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Effect of Spectrum Sensing Errors in Multiband Cognitive Radio Systems in the Presence of PUEA

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***Abstract*— In recent years, cognitive radio (CR) technology has been proposed as a solution to overcome inefficient spectrum allocation strategies by enablingunlicensed users to opportunistically use allocated bands to the licensed users.However, one severe threat to CR systems is the primary user emulation (PUE) attack, where an attacker mimics the signals of the PUs, resulting in false alarms during the spectrum sensing phase at well-behaving SUs even though the PUs are actually not present. This attackers can thus significantly degrade the performances of the well-behaving SUs.In classical energy detection method, CR system decides about the presence and absence of the PU, in each frequency band, by comparing the measured energy to a predefined threshold. Due to noise and spectrum sensing errors, this approach may lose some opportunities in the CR system. In this paper, we investigate the effect of the spectrum sensing errors in a multiband CR system in the presence of a PUEA.**

***Index Terms*—Cognitive Radio, Energy Detection, PUEA,Spectrum Sensing Errors.**

I. INTRODUCTION

In a cognitive radio (CR) network, unlicensed users called secondary users (SUs), are permitted to use allocated bands to the licensed primary users (PUs), as long as interference introduced to the PU remains tolerable [1]. So, cognitive network should senses the radio environment and after detecting vacant bands, shares its resources in a way, maximum exploitation is achieved and minimum interference is introduced to the PU. Due to main CR nature, some malicious users, known as primary user emulation attacker (PUEA), try to send fake signals similar to the PU with the aim of deceiving CR users and make them vacate unoccupied bands [2]. CR resource allocation methods aiming at maximizing transmission capacity, operate based on spectrum sensing results and calculated interferences introduced to the CR and PU. So, it is vital to reconsider these parameters while existing fake signals in the environment to perform resource allocation more efficiently.In [3], a detection method based on distance ratio and difference to detect PUEA is proposed. In [4] based on an analytical model on the probability of successful, without any knowledge about the location information, PUEA is detected through a sequential test. The defense strategies against PUEA have been studied for example in [5]-[7]. In [5], a localization based defense technique has been proposed in which a number of sensors are deployed to pinpoint the PUE attacker. In [6] and [7], the defense against PUEA is modeled as a game theoretic problem, with or without the knowledge of channel statistics respectively. Also, in [8] a cooperative spectrum sensing in the presence of PUEA is modeled and an approach to maximize the detection probability of primary user has been proposed. However, the optimal weights are related to the channel state information between the attacker and secondary users and between the primary user and secondary users, which assumed that CR user can estimate by using channel estimation algorithms.

Sensing a PU is a difficult task due to the presence of variable path losses, fading and noise [9], [10]. Therefore, sensing is never completely reliable and will always produce some errors depending upon the channel conditions between the primary transmitter and CR sensors.Mostly, energy detector based sensing is used in spectrum sensing phase of CR network because of its simplicity [11]. The decision on the occupancy of a band can be obtained by comparing the measured energyY_n against a fixed threshold which is obtained from Neman-Pearson criteria. If the decision metric Y_n is greater than threshold, CR network decides the PU is present. Otherwise, if the decision metric Y_n is lower than threshold, CR network decides that PU is absent and tries to use the spectrum. Due to noise and errors in spectrum sensing measurements, this method may result in missing lots of opportunities in CR network.

In this paper, we propose a resource allocation scheme for a CR system by considering the presence of fake signals in the radio environment and spectrum sensing errors.Spectrum sensing parameters are formulated by considering the PUEA into consideration. We show through simulation studies that taking PUEA into account, CR system achieveshigher data rates.

The rest of this paper is organized as follows. The system model and sensing parameters is presented in Section II. In SectionsIIIandIV we formulate the mutual interferences that introduced to the PU and CR. The problem of optimal resource allocation is presented in section V. Section VIprovides Simulation results and finally, in section VII,we conclude the paper.

II. System Model and Main Assumptions

Consider aMultibandcognitive radio (CR) system where one secondary user pair (transmitter and receiver) detects the presence or absence of a primary user (PU) over N subbands by measuring the energy of received signal over each subband. A PUEA is assumed to be in the environment and transmit signals similar to the primary signal to deceive CR system and prevent the secondary user from exploiting vacant bands. Each subband may be occupied by PU, PUEA and CR signals.

Let $\sqrt{P_n}x_{n,k}$ and $\sqrt{\hat{P}_n}\hat{x}_{n,k}$ be the signals transmitted by PU and PUEA over n-th subband and k-th time instant, and $y_{n,k}$ denotes the signal received at CR user through n-th subband and k-th time instant. Denoting the presence (absence) of the PU and PUEA by $H_1^{(n)}(H_0^{(n)})$ and$\hat{H}_1^{(n)}(\hat{H}_0^{(n)})$, respectively, there are four possible cases for expressing $y_{n,k}$, depending on the presence or absence of PU and PUEA. We represent these four cases by$S_1 = (H_1^{(n)}, \hat{H}_1^{(n)})$, $S_2 = (H_1^{(n)}, \hat{H}_0^{(n)})$,$S_3 = (H_0^{(n)}, \hat{H}_1^{(n)})$ and $S_4 = (H_0^{(n)}, \hat{H}_0^{(n)})$. In each state, $y_{n,k}$ is given as,

$$y_{n,k} = \begin{cases} \sqrt{P_n}x_{n,k}h_{n,k} + \sqrt{\hat{P}_n}\hat{x}_{n,k}\hat{h}_{n,k} + z_{n,k}, & \text{under} S_1 \\ \sqrt{P_n}x_{n,k}h_{n,k} + z_{n,k}, & \text{under} S_2 \\ \sqrt{\hat{P}_n}\hat{x}_{n,k}\hat{h}_{n,k} + z_{n,k}, & \text{under} S_3 \\ z_{n,k}, & \text{under} S_4 \end{cases} \quad (1)$$

where $z_{n,k}$ is the zero mean additive white Gaussian noise through n-th CR subband and in the k-th time instant, with the varianceσ_n^2. The coefficients$h_{n,k}$ and $\hat{h}_{n,k}$ are the channel gains in spectrum sensing phase, through n-th subband and k-th time instant, between PU and CR, and PUEA and CR, respectively.In this paper, we assume that the channel gains $|h_{n,k}|$ and $|\hat{h}_{n,k}|$ are distributed according to a Rayleigh distribution with parameters λ_n and $\hat{\lambda}_n$ and the PU and PUEA signals $x_{n,k}$ and $\hat{x}_{n,k}$ have known powersP_n and $\hat{P}_n$, respectively. For simplicity, we assume that $E\left\{|x_{n,k}|^2\right\} = E\left\{|\hat{x}_{n,k}|^2\right\} = 1$.

According to (1), $y_{n,k}$is a zero mean random variable with variance $\sigma_{j,n}^2$ under S_j for $j \in \{1,2,3,4\}$,where

$$\sigma_{1,n}^2 = P_n\lambda_n^2 + \hat{P}_n\hat{\lambda}_n{}^2 + \sigma_n^2$$
$$\sigma_{2,n}^2 = P_n\lambda_n^2 + \sigma_n^2$$
$$\sigma_{3,n}^2 = \hat{P}_n\hat{\lambda}_n{}^2 + \sigma_n^2$$
$$\sigma_{4,n}^2 = \sigma_n^2$$

To detect the PU, CR user performs energy detection over every subband.In energy detection phase, M samples of the energy of$y_{n,k}$ are summed during one detection interval,

$$Y_n = \sum_{k=1}^{M} |y_{n,k}|^2 \quad (2)$$

According to the *central limit theorem*, for large M, in each state,$Y_n$has a normal distribution with mean $E(Y_n)$ and variance $\mathrm{Var}(Y_n)$, where $E(Y_n)$ and $\mathrm{Var}(Y_n)$ is given by [12]

$$E(Y_n) = \begin{cases} M\left(P_n\lambda^2 + \hat{P}_n\hat{\lambda}^2 + \sigma_n^2\right), & \text{under} S_1 \\ M\left(P_n\lambda^2 + \sigma_n^2\right), & \text{under} S_2 \\ M\left(\hat{P}_n\hat{\lambda}^2 + \sigma_n^2\right), & \text{under} S_3 \\ M\sigma_n^2, & \text{under} S_4 \end{cases}$$

and

$$\mathrm{Var}(Y_n) = \begin{cases} 2M\sigma_n^2\left(2P_n\lambda^2 + 2\hat{P}_n\hat{\lambda}^2 + \sigma_n^2\right), & \text{under} S_1 \\ 2M\sigma_n^2\left(2P_n\lambda^2 + \sigma_n^2\right), & \text{under} S_2 \\ 2M\sigma_n^2\left(2\hat{P}_n\hat{\lambda}^2 + \sigma_n^2\right), & \text{under} S_3 \\ 2M\sigma_n^4, & \text{under} S_4 \end{cases}$$

The sensing system tries to classify the subbands into vacant and occupied subbands. This can be accomplished by comparing the measured energy in each subband with a predefined threshold γ_n. The threshold γ_n can be obtained from Neyman-Pearson criteria, where a constant false alarm rate is expected. The false alarm probability in the n-th subband can be formulated as

$$\begin{aligned} P_{fa}^{(n)} &= \Pr\left\{Y_n > \gamma_n | H_0^{(n)}\right\} \\ &= \Pr\left\{Y_n > \gamma_n | H_0^{(n)}, S_3\right\}\Pr\{S_3\} \\ &+ \Pr\left\{Y_n > \gamma_n | H_0^{(n)}, S_4\right\}\Pr\{S_4\} \\ &= \Pr\{Y_n > \gamma_n | S_3\}\Pr\{S_3\} + \Pr\{Y_n < \gamma_n | S_4\}\Pr\{S_4\} \\ &= \Pr\{S_3\}\int_{\gamma_n}^{\infty} f_Y(y|S_3)dy + \Pr\{S_4\}\int_{\gamma_n}^{\infty} f_Y(y|S_4)dy. \end{aligned}$$

It is assumed that the sensing system has identified set O of N_O subcarriers that are being used by the primary users. Also, a set V of N_V subcarriers have determined to free of PU signal.In this paper, we assume that the channel gain h_n^{ss} between the CR transmitter and CR receiver in the n-thsubcarrier is known perfectly at the CR transmitter. Further,we assume that mean and fading statistics of the channel gain $h_n^{sp}$are known. Asthe channels gains and noise are not known perfectly, interference can beguaranteed only in a statistical manner, i.e., the expectation of the mutual interference introducedto the PU would be below a tolerable threshold.

Depending on the presence or absence of PU and PUEA, in addition to the additive white Gaussian noise, the interference introduced to the CR network by PU and/or PUEA should be considered. Hence, the normalized transmission rate achieved in the n-th CR subband, can be written as

$$r_n = \log_2\left(1 + \frac{p_n|h_n^{ss}|^2}{U_n + \sigma_n^2}\right) \quad (3)$$

where r_n is the normalized transmission rate in the n-th subcarrier,p_n is the transmission power, σ_n^2 denotes the additive whiteGaussian noise (AWGN) variance, and $U_n$is thesummation of interference introduced by all subcarriers thatare occupied by PU and/or PUEA into the CR system in the n-th subband. Itis assumed that the CR user can estimate U_n. In Section IV, we formulate the average interference U_n. The average capacity in CR network, denoted by $\bar{R}$, can be formulated as

$$\bar{R} = \sum_{n=1}^{N} r_n = \sum_{n=1}^{N} \log_2\left(1 + \frac{p_n|h_n^{ss}|^2}{U_n + \sigma_n^2}\right) \quad (4)$$

III. INTERFERENCE INTRODUCED TO THE PU

We assume an underlay/overlay system in which the power is not only transmitted in subcarriers not occupied by PU users but also in subcarriers occupied by the PU users. Even when the CR only transmits in the overlay subcarriers, due to mutual interference, it still interferes with PU in adjacent bands. Hence, in this section, we try to formulate the mutual interferences introduced to the PU. For this end, we need to define parametersα_n and β_n as follows. These parameters defines the *Vacancy Decision Accuracy* and *Occupancy Decision Accuracy*, respectively. We have

$$\alpha_n = \Pr\left\{H_0^{(n)} \mid Y_n \le \gamma_n\right\}$$

From Bayes' law, we can write

$$\Pr\left\{H_0^{(n)} \mid Y_n \le \gamma_n\right\} = \frac{\Pr\left\{Y_n \le \gamma_n \mid H_0^{(n)}\right\}\Pr\left\{H_0^{(n)}\right\}}{\Pr\{Y_n \le \gamma_n\}}$$

where $\Pr\{Y_n \le \gamma_n\}$ is given in terms of false alarm and miss detection probabilities as

$$\begin{aligned}\Pr\{Y_n \le \gamma_n\} &= \Pr\left\{Y_n \le \gamma_n \mid H_0^{(n)}\right\}\Pr\left\{H_0^{(n)}\right\} \\ &\quad + \Pr\left\{Y_n \le \gamma_n \mid H_1^{(n)}\right\}\Pr\left\{H_1^{(n)}\right\} \\ &= \left(1 - P_{fa}^{(n)}\right)\Pr\left\{H_0^{(n)}\right\} + P_{md}^{(n)}\Pr\left\{H_1^{(n)}\right\}\end{aligned}$$

Hence,

$$\alpha_n = \frac{\left(1 - P_{fa}^{(n)}\right)\Pr\left\{H_0^{(n)}\right\}}{\left(1 - P_{fa}^{(n)}\right)\Pr\left\{H_0^{(n)}\right\} + P_{md}^{(n)}\Pr\left\{H_1^{(n)}\right\}}$$

In a similar way, it can easily be shown that

$$\begin{aligned}\beta_n &= \Pr\left\{H_1^{(n)} \mid Y_n > \gamma_n\right\} \\ &= \frac{\left(1 - P_{md}^{(n)}\right)\Pr\left\{H_1^{(n)}\right\}}{P_{fa}^{(n)}\Pr\left\{H_0^{(n)}\right\} + \left(1 - P_{md}^{(n)}\right)\Pr\left\{H_1^{(n)}\right\}}\end{aligned}$$

The legal CR transmission procedure over licensed subbands is due to the imposed interference introduced to the PU. So, the CR network should consider its interference to the PU, constantly. We denote the interference introduced by CR due to transmitting over the l-th subband to the n-th subband of PU receiver, by $I_{l\to n}$. Let $S_l(f)$ be the PSD of CR transmitted signal over l-th subband and h_l^{sp} be the channel gain through l-th subband between CR transmitter and PU receiver. So, $I_{l\to n}$ can be written as,

$$I_{l\to n} = \left|h_n^{sp}\right|^2 \int_{f_n-\frac{\Delta f}{2}}^{f_n+\frac{\Delta f}{2}} S_l(f - f_l)df \qquad (8)$$

where f_n and f_l are the frequency centers of subbands n and l, respectively. In this paper, we assume CR transmission is performed by ideal Nyquist pulse with the power of p_l in l-th subband.So, the PSD of l-th CR subcarrier can be written as,

$$S_l(f) = p_l\tau_s\left(\frac{\sin(\pi f\tau_s)}{\pi f\tau_s}\right)^2, \qquad (9)$$

where τ_s is the symbol duration. Then we can write,

$$I_{l\to n} = p_l\theta_{ln}, \qquad (10)$$

where

$$\theta_{ln} = \tau_s E\left\{\left|h_n^{sp}\right|^2\right\}\int_{f_n-\frac{\Delta f}{2}}^{f_n+\frac{\Delta f}{2}}\left(\frac{\sin(\pi(f - f_l)\tau_s)}{\pi(f - f_l)\tau_s}\right)^2 df \qquad (11)$$

The average interference introduced to the n-th subband of the PU is either due to the spectrum leakage of CR subcarriers existing in other subbands, or due to the CR subcarrier in the same subband, which can be written as follow,

$$I_n = \sum_{l\in V} I_{l\to n}\alpha_n + \sum_{l\in O} I_{l\to n}\beta_n \qquad (12)$$

From (10), we have

$$I_n = \sum_{l\in V} p_l\theta_{ln}\alpha_n + \sum_{l\in O} p_l\theta_{ln}\beta_n \qquad (13)$$

So, the total average interference introduced in PU by CR, denoted by $\bar{I}$, is given by

$$\bar{I} = \sum_{n=1}^{N} I_n = \sum_{n=1}^{N}\left(\sum_{l\in V} p_l\theta_{ln}\alpha_n + \sum_{l\in O} p_l\theta_{ln}\beta_n\right) \qquad (12)$$

As discussed, the CR user is allowed to transmit while the average interference$\bar{I}$ remains below a predefined tolerable threshold. In other words, $\bar{I} \le I_{th}$, where I_{th} is the total tolerable interference at the PU receiver.

IV. INTERFERENCE INTRODUCED BY PU AND PUEA SIGNAL TO THE SU SIGNAL

We assume that the power spectral density of the PU and PUEA signal is given by $S_{PU}(f)$ and $S_{PUEA}(f)$, respectively.

Hence, the interference introduced by the PU transmission over l-th subband to the CR over n-th subband, denoted by $U_{l\to n}$, can be expressed as,

$$U_{l\to n} = E\left\{\left|h_n^{(PS)}\right|^2\right\}\int_{f_n-\frac{\Delta f}{2}}^{f_n+\frac{\Delta f}{2}} S_{PU}(f - f_l)\mathrm{d}f \qquad (13)$$

where $h_n^{(PS)}$ is the channel gain between primary transmitter and secondary receiver through n-th subband.

Similarly, the interference introduced by the$l$-th subband of PUEA transmission to the n-th CR user subband, denoted by $V_{l\to n}$, is given as

$$V_{l\to n} = E\left\{\left|h_n^{(ES)}\right|^2\right\}\int_{f_n-\frac{\Delta f}{2}}^{f_n+\frac{\Delta f}{2}} S_{PUEA}(f - f_l)\mathrm{d}f \qquad (14)$$

where h_n^{ES} is the channel gain between PUEA and secondary receiver through n-th subband. Hence, the total average interference introduced to the n-th CR subband is obtained by averaging $U_{l\to n}$ and $V_{l\to n}$ over the subbands that PU and PUEA exist, respectively. So, we can write

$$\begin{aligned}U_n &= \sum_{n\in V} U_{l\to n}(1 - \alpha_n) + \sum_{n\in O} U_{l\to n}\beta_n \\ &\quad + \sum_{n=1}^{N} V_{l\to n}\Pr\left\{\hat{H}_1^{(n)}\right\}\end{aligned}$$

V. POWER ALLOCATION PROBLEM

In this section, we formulate the problem of power allocation in CR downlink to the CR subcarriers which may be present in every N licensed subbands.

Let Ω be the set of subbands that CR tries to transmit over this bands. We aim to maximize achievable data rate in CR network under constraints of imposed interference introduced to the PU and CR power budget. It is assumed that the CR network has a maximum transmit power budget of P_t. We also intend to solve the power allocation problem considering the average interference imposed to the total PU subbands remain below predefined thresholds.

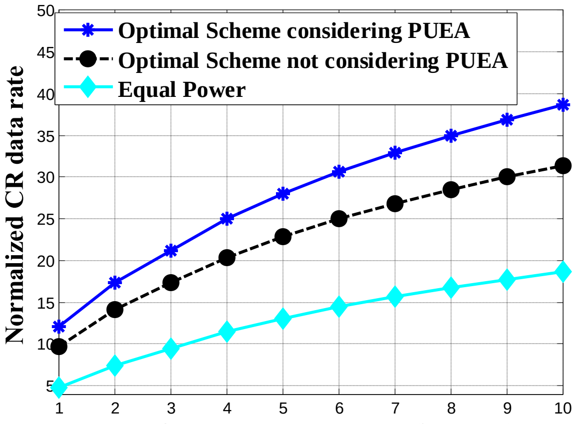

Fig. 1 CR data rate versus maximum tolerable interference introduced to the PU.

Our objective is to find the optimal powers $\{p_n\}_{n=1}^{N}$ which maximize the CR data rate while keeping the interference introduced to the PU below a predefined thresholdI_{th}. Hence, the related optimization problem can be written as

$$\max_{\boldsymbol{p}} \sum_{n=1}^{N} \log_2 \left(1 + \frac{|h_n^{ss}|^2 p_n}{\sigma_n^2 + U_n}\right) \qquad (15)$$

$$\text{subject to: } \sum_{n=1}^{N} \left(\sum_{l \in V} p_l \theta_{ln} \alpha_n + \sum_{l \in O} p_l \theta_{ln} \beta_n \right) \leq I_{th}$$

$$\sum_{n=1}^{N} p_n \leq P_t$$

$$p_n \geq 0, \quad \forall n \in \{1,2,\ldots,\mathrm{N}\}$$

It can easily prove that the optimization problem (15) is convex. So, form convex optimization theory, different methods can be used to obtain the optimal solution.

VI. SIMULATION RESULTS

We consider a multiband with 16 subbands where the subbands {1, 2, 6, 7, 11, 12, 15, 16} determined by the spectrum sensing to be free. In this section, we compared the optimal solution in which spectrum sensing errors and the presence of PUEA has been taken into consideration with the case where PUEA is not considered. Furthermore, we consider equal power allocation scheme in which maximum possible equal power is allocated to all CR subbands.

In Fig. 1, the average CR data rate $\bar{R}$ for various power allocation schemes is compared at different values of interference threshold I_{th}. It can be seen thatconsidering the PUEA and spectrum sensing errors into consideration, a higher data rate can be achieved.In Fig. 2, the average CR data rate $\bar{R}$ for various power allocation schemes is compared versus the vacancy decision accuracy α.

CONCLUSION

In this paper, the power allocation problem in a multiband CR system has been investigated in the presence of spectrum sensing errors and malicious users known as PUEA.Taking PUEA and spectrum sensing errors into consideration, we formulate the sensing parameters and achievable data rates of the CR system as well, the mutual interferences introduced to the CR and PU. Simulation results showed that theconsidering spectrum sensing errors and the PUEA, has a significantly higher data rate.

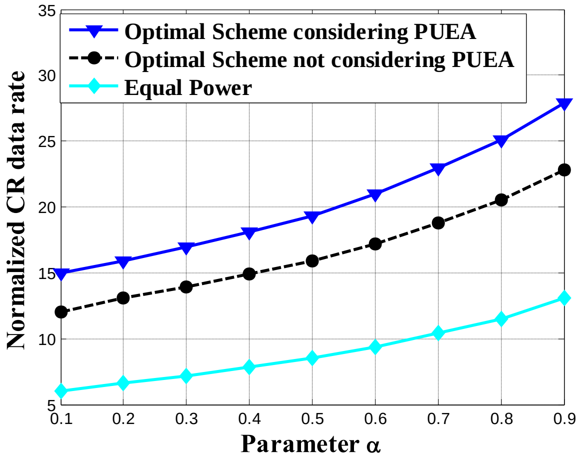

Fig. 2 CR user data rate versus Parameter α for optimal scheme considering and not considering the PUEA.

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