Adaptive Cooperative Spectrum Sharing Based on Fairness and Total Profit in Cognitive Radio Networks

Jian Chen, Xiao Zhang, and Yonghong Kuo

A cooperative model is presented to enable sharing of the spectrum with secondary users. Compared with the optimal model and competitive model, the cooperative model could reach the maximum total profit for secondary users with better fairness. The cooperative model is built based on the Nash equilibrium. Then a conceding factor is introduced so that the total spectrum required from secondary users will decrease. It also results in a decrease in cost which the primary user charges to the secondary users. The optimum solution, which is the maximum total profit for the secondary users, is called the collusion state. It is possible that secondary users may leave the collusion state to pursue the maximum of individual profit. The stability of the algorithm is discussed by introducing a vindictive factor to inhabit the motive of deviation. In practice, the number of secondary users may change. Adaptive methods have been used to deal with the changing number of secondary users. Both the total profit and fairness are considered in the spectrum allocating. The shared spectrum is 11.3893 with a total profit of 65.2378 in the competitive model. In the cooperative model, the shared spectrum is 8.5856 with the total profit of 73.4963. The numerical results reveal the effectiveness of the cooperative model.

Keywords: Spectrum sharing, cognitive radio, Nash equilibrium, cooperative model, stability analysis.

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I. Introduction

Frequency spectrum may become congested when accommodating diverse type of users, applications, and air interfaces in the next generation wireless networks. Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and can be used to improve the efficiency of frequency spectrum by exploiting the existence of spectrum holes [1]. Spectrum management in cognitive radio aims at meeting the requirements from both the primary user and the secondary users [2], [3]. There are three strategies in spectrum sharing: the optimal model, the competitive model, and the cooperative model [4]-[6].

The objective of the optimal model is to maximize the profit for secondary users, which may deprive some secondary users of spectrum sharing [7], [8]. Therefore, it is unfair to all secondary users. The objective of the competitive model is to maximize the individual profit for every secondary user. The result of competition among the secondary users is called the Nash equilibrium. It is stable and fair, but the total profit for secondary users is not the maximum. In the cooperative model, the objective is to maximize the total profit; a state of collusion is kept through the cooperation among all secondary users. It has the advantages of both higher total profit and better fairness. Both competitive and cooperative spectrum sharing [9] have been based on Bertrand model where multiple primary users compete with each other. In [10], focus is on the competitive spectrum sharing among multiple secondary users based on Cournot model [11], [12].

In this paper, the theory and realization of cooperative

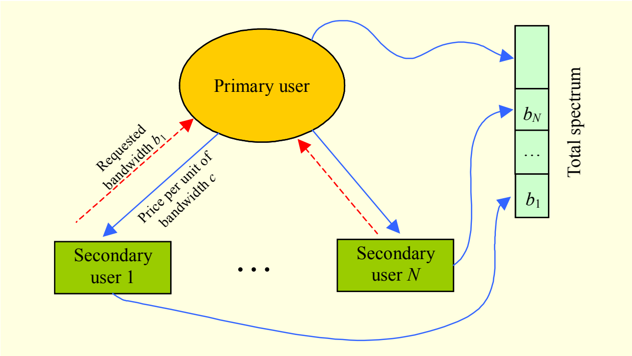

Fig. 1. System model for spectrum sharing.

spectrum sharing is presented in detail, where there is one primary user but also several secondary users (Fig. 1). We also consider the cases with a changing number of secondary users. The advantages of cooperative sharing are proved by simulation.

The paper is organized as follows. Section II describes the system model and assumptions. Spectrum sharing models are presented in section III, including the optimal, competitive, and cooperative models. Section IV presents the simulation results. The performance of the proposed adaptive method is evaluated in section V. The conclusions are stated in section VI.

II. System Model

1. Primary User and Secondary User

We consider a spectrum overlay-based cognitive radio with one primary user and N secondary users. The primary user is willing to share the spectrum b_i, i=1, 2,⋯, N, with secondary user i. The primary user charges secondary users for the spectrum at a rate of c per unit bandwidth, where c is a function of the total size of spectrum available for sharing by the secondary users. By sharing the spectrum with the primary user, the secondary user i can communicate. The revenue of secondary user i is denoted by r_i per unit of achievable transmission rate.

2. Wireless Transmission Model

We assume a wireless transmission model based on adaptive modulation and coding where the transmission rate can be dynamically adjusted based on channel quality. The spectral efficiency [9] can be obtained as (1).

$$k = \log_2^{(1+K\gamma)}, \qquad (1)$$

where $K = \dfrac{1.5}{\ln 0.2 / BER^{\text{tar}}}$, γ is the signal-to-noise ratio (SNR), and BER^{tar} is the target bit-error-rate (BER).

III. Realization on Spectrum Sharing Model

We assume that the pricing function [10], which is used by the primary user to charge the secondary users, is given by

$$c(B) = x + y(b_1 + b_2 + \cdots + b_N)^{\tau}, \qquad (2)$$

where x, y, τ, are non-negative constants, $\tau \geq 1$ (so that this pricing function is convex). The condition $c(B) > w \times \sum_{b_j \in B} b_i$ is necessary to ensure that the primary user is willing to share spectrum. Let w denote the worth of the spectrum for the primary user. B denotes the set of strategies of all secondary users, that is, B={b_1, b_2,⋯, b_N}. Note that the primary user charges all of the secondary users at the same price.

The revenue of a secondary user can be obtained from $r_i \times k_i \times b_i$, while the cost of spectrum sharing is $b_i \times c(B)$. Therefore, the profit of secondary user i can be obtained by

$$p_i(B) = r_i k_i b_i - b_i c(B). \qquad (3)$$

The marginal profit function for secondary user can be obtained from (4).

$$\frac{\partial p_i(B)}{\partial b_i} = r_i k_i - x - y\left(\sum_{b_j \in B} b_j\right)^{\tau} - y b_i \tau \left(\sum_{b_j \in B} b_j\right)^{\tau-1}. \qquad (4)$$

Based on the similar theory, the total marginal profit function for all the secondary users can be denoted as

$$\frac{\partial \sum_{j=1}^{N} p_j[B(t)]}{\partial b_i(t)}.$$

1. Optimal Spectrum Sharing Model

In order to get the solution of the biggest profit for all the secondary users, an optimal equation is built as

$$\begin{aligned} &\text{maximize } \sum_{i=1}^{N} p_i(B), \\ &\text{subject to } b_i \geq 0, \quad \forall b_i \in B. \end{aligned} \qquad (5)$$

For the secondary user i, we assume that the initial sharing spectrum, which is sent to the primary user, is $b_i(0)$. The primary user adjusts the pricing function c and then sends it back to the secondary user. The secondary user estimates the marginal profit function. The size of sharing spectrum the next time can be obtained by

$$b_i(t+1) = b_i(t) + \alpha_i b_i(t) \frac{\partial \sum_{j=1}^{N} p_j[B(t)]}{\partial b_i(t)}, \qquad (6)$$

where α_i is the parameter to adjust its speed, that is, learning speed, and B_{-i} is the strategy set except for secondary user i, that is, $B_{-i}=\{b_j \mid j=1,\cdots,N; j\neq i\}$, $\varepsilon=0.0001$ [4], [9].

The marginal profit can be estimated as

$$\frac{\partial \sum_{j=1}^{N} p_j\left[B(t)\right]}{\partial b_i(t)} \approx \frac{1}{2\varepsilon}\left\{\begin{array}{l}\sum_{j=1}^{N} p_j\left\{[B_{-i}(t)\cup\left(b_i(t)+\varepsilon\right)]\right\} \\ -\sum_{j=1}^{N} p_j\left\{[B_{-i}(t)\cup\left(b_i(t)-\varepsilon\right)]\right\}\end{array}\right\}. \tag{7}$$

When it satisfies the condition $b_i(t+1)=b_i(t)$, the optimal solution of the equation is $B=\{b_1, b_2,\cdots, b_N\}$.

2. Competitive Spectrum Sharing Model

The main objective of the competitive model is to maximize the profits of individual secondary users through the use of a game. The result is called the Nash equilibrium.

In the distributed dynamic game, secondary users may only be able to observe the pricing information from the primary user; they cannot observe the strategies and profits of other secondary users. The Nash equilibrium for each secondary user is built on the interaction with the primary user. Since all secondary users are rational, so as to maximize their profits, they can adjust the size of the requested spectrum b_i based on the marginal profit function. In this case, each secondary user can communicate with the primary user to obtain different pricing functions for different strategies. The adjustment of the requested/allocated spectrum size can be modeled as follows:

$$b_i(t+1)=b_i(t)+\alpha_i b_i(t)\frac{\partial p_i[B(t)]}{\partial b_i(t)}. \tag{8}$$

The initial strategy is denoted by $b_i(0)$. Similar with (7), the marginal profit can be estimated as

$$\frac{\partial p_i\left[B(t)\right]}{\partial b_i(t)} \approx \frac{1}{2\varepsilon}\left\{\begin{array}{l} p_i\left\{[B_{-i}(t)\cup(B_i(t)+\varepsilon)]\right\} \\ -p_i\left\{[B_{-i}(t)\cup(B_i(t)-\varepsilon)]\right\}\end{array}\right\}. \tag{9}$$

When it satisfies the condition $b_i(t+1)=b_i(t)$, the Nash equilibrium points $(b_1^*, b_2^*, \cdots, b_N^*)$ can be obtained.

3. Cooperative Spectrum Sharing Model

In the model of competitive spectrum sharing, the Nash equilibrium is a state wherein the individual profit for the secondary user is at its maximum. The result is not the best because it does not consider the interaction of other users. For cooperative spectrum sharing, the secondary users can communicate with consideration of their behavior on other users.

We assume that they can reach commonality by communicating with each other. Decreasing the size of sharing spectrum a little for all the secondary users on the Nash equilibrium, that is, a conceding factor λ_i, $0<\lambda_i<1$, is multiplied based on the strategy of the Nash equilibrium. Although the size of the sharing spectrum decreased, the cost which the primary user charges to the secondary user also decreased, which results in the increase of the profit for all secondary users and a total profits increase as well.

A strategy for cooperative spectrum sharing is as follows. The Nash equilibrium $(b_1^*, b_2^*, \cdots, b_N^*)$ can be obtained from (8). All secondary users will negotiate and multiply λ_i, which is set to (0.5, 1). In order to keep the fairness, it is required that the value of λ_i, $i=1, 2,\cdots, N$, should be similar. Within the scope of λ_i, $(\lambda_1 b_1^*, \lambda_2 b_2^*, \cdots, \lambda_N b_N^*)$ is chosen so that the profit $p(B)=p_1(B)+p_2(B)+\cdots+p_N(B)$ is the maximum, which is called the collusion state.

4. Instability in the Cooperative Model

Instability. The collusion is unstable because this strategy is not acquired from the marginal profit function of secondary users; it is possible that one or more secondary users may deviate from the Nash equilibrium. Suppose secondary user u_1 deviates, its profit may increase by setting its marginal profit function (4) to zero. If secondary user u_2 does not change its strategy, the profit of secondary user u_2 will decrease. Therefore, any secondary user has the motive to deviate from collusion.

Avoidance of Instability. A vindictive mechanism should be applied to the deviating secondary users so that it has no motive to deviate from the collusion state. Suppose secondary user i deviates, and secondary user j, $j\neq i$, is still in the state of collusion. Before secondary user i deviates, it will compute the long term profit.

The profit in future stages will multiply a weight δ_i, $0<\delta_i<1$. It would insure the profit in future stages was not higher than that of the previous stages, which means that the current profit is more valuable than in future stages. For secondary user i, p_i^{c}, p_i^{n}, and p_i^{d} denote the profits due to collusion, Nash equilibrium, and deviation, respectively. There are two cases. In the first case, they are in collusion at all stages, so there is not any secondary user to deviate from the optimal solution. The long term profit of the secondary user i is shown in (10). The other case is that the secondary user i deviates from the optimal solution at the first stage. It will be in a Nash equilibrium state in the following stages, and the long term profit of the secondary user i is shown in (11).

$$p_i^c+\delta_i p_i^c+\delta_i^2 p_i^c+\delta_i^3 p_i^c+\cdots=\frac{1}{1-\delta_i}p_i^c, \tag{10}$$

$$p_i^d+\delta_i p_i^n+\delta_i^2 p_i^n+\cdots=p_i^d+\frac{\delta_i}{1-\delta_i}p_i^n. \tag{11}$$

The collusion will be maintained if the long-term profit due to adopting collusion is higher than that due to deviation:

$$\frac{1}{1-\delta_i} p_i^{\mathrm{c}} > p_i^{\mathrm{d}} + \frac{\delta_i}{1-\delta_i} p_i^{\mathrm{n}},$$

that is,

$$\delta_i \geq \frac{p_i^{\mathrm{d}} - p_i^{\mathrm{c}}}{p_i^{\mathrm{d}} - p_i^{\mathrm{n}}}. \tag{12}$$

From (12), we know that the collusion will be maintained because of low long term profit for the secondary user who wants to deviate. The weights δ_i are the vindictive factors to inhabit the motive of leaving the collusion state.

5. Change of Number of Secondary Users

It is possible that the number of secondary users may change. Sometimes there are more secondary users applying for spectrum sharing with the primary user, and sometimes the secondary users have finished the communication and retreated from the spectrum they have taken up.

Suppose there are two secondary users that have been in collusion state. Suppose also that there is a third secondary user to apply for spectrum sharing. We assume that the primary user has no more spectrums to share, and that the two secondary users should release some of their spectrums to the newcomer.

During the process of spectrum reallocating, an adaptive method is applied considering fairness and total profit. The fairness is subjected to QoS, which means that the allocated spectrum among the secondary users should be similar, they pursue the maximum of throughput at the same time. Suppose the channel qualities are different for the secondary users. Those secondary users in the channel with good quality will obtain more spectrums by competition when they are in the Nash equilibrium. It is also true in the collusion state.

During the adaptive process, the total profit will be computed assuming a fixed portion of individual spectrum is released by prior secondary users in next step. The process will continue if the total profit increases. When the decrease of total profit is caused by one secondary user, this secondary user will stop the spectrum release. The other secondary user can continue the adaptive process.

The secondary user which stops the spectrum release earlier is the secondary user in the channel with good quality. Because of the good quality of the channel, the secondary user can take up more spectrums with a higher profit than those in a bad channel because of competition. It also has a higher throughput.

Suppose there are two secondary users. We use a parameter f_i, i=1, 2, to describe the real sharing spectrum at the given channel quality:

$$f_i = \frac{b_i k_i}{\gamma_i}, \tag{13}$$

where b_i is the sharing spectrum for secondary user i, k_i is the spectral efficiency in (1), and γ_i is the SNR.

The fairness of sharing spectrum is represented by the ratio R.

$$R = f_1 : f_2. \tag{14}$$

The better the fairness, the nearer R approximates to 1.

When secondary users reach the optimal solution, the fairness will not be as good as the three secondary users getting into the collusion state directly. The reason is that the previous secondary user of good quality has a higher priority than the one in a bad channel and the later secondary users.

When secondary users have finished the communication, they retreat from the spectrum they had shared by an adaptive algorithm. Suppose a fixed portion of the retreated spectrum will be allocated to the rest of the secondary users equally or sent to any one of the rest users, the total profits for all cases will be computed. The allocation with the highest total profit will be carried out. The process will be repeated until the spectrum has been allocated.

In order to guarantee the maximum total profit, it is possible for the secondary users with better channel quality to obtain more spectrum than the others in bad channel, that is, the secondary users in bad channel may stop the spectrum addition earlier.

IV. Simulation Results

1. Parameter Setting

We consider a cognitive radio environment with one primary user and two secondary users sharing a frequency spectrum of 20 MHz. For the pricing function, we use x=0, y=1, τ=1 [10]. For the primary user, the value of spectrum for the primary user is assumed to be w=1. The revenue of a secondary user per unit transmission rate is r_i=10, $\forall i$. The target average BER is $BER^{\mathrm{tar}}=10^{-4}$. The initial value is $b_i(0)$=2. The learning rate is α_i=0.09. The SNR for secondary users u_1 and u_2 are denoted by γ_1 and γ_2, where γ_1 =11 dB and γ_2=12 dB.

2. Simulation Results

A. Optimal and Competitive Spectrum Sharing

The total profit is represented by $p(B)=p_1(B)+p_2(B)$. In Fig. 2, the total profits in the optimal model arrived at its biggest value, 76.7333, when (b_1, b_2)=(0, 8.75).

The trajectories of the optimal and competitive models shown in Fig. 3 have the initial value of (2, 2). In the competitive model, the shared spectrum is determined by a game, in which

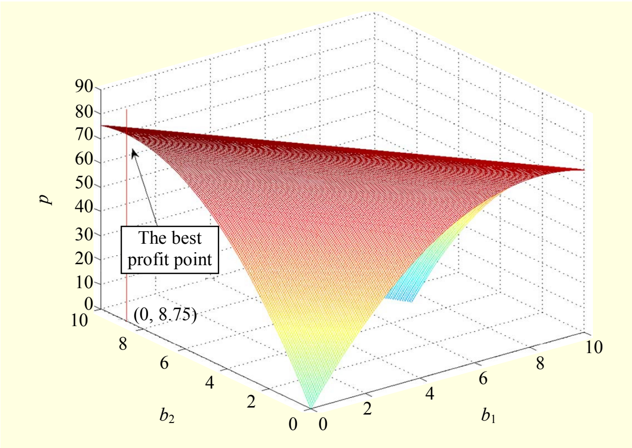

Fig. 2. Total profit versus sharing spectrum in optimal model.

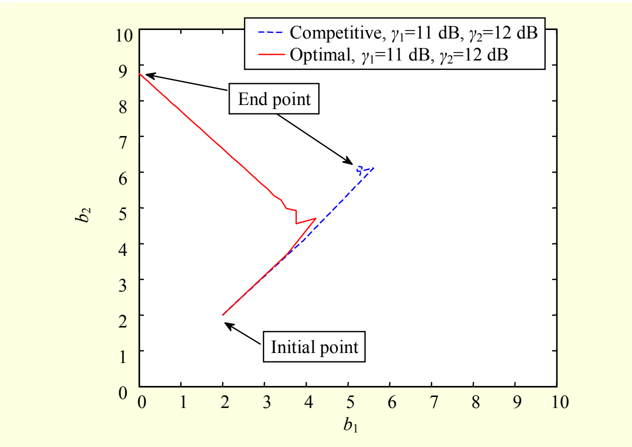

Fig. 3. Trajectories of optimal model and competitive model.

the two secondary users have been in the Nash equilibrium. In our simulation, the Nash equilibrium is at (5.2591, 6.1302). The sum of spectrum sharing is 11.3893 with the total profit of 65.2378.

It can be seen that the total profit for the optimal model is higher than that of the competitive model obviously. However, one secondary user has no spectrum sharing in the optimal model, which indicates the lack of fairness. The advantage of the competitive model is that, although it has a lower profit sum, it is fair.

B. Cooperative Spectrum Sharing

Based on the Nash equilibrium, we set the weight λ_i in the range of [0.5, 1]. In order to maintain the fairness, we assume $|\lambda_2 - \lambda_1| \le 0.1$ to guarantee the size of sharing spectrum is similar for both two secondary users.

Two secondary users reached their Nash equilibrium at (5.2591, 6.1302). The relationship between the total profit p and λ_1 and λ_2 is shown in Fig. 4. At λ_1=0.70 and λ_2=0.80, the

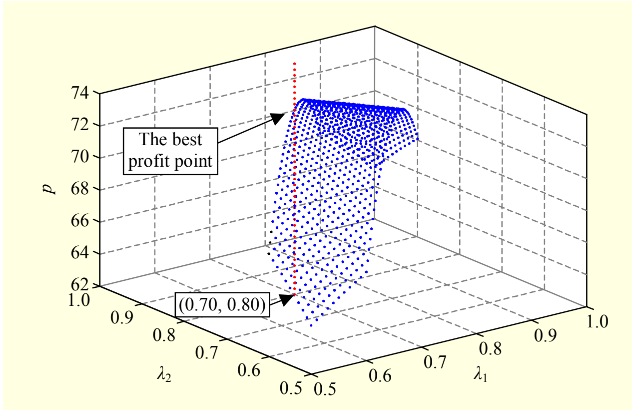

Fig. 4. Relationship between total profit and weights.

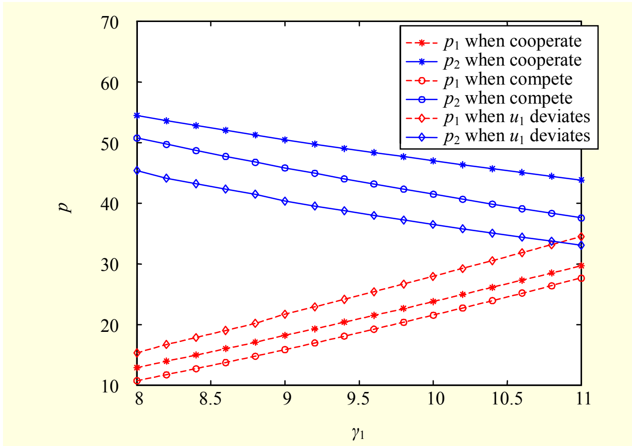

Fig. 5. Comparison of individual profit for three cases.

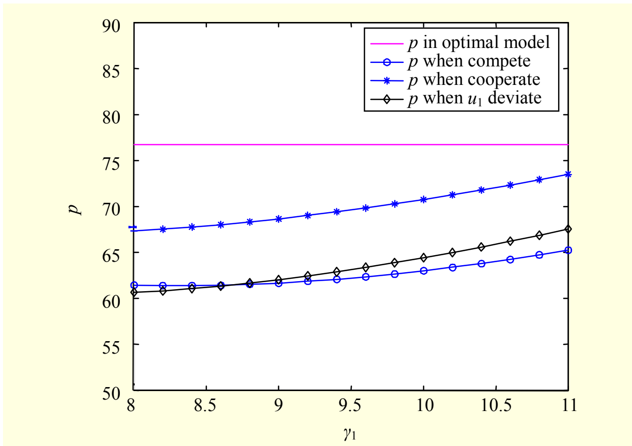

Fig. 6. Comparison of total profit for four cases.

total profit got to its maximum where the collusion is at (3.6814, 4.9042), and the shared spectrum is 8.5856 with the total profit of 73.4963.

Compared with the competitive model, we found that the shared spectrum in the cooperative model is less than that of the competitive model; it has a bigger total profit than that of the Nash equilibrium. The reasons for this are that we set $(\lambda_1 b_1^*, \lambda_2 b_2^*)$ as the strategies to share the spectrum, the price is lower, and the total profit increases.

Suppose secondary user u_1 deviates from the optimal solution. The strategy of secondary user u_2 does not change. Secondary user u_1 adopts the strategy based on the marginal profit function. The profit for the two secondary users will change when secondary user u_1 deviates.

A comparison of the individual profit in the cooperative model, competitive model, and deviation is shown in Fig. 5. The total profit for the secondary users is shown in Fig. 6. p_1 and p_2 are the profits of secondary users u_1 and u_2. γ_1 is a variable, which changes in the range of 8 dB to 11 dB, and γ_2 is 12 dB. p_1 and p_2 are bigger in the cooperative model than in the competitive model. Also, the total profit is bigger in the cooperative model. When secondary user u_1 deviates from the collusion state, p_1 is higher and p_2 is lower. The total profit is lower, that is, the amount of increasing p_1 is smaller than that of decreasing p_2.

C. Cooperative Model with More Secondary Users

The previous analysis is based on two secondary users. The analyzing method is similar for more secondary users. In practice, the number of secondary users may change. For example, there is a third secondary user denoted by u_3 to apply for spectrum sharing. We assume that the channel quality for u_3 is the same with secondary user u_2 (γ_1 is a variable, $\gamma_2=\gamma_3=12$ dB). There are no more spectrums for the primary user to share, and an adaptive method is applied in the allocation of spectrum.

First, u_1 and u_2 release a fixed portion of spectrum to u_3, and the total profit is computed. If the total profit could increase, the process will go on. If the total profit decreases, the secondary user with a better channel state will stop the process of release because it causes the decrease of the total profit. The trajectory of the process is shown in Fig. 7. The corresponding total profit is shown in Fig. 8.

When a new secondary user applies for spectrum sharing, it

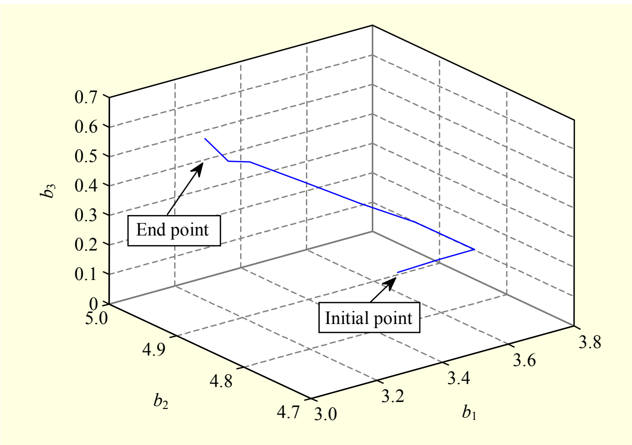

Fig. 7. Trajectory of spectrum for new secondary user.

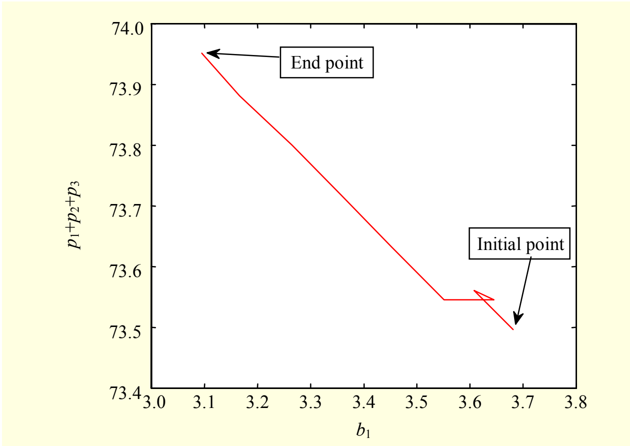

Fig. 8. Trajectory of profit sum for new secondary user.

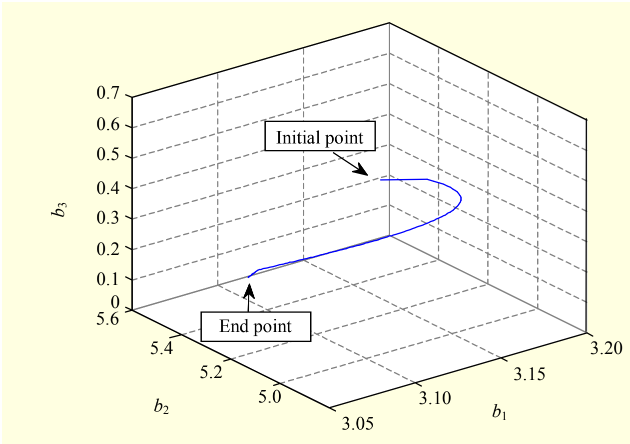

Fig. 9. Trajectory for spectrum retreating.

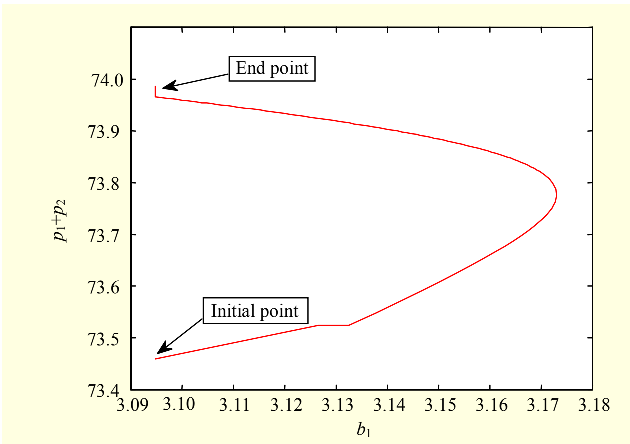

Fig. 10. Trajectory of profit sum for new secondary user while retreating.

would converge at (3.0948, 4.9042, and 0.6349) with the total spectrum of 8.6339, which is a little higher than the case with two secondary users. The total profit is 74.0218 which is also a little higher.

When the third secondary user releases the spectrum, the adaptive method is applied to reallocate the spectrum as shown in Fig. 9. The left two secondary users converge at (3.0948, 5.4393) with the total shared spectrum of 8.5341. The total profit is 73.9867 as shown in Fig. 10.

V. Discussion

We will compare the fairness and primary profit in the cooperative and competitive models.

1. Fairness Comparison

Suppose there are three secondary users, and the condition is the same as that in Fig. 7. The three secondary users reach their Nash equilibrium, which is at (3.7269, 4.5974, 4.5974). The total shared spectrum in the competitive model is 12.9217. The total profit is 56.1652.

The collusion is set by finding weight vectors so that the total profits for the three secondary users reach the maximum. The weight vectors are λ_1=0.60 and λ_2=λ_3=0.70. Also, the collusion point is at (2.2362, 3.2182, 3.2182). The total shared spectrum in the cooperative model is 8.6726 with the total profit of 74.7779. Because the channel state and SNR are the same for u_2 and u_3, their weights are same, too. Based on the definition in (14), the fairness represented by R is defined as

$$R = f_1 : f_2 : f_3 ,$$

where f_i is defined in (13). The corresponding ratio R in the

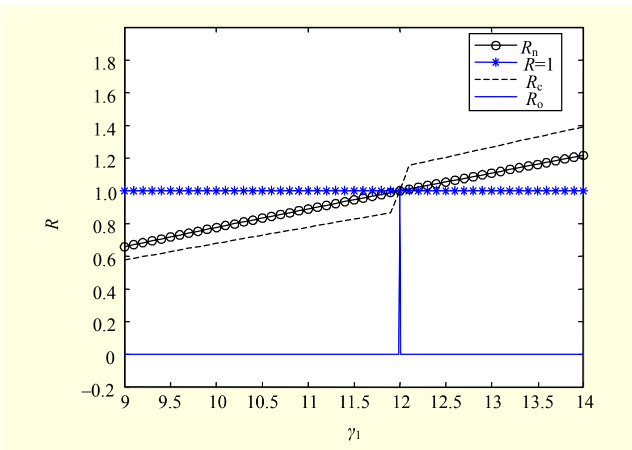

Fig. 11. Comparison of fairness between cooperative, non-cooperative (competitive), and optimal models.

competitive model is (29.6%, 35.2%, and 35.2%). It is (25.8%, 37.1%, and 37.1%) in the cooperative model when three secondary users getting into collusion directly.

When two secondary users have been in a collusion state, a third secondary user comes and applies for spectrum sharing. The corresponding ratio R is (36.68%, 56.06%, and 7.26%). The fairness is worse than that of three secondary users getting into collusion state directly, which means that prior secondary users in the good channel has taken up more spectrum resource.

When there are two secondary users, the comparison of the fairness is shown in Fig. 11, where γ_2=12 dB, γ_1 is a variable. R_c, R_n, and R_o stand for the fairness ratio in the cooperative, non-cooperative (competitive), and optimal models, respectively. The nearer R approximates to 1, the better the fairness. R_n is 0.8894 in the competitive model, R_c is 0.7782 in the cooperative model, and R_o is 0 in the optimal model. It can be seen that the fairness of the competitive model is the best.

2. Primary User Profit

The profit of the primary user p_f is determined by revenue and cost. This profit consists of four parts: the income p_{f1} from communication by itself, charges from secondary users p_{f2}, fees paid to the spectrum management p_{f3}, and the loss from QoS attenuation p_{f4}. p_{f4} is caused by the interference from secondary users. The profit of the primary user is represented as

$$p_f = p_{f1} + p_{f2} - p_{f3} - p_{f4} ,$$

$$p_{f2} = c(B)B ,$$

$$p_{f3} = wB_w ,$$

$$p_{f4} = m_2 \left[B^{\text{req}} - k_f (B_w - B) \right]^2 , \qquad (15)$$

where m_1 is the constant for the primary cost function, $c(B)$ is the income that the primary user charges to the secondary users, B is the sharing spectrum size, w and B_w are the cost and size for the primary user to take up the spectrums, B^{req} is the bandwidth required by primary user, and k_f is the spectrum efficiency of the primary user.

When the SNRs of the channel for secondary users are γ_1=11 dB and γ_2=12 dB, the channel quality for primary user is γ_f=12 dB. The other parameters are set as p_{f1}=50, m_1=1, B_w=20 MHz, and B^{req}=20 Mbps. The primary user's profit is p_{fn}=135.5642 in the competitive model, p_{fo}=106.6394 in the optimal model, and p_{fc}=103.7125 in the cooperative model. This shows that it is the best for the primary user when the secondary users are competitive. The primary user's profits decrease when the secondary users cooperate.

VI. Conclusion

Cognitive radio is regarded as the key technology for next generation of wireless network. Dynamic spectrum sharing is one of the most important problems for cognitive radio. Based on the competitive spectrum sharing on game theory, cooperative spectrum sharing is presented in this paper. The advantages over the optimal and competitive models have been shown by simulation. A general solution for the instability problem has been proposed, and an adaptive method is used for the changing number of secondary users. We have shown a solution with the maximum of total profit and better fairness in spectrum sharing. In future work, we will do further research on fairness evaluation and spectrum allocation.

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