Dynamic Spectrum Access Algorithm Based on Cournot Game Theory in Cognitive Radio Networks

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***Abstract* — As the key technology in cognitive radio network, dynamic spectrum access provides a feasible scheme for secondary users (SUs) reasonably and efficiently using the licensed spectrum in dynamic environment. To solve the problem of mutual interference among SUs and selection of spectrum rented by SUs during dynamic spectrum access, therefore, this paper studies spectrum access algorithm based on cournot game theory, which is suitable for cognitive radio network among SUs. Finally, spectrum bandwidth rented by multiple SUs in the cournot model algorithm along with the increase of the number of SUs was simulated. Simulation results show that when the spectrum bandwidth rented by SUs has reached Nash equilibrium, the scheme can obviously make SUs reasonably and efficiently use the licensed spectrum in dynamic environments, so as to realize the spectrum sharing between secondary users and primary users as well as to maximize the spectrum utilization rate.**

Keywords - Cognitive radio; dynamic spectrum access; cournot game theory; nash equilibrium

I. INTRODUCTION

With the rapid development of wireless communication technology and rapid growth for spectrum demand, spectrum resources become increasingly scarce, and also has been one of the bottlenecks restricting the development of wireless communications. Scarce spectrum resources resulting main reasons: the one hand, the spectrum management scheme now used uses a fixed spectrum allocation system. The other hand, the utilization of licensed spectrum resources is very low. In recent years, the survey found that fixed wireless spectrum allocation led to partial spectrum efficiency is only 15% to 85% [1], highlighting the fixed wireless spectrum allocation unreasonable. In order to solve the problem of the spectrum resource scarcity and low licensed spectrum utilization, in 1999, Motorola [2] first proposed the concept of cognitive radio (CR).

Further research based on the theory of cognitive radio, research institutions such as Motorola and Virginia Tech jointly proposed the concept of Cognitive Radio Network (CRN). Through to the licensed spectrum resources "secondary use", cognitive wireless networks can efficiently use licensed spectrum resources of lower utilization, which can effectively alleviate contradiction between the lack of spectrum resources and the growing demand for wireless access. However, Dynamic Spectrum Access (DSA) as core technology in cognitive radio networks provides a feasible solution for SUs reasonably and efficiently using licensed spectrum in a dynamic environment, and using spectrum holes or white area to communicate in a certain time domain, space domain and frequency domain.

The academic circles have reported a large number of literatures about research work of dynamic spectrum access in cognitive radio networks [3,4]. Currently, research on dynamic spectrum access technologies in cognitive radio networks, mainly in the following aspects [5, 6]: network architecture, spectrum access behavior, spectrum sharing mode and spectrum access mode. From the perspective of network architecture, spectrum access can be divided into distributed and centralized; from the perspective of spectrum access behavior, spectrum access can be divided into cooperative and non-cooperative; from the perspective of spectrum sharing mode, spectrum access can be divided into overlay and underlay; from the perspective of spectrum access mode, spectrum access can be divided into competitive access, non-competitive access and hybrid access.

Most of the literatures are studied based on the performance analysis of dynamic spectrum access in cognitive radio networks; A small part of the relevant literature are studied based on spectrum access strategy, the mainstream trend is the use of game theory, auction theory, graph coloring theory and mathematical programming theory to make the optimal spectrum access strategy. Reference [7, 8] enables SUs to select the shortest time delay to access network through the analysis of the SUs waiting transmission delay in the network. In the analysis of asynchronous multi-channel spectrum access, the analysis method was explored in [9] for the control channel bottleneck, using RTS/CTS control frame time constraint in the channel negotiation process, But it did not consider control frame constraints limiting factor that the PU protection mechanisms lead to two-dimensional Markov chain model were used in [10] to analyze the performance of IEEE 802.11DCF protocol, but the model does not apply to multi-channel spectrum access. For multi-channel spectrum access, reference [11] proposed an analysis scheme based on IEEE802.11, but not suitable for dynamic channel state network. Reference [8, 12] uses M/G/1 queuing model to simulate the situation of the primary user using channel, theoretically derive that SUs need waiting time to receive services, but the model is for the situation of a primary user and a licensed channel, and is not universal.

The deficiencies of the existing studies are as follows：

(1) Most of the literatures only consider secondary users share spectrum opportunity of the same licensed network. However, in a new generation of mobile communication network, cognitive users can select to access different licensed networks.

(2) Most of the literatures are studied based on the performance analysis of dynamic spectrum access in cognitive radio networks, A small part of the relevant literature consider the selection problem of spectrum access strategy, namely SUs select which of the spectrum to access so that the throughput is the highest in cognitive radio network.

(3) Most of the literatures only consider the secondary users interference to the primary user, while multiple SUs simultaneously and competitively access channel in cognitive radio networks, SUs will interfere with each other.

Therefore, to solve the problem of mutual interference among SUs and selection of spectrum rented by SUs during dynamic spectrum access, the paper studies spectrum access algorithm based on game theory, which is suitable for cognitive radio network among SUs. Then the problem is abstracted as oligopolistic competition model of Cournot game theory. Finally, spectrum bandwidth rented by multiple SUs (2, 4 or 6) in the algorithm along with the increase of the number of SUs was simulated. Simulation results show that with the greater the number of cognitive users, the more the number of game to reach the Nash equilibrium and the greater the amount of spectrum bandwidth rented by SUs.

II. SPECTRUM ACCESS ALGORITHM BASED ON GAME THEORY

Cognitive radio network can be able to observe around wireless network environment, the use of spectrum sensing to obtain available spectrum information, so as to change its own communication parameters to adapt to the wireless environment for communication of a new generation of wireless networks, which are involved to the selection of strategy in many of its key technologies. Therefore, the use of game theory to analyze the cognitive radio network must be feasible and effective method.

The first part of this section gives a general model of dynamic spectrum access based on game theory in cognitive radio networks; The second part of this section gives system model of SUs dynamic access to cognitive radio networks; The third part of this section analyzes the game algorithm among SUs in the spectrum access, namely the Cournot model algorithm and gives the secondary user's utility function; The fourth part of this section introduces Nash equilibrium solution of the algorithm, by maximizing the utility of SUs, obtaining spectrum bandwidth rented by all SUs, namely Nash equilibrium. In order to facilitate the reader to understand, the paper first will represent the meaning that this section will use all the parameters in Table1 and Table 2, wherein Table 2 shows the parameters used in the algorithm.

Table 1.Meaning of Parameter

Parameter	Representative Meaning
N	The number of game participants
S_i	The strategic space that each game player i can choose
μ_i	The utility function for each game player i
s_i	Any one particular strategy

Table 2. Meaning of each parameter in the algorithm

Parameter	Representative Meaning
$u_s(b_i)$	The utility function that SU_i takes advantage of the bandwidth b_i for data transmission
$u_p(B)$	The total utility function of the *PUS*
$C(B)$	Rental costs of *PUs*
$k_i^{(s)}$	Transmission efficiency
v	Spectrum Alternative Factor
γ	Receiver signal-to-noise ratio (SNR)
BER_{tar}	The threshold of the bit error rate
b_i	Spectrum bandwidth that SU_i shares
p	Spectrum price that *SUs* pay to PUS
x, y, τ	Non-negative constant

A. System model

In the expression of standard formula of N game players, strategic space of the players is $S_1,\cdots,S_N$, the utility function is $\mu_1,\cdots,\mu_N$, therefore, a general model of game theory is expressed as[13, 14]:

$$G=\{N,S_1,\cdots,S_N;\mu_1,\cdots,\mu_N\} \quad (1)$$

In equation (1), the strategic space for each game player i is S_i, any of which particular strategy represented by s_i and $s_i \in S_i$. $\{s_1,\cdots,s_N\}$ is selected as the strategic combination of strategic component for all players. The utility function for each game player i is μ_i, in which $\mu_i\{s_1,\cdots,s_N\}$ represents the utility of game players i choosing strategic component $\{s_1,\cdots,s_N\}$.

The standard formula of Game theory should at least satisfy three basic requirements: 1) the number of game players is N ; 2) each player i can choose strategic space S_i; 3) For all players may choose the strategic combination $\{s_1,\cdots,s_N\}$, the utility for each game player i is $\mu_i\{s_1,\cdots,s_N\}$.

B. Cournot Model Algorithm

In the Cournot model algorithm, All SUs rent the same quality spectrum, and the same price fluctuates with the market demand. SUs's behavior is selfish and uncooperative, and it carries out the game among the SUs according to the spectrum bandwidth loaned by the SUs. All the SU stake the loan policy at the same time(decision leased spectrum bandwidth), and can learn to the strategy before other SU takes. The SUs determine the most suitable for their own strategy according to historical strategy. After repeated games, the spectrum bandwidth loaned by SUs has reached Nash equilibrium.

The ultimate goal of the algorithm is to maximize the spectrum band width rented by SUs, but the goal of the solution is to maximize the utility of the SUs, According to the Reference [15], we can get the utility function through SUi takes advantage of the bandwidth b_i for data transmission:

$$u_s(b_i) = k_i^{(s)} b_i - \frac{1}{2}\left(N{b_i}^2 + 2\nu b_i \sum_{j \neq i}^{N} b_j \right) - pb_i \quad (2)$$

ν is spectrum alternative factor [16], which means the size of the bandwidth requested by the SU is affected by other SUs. When $\nu = 0$, the SU is not affected by other SUs, when $\nu = 1$, the SU is affected by other SUs maximum. We only consider the utility of the SUs when $\nu = 0$, and therefore according to equation (2), we can obtain the utility function of the SUs:

$$u_s(b_i) = k_i^{(s)} b_i - \frac{1}{2} N{b_i}^2 - pb_i \quad (3)$$

To maximize the utility of the PUS, the utility of the PUS can be set as a function of bandwidth price, so the total utility function of the PUS is:

$$u_p(B) = \sum_{i=1}^{N} pb_i - \sum_{i=1}^{N} C(B) \quad (4)$$

In equation (4), p is the spectrum price that the SUs pay to the PUs, b_i is the spectrum bandwidth that the SUs loan, and $C(B)$ is rental costs of the PUs. Rental costs are defined as follows:

$$C(B) = x + y\left(\sum_{i=1}^{N} b_i \right)^{\tau} \quad (5)$$

where x, y, τ are non-negative constant, $\tau \geq 1$ (so that the pricing function is a convex function).

In order to obtain $k_i^{(s)}$, we must understand the wireless transmission model in cognitive radio [17], as described below:

The SUs use the adaptive modulation technology, and the transmission rate can dynamically adjust according to the channel quality. By adopting multiple quadrature amplitude modulations (MQAM) (rectangular constellation diagram, such as 4-QAM,16-QAM), single-input single-output Gaussian noise channel bit error rate (BER) can be approximated expressed as:

$$BER \approx 0.2 \exp\left(-1.5\gamma \big/ \left(2^k - 1 \right) \right) \quad (6)$$

where γ is receiver signal-to-noise ratio, k is the transmission efficiency, namely $k_i^{(s)}$ in equation (2).

BER_{tar} is the threshold of the bit error rate, and then the transmission efficiency is:

$$k = \log_2(1 + K\gamma) \quad (7)$$

where K is:

$$K = \frac{1.5}{\ln\left(0.2 / BER_{tar} \right)} \quad (8)$$

Combining equation (6), (7) and (8), we can obtain $k_i^{(s)}$ are:

$$k_i^{(s)} = \log_2\left(1 + \frac{1.5}{\ln\left(0.2 / BER_{tar} \right)} \gamma \right) \quad (9)$$

The derivative of the utility function of the PUS is with respect to spectrum bandwidth, which can obtain the maximum utility. At the same time we obtain the relationship between spectrum price and spectrum bandwidth is:

$$u_p(B) = \sum_{i=1}^{N} pb_i - \sum_{i=1}^{N} C(B) \quad (10)$$

$$\frac{\partial u_p(b)}{\partial b_i} = p - \tau y\left(\sum_{i=1}^{N} b_i \right)^{\tau-1} = 0 \quad (11) \qquad p = \tau y\left(\sum_{i=1}^{N} b_i \right)^{\tau-1} \quad (12)$$

Through the above formula, we can get the utility function of the SUs, which can be expressed as:

$$\begin{aligned} u_s(b_i) &= k_i^{(s)} b_i - \frac{1}{2} N{b_i}^2 - pb_i \\ &= k_i^{(s)} b_i - \frac{1}{2} N{b_i}^2 - \tau y\left(\sum_{i=1}^{N} b_i \right)^{\tau-1} b_i \\ &= \log_2\left(1 + \frac{1.5}{\ln\left(0.2 / BER_{tar} \right)} \gamma \right) b_i - \frac{1}{2} N{b_i}^2 - \tau y\left(\sum_{i=1}^{N} b_i \right)^{\tau-1} b_i \quad (13) \end{aligned}$$

C. *Analysis of game algorithm*

In the algorithm, we assume that the SU_i can obtain own utility function $u_s(b_i)$ through spectrum pool. All SUs take loan strategy at the same time, and can learn the strategy that other SU has previously taken. The SUs determine the most suitable for their own strategy according to historical strategy. After repeated games, the spectrum bandwidth loaned by SUs has reached Nash equilibrium.

The solution process flow chart of Cournot model algorithm shown in fig.1.

Thus, the spectrum access algorithm based on Cournot game model is expressed in table 3.

The algorithm steps are explained as follows:

Step 1: The initial value $BER_{tar} = 10^{-4}$, $\gamma = 15.4\text{dB}$, $\tau = 2$, $y = \frac{1}{2}$ is substituted into the formula(13),the utility function of the SU_i is:

$$u_s(b_i) = \left(2 - \sum_{j \neq i}^{n} b_j - b_i \right) b_i - \frac{1}{2} n{b_i}^2 \quad (14)$$

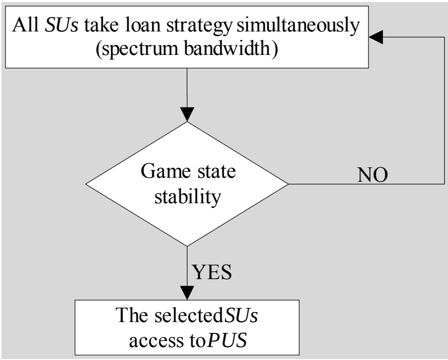

Figure1. Solution process flow chart of cournot model

Step 2: Equation (14) is a quadratic function, and solve the value of b_i when the function obtain the maximum value. The value is a function of equilibrium value b_j of other SU when the game reaches Nash equilibrium:

$$b_i = \frac{1}{2+n}\left(2 - \sum_{j \neq i}^{n} b_j\right) \quad (15)$$

Step 3:According to the equation (15),we obtain strategy values of n *SUs* .

$$\sum_{i=1}^{n} b_i = \frac{2n}{1+2n} \quad (16)$$

Table 3. Algorithm descriptions

Spectrum access of the *SU* Input: $N, BER_{tar}, \gamma, x, y, \tau$ Output: Spectrum bandwidth b_i and Utility function $u_s(b_i)$ when spectrum bandwidth loaned by SU_i has reached Nash equilibrium.
1. Utility function $u_s(b_i)$ of the SU_i according to the initial value; 2. According to the formula (14), calculate spectrum bandwidth b_i when utility function of the SU_i obtain the maximum value; 3. According to the formula (15), obtain strategy values of *n SUs*.

III. PERFORMANCE ANALYSIS

A. *Nash equilibrium*

Fig.2 represents the reaction function curves between the two SUs. According to the formula(15), the range of b_1 and b_2 is [0,2]respectively. Assume that b_1 gets value by 0.1step, the value of b_2 gradually less until 0 with the increase of the value of b_1; On the contrary, if b_2 gets value by 0.1step, the value of b_1 gradually less until 0 with the increase of the value of b_2, the intersection of which is Nash equilibrium point.

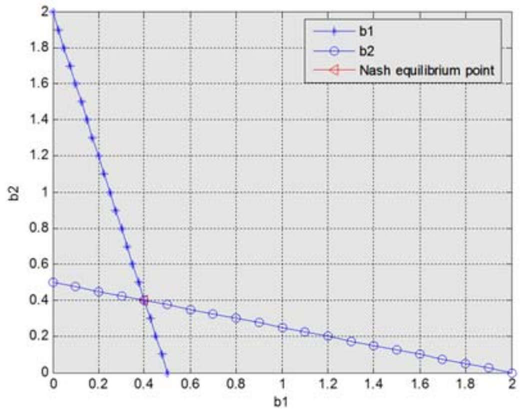

Figure2. Nash Equilibrium

B. *Game process*

Arbitrarily setting strategy values taken by multiple SUs (2, 4 and 6)for the first time in small-scale cognitive radio network environment, we can obtain their process diagrams until the game reaches equilibrium, respectively shown in fig.3, fig.4 and fig.5.

Infig.3, we set that the initial strategy values of two SUs were 0.25MHzand0.8MHZ respectively. During initialization, the strategy value ofSU1 is 0.25MHz, which is less than the strategy value ofSU2 0.8MHZ.And the strategy value ofSU1 is less than Nash equilibrium point, while the strategy value ofSU2is greater than Nash equilibrium point. Therefore, each Sui can adjust its own strategy. As we can have seen from the fig.3, after 5 games, strategy values two SU stake that will reach a steady state namely Nash equilibrium point.

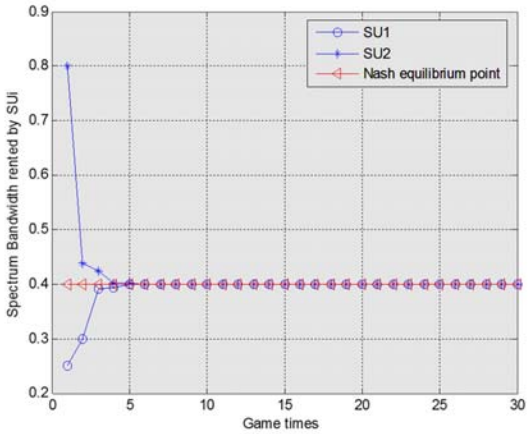

Figure3.Games between SUs

In Fig.4, we set that initial strategy values of4 SUswere0.1MHz, 0.25MHz,0.5MHZ and 0.75MHZrespectively. During initialization, the strategy value ofSU1 is 0.1MHz, which is less than strategy value ofSU2 0.25MHZ, strategy value ofSU3 0.5MHZ and strategy value ofSU4 0.75MHz respectively. And strategy value ofSU1 is less than Nash equilibrium point, while

DOI 10.5013/ IJSSST.a.17.36.36 ISSN: 1473-804x online, 1473-8031 print

strategy values ofSU2, SU3and SU3 are greater than Nash equilibrium point. Therefore, each Sui can adjust its own strategy. As we can have seen from the fig.4, after 8 games, the strategy values 4 SU stake that will reach a steady state namely Nash equilibrium point.

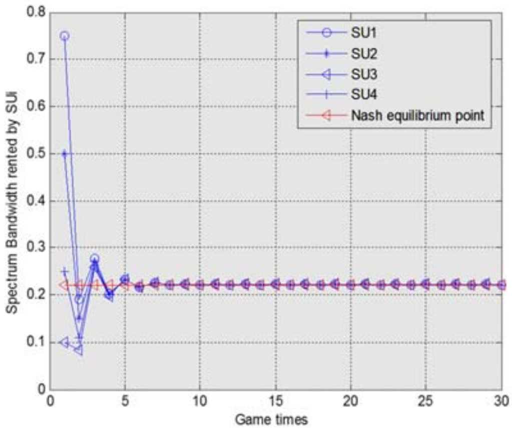

Figure4.Games process among 4 SUs

In fig.5, we set that initial strategy values of6 SUswere0.1MHz, 0.3MHz,0.4MHZ, 0.5MHZ, 0.6MHZ and 0.8MHzrespectively. During initialization, the strategy value ofSU1 is 0.1MHz, which is less than the strategy value ofSU2 0.3MHZ,the strategy value ofSU3 0.4MHZ, the strategy value ofSU4 0.5MHz, the strategy value ofSU5 0.6MHz and the strategy value ofSU6 0.8MHz respectively. And strategy value ofSU1 is less than Nash equilibrium point, while strategy values ofSU2, SU3, SU4, SU5 and SU6 are greater than Nash equilibrium point. Therefore, each Sui can adjust its own strategy. As we can have seen from the fig. 5, after 10 games, the strategy values 6 SU stake that will reach a steady state namely Nash equilibrium point.

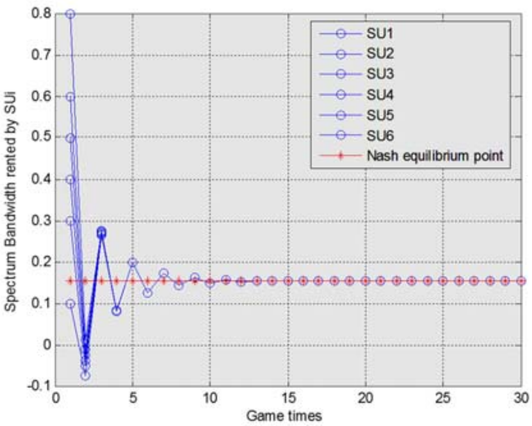

Figure5.Games process among 6 SUs

As can be seen from fig.3, fig.4 and fig.5, with the increase of the number of SUs, when game reaches Nash equilibrium, the number of game gradually increases and spectrum bandwidth rented by each SUi gradually decreases. However, the total amount of spectrum bandwidth rented by all SUs gradually increases, so as to maximize spectrum utilization rate.

Arbitrarily setting strategy values taken by multiple SUs (10, 20 and 30)for the first time in general-scale cognitive radio network environment, we can obtain their process diagrams until the game reaches equilibrium, respectively shown in fig.6, fig.7 andfig.8.

Infig.6, we set that the initial strategy values of10 SUs were 0.9MHz, 0.8MHZ, 0.7MHZ, 0.6MHZ, 0.5MHZ, 0.4MHZ, 0.3MHZ, 0.2MHZ, 0.15MHZ and 0.05MHZ respectively. During initialization, the strategy value ofSU1 is 0.05MHz, which is less than the strategy value ofSU2 0.15MHZ, the strategy value ofSU3 0.2MHZ, the strategy value ofSU4 0.3MHZ, the strategy value ofSU5 0.4MHZ, the strategy value ofSU6 0.5MHZ, the strategy value ofSU7 0.6MHZ, the strategy value ofSU8 0.7MHZ, the strategy value ofSU9 0.8MHZ and the strategy value ofSU10 0.9MHZ respectively. And the strategy value ofSU1 is less than Nash equilibrium point, while the strategy value of other Sui is greater than Nash equilibrium point. Therefore, each Sui can adjust its own strategy. As we can have seen from the fig. 6, after 16 games, strategy values 10 SU stake that will reach a steady state namely Nash equilibrium point.

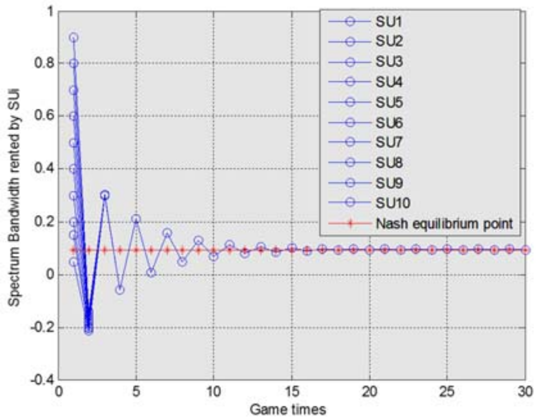

Figure6.Games process among 10 SUs

Infig.7, we set that the initial strategy values of20 SUs were 0.02MHz, 0.075MHz, 0.1MHz, 0.125MHz, 0.15MHz, 0.2MHz, 0.3MHz, 0.35MHz, 0.4MHz, 0.45MHz, 0.5MHz, 0.55MHz, 0.6MHz, 0.65MHz, 0.7MHz, 0.75MHz, 0.8MHz, 0.85MHz, 0.9MHz and 1MHz respectively. During initialization, the strategy value ofSU1 is 0.02MHz, which is less than the strategy value ofSU2 0.075MHZ, the strategy value ofSU3 0.1MHZ, the strategy value ofSU4 0.125MHZ, the strategy value ofSU5 0.15MHZ, the strategy value ofSU6 0.2MHZ, the strategy value ofSU7 0.3MHZ, the strategy value ofSU8 0.35MHZ, the strategy value ofSU9 0.4MHZ, the strategy value ofSU10 0.45MHZ, the strategy value ofSU11 0.5MHZ, the strategy value ofSU12 0.55MHZ, the strategy value ofSU13 0.6MHZ , the strategy value ofSU14 0.65MHZ, the strategy value ofSU15 0.7MHZ, the strategy value ofSU16 0.75MHZ , the strategy value ofSU17 0.8MHZ, the strategy value ofSU18 0.85MHZ, the strategy value ofSU19 0.9MHZ and the strategy value ofSU201MHZ

DOI 10.5013/ IJSSST.a.17.36.36

ISSN: 1473-804x online, 1473-8031 print

respectively. And the strategy value ofSU1 is less than Nash equilibrium point, while the strategy value of other Sui is greater than Nash equilibrium point. Therefore, each Sui can adjust its own strategy. As we can have seen from the fig.7, after 18 games, strategy values 20 SU stake that will reach a steady state namely Nash equilibrium point.

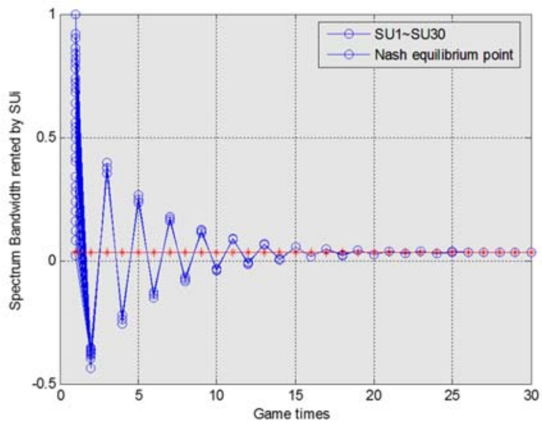

Figure7. Games process among 20 SUs

Infig.8, we set that the initial strategy values of30 SUs were 0.02MHz, 0.08MHz, 0.12MHz, 0.16MHz, 0.2MHz, 0.24MHz, 0.28MHz, 0.3MHz, 0.34MHz, 0.4MHz, 0.42MHz, 0.46MHz, 0.5MHz, 0.52MHz, 0.54MHz, 0.56MHz, 0.6MHz, 0.64MHz, 0.68MHz, 0.7MHz, 0.72MHz, 0.74MHz, 0.78MHz, 0.8MHz, 0.82MHz, 0.84MHz, 0.86MHz, 0.9MHz, 0.92MHz and 1MHz respectively. During initialization, the strategy value ofSU1 is 0.02MHz, which is less than the strategy value ofSU2 0.08MHZ, the strategy value ofSU3 0.12MHZ, the strategy value ofSU4 0.16MHZ, the strategy value ofSU5 0.2MHZ, the strategy value ofSU6 0.24MHZ, the strategy value ofSU7 0.28MHZ, the strategy value ofSU8 0.3MHZ, the strategy value ofSU9 0.34MHZ, the strategy value ofSU10 0.4MHZ, the strategy value ofSU11 0.42MHZ, the strategy value ofSU120.46MHZ, the strategy value ofSU130.5MHZ, the strategy value ofSU140.52MHZ, the strategy value ofSU150.54MHZ, the strategy value ofSU160.56MHZ, the strategy value ofSU170.6MHZ, the strategy value ofSU180.64MHZ, the strategy value ofSU190.68MHZ, the strategy value ofSU200.7MHZ, the strategy value ofSU21 0.72MHZ, the strategy value ofSU22 0.74MHZ, the strategy value ofSU230.78MHZ, the strategy value ofSU240.8MHZ, the strategy value ofSU250.82MHZ, the strategy value ofSU260.84MHZ, the strategy value ofSU270.86MHZ, the strategy value ofSU280.9MHZ, the strategy value ofSU290.92MHZ and the strategy value ofSU301MHZ respectively. And the strategy value ofSU1 is less than Nash equilibrium point, while the strategy value of other Sui is greater than Nash equilibrium point. Therefore, each Sui can adjust its own strategy. As we can have seen from the fig.8, after 15 games, strategy values 30 SU stake that will reach a steady state namely Nash equilibrium point.

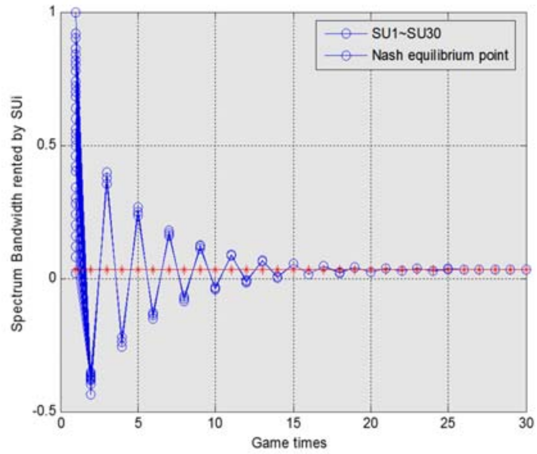

Figure8.Games process among 30 SUs

As can be seen from fig.6, fig.7 and fig.8, compared with fig.3, fig.4and fig.5: when game reaches Nash equilibrium, the number of game in small-scale cognitive radio network environment is much greater than the number of game in general-scale cognitive radio network environment; With the increase of the number of SUs, when game reaches Nash equilibrium, spectrum bandwidth rented by each SUi gradually decreases. However, the total amount of spectrum bandwidth rented by all SUs gradually increases, so as to maximize spectrum utilization rate. In addition, because the signal transmission time is very short, the total game time is still very short.

IV. CONCLUSIONS

This paper introduces the game theory of economics into the study of cognitive radio network, expounds game theory analysis scheme in cognitive radio network and gives spectrum access algorithm based on game theory, which is suitable for cognitive radio network among SUs. Then the problem is abstracted as oligopolistic competition model of game theory, namely the Cournot model. This paper introduces the Nash equilibrium solution of the algorithm, by solving the SUs utility maximization in order to obtain the spectrum bandwidth rented by SUs, namely the Nash equilibrium solution. Cournot model is without delay for each SU and each SU takes strategies at the same time; Simulation results show that the algorithm can significantly improve the total spectrum bandwidth rented by SUs, while improving the spectrum utilization of primary user system.

ACKNOWLEDGMENTS

This work is supported by the project of National Natural Science Foundation of China (No. 61379059) and Hubei Province Natural Science Foundation (No. 2014CFB912).

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