Cooperative Game and Relay Pairing in Cognitive Radio Networks

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Abstract. In this paper, we focus on cooperative spectrum access in a cognitive radio networks (CRN), where secondary users (SUs) serve as relays for primary users (PUs) to improve their throughput, and in return SUs can gain transmission opportunities. To optimize the overall utility of a cooperative CRN, we first investigate the cooperation between a single pair of PU and SU with Stackelberg game model, where PU determines access time allocation while SU determines relaying power for the PU. Based on the analytical results, cooperation pairing between multiple PUs and SUs is modeled as a bipartite matching problem and solved using *Gale-Shapley* algorithm. Numerical results demonstrate that, with the proposed schemes, overall utility for PUs and SUs can be balanced with low computational complexity.

Keywords: Cognitive radio · Cooperative communications · Stable matching

1 Introduction

With the rapid development in wireless applications and services, the demand for radio spectrum resource has significantly increased. However, the radio spectrum is limited and much of it has already been licensed exclusively to existing services. What's more, it is widely recognized that the licensed spectrum is in fact underutilized since licensed users typically do not fully utilize their allocated spectrum at most of the time. On the contrary, unlicensed users are starved for spectrum availability [1].

To cope with such a dilemma, a great number of solutions have been discussed and cognitive radio (CR) turns out to be the one with most potential by allowing secondary users (SUs) opportunistically to utilize the spectrum resource, which is found temporarily unused by primary (licensed) users (PUs) via spectrum sensing. However, due to PU's dynamics and unreliability of spectrum sensing resulted from channel fading or shadowing, SUs are forced to terminate the ongoing transmission once it detects that the spectrum band is reoccupied by a PU, which making SU's transmission highly unstable.

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Moreover, cooperative spectrum access has emerged as a powerful technique. In CR systems, instead of keeping silent when PUs are busy, SUs can actively relay PUs' data and in return gain opportunities for its own transmission [2,3]. In [4], a scenario in which the SU acts as a relay for the packets that the SU can receive from the primary source but the primary destination can't, is considered and the stable throughput of the SU under this model is derived. The authors in [5] propose that the PU has the possibility to lease the owned spectrum to an *ad hoc* network of secondary nodes in exchange for cooperation in the form of distributed space-time coding. In [6], the authors studied the optimal cooperation strategy with Energy Harvesting by discuss the cooperation and none-cooperation modes. In [7], the authors investigate optimization for the cooperative spectrum sensing with an improved energy detector to minimize the total error rate (sum of the probability of false alarm and miss detection). However, most of the existing works involve only one pair of PU and SU, which may not be fully applied to the whole network.

In this paper, we consider a CR system with multiple pairs of primary and secondary transceivers, which operate in time-slotted mode. Each PU operates on a unique channel and can choose only one SU as relay using *Decode-and-Forward* (DF) mode. This work will use the stable mating algorithm to determine cooperation pairing for PUs and SUs. Moreover, we investigate the optimal cooperation strategy in this CR system, i.e., PUs decides the optimal allocation of channel resource to maximize their summarize transmission rate and SUs decide their optimal cooperative transmitting power to maximize their summarize transmission rate without spending too much power for relaying. The contribution of this work can be summarized as follows. First, we study the cooperation between multiple PUs and SUs and between single PU and single SU. Second, we study the cooperation by using DF mode but most of others are AF mode. Finally, cooperation between PUs and SUs is studied to maximize the primary network utility and secondary network utility.

The remainder of the paper is organized as follows. The detailed description of the system model is given in Sect. 2. Cooperation between one PU and one SU is studied in Sect. 3 and cooperation between multiple PUs and SUs is studied in Sect. 4. Simulation is provided in Sect. 5. Concluding remarks are provided in Sect. 6.

1.1 System Model

As shown in Fig. 1, we consider a CRN that consists of M PUs and N SUs, in which each PU transmits data on an unique channel. Instead of keeping silent when the PU is busy, an SU can alternatively act as a cooperative relay to improve the PU's throughput, which makes SU benefit a fraction of time slot for secondary transmission as reward. In this paper, we consider the DF mode for the cooperation, i.e., the SU firstly decodes the received signal from the PU transmitter, re-encodes it, and then transmits it to the corresponding PU receiver. Notations used in this paper are summarized in Table 1.

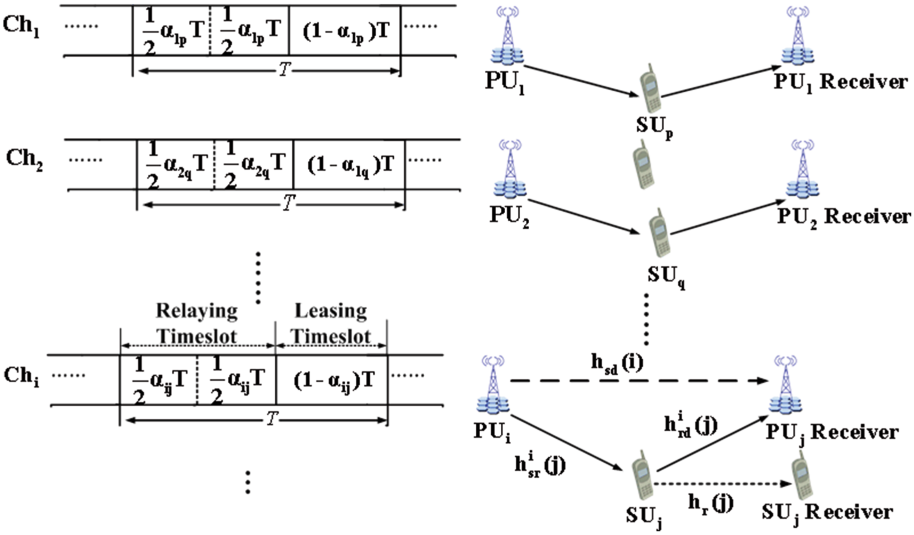

Fig. 1. Cooperative cognitive radio network with multiple channels.

Table 1. Notations

T	Timeslot duration
N_0	The white Gaussian noise
W	The spectrum bandwidth
α_{ij}	The fraction of timeslot that PU_i and PU_j cooperate
P_s^i	The PU_i's transmitting power
$P_r^i(j)$	The SU_j's transmitting power when cooperated with PU_i
h_{sd}^i	The channel gains in the PU_i's direct transmission
$h_{sr}^i(j)$	The channel gains from PU_i transmitter to SU_j
$h_{rd}^i(j)$	The channel gains from SU_j to PU_i's corresponding receiver
$h_r(j)$	The channel gains from SU_j to its corresponding receiver

Both of PUs and SUs operate in time-slotted mode as shown in Fig. 1. A fraction α_{ij} $(0 < \alpha_{ij} < 1)$ of the time slot duration T is used for cooperation between PU_i and SU_j. In the first duration of $\frac{\alpha_{ij}}{2}T$, PU_i transmits its data to SU_j. In the next duration of $\frac{\alpha_{ij}}{2}T$, SU_j relays the received data to the PU_i receiver. In the last period of $(1-\alpha_{ij})T$, the cooperating SU_j is rewarded to transmit its own data while PU_i is silent. A common control channel is assumed for exchanging information on cooperation decision among PUs and SUs.

In such a cooperation model, we study the optimal strategy for the overall utility of the CRN through two steps. Firstly, by analyzing the cooperation between single pair of PU and SU, the optimal decision of cooperation between a single pair of PU and SU, i.e., PU's cooperation fraction and SU's cooperation power is determined. Secondly, based on the analytical result of cooperation between single pair of PU and SU, the overall utility of such a CRN is further investigated by properly pairing PUs and SUs for cooperation.

2 Cooperation Between Single PU and SU

In this section, we will discuss the cooperation between a single pair PU and SU. For ease of presentation, the PU's and SU's index are omitted, e.g., α_{ij} turns to α and $h^i_{sr}(j)$ turns to h_{sr} and so on. In this section, the SU can increase the PU's throughput by relaying PU's data, and in return gains a fraction of time to transmit its own data. The cooperation between PU and SU is modeled as a Stackelberg game. In such a game, utilities of both the PU and the SU are presented and analyzed and close-form solutions are derived.

2.1 Stackelberg Game Between PU and SU

Since both PU and SU are selfish and rational and they just wish to maximize its own utility, i.e., the PU wishes to maximize its throughput while the SU wishes to consume less energy for relaying PU's data in addition to improving throughput. Therefore, the cooperation between PU and SU can be modeled as a Stackelberg game, where the PU acts as the leader and the SU acts as the follower. As the leader, the PU can choose the best strategy, awaring of the effect of its decision on the strategy of the follower (the SU); the SU can just choose its own strategy based on the PU's strategy. The utility functions for both PU and SU are respectively defined in the following. By analyzing the game, the optimal cooperation strategy of both PU and SU can be determined.

PU Utility. Given the fixed time duration T, increasing the throughput is equivalent to increasing the average transmission rate. Suppose the cooperated SU's relay power is known, the PU decides the slot allocation parameter α to maximize the potential profit.

Without cooperation, the transmission rate of the direct communication can be given by

$$R_d = W \log_2(1 + \frac{P_s|h_{sd}|^2}{N_0})$$

With cooperation, the transmission rate R_p through DF cooperative communication between the PU and SU, which serves as the utility function of a single PU, is given as follows:

$$R_p = \min\{\frac{\alpha}{2} W \log(1 + \frac{P_s|h_{sr}|^2}{N_0}), \frac{\alpha}{2} W \log(1 + \frac{P_r|h_{rd}|^2}{N_0})\} \tag{1}$$

The factor $\frac{\alpha}{2}$ accounts for the fact that αT is used for cooperative relaying, which is further split into two phases. Here we specify that both PUs and SUs transmit at a constant power, which are denoted by P_s for PUs and P_r for SUs, respectively. We assume that the PU chooses to cooperate only when the cooperative transmission rate is greater than that achieved by direct transmission. The objective of the PU is to maximize its own utility function by properly choosing the cooperation α and its utility function $U_p = R_p$.

SU Utility. The SU can gain transmission opportunities through cooperation with PU. In particular, the SU relays PU's data in the second phase and transmits its own data in the last phase. When cooperating, the SU decides its transmission power, pertaining to the given α. The target of the SU is to maximize throughput (equivalent to the transmission rate) without expending too much energy. Following the cooperation agreement, the SU spends the same power P_r for both cooperation and its own transmissions. In particular, the transmission rate R_s for secondary transmission from SU to its corresponding receiver is given by

$$R_s = (1-\alpha)W\log(1+\frac{P_r|h_r|^2}{N_0}) \tag{2}$$

With energy consumption $(1-\frac{\alpha}{2})P_rT$, the utility function of SU can be represented by $R_sT - cP_r(1-\frac{\alpha}{2})T$, where $c(0<c<1)$ is the weight of energy consumption in the overall utility. Over the period of T, the utility function of SU is given by

$$U_s = (1-\alpha)W\log(1+\frac{P_r|h_r|^2}{N_0}) - c(1-\frac{\alpha}{2})P_r \tag{3}$$

The objective of SU in the game is to maximize its utility by choosing the optional transmission power P_r.

2.2 Game Analysis

As a sequential game, the Stackelberg game can be analyzed by the backward induction method. First, assuming the strategy of the PU (the leader) is fixed, the optimal strategy of the SU (the follower) is analyzed. Second, the PU decides the optimal strategy, knowing the results of the first step. By doing so, the best response functions of both the PU and the SU are derived such that the corresponding utilities can be maximized. Then, the Stackelberg equilibrium of the proposed game can be achieved based on the best response functions.

SU's Best Response Function. Assuming that the PU uses α for cooperation, SU selects the optimal transmission power to maximize its utility, which can be formulated as the following optimization problem:

$$\max_{P_r} U_s(\alpha) = (1-\alpha)W\log(1+\frac{P_r|h_r|^2}{N_0}) - c(1-\frac{\alpha}{2})P_r$$

Solving the above problem, the optimal transmission power can be determined.

Definition 1. *Let $P_r^*(\alpha)$ be the best response function of the secondary user if the utility of SU can achieve the maximum value. When $P_r^*(\alpha)$ is selected, for any given α, i.e., $\forall 0 < \alpha < 1$, $U_s(P_r^*(\alpha), \alpha) \geq U_s(P_r(\alpha), \alpha)$.*

Theorem 1. *The best response function of the secondary user is given by*

$$P_r^*(\alpha) = \frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_r|^2} \tag{4}$$

Proof. Given the time allocation coefficient α, the utility function of SU is given as (3). From the Eq. (3), it is easy to prove that the utility function first increases and then decreases with the increase of P_r without considering the power constraint. Therefore, there exists an optimal power such that U_s can reach the maximum value at that transmission power. Taking the first order partial derivative of the utility function with respect to P_r yields

$$\frac{\partial U_s}{\partial P_r} = \frac{(1-\alpha)W|h_r|^2}{(1+\frac{P_r|h_r|^2}{N_0})N_0 \ln 2} - c(1-\frac{\alpha}{2})$$

Setting $\frac{\partial U_s}{\partial P_r} = 0$ yields the optimal transmission power. The best $P_r^*(\alpha)$ response function will be

$$P_r^*(\alpha) = \frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_r|^2}$$

This completes the proof.

PU's Best Response Function. Awaring of the best response function of the SU, the PU decides its own best strategy for utility maximization.

Definition 2. *Let α^* be associated with the best response function of the primary user if the utility of the PU can achieve the maximum value when this strategy is selected.*

Theorem 2. *The best response function of the primary user α^* can be given as follows:*

$$\alpha^* = \begin{cases} \alpha_1^*, & if\, U_p(\alpha_1^*) \geq U_p(\alpha_2^*) \\ \alpha_2^*, & otherwise \end{cases} \tag{5}$$

Where α_1^* and α_2^* are respectively the optimal function of the first item and the second item of the two processes from (1). α_1^* and α_2^* are given as follows:

$$\alpha_1^* = \begin{cases} \alpha_1', & if \quad 0 < \alpha_1' < 1 \\ 0, & otherwise \end{cases} \tag{6}$$

and

$$\alpha_2^* = \begin{cases} \alpha_2', & if \quad 0 < \alpha_2' < 1 \;\text{ and } \quad R_p(\alpha_2') \geq R_d \\ 0, & otherwise \end{cases} \tag{7}$$

where

$$\alpha_2' = \arg\max(U_p)$$

$$\alpha_1' = \max(\Psi_1, \Psi_2)$$

and

$$\Psi_1 = 2[1 - \frac{W}{c\ln 2(\frac{2W}{c\ln 2} - \frac{N_0}{|h_r|^2} - \frac{P_s|h_{sr}|^2}{|h_{rd}|^2})}]$$

$$\Psi_2 = 2\frac{\log(1 + \frac{P_s|h_{sd}|^2}{N_0})}{\log(1 + \frac{P_s|h_{sr}|^2}{N_0})}$$

Proof. We can see the cooperative rate of the primary user is determined by smaller item of the two processes from (1). Now we will solve this problem in two ways. (a) When

$$\frac{\alpha}{2}W\log(1 + \frac{P_s|h_{sr}|^2}{N_0}) \leq \frac{\alpha}{2}W\log(1 + \frac{\mathrm{P}_r|h_{rd}|^2}{N_0}) \tag{8}$$

then $U_p = \frac{\alpha}{2}W\log(1 + \frac{P_s|h_{sr}|^2}{N_0})$. From (8) we have

$$P_r \geq \frac{P_s|h_{sr}|^2}{|h_{rd}|^2} \tag{9}$$

Substituting (4) into function (9), the inequality can be expressed as

$$\frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_r|^2} \geq \frac{P_s|h_{sr}|^2}{|h_{rd}|^2} \tag{10}$$

which is a function of α. It can be derived from (10) that

$$\alpha \leq 2[1 - \frac{W}{c\ln 2(\frac{2W}{c\ln 2} - \frac{N_0}{|h_r|^2} - \frac{P_s|h_{sr}|^2}{|h_{rd}|^2})}] \tag{11}$$

The PU chooses cooperation only when the transmission rate via cooperation is greater than that of the direct communication. It can be expressed by

$$\frac{\alpha}{2}W\log(1 + \frac{P_s|h_{sr}|^2}{N_0}) \geq W\log(1 + \frac{P_s|h_{sd}|^2}{N_0}) \tag{12}$$

It can be derived from (12) that

$$\alpha \geq 2\frac{\log(1 + \frac{P_s|h_{sd}|^2}{N_0})}{\log(1 + \frac{P_s|h_{sr}|^2}{N_0})} \tag{13}$$

It's easy to see that U_p increased while α increased from $U_p = \frac{\alpha}{2}W\log(1 + \frac{P_s|h_{sr}|^2}{N_0})$. Now we can conclude from (11) and (13) that

$$\alpha_1' = \max(\Psi_1, \Psi_2)$$

where

$$\Psi_1 = 2[1 - \frac{W}{c\ln 2(\frac{2W}{c\ln 2} - \frac{N_0}{|h_r|^2} - \frac{P_s|h_{sr}|^2}{|h_{rd}|^2})}]$$

$$\Psi_2 = 2\frac{\log(1+\frac{P_s|h_{sd}|^2}{N_0})}{\log(1+\frac{P_s|h_{sr}|^2}{N_0})}$$

Since $0 < \alpha < 1$, we have

$$\alpha_1^* = \begin{cases} \alpha_1', & \text{if} \quad 0 < \alpha_1' < 1 \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

(b) When

$$\frac{\alpha}{2}W\log(1+\frac{P_s|h_{sr}|^2}{N_0}) > \frac{\alpha}{2}W\log(1+\frac{\mathrm{P}_r|h_{rd}|^2}{N_0}) \tag{15}$$

then $U_p = \frac{\alpha}{2}W\log(1+\frac{P_r|h_{rd}|^2}{N_0})$. From (15) we have

$$P_r < \frac{P_s|h_{sr}|^2}{|h_{rd}|^2} \tag{16}$$

Similar (10) and (11), by substituting (4) into function (16), we have

$$\alpha > 2[1 - \frac{W}{c\ln 2(\frac{2W}{c\ln 2} - \frac{N_0}{|h_r|^2} - \frac{P_s|h_{sr}|^2}{|h_{rd}|^2})}] \tag{17}$$

Substituting (4) into utility function $U_p = \frac{\alpha}{2}W\log(1+\frac{P_r|h_{rd}|^2}{N_0})$, the utility can be expressed by

$$U_p = \frac{\alpha}{2}W\log[1+(\frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_r|^2})\frac{|h_{rd}|^2}{N_0})]$$

which is a function of α.

U_p can be maximized because it is easy to proof $\frac{\partial U^2}{\partial \alpha^2} < 0$. The optimal α_2' is given by

$$\alpha_2' = \arg\max(U_p) \tag{18}$$

The PU chooses cooperation only when the transmission rate via cooperation is greater than that of the direct communication. It can be expressed by

$$\frac{\alpha}{2}W\log(1+\frac{P_r|h_{rd}|^2}{N_0}) \geq W\log(1+\frac{P_s|h_{sd}|^2}{N_0}) \tag{19}$$

We can get from (19) that

$$P_r \geq [(1+\frac{P_s|h_{sd}|^2}{N_0})^{2/\alpha} - 1]\frac{N_0}{|h_{rd}|^2} \tag{20}$$

Substituting (4) into function (20), the inequality can be expressed by

$$\frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_r|^2} \geq [(1+\frac{P_s|h_{sd}|^2}{N_0})^{2/\alpha} - 1]\frac{N_0}{|h_{rd}|^2} \tag{21}$$

Also, the time slot α_2^* must satisfy $0 < \alpha_2^* < 1$.

Now we can conclude from (17), (18) and (21) that

$$\alpha_2^* = \begin{cases} \alpha_2', & \text{if} \quad 0 < \alpha_2' < 1 \quad \text{and} \quad R_p(\alpha_2') \geq R_d \\ 0, & \text{otherwise} \end{cases} \tag{22}$$

where

$$\alpha_2' = \arg\max(U_p)$$

3 Cooperation Between PUs and SUs

Although bring benefit to single PU and single SU, the approach aforementioned for the single cooperation can not bring the maximum benefit to the whole network because it only optimizes the interest of individual users. Therefore, it is necessary to consider the cooperation over whole network, which involves multiple PUs and SUs, to exploit the cooperation benefit. A common control channel is assumed for exchanging information among PUs and SUs, it can guide PUs and SUs select the suitable cooperator.

There are M PUs and N SUs in the network. Denote by x_{ij} the indicator which indicates whether PU_i cooperates with SU_j or not. Then, we have

$$x_{ij} = \begin{cases} 1, & \text{if } PU_i \text{ and } SU_j \text{ is paired for cooperation} \\ 0, & \text{otherwise} \end{cases} \tag{23}$$

From primary network perspective and from secondary network perspective, there are two utilities.

Primary Network Utility: The objective of pimary network is maximize total utility of the primary network. Note that, when a certain PU selects a certain SU, the throughput of this PU is obtained using Stackelberg Equilibium strategy. Then, the utility function of primary network is given by

$$U_p^o = \max \sum_{i=1}^{M}\sum_{j=1}^{N} U_p^{ij} x_{ij} + U_p^{'}$$

$$\begin{aligned} s.t. \quad & x_{ij} \in \{0,1\} \; \forall i \in \{1,2,...,M\}, j \in \{1,2,...,N\} \\ & \sum_{i=1}^{M} x_{ij} \leq 1 \qquad \forall j = 1,2,...,N \\ & \sum_{j=1}^{N} x_{ij} \leq 1 \qquad \forall i = 1,2,...,M \end{aligned} \tag{24}$$

where

$$U_p^{'} = \sum_i R_d^i \ , i \in \{i | \sum_{j=1}^{N} x_{ij} = 0, i = 1, 2, ..., M\} \tag{25}$$

refers to the sum rate of direct transmission (since PUs choose to cooperate only when cooperative rate is greater than direct transmission rate) and U_p^{ij} is the utility function of PU_i while cooperating with SU_j. Because one PU can at most cooperate with only one SU and one SU can at most cooperate with one PU, we have $\sum_{i=1}^{M} x_{ij} \le 1$ and $\sum_{j=1}^{N} x_{ij} \le 1$.

Secondary Network Utility: Same as the primary network utility, the secondary network utility is given by

$$\begin{aligned} U_s^o = & \max \sum_{j=1}^{N} \sum_{i=1}^{M} U_s^{ji} x_{ij} \\ s.t. \quad & x_{ij} \in \{0,1\} \ \forall i \in \{1,2,...,M\}, j \in \{1,2,...,N\} \\ & \sum_{i=1}^{M} x_{ij} \le 1 \qquad \forall j = 1,2,...,N \\ & \sum_{j=1}^{N} x_{ij} \le 1 \qquad \forall i = 1,2,...,M \end{aligned} \tag{26}$$

Note that U_s^{ji} is the utility of SU_j when cooperated with PU_i, which is given by (3).

Using Stackelberg Equilibrium strategy calculate U_p^{ij} and U_s^{ji} ($i \in \{1,2,...,M\}$, $j \in \{1,2,...,N\}$), the above problem can be transformed into the bipartite matching problem(deciding x_{ij}). The KM algorithm is known as the most suitable algorithm for maximum matching. However, two utilities, U_p^o and U_s^o, exist in in this model. Therefore, it is not suitable for this model. This will be verified in the section simulation.

The Gale-Shapley Stable Marriage Theorem [8] is very general and states that finding a stable matching between two equally sized sets of elements given an ordering of preferences for each element. It is suitable for this model because each element has its own utility regarding the opposite element like this model. So we use G-S Stable Matching to solve the matching problem. Since number of PUs is not necessarily equal to that of SUs, there are inevitably PUs or SUs left uncooperated. The spectrum allocation algorithm based on stable matching model is summarized in Algorithm 1.

4 Numerical Results

In order to evaluate the performance of the proposed algorithm, we use Matlab to simulate our algorithm. We set up the first simulation as a scenario with a single PU and SU. The PU's transmission power P_s is 5. We set $W = 1$ and

Algorithm 1. Stable Matching

Step1: Initialization

1. Caculate U_p^{ij} and U_s^{ji} where $i \in \{1, 2, ..., M\}$ and $j \in \{1, 2, ..., N\}$.
2. PU_i ranks a preference list of SUs by U_p^{ij}.
3. SU_j ranks a preference list of PUs by U_s^{ji}.
4. construct $x_{ij} = 0$ where $i \in \{1, 2, ..., M\}$ and $j \in \{1, 2, ..., N\}$.
5. construct a list of all PUs which not matched and has SUs not asked.
   for cooperation, denoted by MATCHLIST $= \{PU_1, PU_2,...,PU_N\}$.

Step2: Matching process

6. **while** MATCHLIST is not empty **do**
7.   select $PU_k \in$ MATCHLIST.
8.   find SU_j which is in highest preference and x_{kj}==0.
9.   **if** $\sum_{i=1}^{M} x_{ij} == 0$ which means SU_j not matched **do**
10. $x_{kj} = 1$ and remove PU_k from MATCHLIST
11.   **else**
12.   find PU_h that SU_j is already matched(denoted by $x_{hj} = 1$).
13.   **if** SU_j has a higher preference of PU_k **do**
14. $x_{hj} = 0$.
15.   put PU_h into MATCHLIST if PU_h still has SU not asked.
16. $x_{kj} = 1$ and remove PU_k from MATCHLIST.
17.   **end if**
18.   **end if**
19. **end while**

set $N_0 = 1$ for simplicity. The power gains between PU transmitter and PU receiver, and between SU transmitter and SU receiver, are $h_{sd} = 0.3$ and $h_r = 5$, respectively. h_{sd} is setted relatively small to encourage PU to cooperates with SU. The average power gains between the PU transmitter and SU, and between the SU and PU receiver, are $h_{sr} = 5$ and $h_{rd} = 5$, respectively. The weight c ranges from 0.1 to 1 by step adding 0.02. Figure 2 and the left one of Fig. 3 show that time slot of α, the SU's transmission power P_r and the throughput of PU are decreasing in overall trend with the increase of weight c until $c = 0.66$ where PU transmits data directly. The right one of Fig. 3 shows the SU utility is increased with the increase of weight until where PU transmit data directly. $c = 0.28$ is a mutation point because in left of the point the U_p is determined by the rate from the PU transmitter to the SU and in right of the point the U_p is determined by the rate from the SU to the PU receiver.

Another simulation scenario is similar to the one above, impact of the power gains between PU transmitter and PU receiver (h_{sd}) is investigated, which ranges from 0.3 to 1.3 with step adding 0.1. Different from above, the weight c is static and $c = 0.1$. The PU number is setted 100 and the SU number becomes 100 too. Other variable are the same. Figures 4 and 5 show cooperation can bring great benefit to PUs and SUs by versus none cooperation with stable mathing and other two KM algorithems. The benefit is specially greater when the PU's

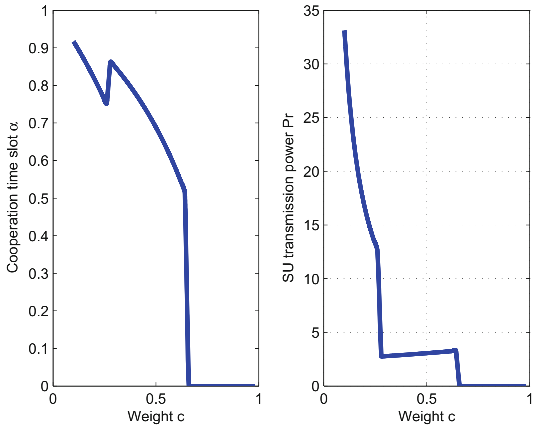

Fig. 2. Cooperation time slot a versus the weight c(left); SU transmission power versus the weight c(right).

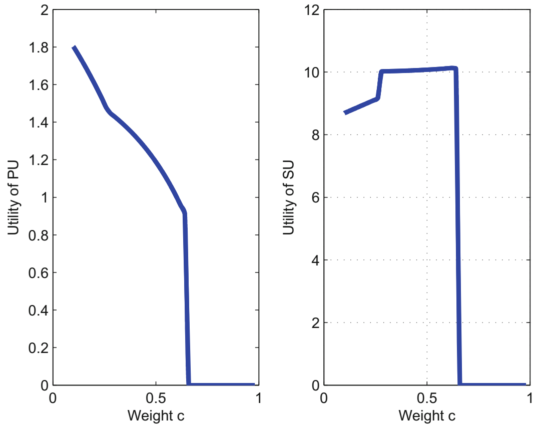

Fig. 3. Utility of PU versus the weight c(left); Utility of SU versus the weight c(right).

direct power gain (h_{sd}) is fairly weak, this is because the transmitting environment is so bad that more cooperation happened. Figures 4 and 5 show that the cooperation matching algorithm of the stable matching algorithm can get less primary network utility but more secondary network utility than the matching algorithm of the KM algorithm by using U_p^{ij} as weight. It also show that the cooperation matching algorithm of the stable matching algorithm can get more secondary utility but less primary network utility than the matching algorithm of the KM algorithm by using U_s^{ji} as weight. So, Figs. 4 and 5 show that the cooperation matching algorithm of the stable matching algorithm can make primary network and secondary both approach optimal. What's more, it's known that stable matching has the lower computational complexity.

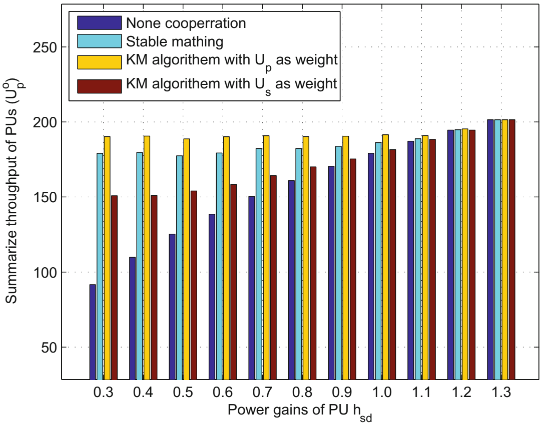

Fig. 4. Summarize throughput of PUs versus the power gains of PU h_{sd}.

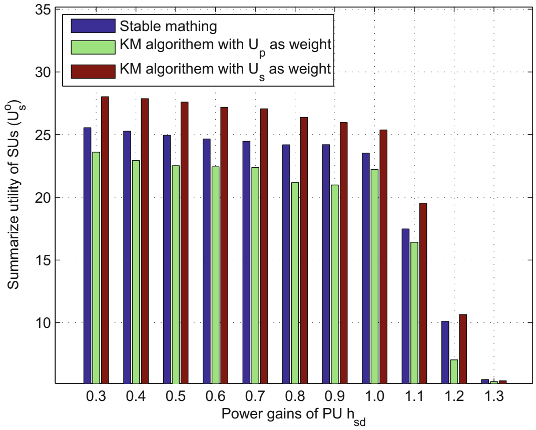

Fig. 5. Summarize utility of SUs versus the power gains of PU h_{sd}.

5 Conclusion

In this paper, we focus on cooperative spectrum access in a cognitive radio networks (CRN), where secondary users (SUs) serve as relays for primary users (PUs) to improve their throughput, and in return SUs can gain transmission opportunities. We first model the cooperation with single PU and single SU as Stackelberg game, through which PU's cooperation fraction and SU's cooperation power are derived. Then based on the above results, we using stable matching algorithm to study the cooperation between multiple PUs and multiple SUs. Through simulations, we show that with the proposed schemes utilities of both PUs and SUs can be balanced. PUs can achieve higher throughput and SUs can obtain more access opportunities. Numerical results also show that the stable matching algorithm is weak Pareto optimal with low complexity.

References

1. Docket, E.T.: Spectrum policy task force. FCC **2**(3), 135 (2002)
2. Zhang, J., Zhang, Q.: Stackelberg game for utility-based cooperative cognitiveradio networks. In: Proceedings of the Tenth ACM International Symposium on Mobile Ad Hoc Networking, Computing, vol. 2(3), p. 135, November 2009
3. Laneman, J.N., Tse, D.N.C., Wornell, G.W.: Cooperative diversity in wireless networks: Efficient protocols and outage behavior. IEEE Trans. Inf. Theory **50**(12), 3062–3080 (2004)
4. Simeone, O., Bar-Ness, Y., Spagnolini, U.: Stable throughput of cognitive radios with and without relaying capability. IEEE Trans. Commun. **55**(12), 2351–2360 (2007)
5. Simeone, O., Stanojev, I., Savazzi, S., Bar-Ness, Y., Spagnolini, U., Pickholtz, R.: Spectrum leasing to cooperating secondary ad hoc networks. IEEE J. Sel. Areas Commun. **26**(1), 203–213 (2008)
6. Yin, S., Zhang, E., Zhaowei, Q., Yin, L., Li, S.: Optimal cooperation strategy in cognitive radio systems with energy harvesting. IEEE Trans. Wireless Commun. **13**(9), 4693–4707 (2014)
7. Singh, A., Bhatnagar, M.R., Mallik, R.K.: Cooperative spectrum sensing with an improved energy detector in cognitive radio network. In: 2011 National Conference on Communications (NCC), pp. 1–5, January 2011
8. Gale, D., Shapley, L.S.: College admissions and the stability of marriage. Am. Math. Monthly **69**(1), 9–15 (1962)