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Spectrum sensing algorithm based on Stackelberg game

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Abstract: For multi-user scenario, a multi-task collaboration spectrum sensing algorithm based on Stackelberg game is proposed. This algorithm models the sub-user as a Stackelberg game. In the subordinate game, a new utility function is constructed to dynamically change the perception time of the sensing user according to the reward given by the platform to obtain the optimal utility. Simulation results show that the proposed mechanism can achieve better performance of collaborative spectrum detection.

Keywords: Game theory; Spectrum sensing; Cognitive radio.

1. Introduction

In recent years, with the rapid development of wireless communication and the increasing number of wireless devices, the shortage of spectrum resources has become more and more serious[1]. The traditional fixed spectrum allocation method can not meet the growing needs of users. In order to solve the problem of low spectrum utilization, cognitive radio (CR) technology came into being. In cognitive radio networks, secondary users are allowed to use the radio resources of the primary user when the primary user does not occupy the spectrum. Therefore, how to efficiently and accurately sense the spectrum is very important.

In this paper, the incentive mechanism of cooperative spectrum sensing is modeled as a Stackelberg game, in which the fusion center acts as a leader and each secondary user (SU) participating in the sensing is a follower. The fusion center publishes the sensing task and its set total incentive R to all SUs. The SUs participating in the sensing task will adjust their detection probability strategy to maximize the utility, and each SU optimizes the sensing time through the game to maximize its utility.

2. System Model

As shown in Figure 1, M primary users are evenly distributed in a circle with a radius of R. Different primary users occupy different frequency bands. N secondary users (i = 1, 2,...,N) can perceive the frequency band of any primary user, but at the same time, secondary users can only perceive the frequency band of one primary user. The fusion center (platform) publishes M (j = 1, 2,...,M) authorized frequency bands for the frequency bands used by M primary users. The secondary user determines the task and time of perception according to the perceived cost, and then sends the perception result to the fusion center. The fusion center fuses the secondary user 's perception information to obtain the final perception result, and gives a certain amount of reward to the participating secondary users.

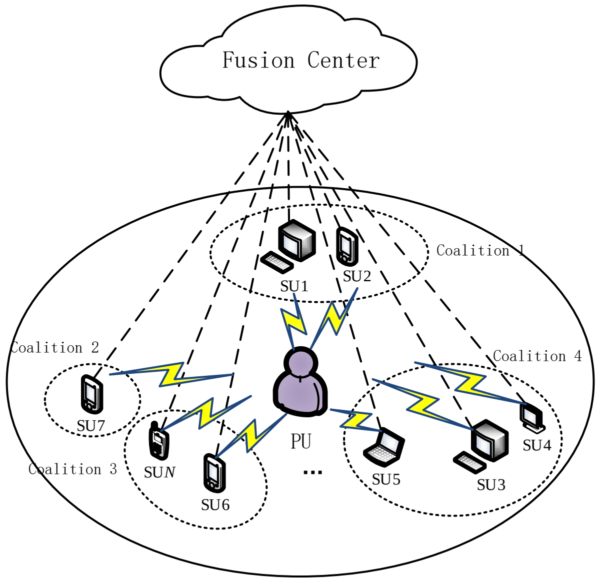

Fig. 1 System model diagram

In the game model, the fusion center first issues a total incentive of R > 0 as a reward for all participating SUs. Based on R, participants will seek their best game strategy, that is, $P_{d,i}$, to maximize their utility.

According to Reference [5], $P_{d,i}$ obtained by cognitive users through energy detection is

$$P_{d,i}(t_i) = Q(\frac{Q^{-1}(P_{f,i}) - \sqrt{t_i f_s} SNR_i}{\sqrt{2SNR_i + 1}}) \tag{1}$$

Where $P_{f,i}$ denotes the false alarm probability, that is, the probability that the authorized user 's occupied state detected by the cognitive user is occupied when the authorized user currently does not occupy the spectrum resources, represents the cognitive user 's sensing time, and represents the signal-to-noise ratio of the cognitive user receiving the signal sent by the authorized user. The expression of the Q function is :

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} e^{-\frac{t^2}{2}} dt \tag{2}$$

The first derivative Y of the detection probability with respect to t_i is

$$Y=\frac{\partial P_{d,i}}{\partial t_i}=\frac{\sqrt{f_s}SNR_i}{2\sqrt{2\pi(2SNR_i+1)}}\frac{1}{\sqrt{t_i}}e^{-\frac{m^2}{2}} \tag{3}$$

which, $m=\frac{Q^{-1}(P_{f,i})-\sqrt{t_i f_s}SNR_i}{\sqrt{2SNR_i+1}}$

According to [6], when the fusion center adopts the OR fusion criterion, the detection probability P_D and false alarm probability P_F of the system are

$$P_D=\sum_{j=k}^{N}\sum_{\sum u_i=j}\prod_i P_{d,i}^{u_i}(1-P_{d,i})^{1-u_i}=1-\prod_i^N(1-P_{d,i}) \tag{4}$$

$$P_F=1-\prod_i^N(1-P_{f,i}) \tag{5}$$

According to the total incentive R announced by the fusion center in the leadership game, each SU decides its own optimal perception strategy. The strategy of any SU participating in the sensing is $P_{d,i}>0$, and when $P_{d,i}=0$, it is unwilling to participate in the cooperative spectrum sensing task published by the fusion center.

3. Follower Cognitive User Incentive Mechanism Based on Game Theory

The utility function is the difference between the perceived reward and the cost, the utility function of the benefit of the coalition, and the utility function of the cognitive user SU_i is defined as :

$$u_i=B(P_{d,i})-C(t_i) \tag{6}$$

which, $B(P_{d,i})$ is the payoff function of the detection probability, $C(t_i)$ is the penalty function of the time, and the penalty factor b_j is assumed to be uniformly distributed with a mean value of 0.5.

$$B\left(P_{d,i}\right)=\begin{cases} b_1\frac{P_{d,i}}{\sum_{j=1}^{N}P_{d,j}}R & u_1 \\ 0 & u_0 \end{cases} \tag{7}$$

$$u_i\left(t_i\right)=b_1\frac{P_{d,i}}{\sum_{j=1}^{N}P_{d,j}}R-b_j t_i \tag{8}$$

The value of i in Formula (8) is 0 or 1, indicating that the cognitive user participates in the sensing task, indicating that the cognitive user does not participate in the sensing task. Only the sensing time can be determined by cognitive users. In order to make their own utility optimal, cognitive users need to determine their own optimal sensing time. There is a game between N cognitive users, and the player is all cognitive users. The game strategy of each cognitive user is the perception time. Since each cognitive user is rational and selfish, they will aim at maximizing their utility. Nash equilibrium is the optimal result of the game of each cognitive user. When other cognitive users do not change their strategies, cognitive users cannot obtain higher returns by changing their strategies alone.

u_i the first derivative of t_i is :

$$\begin{aligned}\frac{\partial u_i}{\partial t_i}&=b_1\frac{\sum_j P_{d,j}-P_{d,i}}{\left(\sum_j P_{d,j}\right)^2}\frac{\partial P_{d,i}}{\partial t_i}-b_2\\ &=b_1 R\frac{\sqrt{f_s}SNR_i}{2\sqrt{2\pi(2SNR_i+1)}}\frac{\sum_{j\in N\backslash\{i\}}P_{d,j}}{\left(\sum_j P_{d,j}\right)^2}\frac{1}{\sqrt{t_i}}e^{-\frac{m^2}{2}}-b_2\end{aligned} \tag{9}$$

The second derivative of u_i with respect to t_i is :

$$\frac{\partial^2 u_i}{\partial t_i^2}=b_1\frac{-2R\sum_{j\in N\backslash\{i\}}P_{d,j}}{\left(\sum_{j=1}^{N}P_{d,j}\right)^3}\frac{\partial P_{d,i}}{\partial t_i}+b_1\frac{R\sum_{j\in N\backslash\{i\}}P_{d,j}}{\left(\sum_{j=1}^{N}P_{d,j}\right)^2}\frac{\partial^2 P_{d,i}}{\partial^2 t_i} \tag{10}$$

The gain coefficient b_1 in the SU utility function, the cost coefficient b_j in the SU utility function, the sensing time t_i, the sampling frequency f_s, the signal-to-noise ratio SNR_i, the cost R of the fusion center, the detection probability of the cognitive user participating in the sensing task and the detection probability of each cognitive user are all greater than 0.

According to the reference [3], $m\le 0$,and that

$$\frac{\partial m}{\partial t_i}=-\frac{SNR_i\sqrt{f_s}}{2\sqrt{2SNR_i+1}}\frac{1}{\sqrt{t_i}}<0,$$

Set

$$X=\frac{\sqrt{f_s}SNR_i}{2\sqrt{2\pi\left(2SNR_i+1\right)}},$$

therefore

$$\frac{\partial^2 P_{d,i}}{\partial t_i^2}=-\frac{1}{2}X\frac{1}{\sqrt{t_i^3}}e^{-\frac{m^2}{2}}-m\frac{1}{\sqrt{t_i}}e^{-\frac{m^2}{2}}\frac{\partial m}{\partial t_i}<0 \tag{11}$$

Obviously, $X>0$,In summary, $\frac{\partial^2 u_i}{\partial t^2}<0$.

Since the second derivative is negative, the utility function is strictly concave relative to SU 's strategy. Therefore, given R, if there is an optimal strategy, the optimal strategy is unique.

4. Simulation Results and Analysis

In this section, the simulation software is used to simulate the algorithm. In the simulation, the radius R of the base station circle is 5km, the position of the fusion center is at the origin, and the sensing users are randomly and evenly distributed in the circle，as shown in the figure 2. This section compares the proposed algorithm with the random selection algorithm. In the random selection algorithm, the sensing user does not consider the sensing cost and incentive, and randomly selects the sensing task and participates in the sensing.

In this section, the value of M is 3, and the SNR of each authorized frequency band is different. In frequency band 1, SNR is 5 ~ 10 dB, in frequency band 2, SNR is 2 ~ 7 dB, and in frequency band 3, SNR is − 1 ~ 5 dB. Figure 3shows the final detection probability of the platform under different frequency bands. It can be seen that the higher the signal-to-noise ratio, the higher the detection probability of the frequency band. This is because the higher the signal-to-noise ratio, the higher the detection probability of a single sensing user under the same sensing time. According to the formula of OR fusion, the total detection probability will also be higher.

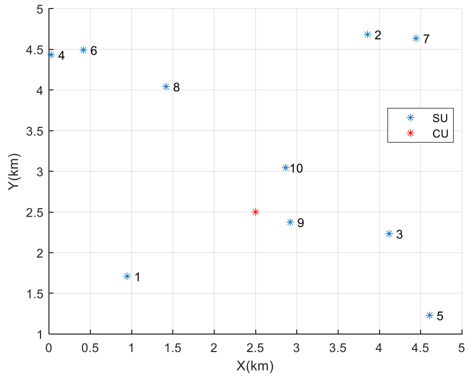

Fig. 2 User random distribution

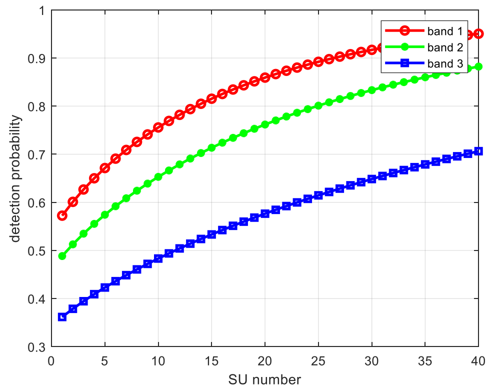

Fig. 3 Different frequency bands PD

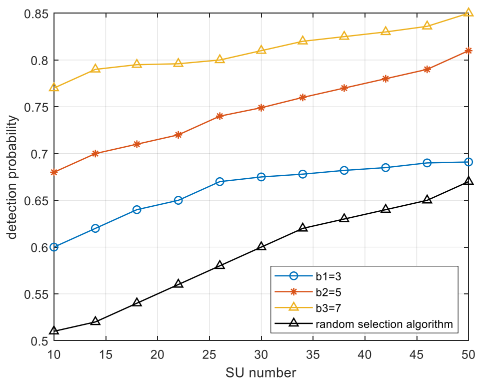

Fig. 4 SU of PD under different coefficients

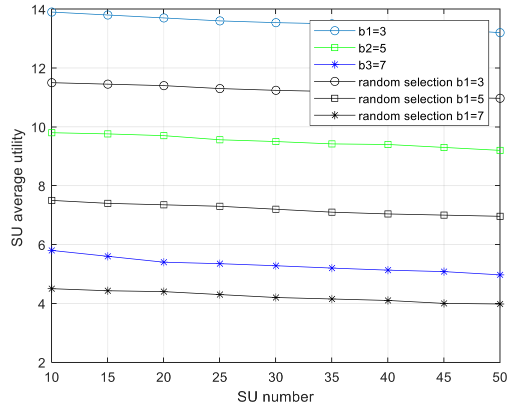

Fig. 5 SU and utility curve

As shown in Figure 4, the larger the value of b, the smaller the detection probability. This is because the larger the value of b, the larger the value of the energy consumption coefficient, the greater the perceived cost of the perceiving user will increase. In order to optimize the utility, the perceiving user will reduce the perception time, resulting in the reduction of the detection probability.

Figure 5 shows the relationship between the average utility of sub-users and the number of sub-users under different B-values. It can be seen from the figure that the sub-user utility of the proposed algorithm is superior to the random selection algorithm, because the focus of this paper is to make the sub-user and the fusion center reach their respective optimal utility through the game. At the same time, it can be seen that the higher the value of b, the higher the utility of sub-users, because the higher the cost of sub-users, the survival of the fittest, only the sub-users with better perceived performance can stay. The smaller b is, the lower the sub-user cost, the more users participate in perception, the fiercer the competition degree, and the smaller the reward for each perceived user.

5. Conclusion

This section proposes a cooperative dynamic spectrum sensing algorithm, which considers a fusion center and multiple SUs.If there is no certain incentive to compensate for the cost of spectrum sensing, the SU without data transmission will not participate in the spectrum sensing task. Therefore, the incentive mechanism is designed to ensure a sufficient number of cooperative sensing users in spectrum sensing and further ensure better detection performance. For each SU, it is hoped to gain more profits by participating in the sensing process. Therefore, an incentive mechanism based on Stackelberg game is designed. In the subordinate level game, all the SUs participating in the perception will aim at maximizing the utility. In this paper, the utility function of SU is reasonably constructed, and the existence of the only Nash equilibrium in the Stackelberg game is proved. This conclusion ensures the feasibility and stability of the proposed game algorithm. In the simulation, the proposed Stackelberg-based game is compared with the random selection algorithm. The results show that the proposed mechanism can achieve better cooperative spectrum detection performance.

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