An Optimized Scheme to Resist Primary User Emulation Attacks

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Abstract—The problem of cognitive radio (CR) network security has become an important problem in cognitive radio technology. One of the most common attacks is primary user emulation attacks (PUEA), where some malicious users simulate CR users to prevent them from accessing the vacant frequency. Here, a cooperative spectrum sensing (CSS) method with optimal weight coefficient based on improved energy detection is proposed. In the proposed scheme, we combine sensing information using the optimal weight coefficient at a fusion center and apply the improved energy detection, which effectively prevent the PUEA. Simulation results show that the method outperforms the traditional energy detection with optimal weight coefficient in detection performance.

Keywords-cognitive radio; cooperative spectrum sensing; primary user emulation attack; energy detection; optimal weight coefficient

I. INTRODUCTION

With the development of wireless communication technology, spectrum resources become so deficient. Hence, CR network has been widely adopted as a promising technology to overcome the spectrum scarcity by CR users (CUs) to operate opportunistically in the idle space of the licensed bands in the co-existence of the primary users (PUs) [1]. Spectrum sensing is a fundamental functionality of CR network [2]. In the spectrum sensing process, it will produce a variety of security issues, which the most common one is primary user emulation attacks (PUEA). The PUEA is that when the malicious users (MU) find idle spectrum, it will send a similar signal with the primary user's signal to prevent the CU to detect the idle spectrum. Recently, in [3] and [4], the authors classify CR attacks and provide some contributions on security threats, detection techniques, new challenges and future research directions. In order to solve this problem, cooperative spectrum sensing (CSS) technology is put forward. At the same time, cooperative spectrum sensing is a method which can improve the detection performance effectively [5].

Typically, the primary user and the CR users are separate to each other. CR users can not accurately know all information of the primary user, so we usually use energy detection. In [6], a soft combing method, equivalent to maximal ratio combining (MRC), is developed where the sensing statistics of different CR users are combined by using the optimal weight coefficient. In [7], the cooperative spectrum sensing scheme with optimal weight coefficient based on energy detection is proposed. Compared with the traditional MRC method, the method proposed in [7] improves

the detection probability. Based on the research of [7], this paper propose an improved energy detection, which can be more effective than the method in [7].

In this paper, we set up a cooperative spectrum sensing model about the presence of PUEA and propose a scheme to maximize the detection probability of primary user in the cognitive radio networks. Each CR user of CR networks sends the received information to the fusion center and is combined with the optimal weight coefficient. Finally, according to the Neyman-Pearson criterion we can make the final decision. In this paper, the maximum detection probability of the primary user is obtained by deriving the optimal weight coefficient. Therefore, this scheme can effectively resist PUEA and improve the detection performance of the system.

The rest of this letter is organized as follows. Section II introduces the system model of cooperative spectrum sensing with the presence of PUEA. In Section III, the optimal weight coefficients based on improved energy detection in the presence of PUEA is derived and the maximum detection probability of primary user is calculated. Discussion along with comparative simulation results is presented in Section IV.

II. SYSTEM MODEL

In this model, we consider cooperative spectrum sensing in a CR network having N CR users coexisting with a malicious user to detect the presence of one primary transmitter, as shown in Figure I.
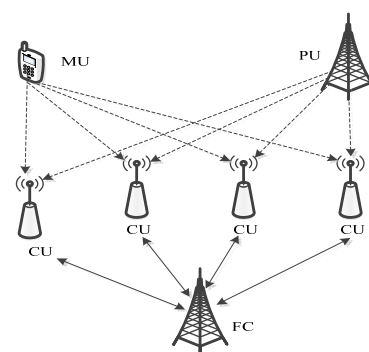

FIGURE I. SYSTEM MODEL OF THE COGNITIVE RADIO NETWORK

In the entire CR network, we assume that PUEA always exists. So, there are two kinds of signal received by the i th $(1 \leq i \leq N)$ CR user at the t th time instant.

$$y_{i1}(t) = h_{mi}(t)x_m(t) + n_i(t) \qquad\qquad H_0$$
$$y_{i2}(t) = h_{pi}(t)x_p(t) + h_{mi}(t)x_m(t) + n_i(t) \quad H_1 \tag{1}$$

where H_0 is the situation at the absence of primary user and H_1 is the situation at the presence of primary user. $h_{pi}(t)$ and $h_{mi}(t)$ denote the instantaneous channel gain between primary user and i th CR user and between malicious user and i th CR user respectively. $x_p(t)$ and $x_m(t)$ are the signal transmitted by primary user and malicious user. $n_i(t)$ is the additive white Gaussian noise at the i th the CR user with zero mean and variance σ_n^2.

In cooperative spectrum sensing, each CR user will send the local decision results to the fusion center, and then the fusion center makes a final decision that PU is presence or not [2]. Under normal conditions, fusion method is mainly divided into two kinds of hard fusion and soft fusion. In this paper, we mainly use the soft fusion method, which the signals received by CR user are weighted by some coefficients w_i ($i = 1, 2 \ldots N$) and fused to make a final decision in fusion center [6].

The assumption is that the channel from the CR user to the fusion center is perfect. The combined signal in the fusion center at the t th time instant is

$$y(t) = \begin{cases} \sum_{i=1}^{N} w_i y_{i1}(t) & H_0 \\ \sum_{i=1}^{N} w_i y_{i2}(t) & H_1 \end{cases} \tag{2}$$

In this paper, we adopt the improved energy detection method in which M samples of $y(t)$ are summed during one detection interval.

$$Y = \sum_{t=1}^{M} |y(t)|^p \tag{3}$$

The fusion center then calculates the decision statistic Y for each detection interval to make a global decision.

III. COOPERATIVE SPECTRUM SENSING UNDER IMPROVED ENERGY DETECTION

In this section, we will derive the optimal weight coefficients based on the improved energy detection to maximize the detection probability of primary user in the presence of PUE attacks. Comparing the statistic Y with the threshold value, the false alarm probability P_f and detection probability P_d over a detection interval are defined as [8],

$$p_f = (Y \geq \lambda \mid H_0) \tag{4}$$

$$p_d = (Y \geq \lambda \mid H_1) \tag{5}$$

where λ in (4) and (5) is a detection threshold value in improved energy detection.

Because of using the Neyman-Pearson criterion, we need to give a value of P_f in advance. For a given P_f and soft fusion method, the most important problem is to find out the optimal weight coefficient $W_{opt} = [w_{1opt}, w_{2opt}, \ldots w_{Nopt}]$ to maximize the detection probability. Among this, $W = [w_1, w_2, \ldots w_N]$ is a vector of weight coefficients for the combination at the fusion center.

In the actual cognitive radio network, the PUE attacker's signal is similar to the primary user's signal. Therefore, we assume that the primary signal $x_p(t)$ follows a complex Gaussian distribution, i.e. $x_p(t) \sim CN(0, \sigma_{PU}^2)$, the $x_m(t)$ follows the complex Gaussian distribution, i.e. $x_m(t) \sim CN(0, \sigma_{PUEA}^2)$. For given h_{pi} and h_{mi}, the combined signal $y(t)$ is also a complex Gaussian distributed random variable,

$$y(t) \sim \begin{cases} CN(0, \sigma_0^2) & H_0 \\ CN(0, \sigma_1^2) & H_1 \end{cases} \tag{6}$$

where, σ_0^2 and σ_1^2 are the variance of $y(t)$ for H_0 and H_1 respectively.

$$\sigma_0^2 = \sigma_{PUEA}^2 \left| \sum_{i=1}^{N} w_i h_{mi} \right|^2 + \sigma_n^2 \sum_{i=1}^{N} |w_i|^2 \tag{7}$$

$$\sigma_1^2 = \sigma_{PU}^2 \left| \sum_{i=1}^{N} w_i h_{pi} \right|^2 + \sigma_{PUEA}^2 \left| \sum_{i=1}^{N} w_i h_{mi} \right|^2 + \sigma_n^2 \sum_{i=1}^{N} |w_i|^2 \tag{8}$$

Give

$$H_m = [h_{m1}(t), h_{m2}(t), \ldots h_{mN}(t)]^T, \ H_p = [h_{p1}(t), h_{p2}(t), \ldots h_{pN}(t)]^T$$

According to (7) and (8), σ_0^2 and σ_1^2 can be denoted,

$$\sigma_0^2 = \sigma_{PUEA}^2 W H_m H_m^H W^H + \sigma_n^2 W W^H \tag{9}$$

$$\sigma_1^2 = \sigma_{PU}^2 W H_p H_p^H W^H + \sigma_{PUEA}^2 W H_m H_m^H W^H + \sigma_n^2 W W^H \tag{10}$$

where, H is the Hermitian transpose.

Based on the paper [9], the decision statistic Y is similar to the gamma distribution by changing the mean and variance. So we have

$$p_f = \frac{\Gamma\left(k_0, \frac{\lambda}{\theta_0}\right)}{\Gamma(k_0)} \quad (11)$$

$$p_d = \frac{\Gamma\left(k_1, \frac{\lambda}{\theta_1}\right)}{\Gamma(k_1)} \quad (12)$$

where,
$$k_0 = k_1 = M \frac{\Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{2p+1}{2}\right)\sqrt{\pi} - \Gamma^2\left(\frac{p+1}{2}\right)} \quad (13)$$

$$\theta_0 = 2^{\frac{p}{2}} \frac{\sqrt{\pi}\Gamma\left(\frac{2p+1}{2}\right) - \Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{p+1}{2}\right)\sqrt{\pi}} \sigma_0^{\ p} \quad (14)$$

$$\theta_1 = 2^{\frac{p}{2}} \frac{\sqrt{\pi}\Gamma\left(\frac{2p+1}{2}\right) - \Gamma^2\left(\frac{p+1}{2}\right)}{\Gamma\left(\frac{p+1}{2}\right)\sqrt{\pi}} \sigma_1^{\ p} \quad (15)$$

$\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are Gamma function and upper incomplete Gamma function respectively.

Given $p_f = \varepsilon, \varepsilon \in [0,1]$, the decision threshold λ is represented as,

$$\lambda = \Gamma^{-1}\left(k_0, \varepsilon \cdot \Gamma(k_0)\right) \cdot \theta_0 \quad (16)$$

where $\Gamma^{-1}(\cdot,\cdot)$ is the inverse incomplete Gamma function [10].

According to (12) and (13), P_d can be rewritten as,

$$p_d = \frac{\Gamma\left(k_1, \Gamma^{-1}\left(k_0, \varepsilon\Gamma(k_0)\right)\frac{\theta_0}{\theta_1}\right)}{\Gamma(k_1)} \quad (17)$$

In this paper, $k_0 = k_1$, for a given M ,we can obtain the value of k_0. Thanks to the monotonicity of Gamma function, to maximize P_d is equivalent to minimize θ_0 / θ_1. According to (14) and (15),

$$\frac{\theta_0}{\theta_1} = \left(\frac{\sigma_0^2}{\sigma_1^2}\right)^{\frac{p}{2}} \quad (18)$$

According to (9) and (10),

$$\begin{aligned}\frac{\sigma_0^{\ 2}}{\sigma_1^{\ 2}} &= \frac{\sigma_{PUEA}^2 W H_m H_m^{\ H} W^H + \sigma_n^2 W W^H}{\sigma_{PU}^2 W H_P H_P^{\ H} W^H + \sigma_{PUEA}^2 W H_m H_m^{\ H} W^H + \sigma_n^2 W W^H} \\ &= \frac{1}{1 + \frac{\sigma_{PU}^2 W H_p H_p^{\ H} W^H}{\sigma_{PUEA}^2 W H_m H_m^{\ H} W^H + \sigma_n^2 W W^H}}\end{aligned} \quad (19)$$

where $\sigma_0^2 / \sigma_1^2 < 1$, when the value of p increase, θ_0 / θ_1 will reduce. Hence, we need to calculate the minimum value of σ_0^2 / σ_1^2 when p is established.

Let $\Phi = \frac{\sigma_{PU}^2 W H_p H_p^{\ H} W^H}{\sigma_{PUEA}^2 W H_m H_m^{\ H} W^H + \sigma_n^2 W W^H}$ to minimize σ_0^2 / σ_1^2 is equivalent to maximize Φ. Take partial derivative of Φ with respect to W.

$$\frac{\partial \Phi}{\partial W} = \frac{\begin{aligned}&\left[2\sigma_{PU}^2 H_p H_p^{\ H} W^H \left(\sigma_{PUEA}^2 W H_m H_m^{\ H} W^H + \sigma_n^2 W W^H\right)\right. \\ &\left. - 2\left(\sigma_{PUEA}^2 H_m H_m^{\ H} W^H + \sigma_n^2 W^H\right)\sigma_{PU}^2 W H_p H_p^{\ H} W^H\right]\end{aligned}}{\left(\sigma_{PUEA}^2 W H_m H_m^{\ H} W^H + \sigma_n^2 W W^H\right)^2} \quad (20)$$

Let $\frac{\partial \Phi}{\partial W} = 0$, the optimal weight coefficient W_{opt} is,

$$W_{opt} = \left[\left(\sigma_{PUEA}^2 H_m H_m^{\ H} + \sigma_n^2 I\right)^{-1} H_p\right]^H \quad (21)$$

where I is the identity matrix, and the minimal σ_0^2 / σ_1^2,

$$\left(\frac{\sigma_0^2}{\sigma_1^2}\right)_{\min} = \frac{1}{1 + \sigma_{PU}^2 H_p \left(\sigma_{PUEA}^2 H_m H_m^{\ H} + \sigma_n^2 I\right)^{-1} H_p^{\ H}} \quad (22)$$

According to (18),

$$\left(\frac{\theta_0}{\theta_1}\right)_{\min} = \left(\frac{1}{1 + \sigma_{PU}^2 H_p \left(\sigma_{PUEA}^2 H_m H_m^{\ H} + \sigma_n^2 I\right)^{-1} H_p^{\ H}}\right)^{\frac{p}{2}} \quad (23)$$

using (17) and (23),

$$p_{d\max} = \frac{\Gamma\left(k_1, \Gamma^{-1}\left(k_0, \varepsilon\Gamma(k_0)\right)\left(\frac{1}{1 + \sigma_{PU}^2 H_p \left(\sigma_{PUEA}^2 H_m H_m^{\ H} + \sigma_n^2 I\right)^{-1} H_p^{\ H}}\right)^{\frac{p}{2}}\right)}{\Gamma(k_1)} \quad (24)$$

We implement the simulations of cooperative spectrum sensing scheme with the existence of PUEA. In this paper, there are one PUEA, one PU and 4 CU in cognitive radio network. The number of samples within a detection interval is M=4.
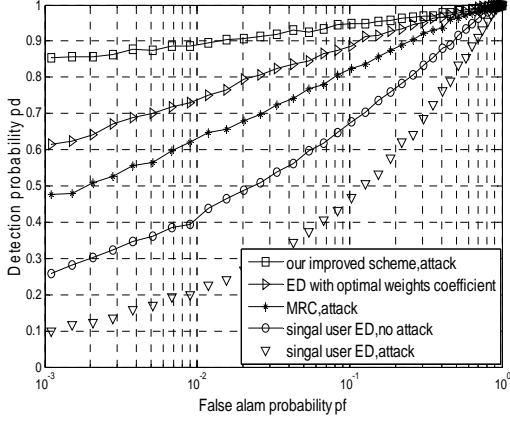

FIGURE II. THE ROC CURVE FOR OUR SCHEME, ENERGY DETECTION WITH OPTIMAL WEIGHT COEFFICIENT, CONVENTIONAL MRC AND SINGLE-USER ENERGY DETECTION.

Figure II display the ROC curve for our scheme, energy detection with optimal weight coefficient, conventional MRC and single-use energy detection scheme. In the simulation, all channel information are assumed to be known for the CR users. Assume $x_p(t) \sim CN(0,1)$, $x_m(t) \sim CN(0,1)$ and the SNR between primary user and every CR user is 0 dB, we can discuss them in the presence of PU EA. For conventional MRC, the weighting coefficients is $w_i = 0.25$ ($i = 1,2,3,4$). The value of p is 3. From FIGURE II, we find that the detection probability of conventional MRC and single-user energy detection schemes are decline so severe under the effect of PUEA. In the case of the same false alarm probability, the detection probability of our scheme is better than that of energy detection with optimal weight coefficient. So our proposed scheme improves the detection performance of system.

Figure III describes the detection performance under different SNR at the presence of PUEA. In the simulation, given $p_f = 0.1$, the SNR between primary user and CR users is same for each CR user. We defined,

$$x = \frac{\sigma^2_{PU}}{\sigma^2_{PUEA}} \qquad (25)$$

x reveals the strength of the attack. Smaller values of x represent a strong attack. In Figure III, detection performance of the proposed scheme is compared with energy detection with the optimal weight coefficient scheme where x is given as 0.1, 1, 10 respectively in [7]. In the case of low SNR, the detection probability of our scheme is relatively high. At the same time, we find that the detection performance is improved effectively with the reduced of x under the low SNR.
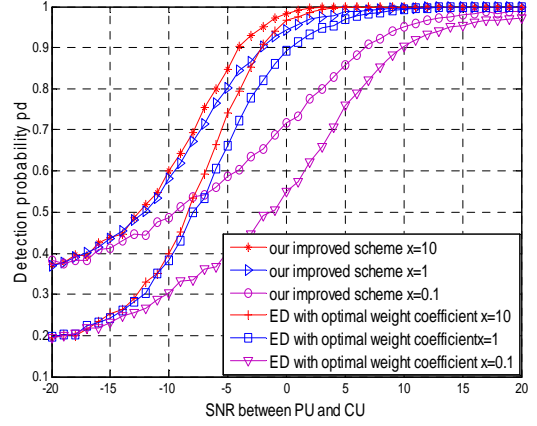

FIGURE III. DETECTION PROBABILITY VERSUS SNR FOR OUR SCHEME, ENERGY DETECTION WITH OPTIMAL WEIGHT COEFFICIENT, $p = 3$.

Figure IV displays the detection probability with the change of SNR for our proposed scheme. According to (18) and (19), a large numerical value of p indicates a small θ_0/θ_1 to make the detection probability bigger. In FIGURE IV, we assume that the value of x is 0.1 and p is set as 2, 3, 4, 5. With the increase of p, the probability of detection is gradually increased at the same SNR. But the magnitude of the increase is in constant decline. When p is set to 10, we can obtain the curve graph of the maximal detection probability. So assuming a stronger attack exist, we can improve the detection probability through increasing the value of p.
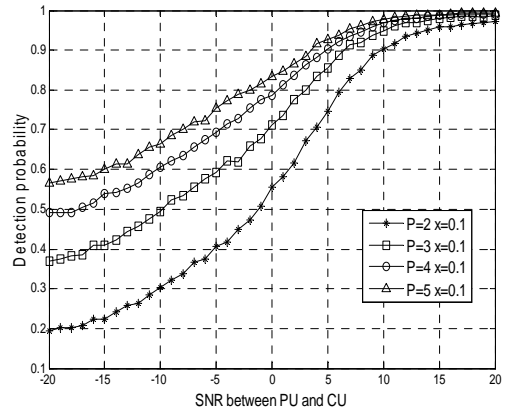

FIGURE IV. THE DETECTION PROBABILITY VERSUS SNR FOR DIFFERENT VALUE OF p, $x = 0.1$

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