Research on Anti PUE Attack Based on CAF Spectrum and Repeated-Game

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Abstract. High imitation of primary user (PU) signal, primary user emulation (PUE) signal is difficulty for discrimination. First, a method based on cross ambiguity function (CAF) is proposed for determining PUE signal. For PUE signal different from PU signal in spatial but same in frequency in one sensing slot, the algorithm with two dimension search is reduced to one dimension search, having no inter-modulation signal influence. Moreover, for defending PUE attack (PUEA), a repeated game between malicious user (MU) and secondary user (SU) is formulated. By introducing credit discipline mechanism, the optimal strategies for both players are investigated. The stability of the strategies is analyzed with replicated dynamic equation, which indicates that the strategies are the final choice no matter what initial strategies they choose. Simulation results demonstrate that the method is effective for discriminating and defending PUEA in terms of lower computation, higher detection probability and greater payoff.

Keywords: PUE attack · Cross ambiguity function · Repeated game
Credit discipline mechanism · Replicated dynamic equation

1 Introduction

Nowadays, spectrum resource available cannot meet the needs of high development of communication. Cognitive radio (CR) is an technology for making dynamic spectrum access (DSA) by letting unlicensed user use white space of licensed bands. However, security vulnerabilities in cognitive radio systems is an key problem [1–5]. One specific type of attack is PUE attack which has been studied in many works. Emulating the characteristic of PU signals, PUEA signals deliberately send by MU during the sensing slot make SU produce wrong estimation of spectrum occupation. PUEA can be divided into two types, one of which occupies the attacked spectrum for own used called selfish PUE attack and the other is malicious PUE attack who wants to prevent the network working normally. Both of them would degrade the performance of CR system [6–10].

The existing works on PUEA are mainly grouped into attack detection and attack defense. The detection approaches are classified into two types: location-based method [11–13] and signal feature-based method [14–16]. Location based method is working

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based on PU being a TV user, the location of which is known in a prior and fixed during the sensing time. By positioning the transmitter, it can decide whether the received signal is PUE attack signal or not. Signal feature-based method available is working for each signal has the unique characteristics due to the special transmitter and propagation path. The received signal having different features would not be considered as PU signal. The defense method is that SU intelligently chooses the spectrum bands to sense and access according to Nash equilibrium strategy of the game [17–21]. Since the DSA mechanism demanding that SU must periodically sense the spectrum bands and incur no violation of primary users, this work mainly investigates the optimal actions for both of the players under the circumstance of PU absenting.

The main work is formulated as follows: First, considering PU and MU separated in spatial, an estimation of Doppler frequency is made for PUEA detection by CAF spectrum. Then, since the competition between MU and SU is repeated and lasts a long time, formulation PUE attack and defense as a repeated game. By introducing credit discipline mechanism, the optimal strategies for both players are obtained. Also, the stability of the optimal strategy is analyzed by using replicated dynamic equation to assure that is the final strategy they choose for higher payoff. Finally, simulation results are presented to confirm the conclusion.

2 System Model

The study is working for IEEE 802.22 networks. Before the analysis, the specific assumptions need to be made as given below.

(1) PU is assume to be a TV broadcast Tower placed at fix location.
(2) SU and MU are mobile users placed at random location. It is assumed that no changes (including frequency and location) happen to PU and MU during the sensing slot.
(3) SU has the ability of self positioning [22].
(4) The working time for SU is consist of discrete periods, one of which is divided into sensing slot and transmission slot. Without loss of generality, SU performs spectrum sensing and MU launches PUE attack signal all in sensing slot. If no PU signal presents, SU transmits signal or if MU grabs the spectrum band successfully, MU transmits signal in the transmission slot.

Consider detection problem as a hypothesis testing problem

$$u(t) = \begin{cases} n(t) & \mathrm{H}_0 \\ A_M x_M(t) + n(t) & \mathrm{H}_1 \\ A_P x_P(t) + n(t) & \mathrm{H}_2 \\ A_P x_P(t) + A_M x_M(t) + n(t) & \mathrm{H}_3 \end{cases} \tag{1}$$

where $n(t)$ is a white Gaussian noise of unknown power. $A_M x_M(t)$ and $A_P x_P(t)$ corresponds to PUE signal and PU signal SU received.

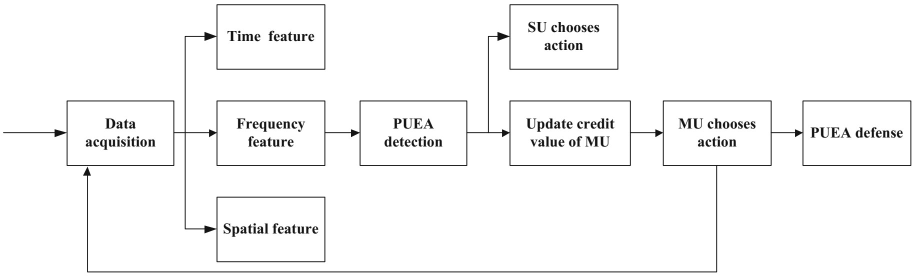

Fig. 1. Architecture of PUEA defense

Architecture of our proposed method is shown in Fig. 1. The main work is divided into two parts:

(1) PUEA detection. Assume that the signals SU received are composed of simultaneous multi signals with uncertain parameters. The signals are firstly separated by FFT filter Banks in frequency domain. Since PUE signal highly mimic PU signal, the frequency of PUE signal is same with PU's. Obviously, it is difficult for separating PUE signal from PU signal in frequency domain. Owning to different in location but same in working time of PU and MU, CAF spectrum derived by mobile SU is effective for discriminate PUE signal from PU signal.

(2) PUEA defense. After analyzing payoffs of SU and MU in one stage of the game, it is found that equilibrium strategy is not the optimal strategy. Since the game lasts over a long period of time and each stage of game is of same structure, repeated game is formulated. By introducing credit discipline mechanism, the optimal strategies for both of players are derived. The credit value of MU minus one if attack is detected. Given that the credit value is lower than the threshold, punishment such as gain smaller benefits despite no attack signal emitted will be put on MU in the penalty slot. Thereby, comparing with the payoffs achieved in short time, MU prefers the long payoffs, which determine the optimal strategic tuples. The stability of the strategies is proved by replicated dynamic equation, which is used for guaranteeing the maximum efficiency of system.

3 PUEA Detection

3.1 System Description

This section details the mathematical proof of the proposed method (see Fig. 2). At first, the signal frequency estimation is performed by fast Fourier transform (FFT) at O. Then, the detection test is carried on each point of the frequency representation. The test over a certain threshold represents the presence of a signal. As mentioned before, the fixed frequency of PU signal is known in prior and PUE signal effectively emulates the characteristics of PU signal such as frequency. The frequency equals to PU frequency, which the test is over the threshold, represents that PU or PUE transmission has worked. In the next section, we will determine the type of transmitter.

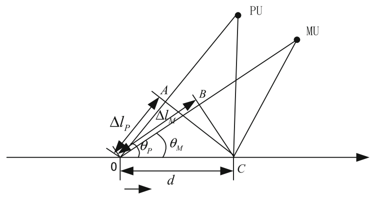

Fig. 2. PUEA detection system layout

Since the signal frequency varies slightly for the movement of SU, it is possible to discriminate PUE from PU by the Doppler frequency. Let v denotes the velocity of SU, θ_P and θ_M denote the yaw angle from PU and MU. $\Delta\varphi_P$ denotes the phase difference between O and A, which is the same with phase difference between O and C for PU signal. $\Delta\varphi_M$ is declared as the phase difference between O and B for MU signal. They can be expressed respectively as

$$\Delta\varphi_P = 2\pi\Delta l_P/\lambda = 2\pi v\Delta t \cos\theta_P/\lambda \tag{2}$$

$$\Delta\varphi_M = 2\pi\Delta l_M/\lambda = 2\pi v\Delta t \cos\theta_M/\lambda \tag{3}$$

Δt denotes the time for SU moving from O to C and $\Delta l_P, \Delta l_M, d$ all represent distance. Then, the Doppler frequency of the PU signal and PUE signal are shown respectively as

$$f_{dP} = \Delta\varphi_P/(2\pi\Delta t) = v\cos\theta_P/\lambda \tag{4}$$

$$f_{dM} = \Delta\varphi_M/(2\pi\Delta t) = v\cos\theta_M/\lambda \tag{5}$$

For PU's fix location, f_{dP} can be obtained in advance. The received signals are compared with PU signal in terms of time, frequency and Doppler frequency. The signal who has the same time duration and frequency with PU signal but different in Doppler frequency would be judged as PUE attack signal. Obviously, CAF spectrum works on the time difference and frequency difference representation and can be implemented effectively for PUE detection.

3.2 CAF Spectrum Representation and PUEA Detection

The CAF spectrum is defined as

$$A(\tau, f_d) = \int_0^T C_{uu}^{(n)}(\tau, t)e^{j2\pi f_d t}dt \tag{6}$$

Where $C_{uu}^{(n)}$ is the nth order cumulant. For the sake of low computation, n is set to be 2, the express becomes $C_{uu}^{(2)} = u_1(t)u_2^*(t-\tau)$. T refers to the integration length. $u_1(t)$ represents the signal SU received at O.

$$u_1(t) = s_1(t) + n_1(t) = \alpha A_P x_P(t) + \beta A_M x_M(t) + n_1(t) \tag{7}$$

After SU moving to the C, the signal obtained as follows:

$$\begin{aligned} u_2(t) &= s_2(t) + n_2(t) \\ &= \alpha B_P x_P(t + \tau_P) e^{j2\pi f_{dP}(t+\tau_P)} + \beta B_M x_M(t + \tau_M) e^{j2\pi f_{dM}(t+\tau_M)} + n_2(t) \end{aligned} \tag{8}$$

Where τ_P and τ_M are respectively the duration time of PU signal and PUE signal and assume $\tau_P \approx \tau_M \leq \tau_S < T_0$. Let τ_S be the time difference defined by SU moving from O to C and T_0 be the time of sensing slot. f_{dP} and f_{dM} are the Doppler frequency of PU signal and PUE signal due to the movement of SU. $n_1(t)$ and $n_2(t)$ are real-valued zero-mean white Gaussian noise. Index α and β refer to the probability of PU signal and PUE signal present. As PUE signal and PU signal exhibit the same time and frequency arrangement, $u_1(t)$ is rewritten as follow $u_1(t) \approx (A_P + A_M)x_P(t) + n_1(t)$. For no inter-modulation signals exist in $A(\tau, f_d)$, it is just the method for performing signal discrimination. Then, the duration time and Doppler frequency can be estimated using separate optimizations as

$$\hat{\tau} = \arg\max_{\tau} \int_0^T u_1(t) u_2^*(t - \tau) e^{j2\pi f_{dP} t} dt \tag{9}$$

$$\hat{f}_d = \arg\max_{f_d} \int_0^T u_1(t) u_2^*(t - \hat{\tau}) e^{j2\pi f_d t} dt \tag{10}$$

The signal detection based on CAF spectrum is mainly working in three steps:

(1) Detection in frequency. First, filter the received signal by FFT. Then, the FFT outputs of the considered channel i having the same frequency as PU's is tested with the threshold. If lower, the channel is considered has no signal output, namely H_0. If higher, the signal is considered to be present and judged as similar PU signal.
(2) Detection in time. The CAF spectrum can be analytical computed by the signals respectively received by SU at O and C. As f_{dP} is known in prior, the two dimensional research in time and Doppler frequency reduce to one dimensional research in time, the method of which is considered to be more efficient. The signal is determined as PUE signal for no dominate peak corresponding to the f_{dP} in CAF spectrum but having the same frequency with PU's proved by the output of FFT channel, namely H_1. If one dominate peak corresponding to the f_{dP} can be seen, which can be concluded that the signals are consist of at least PU signal.
(3) Detection in spatial. Determine the duration time of the signals from the dominate peak in time. For simultaneous signals, perform the search for the Doppler frequency that is included in the same duration time. The estimated Doppler frequency derived from dominate peak of new search is f_{dM}, namely H_3. In contrast, no peak presence demonstrates the signal is only PU signal, namely H_2, when one dominate peak corresponding to the f_{dP} has been seen.

Procedure 1 Procedure of Setting Threshold for Signal Detection

(1) In the free spectrum band, group the noise-only samples in descending order.

(2) Sample pairs are obtained by collecting first N_0 samples from the ordered samples, which is selected as threshold $T(n) = u'(n)$, and defining local PFA by $P_{fa}(n) = n/N_1$, $n = 1,2,\ldots,N_0$.

(3) By using CAF, the smoothed spectrogram obtained by non coherent integration in time and Doppler frequency is used to realize the signal detection according to above work. Using the appropriate Gaussian relation between threshold and the probability of false alarm P_{fa}, the threshold model is obtained as $T = \hat{k}_a\sqrt{-\ln P_{fa}} + k_b$.

(4) The least square method performs properly on sample pairs, based on which the linear relationship between $\sqrt{-\ln P_{fa}}$ and T is shown.

4 Anti PUE Scheme

4.1 Nash Equilibrium Analysis for Single Stage

Table 1. Payoff matrix of single stage of the game

PU off	Attack	No attack
Switch	$-c_s$, $R_c + G - c_m + R_f$	$-c_s$, R_f
Stay	G, $R_c - c_m + R_f$	G, R_f

PUEA is formulated as a dynamic game between SU and MU, who choose its action respectively from the strategy space A_S = {Switch, Stay} and A_M = {Attack, No Attack}. The payoff matrix of both players as shown in Table 1 and the notation that will be used listed in Table 2. The game has unique pure strategy Nash equilibrium as {Attack, Stay}, which is not optimal for resisting attack. By introducing credit discipline mechanism, the optimal strategy {No Attack, Stay} for defending against PUE is proposed based on repeated multistage game between SU and MU.

4.2 Repeated Game Model

It is noted that MU gains access to the spectrum band exclusively by launching PUE signal, which is severely degrade network performance. Therefore we introduce credit discipline mechanism for defending against PUEA, based on which MU adjust strategy as the credit value refers to the degree to gain the spectrum access. We consider the working period for MU to be divided by normal slot and penalty slot, and set a credit for every MU. The credit value is directly influenced by his action during the sensing time. The credit value goes down each time the MU launches attack. Normal slot represents MU can receive a spectrum gain from using free spectrum band because the credit value of MU is high. When the credit value is lower than the threshold T_C, MU is penalized for prohibiting from using the free spectrum band in the penalty slot.

Based on the game model presented before, we now consider PUEA defending as a multistage game. Assume that PU is absent, MU launches attack for every single stage leading the credit value of MU goes from R_0 down to T_C. We denote R_0 as the initial value of credit. In such case, the payoff for MU related with attack is $R_c - c_m + R_f$ during the normal slot. In penalty slot, the MU would suffer a penalty resulting in a payoff $-R_f$ when the credit value is lower than T_C. The total payoff associated with always attack and always no attack respectively expressed as

$$R_A = (R_c - c_m + R_f)R_0 + (-R_f)\frac{\delta(1-\delta^K)}{1-\delta} \quad (11)$$

$$R_{NA} = R_f\left(R_0 + \frac{\delta(1-\delta^K)}{1-\delta}\right) \quad (12)$$

The payoff of attack is more than no attack in a single stage of game if $-R_f < R_f < R_c - c_m + R_f$ is satisfied. When it is true, the MU would be willing to launch attack which is the driving force behind. However, from the perspective of competing over a long period, MU is unwilling to attack if $R_A < R_{NA}$ exists because the overall gain attained from no attack is greater. Such that penalize factor K should satisfy the following constraints

$$\frac{\delta(1-\delta^K)}{1-\delta} > \frac{(R_c - c_m)R_0}{2R_f}. \quad (13)$$

Table 2. Notations

Notation	Explanation
G	Indirect Attack gain for MU due to SU mistakenly interfere with PU
R_f	Gain for MU received from other available spectrum band
c_m	Attack cost
c_s	Switching cost
R_c	Indirect Attack gain for MU for SU consuming energy to discriminating PUEA
δ	Discount value
K	Penalty time
R_0	Initial credit value
T_C	Threshold for credit value

The larger K is, the more loss is gained due to the long time for prohibited from using the free spectrum band. Thus, no attack is the optimal choice for MU such that more benefits can be obtained by MU with minimum costs. That is, if R_0 is too small, the MU may be penalized mistakenly for making wrong decisions (false alarm and misdetection). If R_0 is too large, the MU still willing to chose attack for the penalty mechanism not working effectively.

4.3 Optimal Strategy Stability Analysis

Since the pure-strategy equilibrium obtained by repeated game would not provide procession for dynamic competition, we introduce the evolution game model and replicated dynamic equation to show the strategies evolution and the stability analysis. Let the PU absent, the total payoff for both players in multistage game as shown in Table 3.

A PUEA is launched while the SU chooses stay the band where it is because SU successfully discriminate PUE from PU. Let the credit threshold T_C be zero. The total payoff regarding to always attack for MU and always stay for SU are respectively shown as

$$R_{A2} = R_A = \left(R_c - c_m + R_f\right)R_0 + \sum_{k=1}^{K} \delta^k\left(-R_f\right) \tag{14}$$

$$R_{St1} = GR_0 + \sum_{k=1}^{K} \delta^k (R - c_s). \tag{15}$$

Under the same circumstance, SU vacated the spectrum band and switch to a different free band as SU mistakes the PUE. Thus, MU attacks successfully resulting in the total payoff for MU is given by

$$R_{A1} = \left(R_c + G - c_m + R_f\right)R_0 + \sum_{k=1}^{K} \delta^k\left(R_c + G - c_m + R_f\right). \tag{16}$$

The total payoff for SU relating to stay strategy is given by

$$R_{Sw1} = (-c_s)R_0 + \sum_{k=1}^{K} \delta^k(-c_s) \tag{17}$$

Table 3. Total payoff matrix of multistage game

PU off	Attack	No attack
Switch	$R_{Sw1},\ R_{A1}$	$R_{Sw2},\ R_{NA1}$
Stay	$R_{St1},\ R_{A2},$	R_{St2}, R_{NA2}

In case of no attack happening, SU falsely detects the PUE and chooses switch as the strategy. The total payoff for SU and MU regarding strategic tuples {Switch, No Attack} are given by

$$R_{Sw2} = (-c_s)R_0 + \sum_{k=1}^{K} \delta^k(-c_s) \tag{18}$$

$$R_{NA1} = R_f R_0 + \sum_{k=1}^{K} \delta^k R_f. \tag{19}$$

Supposed that no attack occurs, SU correctly detects the PUE and chooses stay the band where the SU is. The total payoff for SU and MU regarding strategic tuples {Stay, No Attack} are given by

$$R_{NA2} = R_{NA} = R_f R_0 + \sum_{k=1}^{K} \delta^k R_f \tag{20}$$

$$R_{St2} = GR_0 + \sum_{k=1}^{K} \delta^k G. \tag{21}$$

Let x be the ratio of number of attack to the total stage of repeated game. $1 - x$ denotes the percentage of no attack. Similar, let y be the ratio of number of switch to the total stage. $1 - y$ denotes the percentage of stay. The expected payoff for switch strategy and stay strategy for SU respectively are expressed by

$$U_{ssw} = xR_{Sw1} + (1 - x)R_{Sw2} \tag{22}$$

$$U_{sst} = xR_{St1} + (1 - x)R_{St2}. \tag{23}$$

The total expected payoff for SU is given by

$$\overline{U}_{SU} = yU_{ssw} + (1 - y)U_{sst}. \tag{24}$$

The replicated dynamic equation for SU is given by

$$F_{SU}(y) = y\left(U_{ssw} - \overline{U}_{SU}\right) = y(1 - y)(U_{ssw} - U_{sst}). \tag{25}$$

(1) When $U_{ssw} = U_{sst}$, any $y \in [0, 1]$ is said to be equilibrium by imposing $F_{SU}(y) = 0$.
(2) When $U_{MA} \neq U_{MNA}$, from equilibrium $y = 0$ to $y = 1$, only $y^* = 0$ can be determined as evolution stable strategy (ESS), because $F'_{MU}(y = 0) = -(U_{ssw} - U_{sst}) < 0$ exists. For $U_{ssw} < U_{sst}$, we have constraints

$$R_{St1} = R_{St2} > R_{Sw2} = R_{Sw1}. \tag{26}$$

Using the same logic, we derive the expected payoffs for attack strategy and no attack strategy for MU expressed respectively as

$$U_A = yR_{A1} + (1 - y)R_{A2} \tag{27}$$

$$U_{NA} = yR_{NA1} + (1 - y)R_{NA2}. \tag{28}$$

The total expect payoff for MU is given by

$$\overline{U}_{MU} = xU_{MA} + (1 - x)U_{NA}. \tag{29}$$

The replicated dynamic equation for MU is derived as follows:

$$F_{MU}(x) = x\left(U_A - \overline{U}_{MU}\right) = x(1 - x)(U_A - U_{NA}). \tag{30}$$

If $U_A = U_{NA}$, any $x \in [0, 1]$ would be equilibrium according to $F_{MU}(x) = 0$. When $U_A \neq U_{NA}$ exists, both $x = 0$ and $x = 1$ are equilibrium. For $y^* = 0$ is ESS proved before, it is obvious that $R_A < R_{NA}$. Thus, we have $U_A < U_{NA}$, and in this case $x^* = 0$ would be ESS.

Based on the ESS analysis of evolution game, we can concluded that no matter what initial state both players are working on, MU and SU will finally choose the optimal strategic tuples {No Attack, Stay} based on the proposed game model.

5 Results and Discussion

5.1 Simulation of CAF Spectrum

We now only consider the case that PU is present who has priority license for the spectrum, SU must vacant the spectrum when PU is returned. We have blurred signal with a Gaussian centered white noise such that the SNR is 10 dB. The sampling rate is 330 Hz. In the Fig. 3(a) and (b), CAF spectrum is shown for estimating duration time and Doppler frequency based on peak detection in the presence of noise. It can be observed that the estimator is a good choice for depicting the composition of the signal and time –Doppler frequency structure for PUE detection.

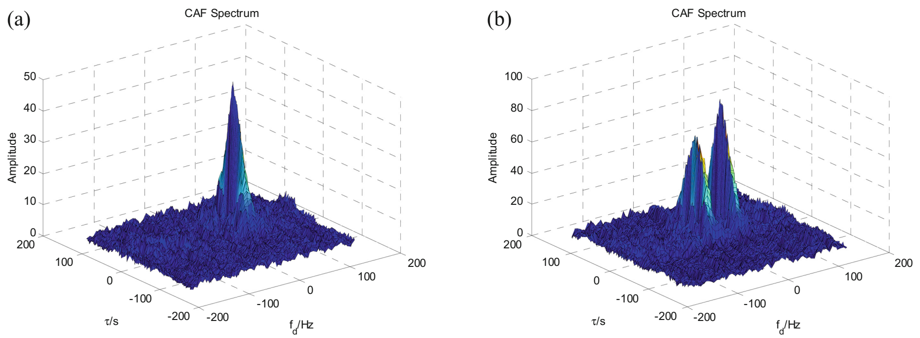

Fig. 3. (a) CAF spectrum for one PU signal ($f_{dP} = 40$, $\tau_S = 15T_s$), (b) CAF spectrum for simultaneous multi-signals ($f_{dP} = 40, f_{dM} = -10, \tau_S = 20T_s$)

5.2 Simulation for Constant False Alarm Rate (CFAR) Detection

For each value N, the threshold corresponding to every non coherent cumulative spectrum is obtained by the proposed method. In Fig. 4(a), the threshold of the detector increases as N increases. For signals with a Gaussian centered white noise, the threshold can become lower since the SNR is greater as shown in Fig. 4(b).

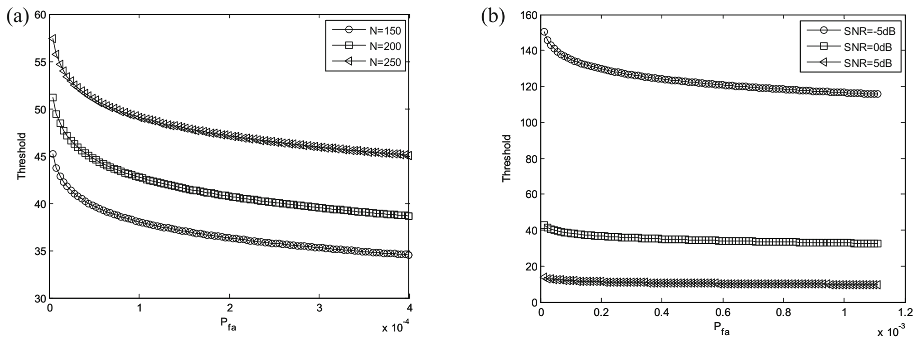

Fig. 4. (a) Threshold estimation versus P_{fa} for selected values of SNR = 0 dB obtained by varying N to take the values: 150, 200, 250, (b) Threshold estimation versus P_{fa} for selected values of $N = 150$ obtained by varying SNR to take the values: −5 dB, 0 dB, 5 dB

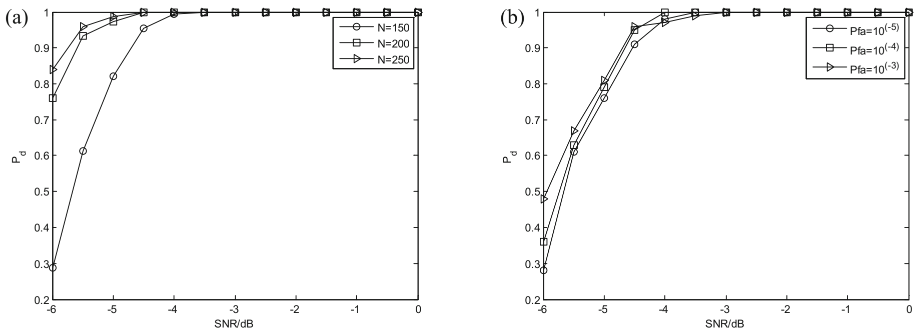

Fig. 5. (a) P_d estimation versus SNR obtained by varying N to take the values: 150, 200, 250, (b) P_d estimation versus SNR for selected values of $N = 150$ obtained by varying P_{fa} to take the values: $10^{(-5)}$, $10^{(-4)}$, $10^{(-3)}$

In Fig. 5, we show the probability of detection as a function of SNR, T and N. We use the system configuration which has different samples N and different T (as different P_{fa}). As can be noticed, the signals are properly detected as the SNR increases. The probability of detection approaches 100% for SNRs above 0 dB.

5.3 Simulation of Repeated Game with Credit Discipline Mechanism

The parameters satisfied for the constraints are: $R_c = 110$, $c_m = 60$, $R_f = 90$, $G = 80$, $c_s = 50$, $R = 100$, $K = 50$, $T_C = 0$. Figure 6 shows the attack probability versus different δ. We observe that the attack probability decreases as δ increases or R_0 decreases although the attacker retards this trend. As the repeated game evolves, we observe that penalty mechanism yields attack probability degradation and slightly better performance in security for the system.

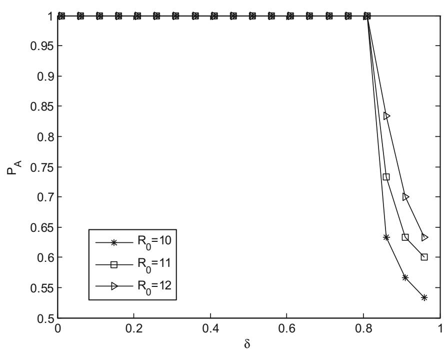

Fig. 6. The distribution of attack probability versus δ obtained by varying R_0 to take the values: 10, 11, 12

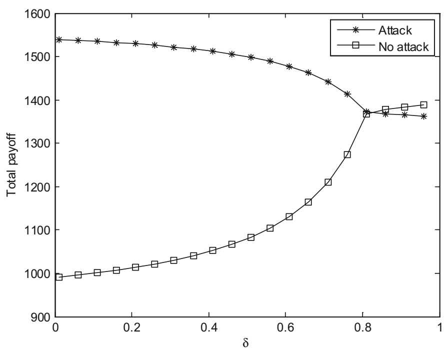

Fig. 7. The respectively total payoffs of MU choosing attack and no attack in one working time

Figure 7 shows the expected payoff of MU with the δ varying between 0 and 1. The curves are plotted corresponding to the procession for dynamic competition. With δ increasing, the payoff of attack is decreasing and no attack is increasing. When δ is above 0.8, MU is willing to choose no attack as optimal strategy instead of attack for $R_{NA} > R_A$ satisfied. And that is corresponding to the point $P_A < 1$ in Fig. 6.

6 Conclusion

PUEA signal emulates the characteristics of PU signal to obtain exclusive spectrum usage, which seriously degrades the performance of cognitive radio systems. Since PUE signal is same with PU signal in time and frequency but in spatial, a detection method based on CAF spectrum received by mobile SU is presented. For thwart PUEA, the optimal strategies for both players are studied. By incorporating credit discipline mechanism, MU would rather choose no attack as dominant strategy than attack by comparing the short payoff with long payoff during the repeated game. Under the circumstance of PU absent, the stability of dominant strategic tuples {No Attack, Stay} for MU and SU is analyzed. Thereby, both players would work in policy-abiding for larger payoffs in the long term. Simulation results show that the method is effective for defense PUEA and the proposed system is proved to have a more efficient and flexible spectrum assignment.

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