# The Research of Non-cooperative Power Control Method Based on Fairness and User Selection Strategy in Cognitive Radio Networks

Guanglong Yang(✉), Xuezhi Tan, and Xiao Wang

School of Electronics Information Engineering, Harbin Institute of Technology,
Harbin 150001, People's Republic of China
yang3616@126.com, {Tanxz1957,hitwx}@hit.edu.cn

**Abstract.** When studying the power control problem of cognitive radio based on non-cooperative game theory, most scholars pay more attention to constraints such as interference, signal-to-noise ratio of secondary users, primary user interference threshold and so on. Optimization objectives focus on system throughput, system energy consumption, convergence rate, etc. The fairness problem caused by secondary users in order to increase system throughput is ignored, and the research on whether all the secondary users participate in the communication meets the communication conditions is in blank state. Based on the fairness problem, an automatic power control game algorithm based on cost function is proposed in this paper. When the cost function is designed, the influence of distance on channel gain is fully considered, and the penalty mechanism is introduced by adjusting the weight adaptively. The interference between users is reduced, and the near-far effect caused by different user location is effectively overcome. In order to solve the problem of whether the secondary users meet the communication conditions, a sub-user selection strategy is proposed to accurately control the secondary users who participate in the communication, thus avoiding the hidden danger to the stability of the system caused by the users who do not meet the communication conditions. The necessity and practical value of the user selection strategy are verified by simulation. At the same time, the performance of the proposed algorithm in convergence speed and energy saving is also highlighted.

**Keywords:** Cognitive radio · Underlay spectrum sharing · Distributed power control

## 1 Introduction

With the rapid development of communication technology and the increase of communication services, the demand for wireless spectrum resources is becoming more and more intense. For example, with the popularity of the Internet of things and the popularization of vehicle networking equipment, the number of frequency points is increasing; for example, the development of video services, the improvement of bandwidth requirements. This requires more advanced wireless systems that can

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accommodate more users and provide higher throughput. Cognitive radio technology has effectively improved the throughput of the next generation communication terminals. Enabling cognitive users to access free spectrum at any time, anywhere, many scholars have done a lot of work on optimization of cognitive users [1–3].

In reference [4–7], the distributed power control of cognitive radio is studied based on the user model. For the cognitive radio network model of a primary user and a secondary user in a cognitive system, Srinivasa and Bansal proposed a distributed power control algorithm. However, a user scenario is a special case, and the proposed algorithm is difficult to extend to multi-user systems. Sun et al. have improved the cognitive model and increased the number of secondary users. In the underlay cognitive radio network, the distributed power control problem is studied with the minimum transmit power as the optimization objective. Jin et al. extended the cognitive model to coexistence of multiple secondary users and multiple primary users, and studied the distributed power control problem in multi-user scenarios [7]. If each cognitive user wantonly increases their transmit power in order to maximize their throughput, the cognitive system will undoubtedly interfere with the primary user and other secondary users. The inherent competition problem of distributed power control problem urges us to use game theory to solve this problem.

In the framework of game theory, utility functions are used to quantify user satisfaction. The goal of each user is to maximize utility functions. So the design of utility function is very important. K-G algorithm and SINR balance algorithm are the classical power control game algorithms. Goodman and Mandayam proposed a model of non-cooperative game power control (Non-cooperative Power Control Game) [8], and proved the existence of Nash equilibrium, but the equilibrium solution is not always optimal. Furthermore, the non-cooperative mode power control problem based on cost (Pricing) [9] is studied. It is proved that Pareto is superior to Pareto in improving (Pareto Dominance), but it affects the fairness of signal quality in the receiver to some extent. Increased computational complexity. Nadkar et al. proposed a distributed power control algorithm based on game theory, which achieves the maximum throughput per secondary user [10].

Although some good results have been achieved in some aspects, most of the literatures do not refine the multi-user interference, do not consider the fairness of the signal quality at the receiver, and ignore the discussion of different parameter selection range and energy consumption.

In reference [11], the author discusses energy efficiency in OFDM cognitive radio networks using a game theory approach. In reference [12], a new utility function based on chaos is introduced to design the power control algorithm, which fully considers the interference from the primary user and the interference threshold constraint of the primary user, and proves the existence of Nash equilibrium, which reduces the power consumption. The convergence rate is improved. In reference [13], a non-cooperative game power control scheme was proposed considering the cognitive user fairness, and the sliding model iterative algorithm was used to improve the total throughput of the system.

In the design of utility function, most scholars think more about convergence, user satisfaction, algorithm complexity, etc. There is less research on whether the convergent user satisfies the communication condition, and how to select the secondary user who meets the communication condition.

In order to solve the above problems, this paper is organized as follows: Sect. 2 establishes the system model and communication scene. Section 3 optimizes the mathematical model. In Sect. 4, a power iterative algorithm is proposed. Section 5 proposes user selection strategy. In Sect. 6, the simulation results are given. Section 7 conclusion.

## 2 System Model

In this paper, the underlay spectrum access mode is considered, so it is unnecessary to consider the communication situation of the primary user, and the time of sensing and judging the primary user's activity is reduced indirectly. This paper considers the underlay multi-user distributed cognitive radio scene, as shown in Fig. 1. Primary and secondary users coexist in the network, including $M$ for secondary users, $N$ for primary users. The secondary user is represented by the set $\mathrm{A} = \{1, 2, \cdots, M\}$ and the primary user by the set $\mathrm{B} = \{1, 2, \cdots, N\}$. Order $\forall i, j \in \mathrm{A}$, $\forall k \in \mathrm{B}$.

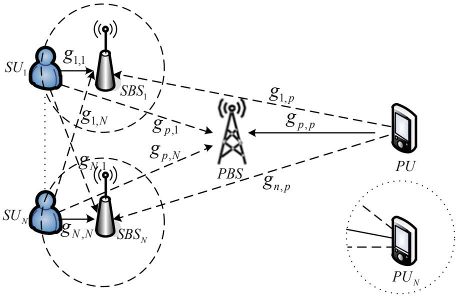

**Fig. 1.** Cognitive system model.

Assuming that the channel is flat fading, the average SINR of $SU_i$ can be expressed as:

$$\bar{\gamma}_i = \frac{\bar{g}_{i,i} p_i}{N_s + N_p + \delta^2} \tag{1}$$

Which is

$$N_S = \sum_{j=1, j \neq i}^{M} \bar{g}_{i,j} p_j, N_P = \bar{g}_{i,p} p_p, p_i \in \left[0, p_i^{\max}\right]$$

$g_{i,i}$, Instantaneous link gain from $SU_i$ to $SBS_i$; $g_{i,j}$, Instantaneous link gain from $SU_i$ to $PBS$; $g_{p,i}$, Instantaneous link gain from $SU_i$ to $PBS$; $g_{p,p}$, Instantaneous link gain from $PU$ to $PBS$; $g_{i,p}$, Instantaneous link gain from PU to $SBS_i$; $p_i$, the $i$ th secondary user transmit power; $p_i^{\max}$, Secondary user maximum transmit power; $p^{total}$, Total interference power from $SU_i$ to primary user; $p^{th}$, Main user's interference threshold; $N_S$, Other secondary user interference; $N_P$, Primary user interference; $\delta^2$, Background noise; $\gamma_i^{th}$, The SINR value for the $i$ th secondary user when the QoS requirement is satisfied.

In order to ensure the normal communication of the primary user, the interference power cannot exceed the interference threshold of the primary user. Therefore, in order to meet the interference threshold, the total interference power of the secondary user must be met

$$p^{total} = \sum_{i=1}^{N} p_i \bar{g}_{p,i} \le p^{th} \tag{2}$$

In a cognitive system, in order to ensure a secondary user's QoS requirements, each secondary user's receiving SINR needs to meet a certain threshold value:

$$\bar{\gamma}_i \ge \gamma_i^{th} \tag{3}$$

## 3 Optimization Mathematical Model

In the following chapters, we select an appropriate utility function and use the iterative algorithm to solve the problem, and prove the existence and uniqueness of Nash equilibrium. In order to ensure the non-negativity and convexity of utility function, the SINR requirement of secondary user $\gamma_i^{th}$ and the maximum transmit power limit $p_i^{\max}$ should be considered in selecting utility function.

$$u_i(p_i, p_{-i}) = \alpha \log(\bar{\gamma}_i - \gamma_i^{th}) + \beta(p_i^{\max} - p_i)^{\frac{1}{2}} \tag{4}$$

Where $\alpha$ and $\beta$ are non-negative weight factors. How to choose the weight Factor in the expression of Utility function $\alpha$ and $\beta$ is very important. Based on the degree of interference, the high power threshold is chosen when the primary user is far from the cognitive network, and the low power threshold is chosen when the primary user is close to the cognitive network. Select the appropriate SINR threshold $\gamma_i^{th}$ according to QoS requirements. If $\bar{\gamma}_i < \gamma_i^{th}$, $\alpha$ and $\beta$ remain unchanged; if $\bar{\gamma}_i > \gamma_i^{tar}$, adaptive weight adjustment by $\beta_{i+1} = \beta_i \bar{\gamma}_i / \gamma_i^{th}$. Secondary users reduce interference with other users by punishing themselves.

## 4 Power Iterative Algorithm

In this section, we propose an iterative power control algorithm. The $i$ th secondary user power iteration function can be represented as

$$p_i^{(m+1)} = \begin{cases} \frac{p_i^{(m)}}{\bar{\gamma}_i^{(m)}}\gamma_i^{th} + \frac{2\alpha_i}{\beta_i}\left(p_i^{\max} - p_i^{(m)}\right)^{\frac{1}{2}} & p_i^{(m+1)} < p_i^{\max} \\ p_i^{\max} & p_i^{(m+1)} \geq p_i^{\max} \end{cases} \tag{5}$$

Each secondary user is updated iteratively until the utility function in (4) is maximized. An automatic non-cooperative power control algorithm designed in this paper (APCGA, Automatic Power Control Game Algorithms). The process is as follows:

Step 1: Initialization power vector $p_i(0)$ and $p_0$, count $\gamma_i(0)$.

Step 2: If $\bar{\gamma}_i < \gamma_i^{th}$, $\beta_i$ remain unchanged; otherwise automatically adjust $\beta_i$ through $\beta_{i+1} = \beta_i \bar{\gamma}_i / \gamma_i^{th}$.

Step 3: Order $m = m + 1$, recalculate power $p_i^{(m+1)}$ using.

If $p_i^{(m+1)}$ meet (2), go on, otherwise the iteration stops.

Step 4: The $i$ th secondary user, $|U_i^{(m+1)} - U_i^{(m)}| < \omega$ (precision $\omega > 0$), the iteration stops; Otherwise, return to step 2.

## 5 User Selection Strategy

If we do not consider whether the secondary user satisfies the communication condition, we can use the power iteration algorithm in Sect. 4 to solve the transmission power of this user. However, by carefully analyzing the utility function of expression (4), we find that the utility function only constrains the convergence of the function itself, but does not correlate with whether the actual secondary user satisfies the cognitive radio communication. As a result, some secondary users appear to converge through iterative algorithms, but they do not meet their own SINR requirements. We assume a multiple user model, in which the $i$ th secondary user is a little far away. This scenario can cause the $i$ th secondary user to converge to transmit power $p_i = p_i^{\max}$ after formula (4) iteration, but it cannot meet the $\bar{\gamma}_i \geq \gamma_i^{th}$ requirements, so the user is an interference source in the system. The existence of these users caused great interference to the system, and even directly affected the stability of the system. As can be seen from formula (2), the excessive number of cognitive users will lead to the failure of formula (2), that is, the cognitive system has a certain limit on the number of cognitive users, if this limit is exceeded, It is bound to interfere with the primary user. These two cases can be called cognitive user selection problem, which has been neglected in the research of cognitive radio power control. However, in practical applications, how to select cognitive users is a problem to be considered.

### 5.1 Cognitive User Selection

The following discusses how to screen and accept cognitive users, eliminating interference and ensuring system capacity.

(1) Primary election

Because the distance between users determines the size of the channel gain, interference constraints can be represented as

$$p_i^{\max} \bar{g}_{p,i}^{\min} \leq p_i^{th(\min)} \tag{6}$$

Assume that the secondary user location can be obtained by perception. Through formula (6), cognitive primary selection can be realized, although it is slightly conservative, the primary user can be protected to the greatest extent. The remaining secondary user collection is

$$\Theta = \mathrm{A} - \Psi \tag{7}$$

Where $\Psi$ is the set of selected users, and $\Theta = \{1, 2, \cdots, K\}$ is the set of excluded users. Order $\forall \lambda, \rho \in \Theta$.

Cognitive user in set $\Psi$ uses 3.5-Section iterative algorithm to solve the transmit Power of Cognitive user.

2. Admit

Formula (1) can be converted into formula

$$\begin{gathered} \frac{\bar{\gamma}_\lambda \times \left(N_\Theta + N_s + N_p + \delta^2\right)}{\bar{g}_{\lambda,\lambda}} = p_\lambda \\ N_\Theta = \sum_{\rho=1, \rho \neq \lambda}^{k} \bar{g}_{\lambda,\rho} p_\rho \end{gathered} \tag{8}$$

All satisfying $p_\lambda < p_i^{\max}$ sub-user sets are accepted by Z and merged with the original $\Psi$ set to form a set of users that ultimately allow communication to recognize

$$\Xi = \mathrm{Z} + \Psi \tag{9}$$

In the set $\Xi$, cognitive users are solved by 3. 5 iterative algorithm.

Through (1) primary selection and (2) admission operation, cognitive user selection is completed.

## 5.2 Cognitive User Capacity

Assuming that the number of secondary users M in the secondary user set A far exceeds the maximum number of users in the cognitive system, it is necessary to select the secondary users who participate in the communication. In order to minimize the energy consumption of the secondary user, it is necessary to solve and compare the different sub-user combinations. One method is to obtain the maximum strategy set of the sub-user combination through exhaustive method, which will greatly increase the system delay. The complexity of the algorithm is increased and the system needs to be optimized again when the secondary user launches the communication or the new secondary user joins in the communication.

Next, we adopt the sub-optimal scheme for the selection of secondary users. The selection criteria are that the set of secondary users can meet the rapid convergence, and the cognitive system can accommodate more user directions and adopt a random selection method.

$$M' \le \frac{p^{th(\min)}}{p_i^{\max}\bar{g}_{p,i}} \tag{10}$$

where

$p^{th(\min)}$ is primary user minimum interference threshold
$p_i^{\max}$ is maximum estimated transmit power for secondary users
$\bar{g}_{p,i}$ is average channel gain

The selection process is as follows

Step 1: Preliminary definition of system capacity $M'$ by formula (9).
Step 2: Perform the 5.1 (1) primary step, if $M' < \Psi$ element number, random extraction of $M'$ th secondary users from a set $\Psi$; if $M' \ge \Psi$ element number, represents that all secondary users in the set $\Psi$ can be accommodated by the cognitive system.
Step 3: The second user set is selected and the cognitive user transmit power is solved by 5 section iterative algorithm.
Step 4: Perform step (2) admission in 5.1 to form a set of users that ultimately allow communication cognition.

## 6 Simulation Results and Analysis

In this section, the performance of the algorithm is simulated. Parameters are set as follows: assumed channel gain $h_i = 0.075 \times d_i^{-3.6}$. The location of the secondary user is randomly generated in the cognitive network. The transmission power initialized is $p_i(0) = 5 \times 10^{-15}\,\mathrm{W}$. The transmission power of the primary user is $p_0 = 0.05\,\mathrm{W}$, maximum transmit power of secondary user is $p_i^{\max} = 1\,\mathrm{W}$. The SINR threshold is set to $\gamma_i^{th} = 7\,\mathrm{dB}$. The threshold for interference temperature is $p^{th} = 3 \times 10^{-3}\,\mathrm{mW}$. Background noise is $\sigma^2 = 5 \times 10^{-15}\,\mathrm{W}$, $\omega = 10^{-15}$, $2\alpha/\beta = 3 \times 10^{-4}$.

### 6.1 Scenario 1

Firstly, the fairness of the proposed algorithm is verified, assuming that four secondary users and one primary user share spectrum resources. After the iteration is stabilized, three new users are added, assuming that the 7 users meet the communication requirements of the cognitive system after selection.

From the above simulation, we can see that the convergence of the proposed algorithm is very obvious, which means that the proposed algorithm can adapt to the dynamic network environment and rapidly converge to the real Nash equilibrium point.

Because of the distributed control, the information exchange between users is less, so the time to converge to the stable point is faster. It can be clearly seen in Figs. 2 and 3 that secondary users converge to different transmit power with different positions, which fully proves the fairness of the proposed algorithm. By comparing Figs. 2 and 3, we can see that as the number of secondary users in the cognitive system increases, the convergent transmit power of each secondary user becomes larger, because as the number of secondary users increases, there is also an increase in inter-system interference. In order to meet their own SINR requirements, secondary users are bound to enhance transmission power.

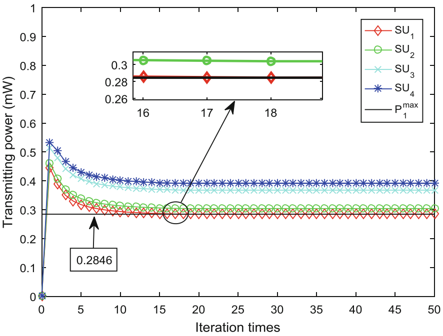

**Fig. 2.** User transmit power converges with iteration number (M = 7, N = 1)

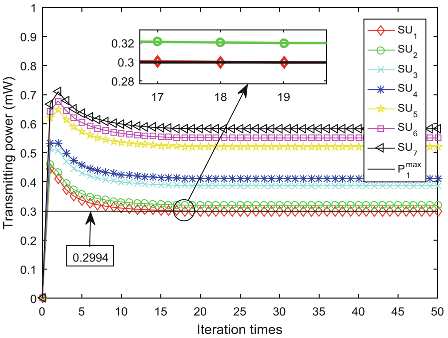

**Fig. 3.** User transmit power converges with iteration number (M = 4, N = 1)

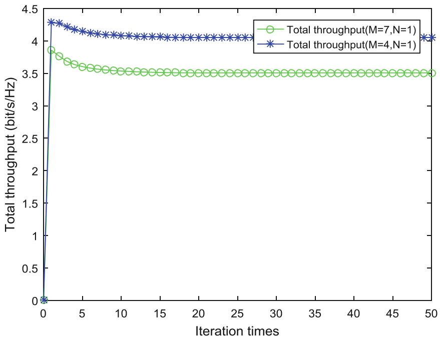

**Fig. 4.** Total user throughout varies with iterations

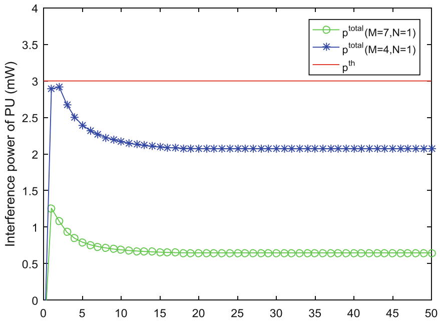

**Fig. 5.** Main user interference power varies with iteration number

Figure 4 shows that the total throughput of the system converges to a stable value, and the throughput increases with the increase in the number of secondary users, but the increase is not directly proportional to the increase in the number of secondary users, because as the number of secondary users increases, so does the interference of the system. The more the secondary users increase, the greater the system interference.

When the number of secondary users tends to saturation, the total throughput of the system also tends to saturation. Figure 5 shows that the primary user interference tends to be stable with the convergence of the secondary user power. The primary user receiver interference mainly comes from other primary user interference, secondary user interference, system noise and so on. This section discusses that there is only one primary user in the model, and the system noise is negligible compared with the secondary user interference, so the primary user interference can approach only from the secondary user interference. It can be seen from Fig. 5 that the increase of interference at the primary user's receiving end is higher than that of the secondary user's increase. This is because secondary users increase their transmit power in order to satisfy their own communication SINR, with the increase of secondary users in the system. It also increases the interference amplitude of the main user.

## 6.2 Scenario 2

Assuming that one secondary user is added on the basis of scenario 1, there are 8 secondary users and 1 primary user in the system, and one of the secondary users does not satisfy the system communication conditions. When the user selection strategy is not considered, it is known from formula 5 that when the transmission power is increased to satisfy its own communication SINR, but due to the limitation of the secondary user's maximum transmission power, when the transmission power reaches the upper limit of the secondary user's transmission power, the iteration stops (Fig. 6).

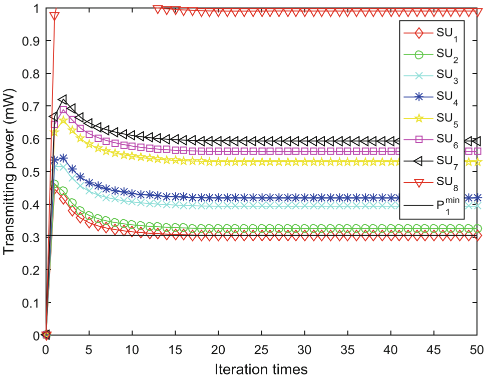

**Fig. 6.** User transmit power converges with iterations (close user selection strategy)

When the user selection strategy is adopted, the secondary user 8 is eliminated in the early stage, and scene 2 becomes scene 1. The simulation results of 7 users participating in communication are shown in Fig. 3. Comparing with Figs. 7 and 3, we can see that when the secondary user 8 is excluded, With the decrease of the interference in the system, the transmit power of the secondary user is also reduced, and the interference of the primary user receiver is also reduced, so the primary user communication is better protected.

### 6.3 Scenario 3

Assuming that there are 13 secondary users and 1 primary user in the system, the location information of the secondary user is given randomly. Figure 7 shows that 13 secondary users are included in the system to communicate without considering the user selection strategy. It can be seen that the number of secondary users involved in the communication exceeds the system capacity, resulting in the sub-user 11-13 unable to communicate normally. Other secondary users of normal communications sacrifice transmit power to ensure communication requirements. After selecting the cognitive user selection strategy, the system accommodates 10 secondary users through preliminary estimation of system capacity. At the same time, according to step 2, the culled secondary users are filtered. Finally, as shown in Fig. 8, the system can accommodate 12 secondary users.

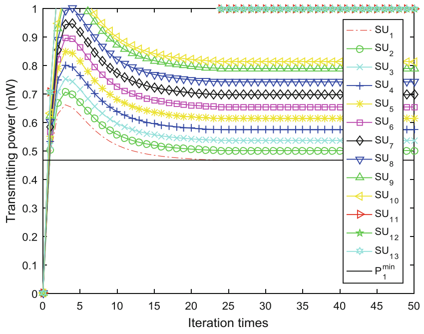

**Fig. 7.** Closing non-user selection policy

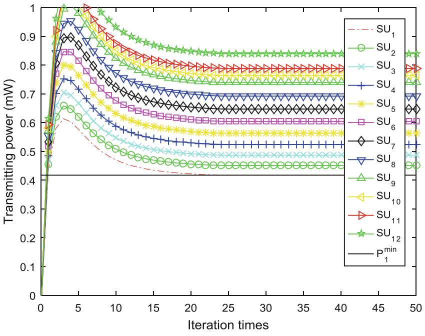

**Fig. 8.** Enable user selection policy

## 7 Conclusion

In this paper, the main user interference threshold, secondary user interference, secondary user communication SINR requirements, system convergence speed and other issues are fully summarized, and a non-cooperative power control model is established. Aiming at the problem of sub-user fairness in cognitive radio systems, an automatic power control algorithm (APCGA), based on game theory is proposed to effectively save energy consumption and overcome the near-far effect. At the same time, the communication situation of secondary users after power convergence is deeply analyzed, and the conclusion that the secondary users can not meet their own communication SINR requirements is concluded, and the user selection strategy is given. The secondary users involved in the system communication are screened from the two perspectives of user selection and user capacity, which effectively ensure the effectiveness of the secondary user communication, reduce the system interference, and improve the stability of the system. Finally, the performance of this algorithm is highlighted by simulation.

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