Spectrum Leasing and Relay Selection in Multiuser Cooperative Cognitive Radio Networks

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Abstract —In this paper, we consider multiple primary and multiple secondary users cooperative cognitive radio networks, in which the primary users (PUs) lease a portion of their spectrum to the secondary users (SUs) for some revenue, and in return the SUs play as relays and help forward the data of the Pus in exchange for being granted spectrum opportunities. Both the PUs and SUs aim to maximize their own utilities. The spectrum leasing and relay selection problem is studied. We formulate the spectrum leasing problem as a Stackelberg game, and transform the relay selection problem as an assignment problem which is solved by the Hungarian method. Numerical results show that, under the proposed cooperative spectrum leasing-optimal-relay-selection scheme, both the primary and secondary network can achieve high utilities.

Index Terms—cognitive radio, utility, cooperative spectrum leasing, relay selection, Stackelberg game, Hungarian method

I. Introduction

The available spectrum resources for wireless communications are becoming increasingly scarce due to rapidly increasing traffic demands in certain situations. Cognitive radio technology is being proposed and adopted to improve the spectrum utilization [1]. Secondary users (SUs) can coexist with licensed users, so called primary users (PUs), on the same spectral resource, provided that they do not cause harmful interference to the PU. The SUs sense and exploit the spectrum licensed to the PUs when they are idle. In addition, in an interference limited model, the SUs can use the spectrum being occupied by the PUs if they do not cause harmful interference to the PUs.

Dynamic spectrum access schemes are proposed to address spectrum sharing problems and are based on perfect or imperfect spectrum sensing [2], [3]. In [4], the authors have proposed the concept of dynamic spectrum leasing (DSL) as a new paradigm for dynamic spectrum access (DSA) in cognitive radio networks, in which the PUs can lease a portion of their spectrum resource to the SUs in return for revenue. The pricing issue has been studied in a competitive cognitive radio network in which the primary service provider charges the secondary users based on their transmitted power levels to enhance its own revenue, and the secondary users strategically adjust their uplink transmission power levels to maximize their own utilities [5].

In recent years, cooperative relay technologies have been incorporated into cognitive radio to help the SU coexist with the PU [6]. Cooperative cognitive radio is a promising paradigm for both primary and secondary networks. Cooperative communication techniques can be applied in cognitive radio networks by making the PU cooperate with the SU. The application of the cooperative communication concept in cognitive radio networks can be classified into three categories: i) cooperation among primary user peers; ii) cooperation among secondary user peers; and iii) cooperation between primary users and secondary users [7]. In the third kind of cooperation, the secondary users help the primary users forward their data and do not cause interference to the primary users, and in return, the primary user will release part of their spectrum to the secondary users. Both the primary and secondary users can obtain mutual benefit from the cooperation.

Usually, the PU is selfish, so besides earning some revenue form leasing spectrum, the PU would like to obtain additional benefits. The work [8] has proposed a spectrum leasing scheme where the PUs lease their spectrum to the cooperating secondary ad hoc networks in return for an improved quality of service (QoS). In [9], the problem of dynamic spectrum leasing in a spectrum secondary market is considered, where secondary service providers lease spectrum from spectrum brokers to provide service to secondary users. Spectrum leasing via multiple primary users is formulated as a generalized Nash equilibrium problem, and solutions to the problem are proposed with different signaling requirements among the primary users [10]. In an uplink code division multiple access (CDMA) network, the base station leasing spectrum to the SUs while the SUs pay for their inference power, and this price-based power control problem can be formulated as a Stackelberg game [11].

The authors of [12] have proposed an Orthogonal Frequency Division Multiplexing (OFDM)-based cooperative communication scheme joint with spectrum leasing where the spectrum is leased in both frequency

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and time domains. In [13], multiple PUs and multiple SUs operate on one channel using TDMA, with the PUs charging the SUs at the same price. In this paper, we propose a cooperative spectrum leasing and optimal relay selection scheme in a scenario where multiple PUs and multiple SUs operate on multiple channels. We consider a utility based cooperative spectrum leasing (CSL) communication model where multiple PUs actively cooperate with multiple SUs, and the SUs play the game as the relays and help forward the PUs' data in return for some spectrum access opportunities. The PUs charge the SUs at different prices due to different channel conditions between them. Thus, as the PUs own the spectrum, it is reasonable that they select the suitable SUs as their relays and lease spectrum to them in order to maximize the utility of the primary network. The SUs rent proper spectrum access time to maximize their utilities. However, the PU would not like to lease part of the spectrum to the SU unless its QoS is guaranteed. In our work, we have investigated following problems: a) the preconditions for cooperation, i.e. when the PU and the SU would like to cooperate with each other; b) the pricing issue, i.e. what the price the PU charges the SU for spectrum; c) the spectrum renting problem, i.e. how much spectrum the SU will rent to maximize its utility; d) optimal relay section, i.e. which SU the PU would like to select as its relay.

The remainder of this paper is organized as follows. Section II describes the system model and assumptions, and introduces the utility functions for the primary and secondary network respectively. In Section III, we analyze preconditions of the cooperative spectrum leasing which is formulated as a Stackelberg game, and the Hungarian method is adopted to solve the relay selection problem. To evaluate the proposed cooperative spectrum leasing scheme, we present a range of simulation results and analyze the performance of the cooperative spectrum leasing in Section IV. Section V concludes the paper.

II. System Model and Problem Formulation

A. System Architecture and Assumptions

In our previous work [14], we assume there is only one primary user and secondary user. Here we consider a cognitive radio system where M primary user link pairs and N secondary user link pairs coexist within the same area, associated with a central controller (CC) which has the information about the entire system, as shown in Fig.1.(a). A primary link pair consists of a primary transmitter (PT) and a primary receiver (PR), with the secondary link being specified in a similar way. It is assumed that each PU and SU can only transmit on one channel. Each PU has a unique licensed channel and can lease a portion of channel access time to the SU in exchange for cooperation. One SU can be the relay and will help only one PU relay message, and one PU can only lease to at most one SU. Therefore, there are M individual channels and N relays in the cooperative cognitive radio network. The primary network can at most select M SUs as the relays for the PUs. In a practical network, the PUs are rational and selfish, they lease their spectrum to obtain some revenue besides cooperation. The CC decides the relay selection and spectrum leasing for the PUs and SUs. We assume that the PUs always have data to transmit and the SU would like to cooperate with the PU as a relay because it benefits from the spectrum leasing once it rents some spectrum from the PUs. The primary network aims to maximize its revenue obtained from cooperation while guaranteeing the QoS for every PU. The secondary network aims to maximize its utility obtained from spectrum leasing.

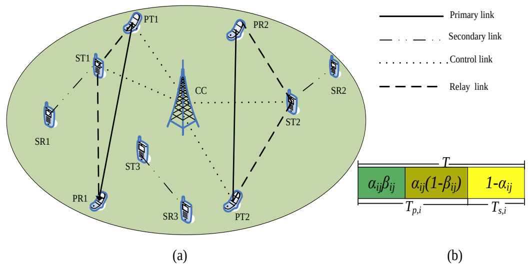

Fig. 1. Cooperative cognitive radio networks (a) system architecture (b) time duration division.

In this work, a decode-and-forward method is adopted as the cooperative relay scheme, and this can be easily extended to other cooperative relay schemes (e.g. Amplify-and-Froward). It is assumed that the PUs operate a rate constraint service, where each PU_i transmits with a nominal data rate $R_{P,i}$ to maintain its QoS, $i \in \{1, 2, ..., M\}$. There is no power control for the SUs, and each SU_j transmits with a fixed power $P_{S,j}$, $j \in \{1, 2, ..., N\}$. It is assumed that the network is time-slotted that the time slot duration is equal to T. The channel fading is flat in a time duration T, but generally varying over the slots (i.e., Rayleigh fading). When the PU_i decides to cooperate with the SU_j, it leases a portion of its spectrum access time to it, as is shown in Fig. 1. (b). The time slot T of the PU_i is first divided into 2 fractions, the primary user data transmission duration $T_{p,i}$ and the secondary user data transmission duration $T_{s,i}$. The primary user data transmission duration $T_{p,i}$ is further divided into 2 subslots. With cooperation of the SU_j, the PT_i first transmits its data to the ST_j in the first subslot $\alpha_{ij}\beta_{ij}T$, $(0 < \alpha_{ij} \le 1, 0 < \beta_{ij} < 1)$, and then the ST_j helps to forward the $PU_i^{'}s$ data to PR_i with fixed transmit power $P_{S,j}$ in the second subslot $\alpha_{ij}(1-\beta_{ij})T$. In return for the cooperative relay, the SU_j transmits its own data in the duration $(1-\alpha_{ij})T$ it rents from the PU_i.

There are multiple primary users who lease spectrum and multiple secondary users who rent spectrum. This is a multi-seller and multi-buyer system. We introduce a binary variable b_{ij} to denote the relay selection.

$$b_{ij} = \begin{cases} 1 & PU_i \text{ selects } SU_j \text{ as its relay} \\ 0 & PU_i \text{ doesnot selects } SU_j \text{ as its relay} \end{cases} \quad (1)$$

We obtain a matrix $\mathbf{B} = \{b_{ij}\}_{M\times N}$ denoting the relay selection of the primary and secondary network. We assume that the noise powers on all the channel are the same (i.e. AWGN), denoted by N_0. In the following sections, we denote the channel gain between $PT_i - PR_i$, $ST_j - SR_j$ on the channel of PU_i, $PT_i - ST_j$, and $ST_j - PR_i$ by h_{pp}^{ii}, h_{ss}^{ij}, h_{ps}^{ij} and h_{sp}^{ij} respectively.

B. *Utility Functions of the Primary and Secondary Network*

The objective of the primary network is to maximize its revenue which consists of energy saving and spectrum leasing reward while keeping nominal data rate for all the PUs. We use the satisfaction function $S_{p,i}$ to measure the energy saving of the PU_i

$$S_{p,i} = \sum_{j=1}^{N} b_{ij}(1 - E_{c,ij}/E_{0,i}) \quad (2)$$

where $E_{c,ij}$ is the energy consumed by PU_i when it cooperates with SU_j, $E_{0,i}$ is a reference energy and is set to $E_{dir,i}$. $E_{dir,i}$ is the energy consumed by the PT_i when it directly transmits to its destination with data rate $R_{P,i}$ in a time slot. The expressions of $E_{c,ij}$ and $E_{dir,i}$ will be given in the following section. Also in the following section, we will study the conditions that makes $S_{p,i} \in (0,1)$.

The utility function of PU_i is defined as the weighted satisfaction plus the revenue it obtains from the SU.

$$U_{p,i} = \omega_{p,i} S_{p,i} + U_{r,p,i} \quad (3)$$

where $\omega_{p,i}$ is the equivalent revenue per unit satisfaction contributing to the utility of the PU_i. $U_{r,p,i}$ is the revenue obtained from the SU which is defined as

$$U_{r,p,i} = \sum_{j=1}^{N} b_{ij} c_{ij} (1 - \alpha_{ij}), \quad (4)$$

where c_{ij} is the price of per unit time charged by the PU_i. It is reasonable to assume that the PU_i charges the SUs at different price, as there are different channel conditions between the PT_i and STs.

The secondary network aims to improve its own data rate when cooperating with the PU under the payment $U_{r,s,j}$. The utility function of the SU_j is given by

$$U_{s,j} = \omega_{s,j} S_{s,j} - U_{r,s,j}, \quad (5)$$

where $\omega_{s,j}$ is the equivalent revenue per unit satisfaction contributing to the utility of the SU_j, $S_{s,j}$ is the satisfaction function of the SU_j corresponding to its data rate $R_{s,j}$, and it is defined as follows [15]

$$S_{s,j} = \sum_{i=1}^{M} b_{ij} (1 - e^{-a_j R_{s,ij}}), \quad (6)$$

where a_j is positive constant, $a_j = -\ln(0.2)/R_{s,i}^0$, $R_{s,j}^0$ is the traffic demand of the SU, the satisfaction level $S_{s,j}$ is 0.8 when the $R_{s,ij}$ equals the data rate $R_{s,j}^0$. The SU_j's own transmission period is $(1-\alpha_{ij})$, with the data rate $R_{s,ij}$ being given by

$$R_{s,ij} = (1 - \alpha_{ij}) R_{s,ij}^0 \quad (7)$$

where $R_{s,ij}^0 = \log_2(1 + \frac{P_{S,j} h_{ss}^{ij}}{N_0})$ is the capacity between the SU link on the channel of the PU_i.

$U_{r,s,j}$ is the expense that the SU_j pays the PUs for the rented spectrum, and it is given by

$$U_{r,s,j} = \sum_{i=1}^{M} b_{ij} c_{ij} (1 - \alpha_{ij}) \quad (8)$$

Specifically, when the PU_i chooses the SU_j as its relay, there is $U_{r,p,i} = U_{r,s,j}$. The utility functions of the primary and secondary networks are given by

$$U_P = \sum_{i=1}^{M} U_{p,i} = \sum_{i=1}^{n} (\omega_{p,i} S_{p,i} + U_{r,p,i}), \quad (9)$$

$$U_S = \sum_{j=1}^{N} U_{s,j} = \sum_{j=1}^{N} (\omega_{s,j} S_{s,j} - U_{r,s,j}). \quad (10)$$

According to the definitions of $U_{p,i}$ and $U_{s,j}$, they are both greater than 0. The primary and secondary networks aim to maximize their individual utility respectively. It is reasonable to assume that the primary network aims to maximize its utility, as the primary network owns the spectrum resource, and that the secondary network tries to maximize its utility on this premise. We assume that the CC has the information about the primary and secondary network, obtained via control links between the CC and the primary and secondary users. In order to maximize the utility of the primary network, the CC determines the best relay selection strategy for the primary network. The CC needs to solve the optimization problem as follows.

OP1:

$$\begin{aligned} \max U_P &= \sum_{i=1}^{N} (\omega_{p,i} S_{p,i} + U_{r,p,i}) \\ &= \sum_{i=1}^{N} b_{ij} (\omega_{p,i}(1 - E_{c,ij}/E_{0,i}) + c_{ij}(1 - \alpha_{ij})) \end{aligned} \quad (11)$$

subject to

$$\sum_{i=1}^{N} b_{ij} \le 1 \quad (12)$$

$$\sum_{j=1}^{M} b_{ij} \le 1 \quad (13)$$

$$b_{ij} \in \{0,1\}, \forall i \in \{1,2,...,M\}, j \in \{1,2,...,N\} \quad (14)$$

$$\alpha_{ij} \in (0,1), c_{ij} > 0, \forall i \in \{1,2,...,M\}, j \in \{1,2,...,N\} \quad (15)$$

The constraints (12), (13) and (14) show that one PU can at most select one SU as its relay, and the SU can be the relay of at most one PU. This is a mixed-integer nonlinear programming problem and is NP hard. To solve the problem, the CC needs to determine the relay selection $\{b_{ij}\}$ and spectrum leasing strategies, including the prices $\{c_{ij}\}$ and time durations $\{\alpha_{ij}\}$. In the following section, we will decompose the problem as two coupled problems.

III. Proposed Spectrum Leasing and Relay Selection Algorithm

In this section, we first study the preconditions of the cooperation between the PU and SU; we formulate the spectrum leasing problem as a Stackelberg game and give the optimal strategies to solve the problem. We then propose the optimal relay selection algorithm based on the spectrum leasing strategies.

A. Preconditions of Cooperation

The PUs and SUs are rational and selfish, given that the PUs would like to lease a portion of their spectrum to the SUs and the SUs would like to help the SUs forward their messages only when they can obtain some revenue from the cooperation. It is assumed that there is a $PT_i - PR_i$ link-pair and a $ST_j - SR_j$ link-pair located in the same area. We consider the cooperation from the PU perspective as the PU owns the spectrum. The PU_i would like to lease some of its bandwidth to the SU_j only when two conditions are satisfied; the PU_i can a) guarantee its QoS (maintaining the nominal data rate $R_{P,i}$), b) and save energy with the cooperation of SU_j in contrast to its direct transmission to its destination during one time slot T .

For any given data rate $R_{P,i}$, the PT_i transmits to its destination directly using power $P_{p,i,dir}$ in the whole time slot.

$$R_{P,i} = \log_2(1 + \frac{P_{p,i,dir} h_{pp}^{ii}}{N_0}) \quad (16)$$

We obtain the transmit power of the PU_i without cooperation as

$$P_{p,i,dir} = \frac{(2^{R_{P,i}} - 1)}{h_{pp}^{ii}} N_0 \quad (17)$$

When the PT_i directly transmits to its destination, it will consume energy $E_{i,dir} = P_{p,i,dir} T$. For simplicity, we assume T is normalized as 1. When the PT_i chooses to cooperate with the ST_j , it first transmits to the ST_j using power $P_{ps,ij}$ in the first subslot $\alpha_{ij}\beta_{ij}$, and in the second subslot $\alpha_{ij}(1-\beta_{ij})$ the ST_j forwards the data of the PU_i to the PR_i with its maximum power $P_{S,j}$. The instantaneous data rates in the two subslots are expressed as follows

$$R_{ps,ij} = \log_2(1 + \frac{P_{ps,ij} h_{ps}^{ij}}{N_0}) \quad (18)$$

$$R_{sp,ij} = \log_2(1 + \frac{P_{S,j} h_{sp}^{ij}}{N_0}) \quad (19)$$

In this decode-and-forward (DF) cooperative relay system, in order to guarantee the QoS of the PU, the cooperative data rate of the PU_i denoted by $R_{coop,ij}$ should satisfy

$$R_{coop,ij} = \min(\alpha_{ij}\beta_{ij} R_{ps,ij}, \alpha_{ij}(1-\beta_{ij}) R_{sp,ij}) \ge R_{P,i}. \quad (20)$$

The SU_j transmits with the maximum power $P_{S,j}$, so from (19) and (20), we obtain the channel gain $h_{sp,ij}$ between the ST_j and PR_i should satisfy

$$h_{sp}^{ij} \ge \frac{(2^{R_{P,i}/\alpha_{ij}(1-\beta_{ij})} - 1)}{P_{S,j}} N_0. \quad (21)$$

Specially, when $\alpha_{ij} \to 1$ and $\beta_{ij} \to 0$, we get $R_{sp,ij} \ge R_{P,i}$, which means the SU_j forwards the PU_i 's data almost in the entire time duration T (similar assumption is given in [16]) , and the minimal $h_{sp,ij}$ constraint is given by

$$h_{sp}^{ij} \ge \frac{(2^{R_{P,i}} - 1)}{P_{S,j}} N_0. \quad (22)$$

It is proved that the primary system gets the optimal performance and the primary user can save the most power when α_{ij} and β_{ij} satisfy the following expression.

$$\alpha_{ij}\beta_{ij} R_{ps,ij} = \alpha_{ij}(1-\beta_{ij}) R_{sp,ij} = R_{P,i}. \quad (23)$$

From (18) and (23), we get the cooperative transmission power of the PU

$$P_{ps,ij} = \frac{(2^{R_{P,i}/\alpha_{ij}\beta_{ij}} - 1)}{h_{ps}^{ij}} N_0. \quad (24)$$

The energy consumed by the PU_i is given by $E_{c,ij} = \alpha_{ij}\beta_{ij}P_{ps,ij}$. Note that $R_{sp,ij}$ is a constant in one time slot, and β_{ij} is given by

$$\beta_{ij} = 1 - \frac{R_{P,i}}{\alpha_{ij}R_{sp,ij}} \quad (25)$$

β_{ij} is totally determined by α_{ij}. We obtain

$$E_{c,ij} = (\alpha_{ij} - \frac{R_{P,i}}{R_{sp,ij}})\frac{(2^{R_{P,i}/(\alpha_{ij}-\frac{R_{P,i}}{R_{sp,ij}})} - 1)N_0}{h_{ps}^{ij}} \quad (26)$$

Intuitively, when α_{ij} is equal to 1 meaning that SU_j helps PU_i forward its data without reward, the PU_i can save the most power. Actually, $E_{c,ij}$ is a decreasing function in α_{ij}, $(0 < \alpha_{ij} \le 1)$. Particularly, when $\alpha_{ij} = 1$, PU_i will consume the least energy that is

$$E_{c,ij}^{\min} = (1 - \frac{R_{P,i}}{R_{sp,ij}})\frac{(2^{R_{P,i}/(1-\frac{R_{P,i}}{R_{sp,ij}})} - 1)N_0}{h_{ps}^{ij}} \quad (27)$$

The energy saving condition of the PU_i is $E_{c,ij}^{\min} \le E_{p,i,dir}$, and we obtain

$$\frac{h_{ps}^{ij}}{h_{pp}^{ii}} \ge \frac{(2^{\frac{R_{P,i}}{1-\frac{R_{P,i}}{R_{sp,ij}}}} - 1)}{(2^{R_{P,i}} - 1)}(1 - \frac{R_{P,i}}{R_{sp,ij}}), \quad (28)$$

where $R_{sp,ij}$ is determined by the channel gain h_{sp}^{ij} when $P_{S,j}$ is fixed. Specifically, h_{sp}^{ij} satisfies (22). From the above analysis, we can infer that the PU_i would like to cooperate with the SU_j when both (22) and (28) stand.

B. Optimal Cooperative Spectrum Leasing Strategy

From the above analysis, when the PU_i selects the SU_j as its relay, we get the optimal cooperative relay strategy problem as follows:

$$\max imize\{U_{p,i}\} \text{ meanwhile } \max imize\{U_{s,j}\} \quad (29)$$

where $U_{p,i}$ and $U_{s,j}$ are expressed respectively as follows:

$$U_{p,i} = c_{ij}(1-\alpha_{ij}) + \omega_{p,i}(1 - \frac{(2^{R_{P,i}/(\alpha_{ij}-\frac{R_{P,i}}{R_{sp,ij}})} - 1)(\alpha_{ij} - \frac{R_{P,i}}{R_{sp,ij}})}{h_{ps,ij}} N_0 / E_{0,i})$$

and

$$U_{s,j} = \omega_{s,j}(1 - e^{-a(1-\alpha_{ij})R_{s,jj}^0}) - c_{ij}(1-\alpha_{ij}) \ .$$

This is a multi-objective optimization problem, where both the PU and SU are rational and selfish, and which is targeted at maximizing their individual utility. The PU owns the spectrum and it is reasonable to assume that the PU decides what price it charges the SU. The SU decides the amount of the spectrum it will rent sequentially. Therefore, it is a typical Stackelberg game in which the PU plays as the leader, while the SU plays as the follower [17]. The action of the PU_i is the price c_{ij} it charges the SU, and the action of the SU_j is the access time $(1-\alpha_{ij})$ it determines under the price c_{ij}. The following game has a unique Nash Equilibrium [18], as the $U_{p,i}$ and $U_{s,j}$ is continuous in c_{ij} and α_{ij}.

$$\max_{\alpha_{ij},c_{ij}} U_{p,i}(a_{ij}, c_{ij}) \ s.t \ c_{ij} \in \operatorname*{argmax}_{c_{ij}^0} U_{s,j}\left(a_{ij}, c_{ij}^0\right) \quad (30)$$

We analyze the game using backward induction method which is divided into two steps [19]. In the first step, it is assumed that the price c_{ij} is fixed, and the SU_j determines the optimal spectrum access time $(1-\alpha_{ij})$ it will rent form the PU_i. In the second step, the PU_i, knowing the decision of the SU_j, determines the optimal spectrum price c_{ij} according to its utility.

Let γ_{ij} denote the access time of the SU_j as $\gamma_{ij} = 1 - \alpha_{ij}$. It is easy to prove that $U_{s,j}$ is first an increasing function in γ_{ij} and then a decreasing function with $c_{ij} < \omega_{s,j}aR_{s,jj}^0$. The first order derivative of $U_{s,j}$ with respect to γ_{ij} is

$$\frac{\partial U_{s,j}}{\partial \gamma_{ij}} = \omega_{s,j}a_jR_{s,jj}^0 e^{-a_j\gamma_{ij}R_{s,jj}^0} - c_{ij} \quad (31)$$

Note that $0 < \gamma_{ij} < 1$, so if $c_{ij} > \omega_{s,j}a_jR_{s,jj}^0$, $\frac{\partial U_{s,j}}{\partial \gamma_{ij}}$ is always less than 0, and the SU_j will rent $\gamma_{ij} = 0$ spectrum access time to maximize $U_{s,j}$, which means the SU_j will not rent the spectrum and the PU_i cannot receive revenue. Therefore the PU_i will adjust its pricing strategy to obtain more revenue, and it will decrease the price c_{ij}. The maximum value of $U_{s,j}$ is achieved when $\frac{\partial U_{s,j}}{\partial \gamma_{ij}} = 0$, that is $\omega_{s,j}a_jR_{s,jj}^0 e^{-a_j\gamma_{ij}R_{s,jj}^0} - c_{ij} = 0$. We obtain the optimal time duration division that is

$$\alpha_{ij} = \frac{1}{a_jR_{s,jj}^0}\ln\frac{c_{ij}}{\omega_{s,j}a_jR_{s,jj}^0} + 1 \quad (32)$$

We obtain $c \in (\omega_{s,j}a_jR_{s,jj}^0 e^{-a_jR_{s,jj}^0}, \omega_{s,j}a_jR_{s,jj}^0)$, as $0 < \alpha_{ij} < 1$,. Furthermore, as $0 < \beta_{ij} < 1$, from (25), we get $\alpha_{ij} > \frac{R_{P,i}}{R_{sp,ij}}$, so finally, we obtain the price c_{ij} strategy domain as follow

$$c_{ij} \in (\omega_{s,j} a_j R^0_{s,jj} e^{-a_j R^0_{s,jj}(1-R_{P,i}/R_{sp,ij})}, \omega_{s,j} a_j R^0_{s,jj}) \quad (33)$$

Once the SU_j decides the amount of spectrum time that it will rent, the PU_i will charges the SU_j at the proper price to maximize its own utility. Submitting $E_{0,i} = E_{i,dir} = P_{p,i,dir} \cdot 1$ and (32) into (29), the optimization problem of the $U_{p,i}$ is expressed by (34),

$$\text{maximize}\, U_{p,i} = \omega_{p,i}\left(1 - \frac{h^{ii}_{pp}\left(2^{R_{P,i}/(\frac{1}{a_j R^0_{s,jj}}\ln c'_{ij} + A_{ij})} - 1\right)\left(\frac{1}{a_j R^0_{s,jj}}\ln c'_{ij} + A_{ij}\right)}{h^{ij}_{ps}(2^{R_{P,i}} - 1)}\right) - \omega_{s,j} c'_{ij} \ln c'_{ij} \quad (34)$$

where $c'_{ij} = \frac{c_{ij}}{\omega_{s,j} a_j R^0_{s,jj}}$, $c'_{ij} \in (e^{-a_j A_{ij} R^0_{s,jj}}, 1)$ and $A_{ij} = 1 - \frac{R_{P,i}}{R_{sp,ij}}$.
In Fig. 2, it is shown that the utilities of the primary and secondary users change as the price increases. We cannot obtain the closed form solution c'_{ij} to the problem, however, $U_{p,i}$ is continuous in c'_{ij}, and the maximum value of the $U_{p,i}$ can be achieved by searching for the optimal c^*_{ij} with $c'_{ij} \in (e^{-a_j A_{ij} R^0_{s,jj}}, 1)$. Consequently, we get the optimal solution $(\alpha^*_{ij}, c^*_{ij})$ to the Stackelberg game.

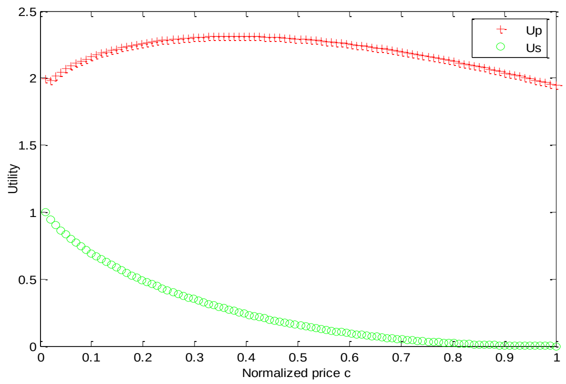

Fig. 2. Utility vs. price.

C. *Optimal Relay Selection Algorithm*

From the above analysis, we know that when the relay selection has been determined, the PU will decide the price it will charge the SU (its relay), and the SU decides the amount of time it will rent to maximize its own utility under the price. Consequently, for any given relay selection, the price c and the leased time duration are determined. We transform the optimization problem OP1 to

OP2:

$$\max U_P = \sum_{i=1}^{N} b_{ij}(\omega_{p,i}(1 - E_{c,ij}/E_{0,i}) + c^*_{ij}(1-\alpha^*_{ij})) \quad (34)$$

subject to (12), (13), (14) and

$$c^*_{ij} \in (\omega_{s,j} a_j R^0_{s,jj} e^{-a_j A_{ij} R^0_{s,jj}}, \omega_{s,j} a_j R^0_{s,jj}), \quad \forall i \in \{1,2,...,M\},\, j \in \{1,2,...,N\} \quad (35)$$

$$\alpha^*_{ij} = \frac{1}{a_j R^0_{s,jj}} \ln \frac{c_{ij}}{\omega_{s,j} a_j R^0_{s,jj}} + 1, \forall i \in \{1,2,...,M\},\, j \in \{1,2,...,N\} \quad (36)$$

Specifically, the channel conditions of PU_i and SU_j satisfy (22) and (28).

OP2 actually is the relay selection problem, and is a 0-1 knapsack problem [20] which can be converted to an assignment problem, and in this work, we adopt the Hungarian method to solve the relay selection problem. The Hungarian method is a combinatorial optimization algorithm which solves the assignment problem in polynomial time [21]. Problem OP2 can be transformed to

OP3:

$$\text{minimize} -U_P = -\sum_{i=1}^{N} b_{ij}\omega_{p,i}(1 - E_{coop,ij}/E_{0,i}) - c^*_{ij}(1-\alpha^*_{ij})) \quad (37)$$

subject to (22) and (28), (14), (35), (36), and

$$\sum_{i=1}^{N} b_{ij} = 1 \quad (38)$$

$$\sum_{j=1}^{M} b_{ij} = 1 \quad (39)$$

Algorithm.1 Cost Matrix Construction

Initialization: Generate the cost matrix $\mathbf{U} = \{u_{ij}\}_{K\times K} = \mathbf{0}$
for i=1:M
 for j=1:N
  if (22) and (28) stand
   Calculate $(\alpha^*_{ij}, c^*_{ij})$ and $E_{c,ij}$
   Calculate $u_{ij} = -\omega_{p,i}(1 - E_{c,ij}/E_{0,i}) - c^*_{ij}(1-\alpha^*_{ij})$
  else
   $u_{ij} = 0$
  end if
 end for
end for

In order to use the Hungarian method, we first need to construct the cost matrix $\mathbf{U} = \{u_{ij}\}_{M\times N}$. The element u_{ij} in the matrix $\mathbf{U}$ is the negative value of the utility of the PU_i when it cooperates with the SU_j. We obtain $u_{ij} = -\omega_{p,i}(1 - E_{c,ij}/E_{0,i}) + c^*_{ij}(1-\alpha^*_{ij})$. From the above analysis, we know that $u_{ij} \le 0$. In particular, when (22) and (28) cannot be satisfied which means the PU_i will not select the SU_j as its relay and will not lease any spectrum to the SU_j, the u_{ij} is set to 0 as any value plus 0 is the value itself, which does not affect the minimal value of $-U_P$. When M is not equal to N, it is an unbalanced Hungarian problem, so we create a number of zeros to complement the cost matrix $\mathbf{U}=\{\mathbf{u_{ij}}\}_{\mathbf{K}\times\mathbf{K}}$, where $K=\max(M,N)$. The construction process $\mathbf{B}=\{b_{ij}\}_{M\times N}$ of the cost matrix is given in Algorithm. 1.

We can obtain the optimal relay selection result using the Hungarian method. However, the situation exists where some of the PUs directly transmit to their destinations and do not choose any SU as its relay. Specifically, when $b_{ij}=1$ and $u_{ij}=0$, which means the PU_i directly transmits to its destination, and we set the b_{ij} to zero. We obtain the relay selection results

$$\mathbf{B}^*=\mathbf{B}=\{b_{ij}\}_{M\times N} \text{ where setting } b_{ij}=0, \text{ if } u_{ij}=0\,. \quad (40)$$

Once, the optimal relay selection is determined, and the spectrum leasing strategies $(\alpha_{ij}^*, c_{ij}^*)$ can be determined, and we can obtain the solution $(\alpha_{ij}^*, c_{ij}^*, \mathbf{B}^*)$ of optimal spectrum leasing and relay selection.

IV. Numerical Results and Analysis

To evaluate the proposed cooperation scheme, we consider a geometrical model where the CC is located at the center of a circle. The radius of the circle is 1000 meters, and the PU link pairs and SU link pairs are uniformly distributed within this area. There are 10 primary link pairs in the system, which means there are 10 channels. The average distance between primary transmitters and receivers is $\frac{2}{3}$ km. Assume that the distances between the SU link pairs are the same and are 200 meters. We assume that the path loss exponent is 4 and Rayleigh multipath fading is present. All the powers are measured in watts. The noise power is 10^{-13} watts on each channel. For simplicity, $R_{P,i}$ is set to 2, and the target data rate $R_{s,j}^0$ of the SU is equal to 1, except when specifically adjusted, for $\forall i\in\{1,2,...,M\}, j\in\{1,2,...,N\}$. The $\omega_{p,i}$ and $\omega_{s,j}$ are set to 2 and 1 respectively, for $\forall i\in\{1,2,...,M\}, j\in\{1,2,...,N\}$. In order to show the performance of our cooperative spectrum leasing and relay selection, we compare it with the following two schemes: one is non-cooperative spectrum leasing (NCSL) with optimal relay selection, where the secondary users do not help relay the data of the PUs; the other is cooperative spectrum leasing with random relay selection, in which the PU randomly selects the a SU as its relay. The simulation results are obtained by averaging over 10,000 channel realizations.

In our model, the number of the secondary users is an important parameter as the secondary users act as relays of the primary users, which can bring cooperative diversity. The traffic demands of the SUs decide how much spectrum the SUs would like to rent, and this will affect the price strategies of the PUs.

Fig. 3 shows the utility of the primary network versus the number of the SUs. The utility of the primary network under the proposed CSL-optimal-relay-selection is larger than those under NCLS-optimal-relay-selection and CSL-random-relay-selection, since the PUs can obtain extra revenue from the cooperation and the optimal relay selection strategy. When the number of the SUs is smaller than that of the primary users, the performance of all the three schemes increase as the number of the SUs increases. When the number of the SUs is larger than that of the primary users, the performance of CSL-random-relay-selection is flat and the performance of NCSL-optimal-relay-selection is increasing slightly; however, the performance of CSL-optimal-relay-selection is still increasing as the proposed scheme can effectively exploit the cooperative diversity. Furthermore, we can see that the performance of the two schemes with cooperation is larger than the one without cooperation; therefore, the PUs would like to actively cooperate with the SUs for extra benefit. The primary network benefits from not only the spectrum leasing, but also the cooperation with the SUs. Comparing the CSL-optimal-relay-selection scheme with CSL-random-relay-selection scheme, we know that the performance of the primary network under the scheme with optimal relay selection is better than that with the random relay selection.

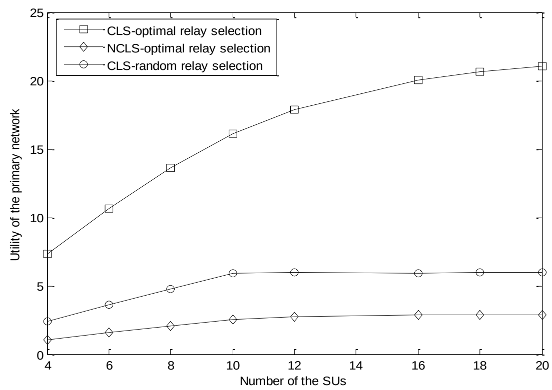

Fig. 3. The utility of primary network vs. the number of the secondary users

Fig. 4 illustrates the utility of the secondary network. Obviously, the utility under the proposed scheme is larger than those under NCLS-optimal-relay-selection and CSL-random-relay-selection. Under the precondition that the PUs lease spectrum to the SUs, the utilities of the schemes with optimal relay selection are better than that of the random relay selection, and they are increasing as the number of the SUs increases; in the two schemes with optimal relay selection, the SUs can exploit the spatial diversity especially when the number of the SUs is larger than that of the PUs, while the utility of the scheme with random relay selection is flat due to inefficient diversity exploiting. The utility of our proposed scheme is better than the NCSL-optimal-relay-selection scheme, since the SUs can rent more spectrum time from the PUs for their cooperation with the PUs. The utility of NCLS-optimal-relay-selection is better than that of the CSL-random-relay-selection, as the secondary network can rent more spectrum, and it mainly benefits from the spectrum leasing.

From the above simulation results and analysis, we know that the utility of the secondary network mainly benefits from the spectrum leasing. This is identical with the results shown in Fig.5. Under our proposed scheme, the secondary network can rent the most spectrum time compared with the other two schemes.

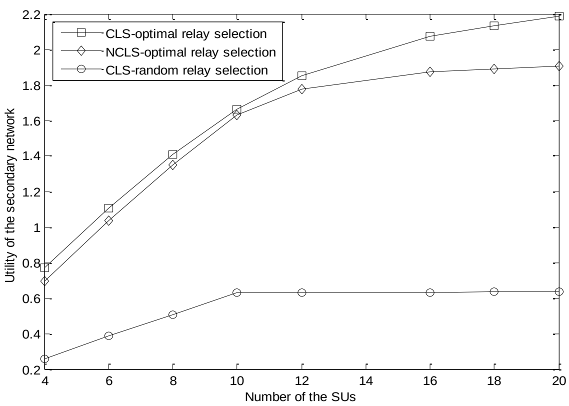

Fig. 4. The utility of secondary network vs. the number of the secondary users

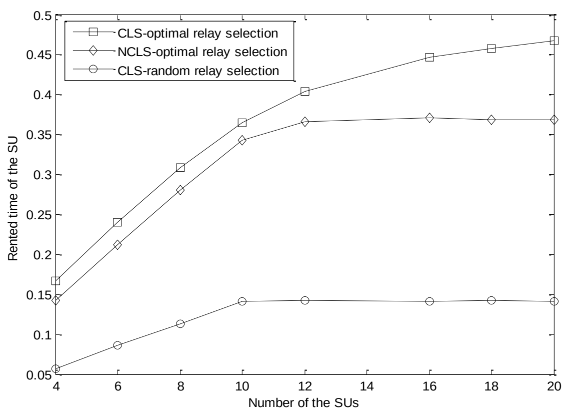

Fig. 5. The rented time of secondary network vs. the number of the secondary users

We assume all the SUs have the same traffic demand and there are 15 secondary users in the system. We investigate how the traffic demand of the SUs affects the performance of the primary and secondary network. Fig.6 shows the total rented spectrum time of the secondary network versus the traffic demand of the SUs. The rented time of the secondary network, as expected, is increasing as the traffic demands increase, since the secondary network needs to rent more spectrum time to satisfy its traffic demand. This is for the same reason as explained above in that the rented time under our proposed scheme is the largest.

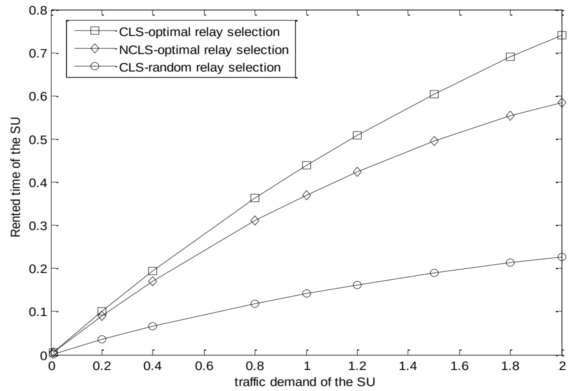

Fig. 6. The rented time of the secondary network vs. the traffic demand of the SU.

It is shown that, in Fig. 7, the utilities of the primary network of the three schemes all decrease as the traffic demands of the SUs increase. The primary network will obtain more revenue from spectrum leasing to the secondary network, as it rents more spectrum time to satisfy the traffic demand. However, there is less spectrum time left for their own transmissions, and the energy saving of the primary network is decreasing; the utility of the primary network is obtained by not only the spectrum leasing but also the energy saving through cooperation. Therefore, synthetically considering the two aspects, the utility decreases.

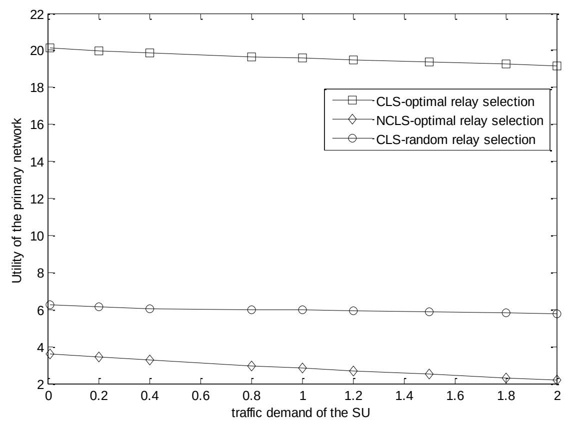

Fig. 7. The utility of primary network vs. the traffic demand of the SU

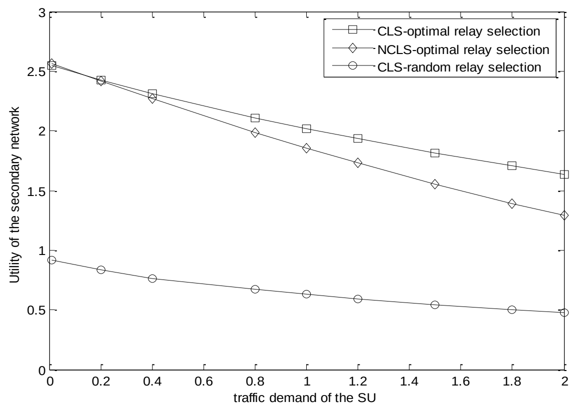

Fig. 8. The utility of secondary network vs. the traffic demand of the SU

Fig. 8 shows the utility of secondary network versus the traffic demand of the SUs. The SUs rent more spectrum to satisfy their traffic demands and improve the utility of secondary network by increasing the data rate of the SUs. However, the secondary network needs to pay more for the rented spectrum time and dramatically decreases the total utility. Still under our proposed scheme, the utility of the secondary network is the highest as it exploits the cooperative diversity and adopts the optimal relay selection.

V. Conclusions

In this work, we formulate a cooperative cognitive radio system model, where multiple secondary users coexist with multiple primary users over multiple channels. The primary users would like to lease a portion of the spectrum to the proper secondary users for some revenue, and the secondary users actively cooperate with the primary users and help them relay the data in return for some spectrum time. We formulate the spectrum leasing and relay selection problem as a multi-seller and multi-buyer market model. We decompose the problem as two coupled sub-problems, adopt the Stackelberg game to solve the spectrum leasing problem and then use Hungarian method to obtain the optimal relay selection problem. Simulation results show that under the proposed scheme, both the primary and secondary network can benefit from the cooperative spectrum leasing and optimal relay selection.

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