Opportunistic Access for Cooperative Cognitive Radio Networks with Requirement Constraint

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***Abstract*—In cognitive radio network, cooperation between primary users and secondary users can improve their data rate and achieve dynamic spectrum sharing. This paper proposes a novel spectrum sharing model to solve the opportunistic access problem in cooperative cognitive radio network (CCRN). In this model, primary users select sets of secondary users as their relays and allocate channel resource to secondary users according to their cooperative transmitting power. Secondary users have their own data rate requirement, and they have to determine their optimal relay power to satisfy their requirement. Primary users have to select the best relay group and maximize their throughput. We model this problem as a Stackelberg game and prove the existence and uniqueness of Nash Equilibrium. A low-complexity algorithm is proposed to realize the cooperative transmission mechanism. Simulation results show significant throughput enhancement in the primary network and more opportunities for secondary users to get access into the spectrum.**

I. Introduction

With the rapid development of wireless devices and networks, spectrum resources have become more and more precious and scarce. Furthermore, historical allocation policies have led to highly unbalanced spectrum utilization [1], because spectrum resources are provided to dedicated users with exclusive use.

Cognitive Radio is envisaged to be a promising approach to solve this problem in wireless networks [2]-[3]. In cognitive radio network, primary users have exclusive use of the spectrum resources and secondary users cannot access the spectrum without authority of primary users. However, due to several reasons, such as channel fading, fierce interference, multipath effects, parts of the primary users may suffer from poor channel conditions. Therefore, these primary users have incentives to rely on secondary users, who have better channel conditions, to improve their transmission quality. Secondary users also have motivation to cooperate with the primary users in order to exploit the channel access opportunities. The cooperation between primary users and secondary users dramatically improves the transmission rates of the primary network and generates more spectrum access opportunities to the secondary users, resulting in a ”win-win” situation.

Cooperative transmission mechanisms have been studied recently by [4]-[7]. However, existing works mainly assume there is no data rate requirement of the secondary users, while in the practical scenario, different secondary users require different data rates in order to guarantee their transmission qualities. Thus, in this paper, we proposed a novel cooperative model with secondary users' data rate requirement constraint. Primary users have to select the best group of cooperative secondary users and determine the optimal allocation of channel resource to maximize their transmission rate. Secondary users have to decide their optimal cooperative transmitting power to fulfill their channel resource requirement. We consider heterogeneous properties, including channel condition, cooperative transmission rate and data rate requirement, of secondary users. We propose an algorithm that maximizes the network throughput of primary users with the constraint of secondary users' requirement.

The rest of the paper is organized as follows. Section II describes the detailed system model. The utility functions are defined for primary and secondary users. In Section III, we use backward induction to analyze the formulated Stackelberg game, and prove the existence and uniqueness of NE. A distributed low-complexity algorithm is proposed to determine the relay group and relay power. Simulation results are presented, discussed and analyzed in Section IV. Finally, we draw conclusions in Section V.

II. System Model And Problem Formulation

We consider a cognitive radio network, where there are M primary users (PUs) $\mathbf{M_p} = \{1, 2, \ldots, M\}$ and N secondary users (SUs) $\mathbf{M_s} = \{1, 2, \ldots, N\}$. PUs and SUs communicate with the access point (AP) in TDMA manner using slotted ALOHA as their MAC protocol. In this paper, we mainly focus on the uplink of both PUs and SUs. Moreover, it is easy to be extended into the downlink scenario.

We assume that each PU can rely on maximum $L \leq N$ number of SUs, and each SU can cooperate with an unlimited number of PUs. We also assume that the noise power is the same around the network. Because we use TDMA model in this paper, the data rate requirement problem can be converted into the time slots requirement problem. Thus, we will analyze the fraction of time slots allocation in the rest of this paper.

A. Primary User Model

In this section, we discuss the transmission rate of primary users and the allocation of time slots.

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We first derive the direct transmission rate $R_{p,i}$ between the PU i and the AP without relay of SUs

$$R_{p,i} = \log_2(1 + \frac{|H_{p,i}|^2 P_{p,i}}{N_0}), \tag{1}$$

in which $H_{p,i}$ is the channel gain between PU i and AP. $P_{p,i}$ denotes PU's transmitting power, and N_0 is the noise power in the channel. For simplicity, we normalize the bandwidth to be 1.

In the first step of cooperative transmission, PU i broadcasts its data to the cooperative SUs $\mathbf{M_{s,i}} \subset \mathbf{M_s}$. The broadcast transmission rate $R_{ps,i,j}$ is dominated by the worst channel condition $H_{ps,i,j}$ between PU i and SU j

$$R_{ps,i,j} = log_2(1 + \frac{\min |H_{ps,i,j}|^2 P_{p,i}}{N_0}). \tag{2}$$

In the second step of cooperative transmission, SUs $j \in \mathbf{M_{s,i}}$ decode the data received in the first step, and then both PU i and SUs $j \in \mathbf{M_{s,i}}$ simultaneously transmit PU's data to the AP. The received signal at the AP is the linear superposition of transmitting signals perturbed by noise [8]. Thus, the forwarding data rate of the second step is

$$R_{s,i} = log_2(1 + \frac{|H_{p,i}|^2 P_{p,i}}{N_0} + \sum_{j \in \mathbf{M_{s,i}}} \frac{|H_{s,j}|^2 P_{s,j}}{N_0}). \tag{3}$$

The average cooperative transmission rate R_r of the first step and second step is

$$R_{r,i} = \frac{1}{\frac{1}{R_{ps,i,j}} + \frac{1}{R_{s,i}}} = \frac{R_{ps,i,j} R_{s,i}}{R_{ps,i,j} + R_{s,i}}. \tag{4}$$

As rewards, fraction of the channel resource should be allocated to SUs, because cooperative transmission improves the transmission rate of PUs. We use $\mathbf{\Pi_P} = (\omega_1^p, \omega_2^p, \ldots, \omega_M^p)$ to denote the resource-sharing vector, in which ω_i^p represents the fraction of time allocated to all SUs $\mathbf{M_{s,i}}$. ω_i^p satisfies the following condition

$$\omega_i^p \leq 1 - \frac{R_{p,i}}{R_{r,i}}, \tag{5}$$

which means that the fraction of time allocated to SUs should not be larger than the fraction of time saved during the cooperative transmission.

B. Secondary User Model

Next we discuss secondary user model and the utility function.

We use vector $\mathbf{\Pi_{S,i}} = (\omega_{1,i}^s, \omega_{2,i}^s, \ldots, \omega_{|\mathbf{M_{s,i}}|,i}^s)$, $\omega_i^p = \sum_{j \in \mathbf{M_{s,i}}} \omega_{j,i}^s$ to denote the fraction of time allocated to each of the SU in $\mathbf{M_{s,i}}$. For SU j, the allocated fraction of time $\omega_{j,i}^s$ is proportional to its cooperative transmitting power $P_{s,j}$ during forwarding stage

$$\omega_{j,i}^s = \frac{\omega_i^p P_{s,j}}{\sum_{k \in \mathbf{M_{s,i}}} P_{s,k}}. \tag{6}$$

Let $\widetilde{\omega}_{j,i}^s$ denote the requirement of SU j. Then we define revenue $\varepsilon_{j,i}$ to be the difference between average transmission rate and transmitting power $P_{s,j}$ in equivalent revenue format respectively

$$\varepsilon_{j,i} = \lambda_1 R_j \min(\widetilde{\omega}_{j,i}^s, \omega_{j,i}^s) - \lambda_2 P_{s,j}, \tag{7}$$

where λ_1 and λ_2 are the equivalent revenue factors. R_j, which is a fixed value, denotes the dedicated transmission rate of secondary user j. For simplicity, we rewrite equation (7) as

$$\varepsilon_{j,i} = \lambda_0 R_j \min(\widetilde{\omega}_{j,i}^s, \omega_{j,i}^s) - P_{s,j}, \tag{8}$$

where $\lambda_0 = \frac{\lambda_1}{\lambda_2}$

When the fraction of allocation time is smaller than its requirement, the SU suffers from loss η_i, because its data rate is constrained. We define the loss of SU j to be the difference between its required data rate and the actual data rate in equivalent value format

$$\eta_{j,i} = \nu_j R_j (\widetilde{\omega}_{j,i}^s - \min(\widetilde{\omega}_{j,i}^s, \omega_{j,i}^s)), \tag{9}$$

where ν_j is the equivalent value factor of unit data rate.

C. Game Formulation with Requirement Constraint

Both PUs and SUs target at maximizing their utilities. However, they have conflicting objectives in the game: PUs expect higher cooperative transmitting power from SUs, while intending to reserve larger fraction of time for cooperative transmission. SUs target at obtaining larger fraction of allocation time, while wishing to reduce their transmitting power.

The interaction between PUs and SUs follows three stages.

- **Initialization stage**: PUs collect channel information from SUs and AP, and then determine the relay groups and fraction of allocation time.
- **Broadcasting & forwarding stage**: PU broadcasts its data to cooperative SUs simultaneously. Cooperative SUs decode the PU's data and forward the data to the AP simultaneously. The increased SNR at the AP will increase the PU's average transmission rate.
- **Free transmission stage**: PU allocates fraction of time to each of cooperative SUs and each SU transmits its own data using its dedicated fraction of time.

Once initialization stage is finished, PUs and SUs will interchange between broadcasting & forwarding stage and free transmission stage. PUs will return to initialization stage when changes of the network occur, such as the departure of cooperative SUs.

III. Resource Allocation With Secondary User Requirement Constraint

A. Secondary User Utility Function Analysis

Now we define utility functions of secondary users and analyze of the existence and uniqueness of the Nash equilibrium.

For fixed ω_i^p and $\mathbf{M_{s,i}}$ decided by the PU, SUs in the set $\mathbf{M_{s,i}}$ compete with each other. They maximize their utilities by selecting the optimal cooperative transmitting power, which forms a noncooperative power game (NPG) $G = \{\mathbf{M_{s,i}}, \{P_{s,j}\}, \{u_j(.)\}\}$.

We define the utility function μ_j of secondary user j to be the difference between its revenue $\varepsilon_{j,i}$ and loss $\eta_{j,i}$

$$\mu_{j,i} = \begin{cases} \frac{\lambda_j \omega_i^p P_{s,j} R_j}{\sum_{k\in\mathbf{M_{s,i}}} P_{s,k}} - P_{s,j} - \nu_j \widetilde{\omega}_{j,i}^s R_j, & \text{if } \omega_{j,i}^s \le \widetilde{\omega}_{j,i}^s \\ \lambda_0 \widetilde{\omega}_{j,i}^s R_j - P_{s,j}, & \text{if } \omega_{j,i}^s > \widetilde{\omega}_{j,i}^s, \end{cases} \tag{10}$$

where $\lambda_j = \lambda_0 + \nu_j$.

Then, we derive the optimal time allocation $\widetilde{\omega}_{j,i}^{s*}$ to SU j. When $\widetilde{\omega}_{j,i}^s \le \widetilde{\omega}_{j,i}^{s*}$, the time requirement $\widetilde{\omega}_{j,i}^s$ of SU j can be satisfied. Otherwise, only part of its requirement can be satisfied.

Theorem 1: For secondary user j, the optimal time allocation $\widetilde{\omega}_{j,i}^{s*}$ is

$$\widetilde{\omega}_{j,i}^{s*} = \omega_i^p - \sqrt{\frac{\omega_i^p \sum_{(k\in\mathbf{M_{s,i}},k\ne j)} P_{s,k}}{\lambda_j R_j}}. \tag{11}$$

Proof: When the allocated time $\omega_{j,i}^s$ equals to the optimal time allocation $\widetilde{\omega}_{j,i}^{s*}$, the utility of secondary user j is maximized. Thus, we have the following equations

$$\omega_{j,i}^s = \frac{\omega_i^p P_{s,j}}{\sum_{j\in\mathbf{M_{s,i}}} P_{s,j}} = \widetilde{\omega}_{j,i}^{s*} \tag{12}$$

$$\frac{\partial u_i}{\partial P_{s,j}} = \frac{\lambda_j R_j \omega_i^p \sum_{(k\in\mathbf{M_{s,i}},k\ne j)} P_{s,k}}{(\sum_{j\in\mathbf{M_{s,i}}} P_{s,j})^2} - 1 = 0. \tag{13}$$

Using equation (12) and (13), we get the optimal time allocation $\widetilde{\omega}_{j,i}^{s*}$ to secondary user j. ■

Then, let $\overline{\omega}_{j,i}^s$ denote the maximum time requirement of SU j. Time requirement $\widetilde{\omega}_{j,i}^s$ of SU j should be smaller than $\overline{\omega}_{j,i}^s$. Otherwise, it will not be selected as cooperative relay.

Theorem 2: For secondary user j, the maximum time requirement $\overline{\omega}_{j,i}^s$ is

$$\overline{\omega}_{j,i}^s = \frac{(\sqrt{\lambda_j \omega_i^p R_j} - \sqrt{\sum_{(k\in\mathbf{M_{s,i}},k\ne j)} P_{s,k}})^2}{\nu_j R_j}. \tag{14}$$

Proof: When the actual time requirement $\widetilde{\omega}_{j,i}^s$ of secondary user j equals to $\overline{\omega}_{j,i}^s$, its maximum utility will be zero. Thus, we have the following equations

$$\frac{\partial u_i}{\partial P_{s,j}} = \frac{\lambda_j R_j \omega_i^p \sum_{(k\in\mathbf{M_{s,i}},k\ne j)} P_{s,k}}{(\sum_{k\in\mathbf{M_{s,i}}} P_{s,k})^2} - 1 = 0 \tag{15}$$

$$\frac{\lambda_j \omega_i^p P_{s,j} R_j}{\sum_{k\in\mathbf{M_{s,i}}} P_{s,k}} - P_{s,j} - \nu_j \overline{\omega}_{j,i}^s R_j = 0. \tag{16}$$

Using equation (15) and (16), we get the maximum time requirement $\overline{\omega}_{j,i}^s$ of secondary user j. ■

Then, we prove the unique existence of NE in the NPG. We divide secondary users $\mathbf{M_{s,i}}$ into two groups, satisfied group $\mathbf{M^1_{s,i}}$ and unsatisfied group $\mathbf{M^2_{s,i}}$. The actual allocation time satisfies $\omega_{j,i}^s \ge \widetilde{\omega}_{j,i}^s, j \in \mathbf{M^1_{s,i}}$ and $\omega_{j,i}^s < \widetilde{\omega}_{j,i}^s, j \in \mathbf{M^2_{s,i}}$.

Theorem 3: When the following condition

$$\omega_i^p < \sum_{j\in\mathbf{M_{s,i}}} \widetilde{\omega}_{j,i}^s \tag{17}$$

is satisfied, the game NPG has a unique equilibrium.

Proof: At first, we allocate ω_i^p without requirement constraint. The unique existence of Nash equilibrium, when allocating resources without requirement constraint, has been proved by [4].

Then, secondary users in $\mathbf{M^1_{s,i}}$ adjust their transmitting power to maximize their utilities. When condition $\omega_{j,i}^s = \widetilde{\omega}_{j,i}^s, j \in \mathbf{M^1_{s,i}}$ is met, their utilities reach maximum. Then, we allocate $(\omega_i^p - \sum_{j\in\mathbf{M^1_{s,i}}} \omega_{j,i}^s)$ fraction of time among $\mathbf{M^2_{s,i}}$ without requirement constraint. Allocation time to some secondary users in $\mathbf{M^2_{s,i}}$ is larger than or equal to their requirement. We transfer these secondary users $\omega_{j,i}^s \ge \widetilde{\omega}_{j,i}^s, j \in \mathbf{M^2_{s,i}}$ into $\mathbf{M^1_{s,i}}$ and reallocate $(\omega_i^p - \sum_{j\in\mathbf{M^1_{s,i}}} \omega_{j,i}^s)$ fraction of time without requirement constraint among $\mathbf{M^2_{s,i}}$, until no SU satisfies $\omega_{j,i}^s \ge \widetilde{\omega}_{j,i}^s, j \in \mathbf{M^2_{s,i}}$. SUs in $\mathbf{M^2_{s,i}}$ reach the Nash equilibrium.

When SUs in $\mathbf{M^2_{s,i}}$ reach NE point, we have the following equation

$$\frac{\omega_i^p \sum_{j\in\mathbf{M^1_{s,i}}} P_{s,j}}{\sum_{j\in\mathbf{M^1_{s,i}}} P_{s,j} + \sum_{j\in\mathbf{M^2_{s,i}}} P_{s,j}} = \sum_{j\in\mathbf{M^1_{s,i}}} \widetilde{\omega}_{j,i}^s. \tag{18}$$

For secondary user j in $\mathbf{M^1_{s,i}}$, its unique optimal transmitting power is $P_{s,j} = \frac{\widetilde{\omega}_{j,i}^s \sum_{j\in\mathbf{M^2_{s,i}}} P_{s,j}}{\omega_i^p - \sum_{j\in\mathbf{M^1_{s,i}}} \widetilde{\omega}_{j,i}^s}$. SUs in $\mathbf{M^1_{s,i}}$ also reach NE point. Therefore, SUs in $\mathbf{M_{s,i}}$ reach NE point. ■

When equation (17) is satisfied, the best response of the secondary user j is

$$P_{s,j}^* = \begin{cases} \frac{\widetilde{\omega}_{j,i}^s \overline{P_{s,j}}}{\omega_i^p - \widetilde{\omega}_{j,i}^s}, & \text{if } \widetilde{\omega}_{j,i}^s \le \widetilde{\omega}_{j,i}^{s*} \\ \sqrt{\kappa_j \overline{P_{s,j}}} - \overline{P_{s,j}}, & \text{if } \widetilde{\omega}_{j,i}^{s*} < \widetilde{\omega}_{j,i}^s \le \overline{\omega}_{j,i}^s \\ 0, & \text{if } \overline{\omega}_{j,i}^s < \widetilde{\omega}_{j,i}^s, \end{cases} \tag{19}$$

in which $\kappa_i = \lambda_j \omega_i^p$, $\overline{P_{s,j}} = \sum_{(k\in\mathbf{M_{s,i}},k\ne j)} P_{s,k}$. We can see that the optimal transmitting power for SU j only depends on the sum of cooperative transmission power chosen by others. It does not require other SUs' private information. This feature will help us to implement the algorithm for SUs to select the optimal transmitting power with incomplete information. Firstly, PU determines its relay groups and calculates the sum of relay power (which will be discussed in III-B). Then, PU broadcasts the sum of relay power to all relay users, and each relay user calculates its relay power using equation (19).

Theorem 4: When the following condition

$$\omega_i^p > \sum_{j\in\mathbf{M_{s,i}}} \widetilde{\omega}_{j,i}^s \tag{20}$$

is satisfied, the NPG game has a unique equilibrium. The optimal transmitting power $P_{s,j}$ for secondary user j is

$$P_{s,j} = 0. \tag{21}$$

Proof: SUs in $\mathbf{M^1_{s,i}}$ have excessive fraction of allocation time, and they target at maximizing their utilities by decreasing their transmitting power. More fraction of time previously allocated to SUs in $\mathbf{M^1_{s,i}}$ will be redistributed among SUs in

$\mathbf{M^2_{s,i}}$. Parts of SUs in $\mathbf{M^2_{s,i}}$ have excessive fraction of time and will be transferred to $\mathbf{M^1_{s,i}}$. Because the total fraction of time is larger than the sum of all SUs' requirement, the number of SUs in $\mathbf{M^2_{s,i}}$ will decrease to 0, and the transmitting power $P_{s,j}$ of SUs in $\mathbf{M^1_{s,i}}$ will also decrease to 0. ■

In this case, the cooperative transmitting power of SUs will be zero. PUs should avoid this case from happening.

Definition 1: (II: Individual Incentive): When the allocation time is smaller than the entire requirement of SUs, SUs will offer non-zero cooperative transmitting power

$$\omega_i^p < \sum_{j \in \mathbf{M_{s,i}}} \widetilde{\omega}_{j,i}^s. \tag{22}$$

Only when the II constraint is satisfied, primary users can receive cooperation from the secondary users.

B. Maximize Primary User Utility

Revenue of primary users comes from the improvement of their data rate. Therefore, we define the utility function of the primary user i to be the difference between its average cooperative transmission rate and the direct transmission rate.

$$u_i^p(\Sigma SNR_i, \omega_i^p) = R_{r,i}(\sum SNR_i)(1-\omega_i^p) - R_{p,i} \tag{23}$$

where $R_{r,i}(.)$ is the cooperative transmission rate function with the sum of cooperative signal-to-noise ratio as variable.

In order to obtain the best cooperative group $\mathbf{M^*_{s,i}}$ and the optimal fraction of allocation time ω_i^{p*}, we devide the searching procedure into two steps. In the first step, we will explore the optimal allocation time ω_i^{p*} given fixed cooperative group $\mathbf{M_{s,i}}$. In the second step, we will search for the optimal cooperative group $\mathbf{M^*_{s,i}}$ and maximize primary users' utility. The idea behind the two steps is that it is beneficial for PUs to select the most competent SUs as relays and create a fierce competition environment among them.

Step I: Search for Optimal Allocation Time

We define $\chi_j = \frac{\theta_j \overline{\theta} - N + 1}{\widetilde{\omega}_{j,i}^s \theta_j \overline{\theta}}$ as the type of SU j, in which $\theta_j = \lambda_j R_j, \overline{\theta} = \sum_{j \in \mathbf{M_s}} \frac{1}{\theta_j}$. Higher type SUs are more likely than the lower ones to be satisfied in the NPG. Without loss of generality, we assume that SUs in $\mathbf{M_{s,i}}$ satisfy $\chi_i > \chi_j, \forall i, j, i > j$.

Under individual incentive (II) constraint, part and only part of the secondary users' time requirement should be satisfied. We define ω_i^k as the fraction of time satisfying $0 \le k < |\mathbf{M_{s,i}}|$ number of secondary users' time requirement

$$\omega_i^k = \frac{\widetilde{\omega}_{k,i}^s \theta_k \sum_{j=k+1}^{|\mathbf{M_{s,i}}|} 1/\theta_j + \sum_{j=1}^{k} \widetilde{\omega}_{j,i}^s}{\theta_k \sum_{j=k+1}^{|\mathbf{M_{s,i}}|} 1/\theta_j - |\mathbf{M_{s,i}}| + k + 1}. \tag{24}$$

For allocation time ω_i^k, the sum of cooperative signal-to-noise ratio is

$$\sum SNR_i^k = \sum_{j=1}^{k} \frac{|H_{s,j}|^2 \widetilde{\omega}_{j,i}^s \sum P_i^k}{\omega_i^k N_0} + \sum_{j=k+1}^{|\mathbf{M_{s,i}}|} \left(\frac{\sum P_i^k}{N_0} - \frac{(\sum P_i^k)^2}{\omega_i^k \theta_j N_0}\right)|H_{s,j}|^2, \tag{25}$$

where $\sum P_i^k = \sum_{j \in \mathbf{M_{s,i}}}$ is

$$\sum P_i^k = \{\sum_{j=1}^{k} \widetilde{\omega}_{j,i}^s + \omega_i^k(|\mathbf{M_{s,i}}| - k - 1)\} / \sum_{j=k+1}^{|\mathbf{M_{s,i}}|} \frac{1}{\theta_j}. \tag{26}$$

By maximizing the utility function of primary user i, we can obtain its optimal fraction of allocation time ω_i^{p*}

$$\omega_i^{p*} = \{\omega_i^k : \arg_k \max[R_{r,i}(\sum SNR_i^k)(1-\omega_i^k)]\}. \tag{27}$$

Step II: Search for Optimal Relay Group

SUs with higher type are capable of offering higher transmitting power when competing with other users. Therefore, higher type SUs are more likely to be chosen by PUs. However, it still needs to be determined whether the channel conditions of these SUs are appropriate for the PU. We assume SUs are arranged by their types in descending order. Primary user i will select first L SUs as the initial cooperative group $\mathbf{M^c_{s,i}}$. The rests of SUs are categorized into noncooperative group $\widehat{\mathbf{M^c_{s,i}}}$.

First, the PU will carry out the secondary user replacement procedure. The PU arranges SUs in $\mathbf{M^c_{s,i}}$ by their channel condition $H_{ps,i,j}$ in descending order, and then examines whether the SU $|\mathbf{M^c_{s,i}}|$ with the worst channel condition has negative influence on the cooperative performance: PU will temporally replace SU $|\mathbf{M^c_{s,i}}|$ with the first SU k in $\widehat{\mathbf{M^c_{s,i}}}$, whose channel condition is better than j. If the tentative replacement leads to an increase in utility, PU will replace SU $|\mathbf{M^c_{s,i}}|$ with k and redo the secondary user replacement procedure. If not, PU will select the next SU in $\widehat{\mathbf{M^c_{s,i}}}$ with better channel condition and repeat the replacement procedure, until there are no selectable SUs in $\widehat{\mathbf{M^c_{s,i}}}$.

Next, the PU will carry out the secondary users elimination process. This process will try to improve the utility of PUs by eliminating the cumbrous SUs in the cooperative group.

Details of relay group selection algorithm, including replacement process and elimination process, are summarized in Algorithm 1.

IV. Simulation Results

We present the network performance in the following scenario. $M = 20$ primary users and $N = 40$ secondary users are randomly placed in a circular cell of radius $R = 200m$. Access point is the center of the network. The transmitting power of PUs is $P_{p,i} = 100mW$. Transmitting power of SUs' own transmission is $P_s = 100mW$. We assume channel gain is determined by distance and propagation path loss. Propagation path loss between PUs and SUs is $\gamma_{ps} = 2.8$, and the noise power is $N_0 = 10^{-11}$.

Fig. 1 compares the PUs' average throughput of the cooperative scheme versus direct transmission as a function of the requirement of SUs. Furthermore, it compares the PUs' throughput of different direct propagation path loss. It is clear that when the requirement of SUs increases, the PUs' average throughput declines. This is mainly because larger channel resources of primary user network will be allocated

Algorithm 1 Relay Group Selection

Order $\mathbf{M_{s,i}}$ by χ_j DESC
Set $\mathbf{M^c_{s,i}} = \mathbf{M_{s,i}}[1, L]$ and $\widehat{\mathbf{M^c_{s,i}}} = \mathbf{M_{s,i}}[L+1, end]$
for $k = 1 : |\widehat{\mathbf{M^c_{s,i}}}|$ **do**
  Order $\mathbf{M^c_{s,i}}$ by $H_{ps,i,j}$ DESC
  $j = |\mathbf{M^c_{s,i}}|$
  if $H_{ps,i,k} \geq H_{ps,i,j}$ **then**
    $\mathbf{M^{c,tmp}_{s,i}} = \mathbf{M^c_{s,i}}$
    $\mathbf{M^{c,tmp}_{s,i}}[end] = \widehat{\mathbf{M^c_{s,i}}}[k]$
    if $Utility(\mathbf{M^{c,tmp}_{s,i}}) > Utility(\mathbf{M^c_{s,i}})$ **then**
      $\mathbf{M^c_{s,i}} = \mathbf{M^{c,tmp}_{s,i}}$
    end if
  end if
end for
$\mathbf{M^*_{s,i}} = \mathbf{M^c_{s,i}}$
for $j = |\mathbf{M^c_{s,i}}| - 1 : 1$ **do**
  $\mathbf{M^{c,tmp}_{s,i}} = \mathbf{M^c_{s,i}}[1 : j]$
  if $maxPU(\mathbf{M^{c,tmp}_{s,i}}) > maxPU(\mathbf{M^c_{s,i}})$ **then**
    $\mathbf{M^*_{s,i}} = \mathbf{M^{c,tmp}_{s,i}}$
  end if
end for
OUTPUT: $\mathbf{M^*_{s,i}}$

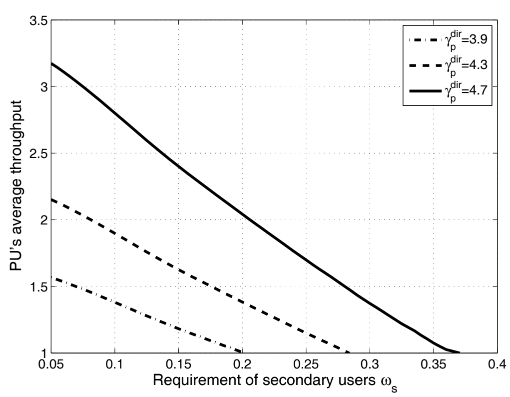

Fig. 1. PUs' throughput vs. requirement of SUs for different direct path loss of PUs. $L = 4$ maximum relay number and $\gamma_s = 3.7$ path loss of SUs

to SUs to satisfy their increasing requirement. As the direct propagation path loss increases, we notice a fast increase in PU's throughput, which shows that it will be more beneficial for PUs to cooperate with SUs.

Fig. 2 compares SUs' average fraction of time as a function of SUs' requirement. Furthermore, it compares the allocation time of different maximum relay number. SUs' average fraction of time increases when they require a larger fraction of time at first, and then declines, because PUs cannot satisfy SUs' requirement and then prefer to reserve more time for themselves. It is noted that average allocation time decreases as the maximum relay number increases. This is mainly because the competition among SUs becomes more fierce and the fraction of time will be shared by more SUs.

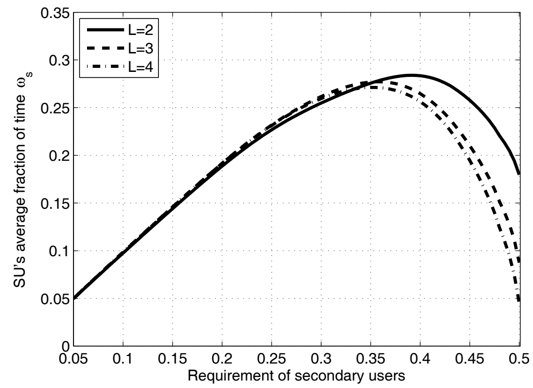

Fig. 2. SUs' average fraction of time vs. requirement of SUs for different maximum number of relay users. $\gamma_P^{dir} = 4.7$ and $\gamma_s = 3.7$

V. Conclusions

In this paper, we study the opportunistic access problem with the constraint of secondary users' data rate requirement. We model this problem as a Stackelberg game and proposed a distributed low-complexity algorithm. Simulation results show significantly improved efficiency of spectrum resource usage.

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References

[1] Lanchao Liu, Husheng Li, and Zhu Han, "Sampling spectrum occupancy data over random fields: A matrix completion approach", *Communications (ICC)*, Ottawa, Canada, Jun. 2012.

[2] Fen Hou and Jianwei Huang, "Dynamic Channel Selection in Cognitive Radio Network with Channel Heterogeneity", *Global Telecommunications Conference (GLOBECOM)*, Florida, USA, Dec. 2010.

[3] Lin Gao, Youyun Xu, and Xinbing Wang, "MAP: Multiauctioneer Progressive Auction for Dynamic Spectrum Access", *IEEE Trans., Mobile Comput.,* vol.10, no.8, pp.1144-1161, Aug. 2011.

[4] Jin Zhang and Qian Zhang, "Stackelberg Game for Utility-Based Cooperative Cognitive Radio Networks", in *ACM MobiHoc*, Louisiana, USA, May 2009.

[5] Lingjie Duan, Lin Gao, and Jianwei Huang, "Contract-based cooperative spectrum sharing", in *Proc. IEEE DySPAN*, Aachen, Germany, May 2011.

[6] Beibei Wang, Zhu Han, and K.J.R. Liu, "Distributed Relay Selection and Power Control for Multiuser Cooperative Communication Networks Using Stackelberg Game", *IEEE Trans, Mobile Comput.,* vol.8, no.7, pp.975-990, Jul. 2009.

[7] Dapeng Li, Youyun Xu, Xinbing Wang, and Guizani, M., "Coalitional Game Theoretic Approach for Secondary Spectrum Access in Cooperative Cognitive Radio Networks", *IEEE Trans. Wireless Commun.,* vol.10, no.3, pp.844-856, Mar. 2011.

[8] Luo, J., Blum, R.S., Cimini, L.J., Greenstein, L.J., and Haimovich, A.M., "Decode-and-Forward Cooperative Diversity with Power Allocation in Wireless Networks", *IEEE Trans. Wireless Commun.*, vol.6, no.3, pp.793-799, Mar. 2007.