Strategy Analysis of an Evolutionary Spectrum Sensing Game*

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Abstract. Evolutionary game has been shown to greatly improve the spectrum sensing performance in cognitive radio. However, as selfish users are shortsighted for the long-term profits, they are not willing to collaborate to sense. In this paper, we propose an evolutionary spectrum sensing game to improve the long-term spectrum utilization. The new spectrum sensing model takes advantage of the long-term effect of the future actions on the current actions by using the concept of present value (PV) in repeated game. The collaboration conditions of two strategies, i.e., tit-for-tat and grim strategy are discussed. It is proved that the grim strategy can enhance secondary users' sensing positivity greatly, and so is the overall spectrum efficiency. Finally these new developments are illustrated in our experiments.

Keywords: Cognitive radio, evolutionary game, present value, spectrum sensing.

1 Introduction

Cognitive radio (CR) is a dynamic spectrum access soft technology [1], which means that secondary users (SUs) can identify whether the licensed spectrum is empty or not by spectrum sensing. If primary users (PUs) are not using the licensed spectrum, the SUs can utilize this vacant spectrum to increase the throughput of CR to its full potential. Game theory provides a theoretical framework that studies the process of how to cooperatively sense the licensed spectrum, which has attracted much attention recently [1--9].

In [2--7], it has been shown that the performance of spectrum sensing can be improved through spectrum sensing game modeling. In [2], light weight cooperation in sensing based on hard decisions was proposed to reduce the sensitivity requirement. It was shown in [3] that cooperative sensing could reduce the detection time of the PU and increase the overall agility. How to choose proper SUs for

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cooperation was investigated in [4]. The design of sensing slot duration to maximize SUs' throughput under certain constraints was studied by [5]. Two energy-based cooperative detection methods using weighted combining were proposed in [6]. The spatial diversity was introduced in [7] to improve spectrum sensing capabilities of centralized cognitive radio networks. The main reason is that the time a SU spent on spectrum sensing can be reduced greatly by sharing sensing results. Recently it was verified in [8, 9] that, the proposed evolutionary framework can achieve a higher throughput than the case where SUs sense individually without cooperation. Among these developments, a fully cooperative scenario is assumed that all SUs voluntarily cooperate to sense and share the sensing results.

However, not all SUs are willing to share their results. The spectrum sensing game, by its very nature is non-cooperative. Given a required detection probability to protect the PU from interference, SUs are willing to sense the licensed spectrum for a higher immediate throughput. For SUs who do not take part in sensing, they can overhear the sensing results and have more time for their own data transmission. If none of them take time to sense the licensed spectrum, all of the users (include the PU) would not get a higher throughput than it obtained by themselves. On the contrary, even if all users succeed in cooperating to sense, the licensed spectrum sharing may be unable to complement the cost of sensing. Therefore, instead of seeking the current maximization of payoffs, SUs need to predict the long-term payoff according to different strategies.

In this paper, we utilize the concept of present value (PV) in repeated game [10] to describe the long-term effect on the current actions from the future actions. The payoffs of SUs are PVs of future possible throughputs, rather than the immediate throughputs. We establish it as an evolutionary spectrum sensing game (ESSG). Two common strategies, i.e., tit-for-tat and grim strategy are discussed. It is proved that the grim strategy can enhance SUs' sensing positivity greatly, and so is the overall spectrum efficiency. Our main contributions are divided to three aspects as follows.

(i) To authors' best knowledge, this is the first to propose ESSG by use of the concept of PV.

(ii) The conditions of cooperation using the tit-for-tat strategy and the grim trigger strategy in ESSG are provided. The grim trigger strategy is tested as a suitable strategy for cooperation in ESSG.

(iii) Our model is tested with a satisfactory performance.

The remainder of the paper is organized as follows. The spectrum sensing model of CR is introduced in Section 2. In Sections 3, ESSG is proposed, where the strategy analysis are provided for two strategies, i.e., tit-for-tat and grim strategy. Simulation and performance is discussed in Section 4. Finally Section 5 concludes this paper and provides some future works.

2 Spectrum Sensing Model

Consider a CR network with a PU and K SUs, where each SU can take spectrum sensing and sharing, and data transmission. The licensed spectrum is divided into K

sub bands, and each SU operates exclusively in one of the K sub bands when the PU is absent. The transmission time is slotted into intervals of length T_s. Once the PU become active, SUs within their transmission ranges can sense the PU jointly.

The received signal $r(t)$ of a SU can be expressed by

$$r(t) = \begin{cases} hs(t) + \omega(t), H_1, \\ \omega(t), H_0. \end{cases} \tag{1}$$

where the hypotheses H_1, H_0 denotes the PU is present or not. The channel gain is h from the PU to SUs; $s(t)$ is the signal from the PU, which is assumed to be an i.i.d. random process with zero mean and σ_s^2 variance; and $\omega(t)$ is an additive circularly symmetric Gaussian noise with zero mean and σ_ω^2 variance. $s(t)$ and $\omega(t)$ are assumed to be independent.

The spectrum is sensed in a SU by use of an energy detector [11]. The test statistics $T(r)$ is defined as

$$T(r) = \frac{1}{N}\sum_{t=1}^{N}|r(t)|^2 \tag{2}$$

where N is the number of received samples.

Assume the PU performs a complex PSK signal, the probability density function (PDF) of $T(r)$ can be approximated by $N\left(\sigma_\omega^2, \frac{\sigma_\omega^4}{N}\right)$ and $N\left((\gamma+1)\sigma_\omega^2, \frac{(2\gamma+1)\sigma_\omega^4}{N}\right)$ under H_0, H_1 respectively, where $\gamma = \frac{|h|^2\sigma_s^2}{\sigma_\omega^2}$ is the received signal-to-noise ratio (SNR) of the PU under H_1.

Definition 1. [8] The probability of detecting the presence of the PU under H_1 is defined as the detection probability P_d; the probability of detecting the presence of the PU under H_0 is defined as the false alarm probability P_f.

$$P_d(\lambda) = \frac{1}{2}erfc\left(\left(\frac{\lambda}{\sigma_\omega^2} - \gamma - 1\right)\sqrt{\frac{N}{2(2\gamma+1)}}\right) \tag{3}$$

$$P_f(\lambda) = \frac{1}{2}erfc\left(\left(\frac{\lambda}{\sigma_\omega^2} - 1\right)\sqrt{\frac{N}{2}}\right) \tag{4}$$

where λ is the threshold of the energy detector and $erfc(\cdot)$ is the complementary error function. □

Given a target detection probability $\bar{P}_d$, the threshold λ can be derived and the false alarm probability P_f can be written as

$$P_f(\bar{P}_d, N, \gamma) = \frac{1}{2}erfc\left(\sqrt{(2\gamma+1)}erfc^{-1}(1-2\bar{P}_d) + \gamma\sqrt{\frac{N}{2}}\right) \tag{5}$$

When a SU is sensing the licensed spectrum, its data transmission cannot be performed. If the sampling frequency is f_s and the frame duration is T_s, the time duration for data transmission can be represented by $T_s - \delta(N)$, where $\delta(N) = \frac{N}{fs}$ is the time spent in sensing spectrum.

Definition 2. [9] When the PU is absent, in those time slots where no false alarm is generated, the average throughput of a SU is defined as R_{H_0}; when the PU is present, but not detected by SUs, the average throughput of a SU is defined as R_{H_1}.

$$R_{H_0} = \frac{T_s - \delta(N)}{T_s}(1 - P_f)C_{H_0} \tag{6}$$

$$R_{H_1} = \frac{T_s - \delta(N)}{T_s}(1 - P_d)C_{H_1} \tag{7}$$

where C_{H_1}, C_{H_0} is the data rate of the SU under H_1 and H_0 respectively. □

If the probability of the absence of the primary user is denoted by P_{H_0}, the total throughput of a SU is represented by

$$R(N) = P_{H_0}R_{H_0}(N) + (1 - P_{H_0})R_{H_1}(N) \tag{8}$$

In dynamic spectrum access, the target detection probability $\bar{P}_d$ required by the PU is very close to 1. Due to the interference from the PU to SUs, the second term can be omitted because it is much smaller than the first term.

$$\tilde{R}(N) \approx P_{H_0}R_{H_0}(N) = \frac{T_s - \delta(N)}{T_s}(1 - P_f)P_{H_0}C_{H_0} \tag{9}$$

Before data transmission, the SUs need to sense the PU's activity. Two kinds of actions can be made by the SUs. The first is that the SUs can cooperate to sense and share the results. The opposite is not to serve for the common goal and act by maximizing own throughputs selfishly. Before take such actions, there are always a cooperative strategy and a defecting strategy. SUs can be labeled, according to their choice of strategy, as either cooperators or defectors.

3 Evolutionary Spectrum Sensing Game

In evolutionary spectrum sensing game (ESSG), actions of the SUs are based on the belief when the game is played repeatedly. In [8, 9], the mixed strategies may change between generations based on the comparison between the current payoffs for SUs and the average payoff. In our ESSG, we use the concept of present value (PV) in repeated game to describe the long-term effect of the future actions on the current actions. The collaboration conditions of two strategies, i.e., tit-for-tat and grim strategy are discussed. It is proved that the strategy of grim strategy can enhance SUs' sensing positivity greatly.

Firstly, we can model the spectrum sensing model as a spectrum sensing game (SSG).

Definition 3. In a SSG with K SUs, the set of players is denoted by $T = \{p_1, \cdots, p_K\}$. Each player p_i can choose one of two actions in $A = \{C, D\}$, where C is the contribute sensing (cooperator) and D is the refuse to contribute sensing (defector). The payoff of each player is the throughput of SUs under different strategies. □

Definition 4. Assume the set $T_c = \{p_1, \cdots, p_J\}$ is the J SUs who cooperate to sense. The false alarm probability of the cooperative sensing among set T_c with a fusion rule 'RULE' and a target detection probability $\bar{P}_d$ is defined by $P_f^{T_c} = P_f(\bar{P}_d, N, \{\gamma_i, i \in T_c\}, RULE)$. The payoff of a cooperator $p_j \in T_c$ is defined as $\widetilde{U}_{C,p_j}$; the payoff of a defector $p_i \notin T_c$ is defined as $\widetilde{U}_{D,p_i}$.

$$\widetilde{U}_{C,p_j} = P_{H_0}\left(1 - \frac{\delta(N)}{|T_c|T_s}\right)\left(1 - P_f^{T_c}\right)C_{p_j}, |T_c| \in [1, K] \tag{10}$$

$$\widetilde{U}_{D,p_i} = \begin{cases} P_{H_0}\left(1 - P_f^{T_c}\right)C_{p_i}, |T_c| \in [1, K] \\ 0, |T_c| = 0 \end{cases} \tag{11}$$

where $|T_c|$ is the number of contributors, C_{p_j} is the data rate of p_j under H_0. □

Given a $\bar{P}_d$ for T_c, the target detection probability $\bar{P}_{d,p_j}$ of each SU can be obtained by solving the following equation.

$$\bar{P}_d = \sum_{k=\left\lceil\frac{1+|T_c|}{2}\right\rceil}^{|T_c|} \binom{|T_c|}{k} \bar{P}_{d,p_j}^k \left(1 - \bar{P}_{d,p_j}\right)^{|T_c|-k} \tag{12}$$

We assume each contributor takes the same responsibility, $\bar{P}_{d,p_j}, p_j \in T_c$ are the same. Similar to (5), we have

$$P_{f,p_j} = \frac{1}{2} erfc\left(\sqrt{\left(2\gamma_{p_j} + 1\right)} erfc^{-1}\left(1 - 2\bar{P}_{d,p_j}\right) + \sqrt{\frac{N}{2|T_c|}} \gamma_{p_j}\right) \tag{13}$$

In this paper, we use the majority rule [14] as the fusion rule 'RULE' in Definition 4, that is

$$P_d = Pr\{at\ leat\ half\ users\ in\ T_c\ report\ H_1 | H_1\}$$

$$P_f = Pr\{at\ leat\ half\ users\ in\ T_c\ report\ H_1 | H_0\}$$

Definition 5. An ESSG is defined as $G = \{T, A, S, U\}$, where the set of players T and the action set A are defined in Definition 3. The number of SUs following strategies s_j is n_j. The population profile is $x = \{x_j\}$ and $x_j = \frac{n_j}{K}$. The strategy set is S.

Consider a two-player game. Let $P = 1 - P_f^{T_c}, T = T_c, B_i = 1 - P_{f,p_i}, D_i = P_{H_0} C_{p_i}, i = 1,2$ and $\tau = \frac{\delta(N)}{T}$, the payoff matrix can be written as Table 1.

Table 1. Payoff matrix

	SU 1 Cooperate	**SU 1 Defect**
SU 1 Cooperate	$D_1P\left(1-\frac{\tau}{2}\right), D_2P\left(1-\frac{\tau}{2}\right)$	$D_1B_1(1-\tau), D_2B_1$
SU 1 Defect	$D_1B_2, D_2B_2(1-\tau)$	0,0

Since this game is not the prisoners' dilemma, we try mixed strategies to solve. Let x_1 and x_2 are the probabilities of SU 1, SU 2 taking action C. If SU 1 choose C, the expected payoff is

$$\widetilde{U}_{s_1}(C, x_2) = D_1P\left(1-\frac{\tau}{2}\right)x_2 + D_1B_1(1-\tau)(1-x_2) \tag{14}$$

$$\widetilde{U}_{s_1}(C, C) = D_1P\left(1-\frac{\tau}{2}\right)x_1x_2 + D_1B_1(1-\tau)x_1(1-x_2) + D_1B_2(1-x_1)x_2 \tag{15}$$

Similarly, If SU 2 choose C, we can obtain the expected payoff accordingly. The replicator dynamics of SU 1 and SU 2 are expressed as the followings [9].

$$\dot{x}_1 = x_1(1-x_1)D_1[B_1(1-\tau) - E_1x_2] \tag{16}$$

$$\dot{x}_2 = x_2(1-x_2)D_2[B_2(1-\tau) - E_2x_1] \tag{17}$$

where $E_1 = B_2 + B_1(1-\tau) - P\left(1-\frac{\tau}{2}\right)$ and $E_2 = B_1 + B_2(1-\tau) - P\left(1-\frac{\tau}{2}\right)$.

We assume that the SNR in each sub band within the same licensed spectrum band is the same, $\gamma_{s_1} = \gamma_{s_2}, C_{s_1} = C_{s_2}$. The steady-state of (16) and (17) is defined as the evolutionary stable strategy (ESS), a detail analysis you can refer to [8, 9].

In dynamic spectrum access, if none of them take time to sense the licensed spectrum, all of the users (include the PU) would not get a higher throughput than it obtained by themselves. On the contrary, even if all users succeed in cooperating to sense, the licensed spectrum sharing may be unable to complement the cost of sensing. Therefore, the current maximization of payoffs is unreasonable. Since the data transmission of SUs is a long-term process, we can describe the effective payoffs using the present valve (PV).

Definition 5. [12] PV is the sum that a player is willing to accept currently instead of waiting for the future payoff, i.e., accept smaller payoff today that will be worth more in the future, similar to making an investment in the current period that will be increased by a rate r in the next period. □

If the payoff is 1 in the next time, the payoff that a player is willing to accept will be $\frac{1}{1+r}$ now. Actually there is a probability p that the game will stop, the payoff that a player is willing to accept will be $\frac{1-p}{1+r} \triangleq \delta$, where $\delta \in [0,1]$ is the discounted factor. If the expected payoff in the next time is X, the PV of the next round game is δX. Assume the current payoff is 1, the PV of the infinite game is $\text{PV} = 1 + \delta + \delta^2 + \cdots = \frac{1}{1-\delta}$.

In repeated games, contingent strategies are frequently used to model the sequential nature of the relationship that users can adopt strategies that depend on behavior in preceding plays of the games. Most contingent strategies are trigger strategies. Two common trigger strategies are the tit-for-tat (TFT) and the grim trigger strategy [10, 12]. This paper only consider the case $p = 0$, that is the infinite game.

Definition 6. In an ESSG, TFT means choosing, in any specified period of game, the action chosen by your rival in the preceding period of play. When playing TFF, you cooperate with your rival if she cooperated during the most recent play of the game and defect (as punishment) if your rival defected. This punishment phase lasts only as long as your rival continues to defect; you will return to cooperation one period after she chooses to do so. □

Theorem 1. In an ESSG, both sides take TFT and tend to cooperate if the discount factor satisfies

$$\delta > \frac{1 - P_{f,s_j}}{1 + P_{f,s_j}}, j = 1,2 \tag{18}$$

Proof. If both sides take TFT, the PV of strategy C is

$$\mathrm{PV}_{Cooperate} = \frac{1}{1-\delta} D_1 P \left(1 - \frac{\tau}{2}\right) \tag{19}$$

The PV of strategy D is the sum of the payoffs

$$\mathrm{PV}_{Cheat} = D_1 B_2 + \delta D_1 B_1 (1 - \tau) + \frac{\delta^2}{1-\delta} D_1 P \left(1 - \frac{\tau}{2}\right)$$

To promote one SU to cooperate, the PV of strategy C is preferable for each SU, we have $\mathrm{PV}_{Cooperate} > \mathrm{PV}_{Cheat}$, that is (18). So far, the proof is completed. □

It is shown in Theorem 1 that if $\delta > 1$, P_{f,s_j} will go to zero. So TFT is impractical. SUs have a strong desire to cheat for a high payoff as increasing N, since the cost of sensing will be increased with a large N.

Another strategy which can promote cooperation is the grim trigger strategy, which is more harsh strategy than TFT.

Definition 7. In an ESSG, the grim strategy entails cooperating with your rival such time as she defects from cooperation; once a defection has occurred, you punish your rival (by choosing the defect strategy) on every play for the rest of the game. □

The punishment for a SU who chooses not to sense is more serious using the grim trigger strategy than that using TFT.

Theorem 2. In an ESSG, both sides take the grim trigger strategy and tend to cooperate if the discount factor satisfies $\delta \geq \frac{1}{2}$.

Proof. If both sides take the grim trigger strategy, the PV of strategy C is

$$\mathrm{PV}_{Cooperate} = \frac{1}{1-\delta} D_1 P \left(1 - \frac{\tau}{2}\right) \tag{21}$$

If a SU chooses the strategy D, it means that it will be punished to sense alone forever. Thus the PV of the strategy C is

$$\mathrm{PV}_{Cheat} = D_1 B_2 + \frac{\delta}{1-\delta} D_1 B_1 (1-\tau) \tag{22}$$

To promote one SU to cooperate, the PV of strategy C is preferable for each SU, we have $\mathrm{PV}_{Cooperate} > \mathrm{PV}_{Cheat}$.

$$\delta > \frac{1-\left(1+P_{f,s_j}\right)\left(1-\frac{\tau}{2}\right)}{\tau}, j = 1,2 \tag{23}$$

As the increase of N, P_{f,s_j} will go to zero and the right term of (23) can reach the maximum $\frac{1}{2}$. □

4 Simulation and Performance

The simulation parameters of ESSG are set as follows. The PU's signal is assumed to be baseband QPSK modulated, where the sampling frequency is $f_s = 1MHz$ and the time duration is $T = 20ms$. The probability of PU's absent is $P_{H_0} = 0.9$ and the required target detection probability $\bar{P}_d = 0.95$. The SNR $\gamma_{s_j} = -12dB$.

Firstly, we do not use the concept of PV. The algorithm of ESSG is shown in Table 2. The initial values are set to $x = 0.8, C = 1$. The comparison between the cases $x_1 = x_2 = 1$ and $x_1 = x_2 = ESS$ is shown in Figure 1, where the evolutionary stable strategy is denoted as ESS.

When τ is smaller than 0.1, the cost of spectrum sensing increases with τ. It is shown that two SUs are willing to sense. However, when τ increases larger than 0.2, the sensing probability of each SU decreases and they tend to defect. The worst is that the throughput decreases at the same time, which is shown in Figure 1. The maximum difference between cooperating completely and cooperating at ESS happens at $\tau = 1$. And the throughput of each SU is decreased too much. The main reason is that each SU only considers the current payoff in each round game.

Table 2. The game algorithm

STEP 1 Parameters initialization.
STEP 2 Compute payoffs (10) and (11) for m circles.
STEP 3 Compute expected payoffs (14) and (15).
STEP 4 Update strategies s_i (16) and (17).
STEP 5 If ESS is achieved, STOP; else go back to STEP 2.

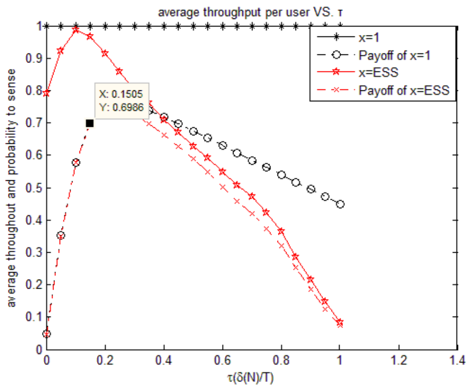

Fig. 1. The average throughput and probability

Now, we use the concept of PV to extend ESSG. To testify the grim trigger strategy can promote cooperation, the game algorithm in Table 2 is adopted with the same parameters. Note the payoffs in STEP 2 are replaced by (21) and (22). The simulation results are shown in Figures 2, 3 and 4. The ESS of ESSG is denoted as $x = ESS'$.

In Figure 2, the sensing probability increases faster at ESS' in ESSG than the result at ESS. The throughput of each SU is improved, especially when τ is close to 1. When a SU choose the strategy D in current period, the other one will choose D forever. So, each SU tends not to take the adventure to wait for the others' sensing result.

The sensing positivity is increased when δ is increased from 0.5 to o.53 in Figure 3. As SUs consider the effect of future actions, the throughput of each SU is increased, especially when τ closes to 1. As shown in Figure 4, x keeps stable when δ is increased to 0.6. It means that, when the cost of sensing is large, both SUs will keep cooperating to share for reducing individual cost. The throughput is just the same as they always choose to cooperate.

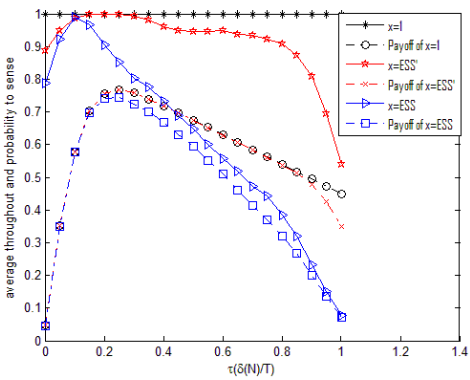

Fig. 2. The average throughput and probability $\boldsymbol{\delta = 0.5}$

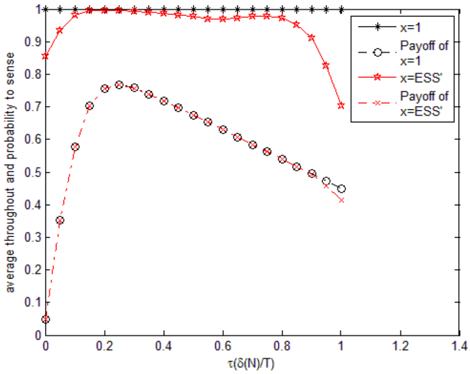

Fig. 3. The average throughput and probability $\boldsymbol{\delta = 0.53}$

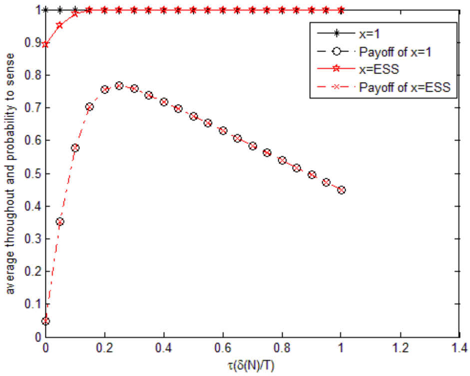

Fig. 4. The average throughput and probability $\boldsymbol{\delta = 0.6}$

5 Conclusion

In this paper, the concept of PV is introduced to improve the evolutionary spectrum sensing game. The SUs not only consider the current payoff, but also the current effect from future payoff. Two strategies, i.e., tit-for-tat and grim strategy are discussed. It is proved that the strategy of grim strategy can enhance secondary users' sensing positivity greatly, and so is the overall spectrum efficiency. The simulation results show that the interaction of the two SUs using the grim trigger strategy can increase the throughput of each SU greatly.

How to utilize the global information to promote the SUs to sense remains a tedious work. Our simulation results show the improvement was obvious. The future work is to investigate the general case of p and find other suitable strategies.

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