationary Feature Detection (CFD) [6] in the context of CR have been extensively studied in the open literature.

The merits and demerits of each of the abovementioned algorithms have also been well researched and documented in the literature [7, 8]. Reliable spectrum sensing is not always guaranteed, due to multipath fading, shadowing, and hidden node terminal problem. Cooperative spectrum sensing (CSS), which involves the cooperating SUs to send their local spectrum sensing information to the fusion center (FC), where the final decision is taken considering all the results from the participating SUs, has been proposed to enhance the sensing performance [9–11]. The cooperation among several cooperating SUs comes at the cost of cooperation overhead and extra bandwidth for control channel. Also CSS is prone to several possible malicious user attacks such as spectrum sensing data falsification attack [12] and PU emulation attack [13].

Multiple antenna schemes have been proposed as another alternative to increase the sensing reliability. Reference [14]
proposed multiantenna based spectrum sensing method for CR using generalized likelihood ratio test (GLRT) approach. The authors showed that, under the mild assumptions on the PU signal, their proposed approach can perform better than conventional energy detector. Reference [15] carried out the performance evaluation of cooperative spectrum sensing with multiple antennas at each CR. The authors demonstrated that it is possible to achieve significant improvement in utilization of the spectrum hole by using the total error rate minimization criterion. A channel assessment method called cascaded CCA based on ED and preamble detector (PD) was proposed in [7]. But the problem with the proposed scheme in [7] was that it cannot perform CCA in any part of the signal. If the preamble of the signal was missed then the post end PD failed to do correlation and arrive at a firm decision regarding the presence of signal. Further, an ED and MF as cascaded CCA in wireless network were suggested in [16] where ED is used as a front end CCA and MF as a post end CCA which can be able to perform CCA in any position of the signal.

The goal to obtain energy efficient method for CR network is inevitable. ED is mostly preferred because of its ease of implementation. Also ED consumes little amount of energy for its operation. However, ED poor performance under low SNR condition made it unreliable and its performance is for its operation. However, ED poor performance under low implementation. Also ED consumes little amount of energy workisinevitable. EDismostlypreferredbecauseofitseaseof posedin[16]andtakingtheadvantageofmultipleantennas, MF consumes enormous amount of power for its successful done anywherewithin a packet. Beside its reliable detection, detector which performs correlation of signal that can be

The idea is to use the mutual benefit of multiple antenna- antennas and do channel sensing task with ED and MF combined with multiple antennas at each CR. The authors demonstrated the performance of our proposed detector at network level.

(iii) We also derived the power consumption for ED and MF from measurement of time execution code by implementing it in LabVIEW for ED and MF, respectively, and testing with NI-USRP-2921.

It should be noted that our proposed method is applicable to any wireless networks.

The rest of the paper is organized as follows. Section 2 describes briefly the conventional approaches to spectrum sensing and the problems thereof. Section 3 explains the proposed MCEM sensing scheme. The operation of cascaded energy and matched filter (CEM) detector scheme on IEEE 802.15.4 upon sensing the channel is also briefly explained and power consumption of our proposed MCEM scheme in IEEE 802.15.4 is elaborated in this section. Performance analysis and simulation of MCEM scheme are carried out in Section 4. Finally the conclusion of our paper is drawn in Section 5.

2. Performance Analysis of Conventional Spectrum Sensing Schemes

2.1. Energy Detector (ED). If the prior knowledge of the PU signal is unknown, the ED is optimal for detecting the radio frequency (RF) energy in the channel or the received signal strength indicator is measured to determine whether the channel is idle or not [17]. ED is a noncoherent detector that detects the presence of the signal by simply squaring its received energy and comparing it with certain threshold. If the threshold is exceeded, it is decided that PU signal is present; otherwise it is absent. However ED is prone to false detection due to the noise uncertainty condition or when the signal is heavily fluctuated, it becomes difficult to distinguish between the presence and absence of PU signal [4]. Also the threshold value used in ED depends on the noise variance and small noise power estimation errors can result in significant performance loss.

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

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

where \( r(t) \) is input signal and \( N_0 \) 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 \( \lambda_{ED} \). Threshold value is set to meet the target probability of false alarm \( P_{fa} \) according to the noise power. The probability of detection \( P_d \) can be also identified. The expression for \( P_{fa} \) and \( P_d \) can be given as [16]

\[
P_{fa}^{ED} = 1 - F_\chi^2 \left( \frac{\lambda_{ED}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{ED}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]

\[
\theta = \frac{1}{N_0} \int_0^T r^2(t) \, dt,
\]

\[
P_{fa}^{MF} = 1 - F_\chi^2 \left( \frac{\lambda_{MF}}{\sigma^2}, 2n \right),
\]

\[
P_d = 1 - F_\chi^2 \left( \lambda_{MF}, 2n \right),
\]
where $F_X$ is cumulative distribution function (CDF) of standard chi-square random variable with $k$ degree of freedom and $n$ is the number of bits during observation interval $T$ and has a variance ($\sigma$) of 1, and

$$P_{d}^{ED} = \varnothing \left( \sqrt{n \text{SNR}}, \sqrt{\frac{\lambda_{ED}}{\sigma^2}} \right),$$

where $\varnothing$ is generalized Marcum-Q function with noncentral chi-square distribution of noncentrality parameter $s^2 = n \text{SNR}$.

2.2. Matched Filter (MF). If there is a prior knowledge of the signal transmitted by the primary transmitter, the MF detector is the optimal detector to detect the presence or absence of the PU signals [5]. MF is a reliable detector but consumes high amount of power. A MF is obtained by correlating a known signal with an unknown signal. This is equivalent to convolving the unknown signal with a time-reversed version of the signal. In the case of IEEE 802.15.4, each symbol in packet data is transmitted using one of the known pseudorandom (PN) codes. MF works using receivers bank of $L$ matched filters, which runs together to correlate the incoming signals. The decorrelators process signal $x(t)$ at each sampling instant $t$. The output on particular interval, say, $(0, T)$ from MF which contains two sample output from a module is given by

$$Y_{MF} = y_{1}^2 + y_{Q}^2, \quad i = 1, 2, \ldots, L.$$  

(4)

The $Y_{MF}$ forms $L$ decorrelators output in which we find the decision variable $V$ from the maximum of $Y_{MF}$ over $M$ offset bits as MF has receivers bank of $L$ matched filters for performing the correlation of the incoming signals. Variable $V$ is then compared to threshold $\lambda_{MF}$ to decide the presence or absence of signal. Consider

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

(5)

The acquisition process of MF will give probability of false alarm $P_{fa}$ and probability of detection $P_{d}$ that can be calculated as [16]

$$P_{fa}^{MF} = 1 - F_X \left( \frac{\lambda_{MF}}{\sigma}, 2 \right),$$

$$P_{d}^{MF} = \varnothing \left( \sqrt{2n \text{SNR}}, \sqrt{\frac{\lambda_{MF}}{\sigma^2}} \right),$$

(6)

where $\lambda_{MF}$ is the threshold setting for MF and the noncentrality parameter $s^2 = 2n \text{SNR}$ 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 degrees of freedom with a variance ($\sigma = \sqrt{n}$).

3. Proposed Multiple Antenna-Aided Cascaded Energy and Matched Filter Detector Scheme

The state diagram of proposed MCEM scheme is presented in Figure 1. The ED block on $i$th antenna is always on, integrates the received RF signal over several symbol durations, and produces an output at symbol rate. If the integrated output exceeds the ED threshold $\lambda_{ED}$, then ED triggers the MF on $i$th antenna to be turned on. Once the MF is turned on, the receiver performs the matched filtering of the received signals and continues to integrate the output over the available number of symbols. If the output exceeds MF threshold $\lambda_{MF}$, the CEM detector on $i$th antenna determines that the PU is present and sets the flag to busy; if not, it returns to observing the channel state via ED as shown in the state diagram.

The block diagram of proposed MCEM scheme is presented in Figure 2 which consists of two stages. In first stage, partial decisions are made by using CEM detector at each antenna. Then a collaborative decision whether the primary user is present (Hypothesis $H_1^i$) or absent (Hypothesis $H_0^i$) is taken at second stage. The collaborative decision at second stage can be made by using different rules such as “AND Rule,” “OR Rule,” or “Majority Rule” [18]. In this paper, we have considered “OR Rule” to make a collaborative decision at second stage as “OR” rule outperforms the other rules such as “AND” rule in terms of energy efficiency [19]. In the first stage, the CEM detector corresponding to $i$th antenna, $i = 1, \ldots, N$, decides on the following hypothesis in observing signal $y_i$ by

$$H_0^i : y_i = n_i,$$

$$H_1^i : y_i = h_i \ast s_i + n_i,$$

(7)
where $h_i$ is the channel response and $H_0$ 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.

There are two main probabilities associated with the spectrum sensing. When the channel is vacant ($H_0^i$ is true), the CEM detector on $i$th antenna can decide that the channel is occupied by the PU. The probability of this event is referred to as the probability of false alarm $p_{fa}^{(i)}$. We can formulate the $p_{fa}^{(i)}$ of CEM scheme equipped on $i$th antenna as a cascaded mechanism of ED and MF as

$$p_{fa}^{(i)} = p_{fa}^{ED^{(i)}} \cdot p_{fa}^{MF^{(i)}}. \tag{8}$$

The presence of the signal is detected when the output from detector is greater than the defined threshold $\lambda$. The probability of correctly deciding the presence of PU when the channel is used by PU ($H_1^i$ is true) is referred to as the probability of detection $p_{d}^{(i)}$. We can formulate the $p_{d}^{(i)}$ of CEM scheme equipped on $i$th antenna as a cascaded mechanism of ED and MF as

$$p_{d}^{(i)} = p_{d}^{ED^{(i)}} \cdot p_{d}^{MF^{(i)}}. \tag{9}$$

As mentioned earlier, a final decision is made at second stage based on all the partial decisions of $i$th receiver antenna equipped with CEM detector. The two similar hypotheses are also defined at the second stage. $H_0$ represents the hypothesis that the channel is vacant. $H_1$ represents the hypothesis that the channel is occupied. The partial decision from the first stage is combined using the “OR Rule” and a collaborative decision is taken at second stage. The probabilities of false alarm $p_{fa}$ and probabilities of detection $p_{d}$ are similarly defined for the MCEM scheme taking “OR Rule” into account.

If $p_{fa}^{(i)}$ and $p_{d}^{(i)}$ are the overall probability of detection and false alarm, respectively, of MCEM scheme, we can formulate the $p_{fa}$ and $p_{d}$ of our proposed MCEM scheme from (8) and (9) considering the “OR Rule” as

$$p_{fa}^T = 1 - (1 - p_{fa}^{(i)})^N,$$
$$p_{d}^T = 1 - (1 - p_{d}^{(i)})^N, \tag{10}$$

where $N$ is the number of antennas.

### 3.1. Operation of Cascaded Energy and Matched Filter (CEM) Detector in IEEE 802.15.4

The block diagram of operation of CEM scheme on IEEE 802.15.4 is shown in Figure 3. When a SU wakes up from idle or sleep state to perform CCA in the middle of packet transmission as shown in Figure 3(b), it will do some random back-off as it will sense the channel as busy. When the back-off (BO) counter starts to decrease, a SU node performs CCA again to determine the channel whether it is free or not. If the channel is found busy again during the CCA, the node increments the back-off exponent (BE) period (up to macMaxBE) and repeats the CCA process to sense the channel. When the channel is available for transmission after successful CCA, that is, when BO = 0, SU will transmit packet during this period. In the duration of specified CCA defined by [20], our CEM scheme must be able to determine the channel state. Given the consideration of limited CCA duration, our proposed scheme has two chances to detect the channel state within 8-symbol duration by integrating 2 symbols per ED and MF as clearly shown in Figure 3(a). ED as front end detector integrates symbols as the CCA starts and continues its operation. Once $\lambda_{ED}$ is crossed, that is, channel condition is assumed to be $H_1$, CEM scheme triggers MF operation if and only if CCA duration left is $T_{CCA} - T_{ED} < 2 + T_{switch}$ to make sure the channel condition is as detected by front end ED. Else, CEM scheme considers the channel condition to be idle; that is, PU is absent. It continues to monitor the channel as long as there are packets to be transmitted by the SU. Otherwise it stops channel monitoring and enters into idle state to save energy.

In our proposed MCEM scheme, the operation of ED interchanges with MF. Hence, the power consumed by the ED and MF has the factor of ($c = 1, 2$). The factor $c$ depends on whether the threshold of ED is crossed at the first or second
attempt. During CCA, if $\lambda_{ED}^i$ on $i$th antenna is crossed at the first attempt, that is, $c_1 = 1$, then MF on the same $i$th antenna will have two chances of performing CCA ($c_2 = 2$); else MF will have one chance of performing CCA ($c_2 = 1$) as depicted in Figure 3(a).

3.2. Power Consumption of Multiple Antenna-Aided CEM in IEEE 802.15.4. It is very important to analyze the power consumption as IEEE 802.15.4 devices are meant to work for battery operated low powered devices. In our proposed multiple antenna-aided CEM scheme, the channel is first detected by ED on $i$th antenna and then MF on the same $i$th antenna is turned on when ED output is greater than $\lambda_{ED}^i$. Hence, the power consumption of our MCEM detector can be emphasized as three states. The first state is when the device is in idle state. In this state, the power being drained by the device is the lowest, and the power consumption that is spent in this state solely depends on the idle duration. The second state is the channel sensing state. In this state, the device starts CCA to sense the channel whether it is free or not. The power spent in this state depends on CCA duration. In the third state, when the channel is idle, the device is ready to transmit the packet. The power consumption in this state depends on the data transmission by the device in the transmission slot. However, it is to be noted that more power is consumed in this state.

The parameters of the radio were obtained from [21], which has idle, transmit, and receive states. To the best of our knowledge, accurate models for power consumption of the multiple antenna modules of IEEE 802.15.4 are not available as of now. We therefore resort to certain heuristic arguments to arrive at reasonable numbers for the power consumption in IEEE 802.15.4 multiple antenna case as shown in [22]. It should be observed that receive power for multiple antenna case in IEEE 802.15.4 is greater than the transmit power. It is because of the fact that the low powered IEEE 802.15.4 should turn on the circuitry at the receiver side to enforce necessary signal processing techniques. The power consumption for ED and MF was derived from measurement of time execution code. The execution code was implemented in LabVIEW for ED and MF, respectively, and was tested in NI-USRP-2921. The power consumption for each state can be seen in Table 1.

The power consumption for our MCEM detector consists of ED and MF part. Our MCEM detector must do CCA within 8-symbol duration as shown in Figure 3(a). Consequently ED and MF acquisition duration is $t_{ED} + t_{MF} \leq 8$. For our MCEM detector, the operation of ED changes alternately with MF, so that the power consumed by ED and MF has the factor of $(c = 1, 2)$. During CCA, if $\lambda_{ED}^i$ on $i$th antenna is crossed at the first attempt, that is, $c_1 = 1$, then MF on same $i$th antenna will have two chances of performing CCA ($c_2 = 2$); else MF will have one chance of performing CCA ($c_2 = 1$) as shown in Figure 3.

In IEEE 802.15.4 channel sensing, the energy consumption for ED, MF, and MCEM when $BE = 0$ consists of CCA part only as SU will only spend energy in sensing the channel in this period. If $p_{ED}^i$ and $p_{MF}^i$ are the power consumption of ED and MF, respectively, equipped on $i$th antenna, $T_{slot}^i$ is the total slot duration, $T_{CCA}^i$ is the CCA duration, and $T_{sw}^i$ is switching duration from ED to MF then power consumption in this period is clearly depicted as explained by (11). Here the factors $c_1 = 1$ and $c_2 = 2$ depend on whether $\lambda_{ED}^i$ on $i$th antenna is crossed at the first or second attempt as explained earlier.

After successful CCA, $BE = 0$ which means that the channel is free and the node is ready to transmit the packet during this period. This period consists of energy consumption during CCA and transmit $P_{tx}$ energy as described by (12). Consider

$$E_{BE=0} = \begin{cases} p_{ED}^i T_{CCA}^i + p_{ED}^i (T_{slot} - T_{CCA}^i) & \text{ED}^i \\ p_{MF}^i T_{CCA}^i + p_{MF}^i (T_{slot} - T_{CCA}^i) & \text{MF}^i \\ p_{ED}^i T_{sw}^i c_1 + p_{MF}^i (T_{CCA}^i - T_{sw}^i) c_2 + p_{ED}^i (T_{slot} - T_{CCA}^i) & \text{MCEM} \end{cases}$$

$$E_{BE=0} = \begin{cases} p_{ED}^i T_{CCA}^i + P_{tx}^i (T_{slot} - T_{CCA}^i) & \text{ED}^i \\ p_{MF}^i T_{CCA}^i + P_{tx}^i (T_{slot} - T_{CCA}^i) & \text{MF}^i \\ p_{ED}^i T_{sw}^i c_1 + p_{MF}^i (T_{CCA}^i - T_{sw}^i) c_2 + P_{tx}^i (T_{slot} - T_{CCA}^i) & \text{MCEM} \end{cases}$$

4. Performance Evaluation

Our simulation was conducted in MATLAB to investigate the performance of our proposed multiple antenna-aided cascaded energy and matched filter detector scheme. AWGN channel is considered for our analysis. Generated signal $s_i$ for signal to noise ratio (SNR) 5 dB is mapped to 16 nearly orthogonal 32-chip-long pseudo noise (PN) sequences. According to IEEE 802.15.4, CCA must determine the channel state within 8-symbol durations (128 $\mu$s corresponding to one-symbol duration of 16 $\mu$s). Back-off slot duration of IEEE 802.15.4 is 20-symbol durations, that is, 320 $\mu$s. The switching time between the ED and MF for our proposed scheme is assumed to take 2-symbol time of IEEE 802.15.4 in our analysis. We have considered two antennas at the receiver side ($N = 2$) equipped with energy efficient ED and reliable MF and applied the “OR Rule” criterion for collaborative decision making in the second stage of our proposed MCEM scheme.
Table 1: Power consumption.

| Notation | Operation       | Value  |
|----------|-----------------|--------|
| $P_{id,1\text{ Ant}}$ | Inactivity      | 0.6 mW |
| $P_{tx,1\text{ Ant}}$ | Transmit        | 23.5 mW |
| $P_{rx,1\text{ Ant}}$ | Receive         | 21 mW  |
| $P_{id,2\text{ Ant}}$ | Inactivity      | 0.9 mW  |
| $P_{tx,2\text{ Ant}}$ | Transmit        | 27.3 mW |
| $p_{CEM}^{ED}$  | Energy detector CCA | 7.83 mW |
| $p_{MCEM}^{MF}$ | Matched filter CCA | 23.5 mW |
| $T_{CCA}$     | Cascade duration | 8 symbols |
| $T_{sw}$      | Switching duration | 1 symbol |
| $T_{\text{slot}}$ | Slot duration   | 281250 slots |

Figure 4: Complementary ROC of IEEE 802.15.4 for proposed multiple antenna-aided cascaded energy and matched filter detector scheme with $p_{fa}^{ED}$ set at 40% and 20%.

Figures 4 and 5 show the complementary ROC curve ($p_d$ versus $p_{fa}$) for the proposed MCEM scheme, CEM scheme employing single antenna, and conventional ED and MF schemes. Analytical (solid line—only) and simulation results (dashed line—sim) of MCEM scheme with $p_{fa}^{ED} = 40\%$ and 20\% with 2-symbol integration of the front end ED are shown in Figure 4 and MCEM scheme with $p_{fa}^{ED} = 30\%$ and 10\% with 2-symbol integration of the front end ED is shown in Figure 5. Our MCEM scheme is marked as “MCEM” and CEM detector with single antenna is marked as “CEM” throughout the simulation results presented in this paper. Clearly from simulation results as shown in Figures 4 and 5, MCEM scheme detection performance is better than the CEM scheme employing single antenna and conventional energy detector scheme. Also, we can see from the simulation results 4 and 5 that as the front end detector $p_{fa}^{ED}$ increases from 10\% to 40\%, the detection performance of our MCEM scheme increases more. This is due to the fact that the less reliable ED will trigger more reliable post end detector MF for CCA with the increase in $p_{fa}^{ED}$ of front end ED. Both analytic and simulation results are compared to validate the analysis.

Figure 6 shows the ROC of IEEE 802.15.4 for proposed MCEM scheme with $p_{fa}^{ED}$ set at 40\%, 30\%, 20\%, and 10\% against CEM scheme employing single antenna when performed in the middle of transmission as explained in Figure 3. As expected, detection performance of MCEM scheme outperforms the single antenna CEM scheme. It means that, during the data transmission by the PU, if our MCEM detector wakes up from idle state to sensing state, it can detect the PU activities more precisely than single antenna CEM scheme. Our proposed scheme can give more protection to the PUs by correctly sensing the PUs activities during CCA which is the ultimate goal of CR network.

4.1. Network Throughput Analysis. The aggregate network throughput is considered as the fraction of time that the device spends in successful data transmission after successful CCA; that is, channel is free. Hence, it represents the normalized throughput and does not have any units. If $\alpha$ and $\beta$ denote the probability that the channel is successfully
throughput analysis for proposed MCEM with $N$ is the total number of slots for data transmission. where \( \alpha = P_{fa}^{ED} \) and \( \beta = P_{fa}^{MF} \), then, by following two-dimensional Markov chain with transition probabilities as in [23], the throughput \( Z \) and normalized throughput \( Z_{\text{norm}} \), respectively, are given by

\[
Z = \ln (1 - \alpha) \cdot (1 - \beta),
\]

\[
Z_{\text{norm}} = \frac{Z}{N \cdot \text{Slot}}.
\]

(13)

where \( L \) is the number of successful packet transmissions and \( N \) is the total number of slots for data transmission.

Figure 7 shows the simulation results for the network throughput analysis for proposed MCEM with \( p_{fa}^{ED} \) set at 40%, 30%, 20%, and 10%, single antenna CEM with \( p_{fa}^{ED} \) set at 40%, 30%, 20%, and 10%, and ED and MF scheme in IEEE 802.15.4.

For a given \( p_{fa}^{ED} \), ED gives the worst detection performance and MF gives the highest detection performance as shown in complementary ROC Figures 4 and 5. This leads to worst throughput for ED and highest throughput for MF. It should be noted that as the packet arrival rate per slot increases, that is, greater than \( 10^{-3} \), ED cannot detect the channel precisely so the overall throughput of ED almost becomes zero except for the packet arrival rate per slot less than \( 10^{-3} \) as shown in Figure 7. CEM has intermediate throughput between ED and MF. Our MCEM scheme has superior detection performance compared to CEM scheme, so the detection of the PUs channel is more accurate. Hence its throughput is higher as compared to ED and CEM scheme. From Figure 7, we can see that our MCEM scheme has 28% higher throughput than CEM scheme employing single antenna.

4.2. Network Power Consumption Analysis. The power consumption and parameters for our MCEM scheme are detailed in Section 3 of this paper. Figure 8 shows the simulation results for the network power consumption analysis for MCEM with \( p_{fa}^{ED} \) set at 40%, 30%, 20%, and 10%, single antenna CEM with \( p_{fa}^{ED} \) set at 40%, 30%, 20%, and 10%, and ED and MF scheme in IEEE 802.15.4. ED consumes the smallest energy because its operation is simple and remains in idle state except when there is a packet to be transmitted. Although MF shows higher throughput as compared to other schemes, it is more power hungry as it simultaneously runs 16 pseudorandom PN codes and each code matches to a different PN code to do the correlation. MF requires receiver to stay awake to do the correlation, thus consuming high amount of power. CEM employs energy efficient ED as front end detector which allows it to stay in idle state when there are no packets to be transmitted and only triggers power hungry and reliable post end MF when the output of ED crosses the threshold, thus making it energy efficient. Power consumption of our MCEM scheme is more than the CEM and ED scheme as we are taking advantage of multiple antennas for the correct detection performance. It is obvious that multiple antenna consumes more energy than single antenna. This trade-off can be justified with the high detection performance and higher throughput achieved compared to other schemes.

4.3. Energy Efficiency Analysis. Figure 9 shows the simulation results for the energy efficiency metric (kbyte/J) for proposed MCEM with \( p_{fa}^{ED} \) set at 40%, 30%, 20%, and 10%, single antenna CEM with \( p_{fa}^{ED} \) set at 40%, 30%, 20%, and 10%, and ED and MF scheme in IEEE 802.15.4. Although MF shows the best throughput, its energy efficiency is lower than
5. Conclusion

In this paper, a new multiple antenna-aided cascaded energy and matched filter detector (MCEM) for CRN was proposed. Our proposed scheme blends the energy efficiency of an ED and reliability of MF detector. Multiple receive antennas are used to mitigate the channel fading and increase the detection performance of the SUs. Receiver operating characteristics of proposed MCEM scheme in IEEE 802.15.4 were analyzed mathematically and the analysis was validated via MATLAB simulation and compared with CEM scheme employing single antenna and other conventional ED and MF schemes. Our proposed MCEM scheme outperformed the single antenna CEM scheme and other conventional energy detection schemes in terms of detection performance. Although the power consumption of our proposed MCEM scheme is shown higher than ED and single antenna CEM scheme, the performance metric like throughput and energy efficiency of our MCEM scheme is higher than other schemes which makes it a more suitable choice for the channel sensing in the CRNs. It was shown that our proposed MCEM scheme achieved 28% higher throughput and 22% more energy efficiency than the CEM scheme employing single antenna.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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