Resource Allocation in OFDMA-Based Cognitive Radio Networks via Cooperation with Primary Users

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Abstract —This paper considers an OFDMA-based cooperative cognitive radio network where the secondary users (SUs) act as the relay of the primary users (PUs) while guaranteeing the quality of service (QoS) of the PUs. In return, the SUs access the spectrum licensed to PUs in both time and frequency without impacting the communication of the PUs. A joint resource allocation problem is formulated to maximize the data rate of the SUs. It is proven that the optimization problem can be decomposed into two coupled subproblems which are power allocation and relay selection. The power allocation adopts the water-filling algorithm using the Lagrangian method, and the optimal relay selection is solved by Hungarian method. Simulation results show that the proposed algorithm can bring revenue to both the PUs and SUs.

Index Terms—OFDMA, cooperative cognitive radio network, QoS, resource allocation, Hungarian method

I. Introduction

Cognitive radio has been proposed to improve the radio spectrum utilization, in which secondary users (SUs) exploit the underutilized spectrum owned by the primary users (PUs) [1]. Over the past few years, cooperative and relay communications have been one of the most widely explored topics in communications and have been incorporated into many modern wireless applications, such as cognitive radio and secret communications [2]. Typically, the application of the cooperative communication technology in cognitive radio networks is to deal with spectrum sensing and spectrum sharing. In [3], Khaled Ben Letaief presents an overview of the application of these technologies to spectrum sensing and spectrum sharing. With high detection performance, cooperative and relay technology has been used to find available spectrum in cognitive radio networks [4]-[6].

Many related works in spectrum sharing with cooperative relay technology have been produced over the last decade [7], [8]. In this paper, our interest is to study spectrum sharing with cooperation in cognitive radio networks. In [7], power allocation is studied with consideration of the interference to the licensed primary system and the power budget of the cognitive radio network in single PU and single SU OFDM systems. However, Ref [7] does not study the cooperation between the PU and SU. In [9], the PU leases a fraction of spectrum time to secondary nodes in exchange for appropriate remuneration that the SUs play as the relay and help forward data of the PU. In cognitive radio networks, this new paradigm of cooperation will not bring any interference to the PUs, and both the PUs and SUs may benefit from the spectrum leasing. Spectrum leasing has been proposed to improve the spectrum utilization through negotiation between the PU and SU networks, and enhance their network performances, and additionally PUs maximize their respective monetary gains [10]. Usually, this kind of spectrum sharing and access scheme is called spectrum leasing. Spectrum leasing is studied with cooperating to multiple PUs in [11]. In [12], the resource allocation problem is studied in a spectrum leasing scenario in a multiple PU pairs and single SU pair cooperative cognitive radio network.

In [13], the authors have stated the details of cognition and cooperation in an underlay scheme in cognitive radio networks. The cooperative relay strategies, such as decode-and-forward (DF), compress-and-forward (CF) and amplify-and-forward (AF) can be used to improve the system performance within not only a single communicating pair but also multiple-relay networks. However, most of the works adopt DF cooperative relay strategy, as the two hops can easily keep time adaptation. An adaptive spectrum-leasing scheme is proposed for multiuser cognitive radio networks based on two-path successive relaying and decode-and-forward protocols, the spectrum is leased to the SU that can achieve the largest secondary rate while satisfying primary rate target [14]. Ref [15] studies the optimal transmission scheduling in cognitive radio networks under spectrum leasing model. However, the power control is not considered in [14], [15]. The power allocation and relay selection problem is studied in an orthogonal frequency division multiplexing (OFDM) cognitive radio system in [16], and a dynamic non-cooperative game with Nash Equilibrium (NE) is suggested to solve the problem.

OFDM promises a high user data rate transmission capability at a reasonable complexity and precision.

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Orthogonal frequency division multiple access (OFDMA) is a promising technology which can exploit the diversity gain in frequency. It has been incorporated into cognitive radio as it can flexibly incorporate dynamic resource allocations in cognitive radio networks [17], [18]. In [19], the authors propose a low complexity resource allocation algorithm for OFDMA cognitive radio networks by introducing relays to help forward the date of the SUs. Ref [20] has studied the cooperation strategies among the primary and secondary networks so as to maximize the sum-rate of SUs while maintaining the intended data rate requirements of PUs. It shows that in the multi-channel cooperative cognitive radio networks, the optimal strategy is to let a SU exclusively act as a relay for a PU or transmit data for itself on a cooperated channel. According to [21], the SUs need to seek to access the spectrum without significantly impacting the communication of the PUs. In this paper, we formulate an OFDMA-based uplink network where multiple PUs and multiple SUs coexist in the same area, the SUs access the spectrum without affecting the power allocation and subcarriers assignment of the PUs. One SU can act as the relay of one PU over all the subcarriers that the PU occupies in a symbol time and guarantee the data rate of the PU. The PUs keep their allocated transmission powers over the available subcarriers without any adjustment and can save energy with transmitting less time. The SU adopts a DF strategy to help the PU over all the subcarriers that the PU occupies. Here, a joint optimization problem of time duration division, relay selection, and power allocation is formulated, and this is a mixed integer programming problem and is computationally complex. This joint optimization problem is decomposed into two coupled subproblems, i.e., power allocation and relay selection, which are solved by iterative water-filling using Lagrangian method and Hungarian method, respectively. It is shown that both the PUs and SUs can benefit from the cooperation.

The remainder of this paper is organized as follows. Section II describes the system model and formulates the resource allocation problem. In Section III, we propose an optimal power allocation and relay selection algorithm for the SUs. To evaluate the proposed algorithm, we show some simulation results and analyze the performance of the proposed resource allocation algorithm in Section VI. Section V concludes the paper.

II. Problem Description and Formulation

We formulate a new OFDMA-based cooperative cognitive network with cooperation between PUs and SUs in this section. Assuming there is an OFDMA-based uplink network where M primary users operate on N orthogonal subcarriers. Let Ω denote the set of the subcarriers, $\Omega = \{1, 2, 3, \cdots, N\}$. For any PU m, Ω_{m} is the set of subcarriers allocated to him/her. The N subcarriers are occupied by the M PUs, we obtain $\Omega = \Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_m$. In an OFDM symbol duration, each PU has a fixed transmit power, and the power allocated to its occupied subcarrier n is p_{pm}^{n}, $n \in \Omega_{\mathrm{m}}$.

K secondary users (usually consisting of K link pairs) coexist in the same area and intend to access the spectrum licensed to the PUs. In order to admit the SUs access, here we introduce cooperation between the PUs and SUs. The SUs act as the relays and help forward the data of the PUs to the base station. In return, the PUs share a portion of their spectrum resource in both time and frequency to the SUs. Every SU k has a maximum transmit power P_s^k. As cooperation exists between PUs and SUs, system information can be exchanged among all the users including PUs and SUs. The power allocation of the PU on every subcarrier and channel state information of the entire network are known to all PUs and SUs. The spectrum sensing is not studied in this scenario. One SU can only play as the relay for one PU, but can operate over multiple subcarriers. The PU can only select one SU as relay. The DF strategy is adopted in this scenario, as shown in Fig. 1.

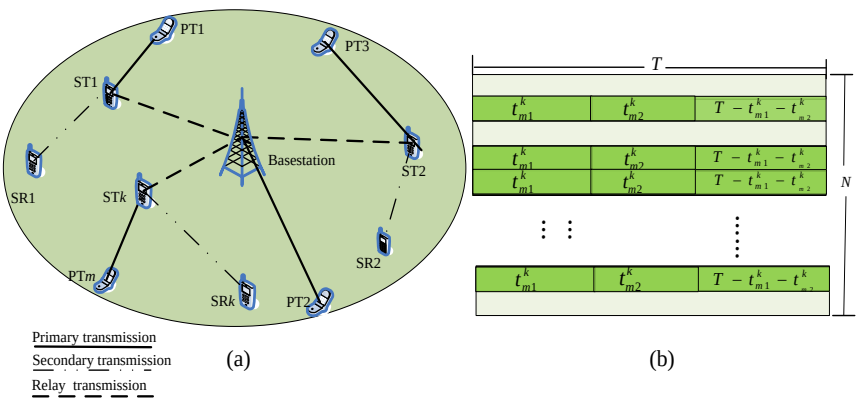

Fig. 1. OFDMA-based cooperative cognitive radio networks (a) system architecture (b) time duration division.

Different from [20], the OFDM symbol duration T is divided into 3 subslots, where the first 2 subslots are not equal. This is because the amplify-and-forward (AF) relaying strategy needs an equal time allocation, while DF strategy is more flexible and the two hops can pursue time adaptation. In the first subslot t_{m1}^{k}, the PU m

transmits data to the relay SU k over the subcarriers Ω_m, and in the second subslot t_{m2}^k, SU k decodes the data received from PU m and re-orders the data, and then forwards it to the base station. In the third subslot $T-t_{m1}^k-t_{m2}^k$, the SU k transmits its own data over the subcarriers Ω_m.

In order not to affect the PUs, once the power allocation of the PUs has been determined, the power allocation on each subcarrier will be maintained. All the adjustment work of the cooperation is to be done by the SUs. We use H_{pp}^{mnd}, H_{ps}^{mnk} and H_{sp}^{knd} to represent the channel gains between PU m and SU k, the base station, and SU k and the base station, respectively, on subcarrier n. Let H_{ss}^{knk} denote the channel gain between the transmitter and receiver of SU k. p_{sk}^n and $p_{ss.k}^n$ are the allocated powers of SU k for relaying PU's data and transmitting its data on subcarrier n.

The data rate of PU m without cooperation over Ω_m is expressed as follows

$$R_m = T\sum_{n\in\Omega_m}\log_2(1+\frac{p_{pm}^n H_{pp}^{mnd}}{\sigma_{p,mnd}^2}) \tag{1}$$

When the SU k plays as the relay of PU m, the data rates in the first 2 subslots can be obtained by

$$R_{ps,m}^k = t_{m1}^k\sum_{n\in\Omega_m}\log_2(1+\frac{p_{pm}^n H_{ps}^{mnk}}{\sigma_{p,mnk}^2}) \tag{2}$$

$$R_{sd,m}^k = t_{m2}^k\sum_{n\in\Omega_m}\log_2(1+\frac{p_{sk}^n H_{sp}^{knd}}{\sigma_{s,knd}^2}) \tag{3}$$

In DF cooperative communication systems, we obtain the data rate of PU m expressed by [22]

$$R_{m,coop}^k = \min(R_{ps,m}^k, R_{sd,m}^k) \tag{4}$$

In the third subslot, the data rate of SU k for its own transmission is

$$R_{ss,m}^k = \sum_{n\in\Omega_m}(T-t_{m1}^k-t_{m2}^k)\log_2(1+\frac{p_{ss.k}^n H_{ss}^{knk}}{\sigma_{s,knk}^2}) \tag{5}$$

The target is to maximize the system capacity of the secondary network while guaranteeing the QoS of the PUs, i.e. the transmission data rate. In order to achieve this, we need to solve the power allocation and the optimal relay selection problem for the SUs over the subcarriers Ω. Here we introduce a binary variable a_m^k to denote the relay selection. The SUs transmit at their maximum power levels to earn more transmission time. The optimization problem (OP) for the secondary network is formulated as

OP1:

$$\max\sum_{k=1}^{K}\sum_{m=1}^{M}a_m^k R_{ss,m}^k \tag{6}$$

s.t.

$$\begin{aligned}
&C_1:\ \sum_{n\in\Omega_m}p_{ss,k}^n \le P_s^k,\ \forall k\\
&C_2:\ p_{ss,k}^n \ge 0,\ \forall n,k\\
&C_3:\ \sum_{k=1}^{K}a_m^k \le 1,\ \forall m\\
&C_4:\ \sum_{m=1}^{M}a_m^k \le 1,\ \forall k\\
&C_5:\ a_m^k \in\{0,1\},\ \forall m,k\\
&C_6: R_{m,coop}^k \ge R_m\ if\ a_m^k = 1,\ \forall m,k
\end{aligned} \tag{7}$$

C_3 of (7) represents the case where one PU can only select one SU as its relay or not. C_4 of (7) represents that one SU can at most select one PU to help forward data, C_6 guarantees the data rate of the PUs. OP1 is a nonlinear integer programming problem and is NP hard. In the following section, we decompose the optimization problem into 2 coupled problems, power allocation and relay selection problem, it becomes a work assignment problem and can be solved by Hungarian method.

III. Optimal Power Allocation and Relay Selection

In multiple PU and multiple SU systems, we need to solve the relay selection problem to maximize the system capacity of the secondary network. We first consider single SU and single PU case. Given SU k and PU m, we obtain some analytical results.

Instead of guaranteeing the data rate on every subcarrier, we guarantee the total data rate of PU m over its subcarriers Ω_m. The SU receives all the data from the PU m, decodes, re-orders and then forwards it. The SU will forward the PU's data with minimum energy consumed, in the first 2 subslots, we obtain

$$R_m = R_{m,coop}^k = R_{ps,m}^k = R_{sd,m}^k \tag{8}$$

As the PUs and SUs are randomly distributed in the same geographic area, not all the SUs can act as the relays of the PUs. The PU would like to cooperate with the SUs on the condition that its data rate can be guaranteed and that it can save some energy as it transmits less time and consumes less energy. The SU can be the relay of the PU only if

$$T-t_{m1}^k-t_{m2}^k > 0 \tag{9}$$

Notice that the items $\sum_{n\in\Omega_m}\log_2(1+\frac{p_{pm}^n H_{pp}^{mnd}}{\sigma_{p,mnd}^2})$ and $\sum_{n\in\Omega_m}\log_2(1+\frac{p_{pm}^n H_{ps}^{mnk}}{\sigma_{p,mnk}^2})$ are known when the power allocation of the PU m is determined. The value of the first subslot time t_{m1}^k is known. From (1), (2), (3), (8) and (9), we obtain

$$\sum_{n\in\Omega_m}\log_2(1+\frac{p_{pm}^n H_{pp}^{mnd}}{\sigma_{p,mnd}^2})$$
$$\times\left(\frac{1}{\sum_{n\in\Omega_m}\log_2(1+\frac{p_{pm}^n H_{ps}^{mnk}}{\sigma_{p,mnk}^2})}+\frac{1}{\sum_{n\in\Omega_m}\log_2(1+\frac{p_{sk}^n H_{sp}^{knd}}{\sigma_{s,knd}^2})}\right)<1 \quad (10)$$

We need to propose a power allocation algorithm to determine the forwarding power p_{sk}^n of the SU k and validate if (10) stands.

The power allocation problem of the SUs contains two parts, the power allocated to forward the PU data and the power used to transmit its own data over subcarriers Ω. The former power allocation determines t_{m2}^k, and the later determines $\log_2(1+\frac{p_{ss.k}^n H_{ss}^{knk}}{\sigma_{s,knk}^2})$. These two items determine $R_{ss,m}^k$. Let $R_{ss,m}^{*k}$ denote the maximum data rate of SU k with an optimal power allocation. It is obvious that

$$\sum_{k=1}^{K}\sum_{m=1}^{M}a_m^k R_{ss,m}^{*k} \geq \sum_{k=1}^{K}\sum_{m=1}^{M}a_m^k R_{ss,m}^k \quad (11)$$

For any given {m, k}, we maximize $R_{ss,m}^k$ which is equivalent to maximizing $T-t_{m1}^k-t_{m2}^k$ and $\sum_{n\in\Omega_m}\log_2(1+\frac{p_{ss.k}^n H_{sp}^{knk}}{\sigma_{s,knk}^2})$, respectively.

As T and t_{m1}^k are known, we try to minimize t_{m2}^k and that is meant to forward the data of PU m with maximum rate $\sum_{n\in\Omega_m}\log_2(1+\frac{p_{sk}^n H_{sp}^{knd}}{\sigma_{s,knd}^2})$. We write the maximization problem as follows.

$$\max\sum_{n\in\Omega_m}\log_2(1+\frac{p_{sk}^n H_{sp}^{knd}}{\sigma_{s,knd}^2}) \quad (12)$$

s.t.

$$C_1:\ \sum_{n\in\Omega_m}p_{sk}^n \leq P_s^k,\quad C_2:\ p_{sk}^n>0,\forall n \quad (13)$$

This optimization problem is a standard power allocation in OFDM systems; we use the Lagrangian method to obtain the optimal power allocation for the SU. The Lagrangian of (12) is expressed by

$$L_{sp}^{km}=\sum_{n\in\Omega_m}\log_2(1+\frac{p_{sk}^n H_{sp}^{knd}}{\sigma_{s,knd}^2})-\lambda(\sum_{n\in\Omega_m}p_{sk}^n-P_s^k) \quad (14)$$

where λ is a Lagrangian multiplier. Let $\frac{\partial L_{sp}^{km}}{\partial p_{sk}^n}=0$, we obtain the power allocation

$$p_{sk}^n=\frac{1}{\lambda\ln 2}-\frac{\sigma_{s,knd}^2}{H_{sp}^{knd}} \quad (15)$$

Let $\beta=\lambda\ln 2$, notice that $\sum_{n\in\Omega_m}p_{sk}^n=P_s^k$, we obtain the water-filling level β satisfying

$$\frac{1}{\beta}=\frac{P_s^k}{N_m}+\frac{1}{N_m}\sum_{n\in\Omega_m}\frac{\sigma_{s,knd}^2}{H_{sp}^{knd}} \quad (16)$$

where N_m is the number of subcarriers of in Ω_m. The power allocation by water filling is

$$p_{sk}^n=\left[\frac{1}{\beta}-\frac{\sigma_{s,knd}^2}{H_{sp}^{knd}}\right]^+ \quad (17)$$

where $[x]^+=\max(0,x)$. Here we adopt the iterative water-filling algorithm in [23]. When the power allocation of the SUs for forwarding the data of PU has been determined, we obtain the maximum $T-t_{m1}^k-t_{m2}^k$, and validate whether the SU k can be the relay of PU m.

From (5), we infer that $R_{ss,m}^k$ is maximized when $\sum_{n\in\Omega_m}\log_2(1+\frac{p_{ss.k}^n H_{ss}^{knk}}{\sigma_{s,knk}^2})$ achieves the maximum value with maximum $T-t_{m1}^k-t_{m2}^k$. We need to obtain the power allocated for SU's own transmission. Similarly, we obtain the optimization problem

$$\max\sum_{n\in\Omega_m}\log_2(1+\frac{p_{ss.k}^n H_{ss}^{knk}}{\sigma_{s,knk}^2}) \quad (18)$$

s.t.

$$C_1:\ \sum_{n\in\Omega_m}p_{ss,k}^n \leq P_s^k$$
$$C_2:\ p_{ss,k}^n>0,\forall n \quad (19)$$

Using the same water-filling method as above, we obtain the power allocation of SU's own transmission

$$p_{ss,k}^n=\left[\frac{P_{sk}}{N_m}+\frac{1}{N_m}\sum_{n'\in\Omega_m}\frac{\sigma_{s,kn'k}^2}{H_{ss}^{kn'k}}-\frac{\sigma_{s,knk}^2}{H_{ss}^{knk}}\right]^+ \quad (20)$$

With the above power allocation, the maximum data rate $R_{ss,m}^{*k}$ is obtained, and the OP1 becomes a work assignment problem which can be solved by Hungarian method [24]. OP1 is transformed to

OP2:

$$\min-\sum_{k=1}^{K}\sum_{m=1}^{M}a_m^k R_{ss,m}^{*k} \quad (21)$$

s.t.

$$C_1:\ \sum_{k=1}^{K}a_m^k=1,\forall m,\quad C_2:\ \sum_{m=1}^{M}a_m^k=1,\forall k$$
$$C_3:\ a_m^k\in\{0,1\},\forall m,k \quad (22)$$

In order to use Hungarian method, we need to construct the cost matrix

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1M} \\ c_{21} & c_{22} & \cdots & c_{2M} \\ \vdots & \vdots & \cdots & \vdots \\ c_{K1} & c_{K2} & \cdots & c_{KM} \end{bmatrix} \tag{23}$$

where the matrix element c_{km} is given by

$$c_{km} = \begin{cases} -R^{*k}_{ss,m} & (T - t^k_{m1} - t^k_{m2}) > 0 \\ 0 & (T - t^k_{m1} - t^k_{m2}) \le 0 \end{cases} \tag{24}$$

Specifically, c_{km} represents that SU k cannot act as the relay of PU m, and it will not affect the result of the relay selection. In general, K is not equal to M; it is an unbalanced Hungarian problem. We select at most one element from each row and from each column of the cost matrix **C** and make the sum of these elements minimized. Then, we can obtain the solution $\{a^k_m\}$ of this assignment problem that is the optimal relay selection. By now, we have obtained the power allocation algorithm and relay selection. The energy saving of the PUs can be given by

$$E_{saving} = 1 - \frac{\sum_{m=1}^{M} \sum_{n \in \Omega_m} p^n_{pm} \sum_{k=1}^{K} a^k_m t_{m1}}{T \sum_{m=1}^{M} \sum_{n \in \Omega_m} p^n_{pm}} \tag{25}$$

IV. Numerical Results and Analysis

In this section, we present some numerical results to show the performance of the proposed algorithm. Assuming there is a cooperative cognitive radio network including 5 PUs licensed 32 orthogonal subcarriers. The bandwidth of the subcarriers is normalized as 1. We consider a geometrical model where the primary base station is located at the center of a circle. The PUs are randomly distributed on the circle, and the secondary users are randomly distributed within the circle. The radius of the circle is normalized as 1. The distance between the secondary transmitter and secondary receiver is randomly distributed within [0.1, 0.5]. We assume that the path loss exponent is 2, the variance of shadowing is 0 dB, and the multipath fading is Rayleigh [16]. Without loss of generality, all the noise powers are set to 1, and all the PUs and SUs transmit at same power levels respectively. Throughout the simulations, the power of PUs is 1 W. For simplicity, the OFDM symbol duration T is set to 1. We study the data rate of the SUs and energy saving of the PUs.

Conventionally, the system performance takes random relay selection (RRS) algorithm in cooperative relay networks [25], [26], and equal power allocation (EPA) in OFDM(A) networks as a reference point[27]-[29], respectively. We compare the performance of the proposed algorithm with two other algorithms, random relay selection with optimal power allocation (RRS-OPA) and optimal relay selection with equal power allocation (ORS-EPA). The proposed algorithm in this paper is named as ORS-OPA. In RRS-OPA algorithm, the power allocation of SUs over the subcarriers adopts the proposed iterative water filling method, and then random relay section is operated. While in ORS-EPA algorithm, the power allocation of SUs over the subcarriers adopts equal power allocation, and then Hungarian method is used to execute relay selection. The results are obtained by 10,000 channel realizations.

The power of SUs is normalized to 1. Fig. 2 shows the data rate of the SUs as a function of the numbers of the SUs. When the number of SUs is smaller than 5, the data rates of all the three algorithms increase as the number of SUs increases. While the number of SUs is greater than 5, the performances of the ORS-OPAand ORS-EPA increase as they can exploit the diversity of the SUs, and the data rate of RRS-OPA is flat as it cannot efficiently exploit the diversity gain. The performance of the proposed algorithm is the best.

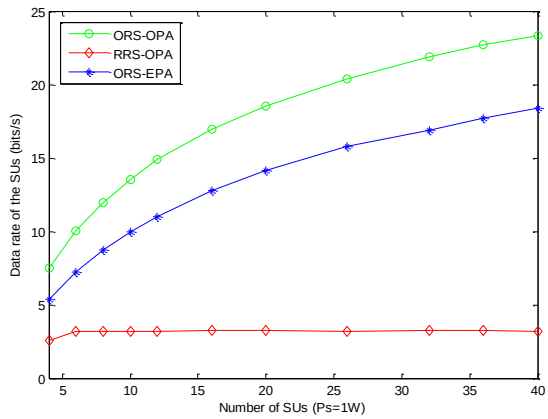

Fig. 2. Data rate of the SUs vs. Number of SUs

In Fig. 3, it is shown that the PUs can save energy by cooperating with the SUs. The curves are very similar to those in Fig. 2. When the numbers of the SUs increase substantially, the energy savings of the proposed algorithm and ORS-EPA increase more slowly. The diversity of the SUs brings little effect.

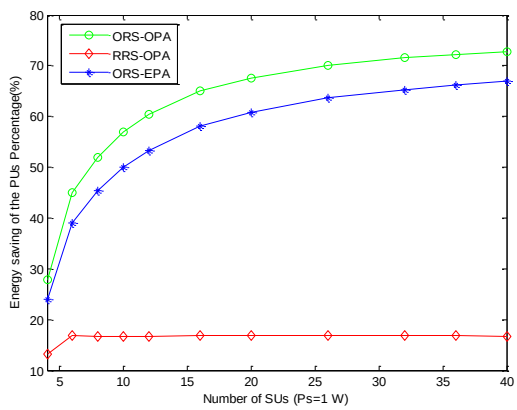

Fig. 3. Energy saving of the PUs vs. Number of SUs

We fix the number of the SUs at 16, and study how the power of the SUs affects the performances of the three

algorithms. In Fig. 4, the data rate of the SUs increases as the powers of the SUs increase. It is obvious that the SUs can easily satisfy (9) and play as the relays of the PUs, and the SUs transmit at high power levels, which lead to high data rate of the SUs.

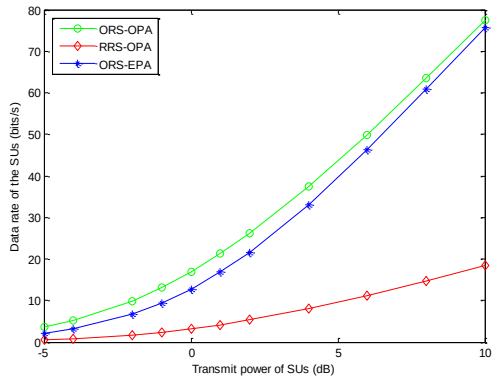

Fig. 4. Data rate of the SUs vs. Transmit power of SUs

As shown in Fig.5, the energy saving of the three algorithms become flat as the transmit power of the SUs increase. From (25), we know that the energy saving depends on the PUs own transmission time $\{t_{m1}^k\}$ and relay selection $\{a_m^k\}$. $\{t_{m1}^k\}$ is mainly determined by the channel conditions between the PUs and the SUs , in fact, which are the locations of the PUs and SUs . Thus, the energy savings of the proposed algorithm and ORS/EPA are very close with high transmit power levels.

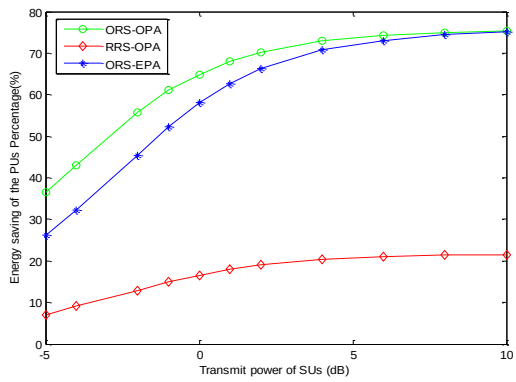

Fig. 5. Energy saving of the PUs vs. Transmit power of SUs

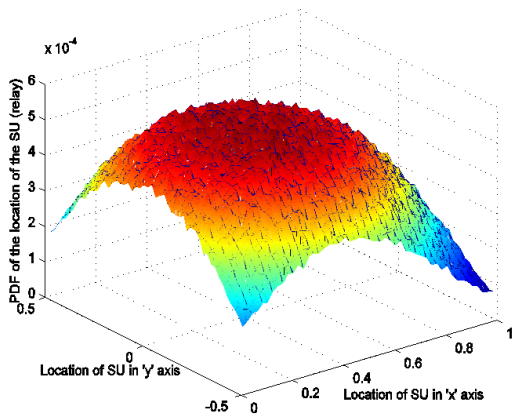

Fig. 6. Probability density of the location of the selected relays

Considering a cognitive network including 1 PU and 1 SU, we study the cooperation conditions of the PU and SU. The location of PU is (0, 0), and the location of base station is (1, 0). The SU is randomly distributed in this square with a fixed power level Ps=1W. Fig. 6 shows the probability density of the location of the selected relays. The SU is more easily selected as the relay when it is located near the middle of the line between the PU and base station.

V. Conclusions

In this paper, we consider an OFDMA-based cognitive radio network where the SUs access the spectrum by cooperating with the PUs. In exchange for some spectrum resource, the SUs act as the relays of the PUs and guarantee the data rate of the PUs. The SUs access the spectrum licensed to the PUs in both time and frequency. We propose a joint resource allocation algorithm to maximize the data rate of the SUs. The optimization problem is decomposed into 2 subproblems, power allocation and relay selection, which are solved by water-filling algorithm using Lagrangian method and Hungarian method respectively. Numerical results show that proposed algorithm can improve the networks performances, and both the PUs and SUs can benefit from the cooperation. The procedure of handling the optimization problem with some mathematical methods can be used to solve the similar resource allocation problems, i.e., relay selection and subcarrier assignment with constraints C_3 , C_4 and C_5 of (7), in wireless networks.

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