# Efficient Resource Allocation for Cognitive Radio Networks with Cooperative Relays

Shaowei Wang, *Senior Member, IEEE*, Mengyao Ge, and Chonggang Wang, *Senior Member, IEEE*

***Abstract*—Cognitive Radio (CR) is an attractive technology to deal with current spectrum scarcity problem, while cooperative relay can make distributed receivers benefit from spatial diversity and combat severe fading in wireless environment. CR with cooperative relay is potentially a promising paradigm for developing spectrum-efficient wireless systems. In this paper, we study the resource allocation in Orthogonal Frequency Division Multiplexing (OFDM)-based CR networks with cooperative relays. Since the formulated optimization task defines a mixed integer programming problem that is generally hard to solve, we propose a two-stage method to produce near optimal solutions. Particularly, by jointly considering the Signal-to-Noise Ratios (SNRs) of OFDM subchannels and the interferences introduced to primary users, we propose an efficient subchannel assignment scheme for the CR system, as well as transmission mode selection strategy. Furthermore, we develop a fast algorithm to distribute power among subchannels, which can always work out the optimal power allocation with a reasonable complexity by exploiting the structure of the problem. Numerical results show that our proposal can significantly increase the throughput of the CR system compared with other schemes, and the proposed algorithm converges quickly and stably.**

***Index Terms*—Cognitive radio, cooperative relay, OFDM, optimization, resource allocation.**

## I. INTRODUCTION

AS THE EVER emerging of wireless services, much radio spectrum is required. Within current spectrum regulatory policy, most of radio spectrum is exclusively allocated to licensed systems. However, investigations show that a large portion of the licensed spectrum is underutilized in vast temporal and geographic dimensions. Based on the report of the Federal Communication Commission, the temporal and geographic variations in the utilization of the licensed spectrum range from 15% to 85%. Novel spectrum usage paradigms are urgently needed to improve the usage efficiency of radio spectrum. Cognitive Radio (CR) is deemed as a potential technique to alleviate the looming spectrum scarcity crisis. CR users (also referred to as Secondary Users, SUs) share wireless channels with licensed Primary Users (PUs) who are already assigned specified spectrum [1, 2], as long as the interferences to the PUs are kept below preset thresholds, such as interference temperatures [3]. To meet these requirements, the physical layer of a CR system should be flexible to support the opportunistic access of the SUs. Orthogonal Frequency Division Multiplexing (OFDM) is widely accepted as a powerful air interface of a CR system, owing to its significant ability of allocating radio resource flexibly [4].

Meanwhile, relay is a promising technology to exploit spatial diversity in wireless environment. By means of improving spectral efficiency and extending coverage area, relay communication can boost the overall performance of a wireless system, as shown in [5], in which the channel capacity of a relay system with three nodes: source, destination and relay, is analyzed extensively. There are three representative relay transmission protocols which have been discussed in detail in [6]: Amplify-and-Forward (AF), Decode-and-Forward (DF) and coded cooperation. Low-complexity cooperative diversity protocols are developed in [7], which can combat fading and exploit spatial diversity through cooperating terminals' relaying signals. Because of its advantages in wireless communications, cooperative relay has been introduced to the standard of the next cellular systems, such as the Long Term Evolution Advanced (LTE-Advanced).

CR systems can also benefit a lot from cooperative relay. One of the main challenges in the CR systems is the transmission opportunity exploitation. The SUs in a CR system must exploit the transmission opportunity to satisfy their rate requirements while prohibiting the unacceptable performance degradation of the PUs. Nevertheless, since there frequently exists severe channel attenuation between the source transmitter and destination receiver in wireless systems, reliable communication has to count on large transmission power, which can also cast excessive interference to the PUs and degrade the performance of both the CR and the licensed systems. Hence, conventional end-to-end transmission manner may be no longer suitable for CR scenarios. Instead, an alternative path can be generated to achieve the diversity gain between the source and the destination via relay technology, making the transmission link in the CR system reliable. Moreover, relay is also effective to weaken the effect of fading by taking advantage of spatial diversity over the distributed relay nodes [8, 9], which can reduce the transmit power of the CR system. Consequently, the interference to the PUs introduced by the CR transmitters is mitigated significantly. Hence cooperative relay can enhance the performance of the CR system. OFDM-based CR networks with cooperative relays attract much attention in both academia and industry recently.

An important issue for the OFDM system is Resource Allocation (RA), which usually involves OFDM subchannel assignment and power distribution. RA has been exten-

---

Manuscript received November 17, 2012; revised April 4, 2013. This research was partially supported by the JiangsuSF (BK2011051).

S. Wang and M. Ge are with the School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China (e-mail: wangsw@nju.edu.cn, mengyao89@yahoo.cn).

C. Wang is with the InterDigital Communications, PA 19406 (e-mail: cgwang@ieee.org).

Digital Object Identifier 10.1109/JSAC.2013.131128.

sively studied for both conventional OFDM systems [10] and OFDM-based CR systems [11–16]. Referring to a relay assisted OFDM system, a point-to-point two-hop channel models the basic framework of relay communication, which generally consists of a source, a destination and a relay. The source transmits information during the first time slot, and the relay transfers the information during the second time slot. The destination combines the signals from the source and the relay by maximal ratio combining. For such a fundamental relay model, optimizing the RA for both the source and the relay nodes is the key element for achieving high system performance. In [17], power allocation is investigated for both total and individual power constraints at the source and the DF relay to maximize the sum capacity of the considered system. In [18], a joint subcarrier pairing and power allocation scheme is further studied. In [19], single-relay multiple-access system is investigated, where the sum capacity is maximized by jointly optimizing channel pairing, channel-user assignment and power allocation. Different from the fundamental relay models discussed in [17–19], RA is more complex for multi-relay systems, where the optimization objective is usually a predefined performance metric that takes multiple indexes into consideration. Two RA algorithms are proposed for multiple DF assisted OFDM systems in [20], where transmission mode and relay selection are optimized, as well as power allocation at the source and the relays. In [21], a two-step algorithm is proposed to maximize the weighted sum rate. In [22], relay selection, sub-carrier pairing and power allocation problems are explored for a two-hop cooperative OFDM system with multiple AF relays. The system models in [20–22] involve one source and one destination. Multi-relay OFDM system with one source and multiple destinations is discussed in [23], where fairness among multiple SUs is also considered. Subcarrier pairing, relay selection and power allocation are jointly optimized to maximize the system capacity.

The application of cooperative relay to the CR system is envisioned in [24] and discussed in detail in [25, 26]. A simplified optimization task is considered for the non-convex power allocation problem in a multi-node relay CR network in [27]. In [28], relay selection and power allocation algorithms are proposed to maximize the system throughput with given interference constraints laid by the primary system. In [29], relay selection and power allocation are studied for an OFDM-based CR system with a single pair of cognitive transceiver nodes, where multiple DF relays are employed to help the communication between source to destination. Also for the single CR antenna scenario assisted by a set of relays, a joint relay selection and power allocation scheme is proposed to maximize throughput in [30]. A suboptimal RA algorithm for a DF relay CR network is proposed in [31], however, its computational complexity is too high for applications.

In this paper, we consider a CR system coexisting and sharing radio spectrum with a licensed system. The PUs are served by a Base Station (BS) of the licensed system, while the SUs access the CR network via an Access Point (AP). In the CR network, multiple relays with DF protocol are deployed to help the AP communicate with each SU who is also covered by a certain relay. The SUs adopt OFDM modulation. It is not necessary for the PUs to employ OFDM. We try to maximize the overall system throughput under practical constraints, such as the transmission power budget of the CR system, and the interference to the PUs. Since the formulated optimization task is computationally intractable, we develop a two-stage method to address it efficiently, with which we separate the RA task into two individual procedures: subchannel allocation and power distribution. First, OFDM subchannels are assigned to the SUs based on the channel gains and the interferences to the PUs. Given a subchannel assignment, a fast algorithm is proposed for power loading over each subchannel at the source and the relay simultaneously to maximize the system throughput. The proposed algorithm significantly reduces the computational cost compared to standard techniques, making our proposed method promising for applications.

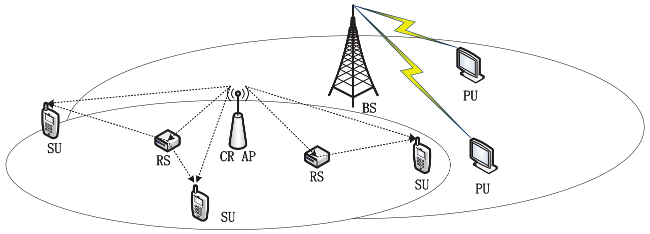


Fig. 1. System model

The rest of this paper is organized as follows. In Section II, we illustrate system model and formulate optimization task. In Section III, we present subchannel allocation scheme in detail. In Section IV, an efficient power allocation algorithm is developed to work out the optimal solutions. Simulation results and discussions are given in Section V, while conclusions are drawn in Section VI.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

### *A. System Model*

Consider the downlink of a multiuser OFDM-based relaying CR system that coexists with a licensed one, as illustrated in Fig.1. There are $L$ PUs in the licensed system. $K$ SUs, denoted as a set of $\mathcal{K} = \{1, 2, \ldots, K\}$, are served by an AP in the CR system assisted by $M$ relays. We assume that perfect channel state information is available at the transceivers of both the licensed system and the CR system. To reduce the deployment cost, relays are always established apart from each other to avoid the overlaps of coverage. Hence, each SU can hear from only one relay, according to its location. For simplicity, we denote the relay which covers user $k$ as $m_k$. The whole bandwidth $B$ is divided into $N$ OFDM subchannels in the CR system, denoted as a set of $\mathcal{N} = \{1, 2, \ldots, N\}$.

The relaying CR network operates as follows: In the first time slot, the source (AP) transmits data while the relays and the SUs receive; the relays are half-duplex, which means that they receive data in the first time slot and transmit data in the second time slot. The subchannel index used in the second time slot is paired to the same as that in the first time slot. All time slots have equal duration. To avoid interference, only one node can transmit in a given time slot for each subchannel. Each relay re-encodes the received message with the same codebook as that used by the source. Besides, the receiver of each SU employs Maximum Ratio Combining (MRC) to receive the signals from the source in the first time slot and from the relay in the second time slot, pertaining to the same message.

Suppose PU $l$'s nominal band ranges from $f_l$ to $f_l + B_l$, where $f_l$ and $B_l$ are the PU $l$'s starting frequency and occupied bandwidth, respectively. When the AP transmits data over the subchannel $n$ in first time slot, the interference introduced to the PU $l$ with unit transmission power is

$$I_{n,l}^{SP} = \int_{f_l-(n-1/2)B/N}^{f_l+B_l-(n-1/2)B/N} g_{n,l}^{SP} \phi^{SU}(f) df, \qquad (1)$$

where $g_{n,l}^{SP}$ denotes the power gain over the subchannel $n$ from the transmitter of the source node (AP shown in Fig.1) to the PU $l$'s receiver. $\phi^{SU}(f)$ is baseband power spectral density (PSD) of OFDM signals, where $\phi^{SU}(f) = T(\frac{\sin \pi f T}{\pi f T})^2$, and $T$ is the OFDM symbol duration. In the second time slot, the interference to the PU $l$ thrown by the transmission of the relay to the $k$th SU's receiver on the subchannel $n$ with unit transmission power is

$$I_{m_k,n,l}^{RP} = \int_{f_l-(n-1/2)B/N}^{f_l+B_l-(n-1/2)B/N} g_{m_k,n,l}^{RP} \phi^{SU}(f) df, \qquad (2)$$

where $g_{m_k,n,l}^{RP}$ represents the power gain from the relay $m_k$ to the PU $l$ on subchannel $n$.

Denote $a_{k,n}^{SD}$, $a_{m_k,n}^{SR}$ and $a_{m_k,k,n}^{RD}$ as the channel gain of the subchannel $n$ from the AP to the SU $k$, the AP to the relay $m_k$, and the relay $m_k$ to the SU $k$, respectively. $\sigma_{m_k}$ and $\sigma_k$ are the variances of Additive White Gaussian Noises (AWGN) at the relay $m_k$ and the SU $k$. The normalized Signal-to-Noise Ratios (SNRs) of the two hops are defined as

$$h_{k,n}^{SR} = \frac{|a_{m_k,n}^{SR}|^2}{\Gamma(\sigma_{m_k}^2 + I_{m_k}^{PR})}, \quad h_{k,n}^{SD} = \frac{|a_{k,n}^{SD}|^2}{\Gamma(\sigma_k^2 + I_k^{PS})},$$
$$h_{k,n}^{RD} = \frac{|a_{m_k,k,n}^{RD}|^2}{\Gamma(\sigma_k^2 + I_k^{PS})},$$

where $h_{k,n}^{SR}$ and $h_{k,n}^{SD}$ are the normalized SNRs of the links from the AP to the relay $m_k$ and the SU $k$, respectively. $h_{k,n}^{RD}$ is the normalized SNR of the link from the relay $m_k$ to the SU $k$. The interference caused by PUs' signals is $I_{m_k}^{PR}$ and $I_k^{PS}$ at the relay $m_k$ and the SU $k$, respectively, which can be regarded as noise and measured by the receivers of relays and SUs. $\Gamma$ is the SNR gap related to a given Bit-Error-Rate (BER) for an uncoded MQAM, and $\Gamma = -\ln(5BER)/1.5$ [32].

Let $r_{1,k,n}$ be the achievable rate of the subchannel $n$ used by the SU $k$ which is assisted by the relay $m_k$

$$\begin{aligned} r_{1,k,n} = \ & \frac{1}{2} \min\{\log(1 + p_{s,k,n} h_{k,n}^{SR}), \\ & \log(1 + p_{s,k,n} h_{k,n}^{SD} + p_{r,k,n} h_{k,n}^{RD})\}, \end{aligned} \qquad (3)$$

where the rate is scaled by $1/2$ because the transmission continues two time slots. $p_{s,k,n}$ and $p_{r,k,n}$ are the power allocated to the subchannel $n$ used by the SU $k$ at the AP and the relay, respectively. On the other hand, if the relay does not forward and the subchannel is only used to transmit information in the first time slot, the achievable rate over the subchannel $n$ employed by the SU $k$ is

$$r_{2,k,n} = \frac{1}{2} \log(1 + p_{s,k,n} h_{k,n}^{SD}). \qquad (4)$$

### *B. Problem Formulation*

We try to maximize the sum rate of all SUs under the transmission power budget of the AP and the relays, while guaranteeing that the interference introduced to each PU does not exceed its tolerable threshold. We introduce a binary variable $t_{k,n}$ to indicate whether the relay $m_k$ is active for the SU $k$ over the subchannel $n$. If $p_{k,n} \neq 0$, then $t_{k,n} = 1$; otherwise, $t_{k,n} = 0$. The RA task is given as follows,

$$\begin{array}{lll}
\max\limits_{\substack{\rho_{k,n}, p_{s,k,n}, \\ p_{r,k,n}, t_{k,n}}} & & \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} t_{k,n} \rho_{k,n} r_{1,k,n} + (1 - t_{k,n}) \rho_{k,n} r_{2,k,n} \\
s.t. & C1 & \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} \rho_{k,n} p_{s,k,n} \leq P_S, \\
& C2 & \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} \rho_{k,n} p_{r,k,n} \leq P_R, \\
& C3 & \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} \rho_{k,n} I_{n,l}^{SP} p_{s,k,n} \leq I_l^{th}, l = 1, \ldots, L, \\
& C4 & \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} \rho_{k,n} I_{k,n,l}^{RP} p_{r,k,n} \leq I_l^{th}, l = 1, \ldots, L, \\
& C5 & \rho_{k,n} \in \{0, 1\}, \forall n, \forall k, \\
& C6 & \sum\limits_{k=1}^{K} \rho_{k,n} = 1, \forall n, \\
& C7 & p_{s,k,n} \geq 0, p_{r,k,n} \geq 0, \forall n, \forall k, \\
& C8 & t_{k,n} = \{0, 1\}, \forall n, \forall k,
\end{array} \qquad (5)$$

where $P_S$ and $P_R$ are the transmission power budgets of the AP and the relays. $I_l^{th}$ is the interference threshold of the PU $l$. C3 and C4 are the interference constraints in the first and second time slot. $\rho_{k,n}$ can be either 1 or 0, informing whether the subchannel $n$ is occupied by the SU $k$ or not. C5 and C6 indicate that each subchannel can not be shared by multiple SUs.

Obviously, (5) defines a mixed integer programming problem, which involves both integer variables $\rho_{k,n}$'s and $t_{k,n}$'s, and real variables $p_{s,k,n}$'s and $p_{r,k,n}$'s. It is generally hard to solve (5) because the integer constraints generate an exponential complexity. We develop a two-stage procedure to address it, which carries out subchannel assignment and power allocation separately.

## III. SUBCHANNEL ALLOCATION

The achievable rate on the subchannel $n$ used by the SU $k$ can be unified into

$$r_{k,n} = \begin{cases} r_{1,k,n} & p_{r,k,n} \neq 0 \\ r_{2,k,n} & p_{r,k,n} = 0 \end{cases}. \qquad (6)$$

***Proposition 1:*** To maximize the sum rate of all SUs, a subchannel that satisfies $h_{k,n}^{SD} \geq h_{k,n}^{SR}$ can achieve higher throughput without the assistant of relays.

***Proof:*** If $h_{k,n}^{SD} \geq h_{k,n}^{SR}$, we have

$$\begin{aligned} & \min\{\log(1 + p_{s,k,n} h_{k,n}^{SR}), \log(1 + p_{s,k,n} h_{k,n}^{SD} + p_{r,k,n} h_{k,n}^{RD})\} \\ & = \log(1 + p_{s,k,n} h_{k,n}^{SR}) \leq \log(1 + p_{s,k,n} h_{k,n}^{SD}). \end{aligned} \qquad (7)$$

On the other hand, direct transmission can eliminate the interference to the PUs in the second time slot. Hence, we can conclude that $r_{2,k,n} \geq r_{1,k,n}$ when $h_{k,n}^{SD} \geq h_{k,n}^{SR}$, which indicates that direct transmission mode is more efficient in this case.

Note that $r_{1,k,n} = r_{2,k,n}$ when $p_{r,k,n} = 0$ and $h^{SD}_{k,n} < h^{SR}_{k,n}$. According to the ***Proposition 1***, we can rewrite (6) into

$$r_{k,n} = \begin{cases} r_{1,k,n} & h^{SD}_{k,n} < h^{SR}_{k,n} \\ r_{2,k,n} & h^{SD}_{k,n} \geq h^{SR}_{k,n} \end{cases}. \tag{8}$$

In (8), $r_{k,n} = r_{1,k,n}, h^{SD}_{k,n} < h^{SR}_{k,n}$ implies that some subchannels may be selected for direct transmission without relaying when the transmission power for the relays is not sufficient because of power limits and interference thresholds.

For subchannel allocation procedure, we need to evaluate the achievable rates of OFDM subchannels. In an OFDM-based CR network, a subchannel with higher SNR may generate more interference to the PUs, which means the interference thresholds of the PUs also set an upper bound of the maximum transmission power of a subchannel. Hence, it is necessary to jointly consider the SNR of a subchannel and the interference to the PUs thrown by it. Hence the achievable rate of each subchannel can be given as follows,

$$r^M_{k,n} = \begin{cases} \frac{1}{2}\log(1+\min\{p^{max}_{s,k,n}h^{SR}_{k,n}, \\ \quad p^{max}_{s,k,n}h^{SD}_{k,n} + p^{max}_{r,k,n}h^{RD}_{k,n}\}) & h^{SD}_{k,n} < h^{SR}_{k,n} \\ \frac{1}{2}\log(1+p^{max}_{s,k,n}h^{SD}_{k,n}) & h^{SD}_{k,n} \geq h^{SR}_{k,n} \end{cases}, \tag{9}$$

where $r^M_{k,n}$ is the maximum achievable rate over the subchannel $n$ used by the SU $k$, $p^{max}_{s,k,n}$ and $p^{max}_{r,k,n}$ are the maximum possible power on the subchannel $n$ used by the SU $k$ at the source and the relay, respectively,

$$\begin{aligned} p^{max}_{s,k,n} &= \min\{P_S, \min_{l\in\mathcal{L}}(I^{th}_l / I^{SP}_{n,l})\}, \\ p^{max}_{r,k,n} &= \min\{P_R, \min_{l\in\mathcal{L}}(I^{th}_l / I^{RP}_{k,n,l})\}. \end{aligned} \tag{10}$$

Since each subchannel can only be allocated to one SU, we can execute the subchannel allocation procedure according to the achievable rate defined by (9). Preferably, each subchannel is always allocated to the SU who has the highest maximum achievable rate over it. The procedure terminates until all subchannels are consumed. Mathematically, we can determine the values of $\rho_{k,n}$'s as follows,

$$\rho_{k,n} = \begin{cases} 1 & k = \operatorname{argmax}_k r^M_{k,n} \\ 0 & \text{otherwise} \end{cases}. \tag{11}$$

Moreover, part of the binary variables $t_{k,n}$'s are determined according to the ***Proposition 1***. The remaining $t_{k,n}$'s will be determined during the following power allocation, which also depends on the maximum possible transmission power.

## IV. EFFICIENT ALGORITHM FOR POWER ALLOCATION

In this section, we propose an effective and efficient power allocation algorithm for a given subchannel assignment. The binary variables $\rho_{k,n}$'s are fixed to be 0's or 1's when subchannel allocation completed, and each subchannel is allocated to an SU. As we discussed in Section III, we can resort and classify all subchannels into two categories according to the ***Proposition 1***. Denote $\mathcal{N}_1 = \{1, 2, \ldots, N_1\}$ as the set of subchannels which satisfy $h^{SD}_n < h^{SR}_n$, and $\mathcal{N}_2 = \{N_1+1, \ldots, N\}$ as the subchannels which satisfy $h^{SD}_n \geq h^{SR}_n$, the power distribution problem can be written as follows,

$$\begin{aligned} \max_{p_{s,n},p_{r,n}} \quad & \sum_{n\in\mathcal{N}_1} r_{1,n} + \sum_{n\in\mathcal{N}_2} r_{2,n} \\ s.t.\ C1 \quad & \sum_{n=1}^{N} p_{s,n} \leq P_S, \\ C2 \quad & \sum_{n=1}^{N_1} p_{r,n} \leq P_R, \\ C3 \quad & \sum_{n=1}^{N} I^{SP}_{n,l} p_{s,n} \leq I^{th}_l, l = 1, \ldots, L, \\ C4 \quad & \sum_{n=1}^{N_1} I^{RP}_{n,l} p_{r,n} \leq I^{th}_l, l = 1, \ldots, L, \\ C5 \quad & p_{s,n} \geq 0, \forall n, \\ C6 \quad & p_{r,n} \geq 0, n \in \mathcal{N}_1, \end{aligned} \tag{12}$$

where we omit the subscript $k$ for all terms because each subchannel is associated with an SU.

The max-min formulation in the objective function can be addressed by introducing extra auxiliary variables $z_n$'s, $n \in \{1, \ldots, N\}$, and transforming the power allocation problem into its equivalent form,

$$\begin{aligned} \max_{p_{s,n},p_{r,n},z_n} \quad & \frac{1}{2}\sum_{n=1}^{N} \log(1+z_n) \\ s.t. \quad & z_n \leq p_{s,n}h^{SR}_n, n \in \mathcal{N}_1 \\ & z_n \leq p_{s,n}h^{SD}_n + p_{r,n}h^{RD}_n, n \in \mathcal{N}_1 \\ & z_n \leq p_{s,n}h^{SD}_n, n \in \mathcal{N}_2 \\ & z_n \geq 0, \forall n \\ & C1 \sim C6 \text{ in } (12). \end{aligned} \tag{13}$$

Indeed, the feasible set of (13) covers that of (12), and the two problems always share the same optimal solution. Notice that (13) is jointly convex with respect to the optimization variables, since the objective function is strictly concave and all inequality constraints are convex.

### *A. Barrier Method*

Barrier method is a standard convex optimization algorithm, which converts an optimization problem with constraints into a sequence of minimization ones by introducing a logarithmic barrier function with a parameter $t$. The solution to each minimization problem is called a central point in the central path related to the optimal solution of the original problem. As $t$ increases, the central point will approximate to the optimal solution of the original problem more and more accurately. Generally, the barrier method consists of two stages: centering step and Newton step. The former is an outer iteration to compute the central point starting from the previously one; the latter is an inner iteration executed at each centering step, where Newton method is preferably employed because of its quadratic convergence property.

First, we convert all inequality constraints into a logarithmic barrier function $\phi(\boldsymbol{x})$,

$$\begin{aligned}\phi(\boldsymbol{x}) = & -\sum_{n\in\mathcal{N}_1}\log(p_{s,n}h_n^{SD}+p_{r,n}h_n^{RD}-z_n)\\ &-\sum_{n\in\mathcal{N}_1}\log(p_{s,n}h_n^{SR}-z_n)\\ &-\sum_{n\in\mathcal{N}_2}\log(p_{s,n}h_n^{SD}-z_n)\\ &-\log f_s-\log f_r-\sum_{l=1}^{L}\log f_{s,l}\\ &-\sum_{l=1}^{L}\log f_{r,l}-\sum_{n=1}^{N}\log p_{s,n}\\ &-\sum_{n\in\mathcal{N}_1}\log p_{r,n}-\sum_{n=1}^{N}\log z_n\end{aligned}\tag{14}$$

where we collect all the variables into a vector $\boldsymbol{x}$, with

$$\boldsymbol{x}=\{p_{s,1},p_{r,1},z_1,\ldots,z_{N_1},p_{s,N_1+1},z_{N_1+1},\ldots,z_N\}.$$

For brevity, denote

$$f_s=P_S-\sum_{n=1}^{N}p_{s,n},$$

$$f_r=P_R-\sum_{n=1}^{N}p_{r,n},$$

$$f_{s,l}=I_l^{th}-\sum_{n=1}^{N}p_{s,n}I_{n,l}^{SP},l=1,\ldots,L,$$

$$f_{r,l}=I_l^{th}-\sum_{n=1}^{N_1}p_{r,n}I_{n,l}^{RP},l=1,\ldots,L.$$

Thus, the optimal solution to (13) can be approximated by solving the following minimization problem,

$$\min_{\boldsymbol{x}}\quad \psi_t(\boldsymbol{x})=-\frac{t}{2}\sum_{n=1}^{N}\log(1+z_n)+\phi(\boldsymbol{x}),\tag{15}$$

where $t$ is a parameter to control the accuracy of solutions, that is, as $t$ increases, the solution to (15) will be more and more close to the optimal solution.

The outline of barrier method is as follows.

```
Given the strictly feasible point $x$, $t := t^{(0)} > 0$, $\mu > 1$,
tolerance $\epsilon_b > 0$
Repeat
  a) Centering step to compute $x^*(t)$ by solving (15)
  b) Update $x = x^*(t)$
  c) Quit if $(3KN + K_1 + L + 1)/t > \epsilon_b$
  d) Increase $t$ with $t = \mu t$
```

During the inner loop of the barrier method, Newton method is always preferred to compute the central point. With a given parameter $t$, the Newton step $\Delta x$ is given by

$$\nabla^2\psi_t(\boldsymbol{x})\Delta\boldsymbol{x}=-\nabla\psi_t(\boldsymbol{x}),\tag{16}$$

where $\nabla^2\psi_t(\boldsymbol{x})$ and $\nabla\psi_t(\boldsymbol{x})$ is the Hessian and gradient of $\psi_t(\boldsymbol{x})$, respectively.

The detail of the method is then as follows.

```
Given feasible point $x$, tolerance $\epsilon_n > 0$
Repeat
  a) Compute $\Delta x$ and $\lambda^2 := -\nabla\psi_t(x)\Delta x$
  b) Quit if $\lambda^2/2 \le \epsilon_n$
  c) Backtracking line search on $\psi_t(x)$, $s = 1$,
       $\alpha \in (0, 1/2), \beta \in (0, 1)$
     while $\psi_t(x + s\Delta x) > \psi_t(x) - \alpha s\lambda^2$
         $s := \beta s$
     endwhile
  d) Update $x = x + s\Delta x$
```

## *B. Speedup of Newton Step*

Suppose that we compute the Newton step via direct matrix inversion of (16), it will generate a complexity of $O(N^3)$, which is evidently too high to apply in practice. Instead, we develop an efficient algorithm to calculate the Newton step quickly by exploiting its special structure.

The gradient of $\psi_t(\boldsymbol{x})$ is

$$\begin{aligned}\frac{\partial\psi_t(\boldsymbol{x})}{\partial p_{s,n}}&=\frac{1}{f_s}+\sum_{l=1}^{L}\frac{I_{n,l}^{SP}}{f_{s,l}}-\frac{1}{p_{s,n}}-h_n^{SD}w_n-h_n^{SR}v_n,\forall n\\ \frac{\partial\psi_t(\boldsymbol{x})}{\partial p_{r,n}}&=\frac{1}{f_r}+\sum_{l=1}^{L}\frac{I_{n,l}^{SP}}{f_{r,l}}-\frac{1}{p_{r,n}}-h_n^{RD}w_n,n\in\mathcal{N}_1\\ \frac{\partial\psi_t(\boldsymbol{x})}{\partial z_n}&=-t\frac{1}{1+z_n}-\frac{1}{z_n}+w_n+v_n,\forall n\end{aligned}\tag{17}$$

where

$$w_n=\begin{cases}\dfrac{1}{p_{s,n}h_n^{SD}+p_{r,n}h_n^{RD}-z_n}, & n\in\mathcal{N}_1\\ \dfrac{1}{p_{s,n}h_n^{SD}-z_n}, & n\in\mathcal{N}_2\end{cases}$$
$$v_n=\begin{cases}\dfrac{1}{p_{s,n}h_n^{SR}-z_n}, & n\in\mathcal{N}_1\\ 0, & n\in\mathcal{N}_2.\end{cases}\tag{18}$$

the Hessian of $\psi_t(\boldsymbol{x})$ follows

$$\begin{aligned}\nabla^2\psi_t(\boldsymbol{x})=&\begin{bmatrix}\boldsymbol{D}_1 & & & \\ & \boldsymbol{D}_2 & & \\ & & \ddots & \\ & & & \boldsymbol{D}_N\end{bmatrix}\\ &+\frac{\nabla f_s\nabla f_s^T}{f_s^2}+\sum_{l=1}^{L}\frac{\nabla f_{s,l}\nabla f_{s,l}^T}{f_{s,l}^2}\\ &+\frac{\nabla f_r\nabla f_r^T}{f_r^2}+\sum_{l=1}^{L}\frac{\nabla f_{r,l}\nabla f_{r,l}^T}{f_{r,l}^2}\end{aligned}\tag{19}$$

with

$$\boldsymbol{D}_n = \begin{bmatrix} \frac{1}{p_{s,n}^2} & & \\ & \frac{1}{p_{r,n}^2} & \\ & & \frac{1}{z_n^2} + \frac{t}{(1+z_n)^2} \end{bmatrix} + w_n^2 \begin{bmatrix} (h_n^{SD})^2 & h_n^{SD} h_n^{RD} & -h_n^{SD} \\ h_n^{SD} h_n^{RD} & (h_n^{RD})^2 & -h_n^{RD} \\ -h_n^{SD} & -h_n^{RD} & 1 \end{bmatrix} + v_n^2 \begin{bmatrix} (h_n^{SR})^2 & 0 & -h_n^{SR} \\ 0 & 0 & 0 \\ -h_n^{SR} & 0 & 1 \end{bmatrix}, n \in \mathcal{N}_1,$$

and

$$\boldsymbol{D}_n = \begin{bmatrix} \frac{1}{p_{s,n}^2} & \\ & \frac{1}{z_n^2} + \frac{t}{(1+z_n)^2} \end{bmatrix} + w_n^2 \begin{bmatrix} (h_n^{SD})^2 & -h_n^{SD} \\ -h_n^{SD} & 1 \end{bmatrix}, n \in \mathcal{N}_2.$$

Accordingly, the Hessian of $\psi_t(\boldsymbol{x})$ can be decomposed into a block-arrow matrix $\boldsymbol{D}$ and $2L+2$ one-rank matrices as follows,

$$\nabla^2 \psi_t(\boldsymbol{x}) = \boldsymbol{D} + \sum_{i=1}^{2L+2} \boldsymbol{q}_i \boldsymbol{q}_i^T \tag{20}$$

where $\boldsymbol{D} = \text{diag}(\boldsymbol{D}_1, \cdots, \boldsymbol{D}_N)$ and

$$\boldsymbol{q}_i = \begin{cases} \nabla f_s / f_s & i = 1, \\ \nabla f_{s,l} / f_{s,l} & l = 1, \ldots, L, i = l+1 \\ \nabla f_r / f_r & i = L+2, \\ \nabla f_{r,l} / f_{r,l} & l = 1, \ldots, L, i = L+l+2 \end{cases} \tag{21}$$

Since $\boldsymbol{D}$ is positive definite and all $\boldsymbol{q}_i \boldsymbol{q}_i^T \geq 0$, the Hessian of $\psi_t(\boldsymbol{x})$ is obviously invertible.

Consider the special structure shown in (20), based on the matrix inversion lemma [33], we derive a fast algorithm to speed up the computation of Newton step. Denote $\boldsymbol{q}_0 = -\nabla \psi_t(\boldsymbol{x})$ and $M = 2L+2$, the detail of an $M$-step iterative algorithm is illustrated in Table I.

The procedure of the iterative algorithm can be explicated as follows: first, we solve $M+1$ matrix system $\boldsymbol{D}\boldsymbol{\nu}_i^0 = \boldsymbol{q}_{i-1}, i = 1, \ldots, M+1$ for initialization; then we exploit the matrix inversion lemma to work out the one-rank update of $\boldsymbol{\nu}_i^0$, that is, $(\boldsymbol{D} + \boldsymbol{q}_M \boldsymbol{q}_M^T)\boldsymbol{\nu}_i^1 = \boldsymbol{q}_{i-1}, i = 1, \ldots, M$, by the known variables $\boldsymbol{\nu}_i^0$'s; such a process is executed step by step until we solve the matrix system (16), which requires $M$ steps for updating.

Particularly, since $\boldsymbol{D}$ is a quasi-diagonal matrix with all $D_i$'s are all positive definite, the $M+1$ matrix systems in the initialization step can be efficiently solved by

$$\boldsymbol{\nu}_i^0 = \begin{bmatrix} \boldsymbol{D}_1^{-1} & & \\ & \ddots & \\ & & \boldsymbol{D}_N^{-1} \end{bmatrix} \boldsymbol{q}_{i-1}, i = 1, \ldots, M+1,$$

which costs $O(N)$ for each system.

TABLE I
FAST CALCULATING OF NEWTON STEP

| | |
|---|---|
| **Initialization** | $\boldsymbol{D}\boldsymbol{\nu}_i^0 = \boldsymbol{q}_{i-1}, i = 1, \ldots, M+1$ |
| **Step *1*** | Solve equations $(\boldsymbol{D} + \boldsymbol{q}_M \boldsymbol{q}_M^T)\boldsymbol{\nu}_i^1 = \boldsymbol{q}_{i-1}$ with $\boldsymbol{\nu}_i^1 = \boldsymbol{\nu}_i^0 - \frac{\boldsymbol{q}_M^T \boldsymbol{\nu}_i^0}{1 + \boldsymbol{q}_M^T \boldsymbol{\nu}_{M+1}^0} \boldsymbol{\nu}_{M+1}^0, i = 1, \ldots, M$ |
| **Step *2*** | Solve equations $(\boldsymbol{D} + \sum_{j=M}^{M-1} \boldsymbol{q}_j \boldsymbol{q}_j^T)\boldsymbol{\nu}_i^1 = \boldsymbol{q}_{i-1}$ with $\boldsymbol{\nu}_i^2 = \boldsymbol{\nu}_i^1 - \frac{\boldsymbol{q}_{M-1}^T \boldsymbol{\nu}_i^1}{1 + \boldsymbol{q}_{M-1}^T \boldsymbol{\nu}_M^1} \boldsymbol{\nu}_M^1, i = 1, \ldots, M-1$ |
| **Step *m*** | Solve equations $(\boldsymbol{D} + \sum_{j=M}^{M+1-m} \boldsymbol{q}_j \boldsymbol{q}_j^T)\boldsymbol{\nu}_i^m = \boldsymbol{q}_{i-1}$ with $\boldsymbol{\nu}_i^m = \boldsymbol{\nu}_i^{m-1} - \frac{\boldsymbol{q}_{M-m+1}^T \boldsymbol{\nu}_i^{m-1}}{1 + \boldsymbol{q}_{M-m+1}^T \boldsymbol{\nu}_{M-m+2}^{m-1}} \boldsymbol{\nu}_{M-m+2}^{m-1}$, $i = 1, \ldots, M-m+1$ |
| | $\vdots$ |
| **Step *M*** | Solve equations $(\boldsymbol{D} + \sum_{j=M}^{1} \boldsymbol{q}_j \boldsymbol{q}_j^T)\boldsymbol{\nu}_1^M = \boldsymbol{q}_0$ with $\boldsymbol{\nu}_1^M = \boldsymbol{\nu}_1^{M-1} - \frac{\boldsymbol{q}_M^T \boldsymbol{\nu}_1^{M-1}}{1 + \boldsymbol{q}_M^T \boldsymbol{\nu}_2^{M-1}} \boldsymbol{\nu}_2^{M-1}$, $\Delta \boldsymbol{x} = \boldsymbol{\nu}_1^M$ |

### *C. Complexity Analysis*

The complexity of the barrier method is mainly caused by the calculation of the Newton step, we can analyze the computation cost of our proposed algorithm as follows. First, the $M+1$ matrix systems can be solved with a complexity of $O(MN)$ in total, as discussed in Section IV-B. Then an $M$-step one-rank update is carried out as in Table I. Thus, we can conclude that the complexity to work out the optimal solution can be measured by $O(M^2 N)$. Compared to the standard matrix inversion which generates a complexity of $O(N^3)$, the computation cost of our proposed algorithm is remarkably reduced since it usually holds that $M \ll N$ in practical systems.

## V. SIMULATION RESULTS

Experiments are conducted to evaluate the performance of our proposed RA scheme. Consider a multiuser OFDM-based CR relaying network, where all PUs are located around a BS within a circle with radius of $1km$. All SUs and relays are located at two concentric ring-shaped discs around the AP in the CR system. The outer boundary has a radius of $600m$ and the inner boundary has a radius of $400m$. There are 4 relays in the CR system, which are equally employed at the inner circle boundary. All SUs are uniformly distributed in the outer ring, each of which is covered by a relay. The PSD of the PU signals is a elliptically filtered white noise process. The channel suffers from frequency selective fading. The path loss exponent is 4, the variance of shadowing effect is $10dB$ and the amplitude of multipath fading is Rayleigh. The bandwidth of each PU is randomly generated by uniform distribution and the maximum value is $2BN/3L$. The variance of the AWGN is $10^{-13}$.

First, we compare our proposed scheme with the following three schemes,

(1) *All SD link w/o relaying (ANR):* In this case, the CR AP communicates with all SUs directly without the assistant of the relays.

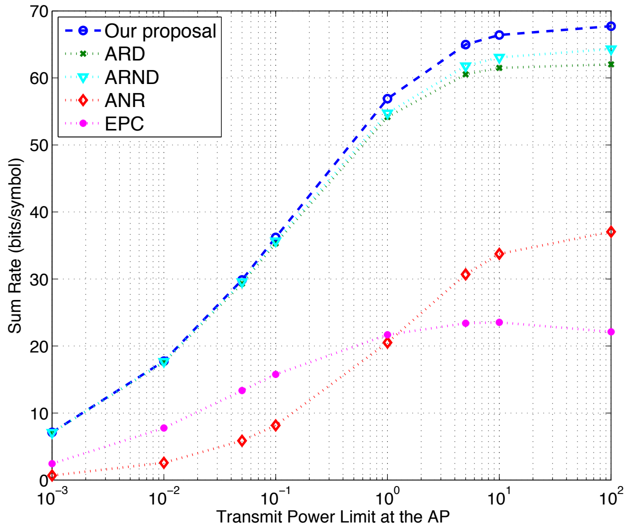


Fig. 2. Sum rate of all SUs as a function of the power limit at the CR AP

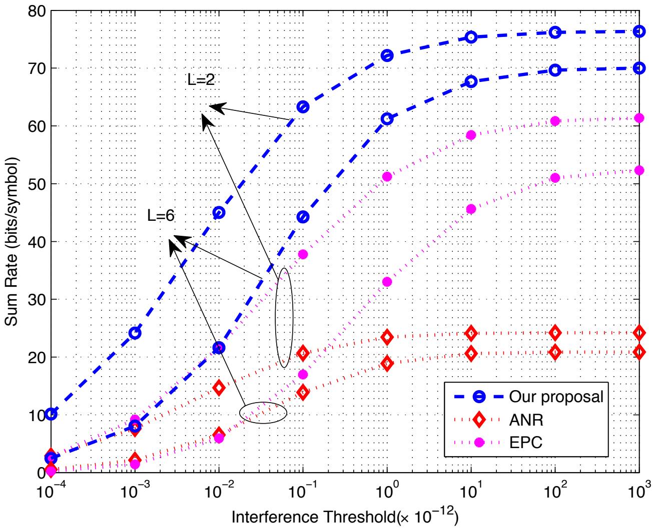


Fig. 4. Sum rate of all SUs as a function of interference threshold

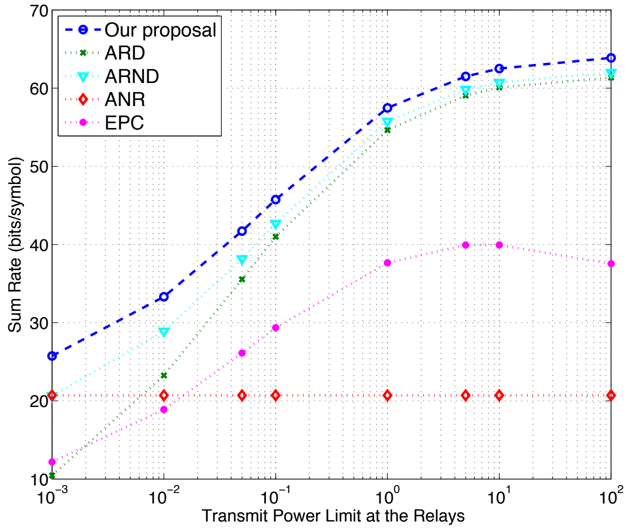


Fig. 3. Sum rate of all SUs as a function of the power limit at the relays

(2) *All relaying with SD link (ARD):* The data transmission from the CR AP to each SUs must be forwarded by one relay, while the direct link between the CR AP and each SU is also employed.

(3) *All relaying without SD link (ARND):* There is no direct transmission link from the CR AP to each SU, and the relays are in charge of the communication from the CR AP to each SU.

All the three schemes employ the subchannel allocation algorithm developed in Section III and the power distribution algorithm proposed in Section IV. We also compare our proposal with equal power allocation scheme (EPC), which allocates power equally to each subchannel.

Fig.2 and Fig.3 show the sum rate of all SUs versus the transmission power budget of the AP and the relays, respectively. There are 32 OFDM subchannels. And the SUs and the PUs are 8 and 2, respectively. The interference threshold of each PU is $10^{-13}W$. The power budgets $P_R$ and $P_S$ are $1W$ for Fig.2-3. We find that the growth of the sum rate becomes slower with the increase of $P_S$ or $P_R$, since more subchannels will be interference limited as the power budget increases. Moreover, the ARD and ARND schemes can achieve about 94% and 92% of our proposed scheme, while the ANR scheme only achieves less than 40% of ours on the average as seen in Fig.2. From Fig.3, we observe that the sum rate keeps unchanging as $P_R$ increases for the ANR scheme because the relays do not participate data transmission, while our proposed scheme reaches about 250% of the ANR on the average. As $P_R$ increases, the ARD and ARND perform more and more closely to our proposal, and the difference between the ARD (ARND) and our proposal is about 10% (18%). These results suggest that our proposed scheme is effective to improve the capacity of the CR system.

Fig.4 depicts the sum rate of all SUs versus interference thresholds for different number of PUs. There are 8 SUs and 32 OFDM subchannels. The power budgets are set to $P_S = 1W$ and $P_R = 1W$. We investigate three cases: $L = 2$, $L = 4$ and $L = 6$. It is shown that the sum capacity increases when the interference threshold gets larger until the subchannels become power limited. On the other hand, more PUs result in a relatively lower capacity because there are more interference limited subchannels with a given power budget. It can be seen from Fig.4 that our proposal is clearly superior to the EPC and the ANR in terms of sum rate.

Fig.5 and Fig.6 show the curves of the sum rate of all SUs for different number of subchannels versus power limits $P_S$ and $P_R$, respectively. There are 2 PUs and 64 OFDM subchannels. The interference threshold for each PU is $10^{-13}W$. For a given power budget, the sum rate of the CR system grows with the increase of subchannels, which implies that channel diversity benefits the system capacity significantly. Additionally, the EPC scheme achieves approximately 50% of

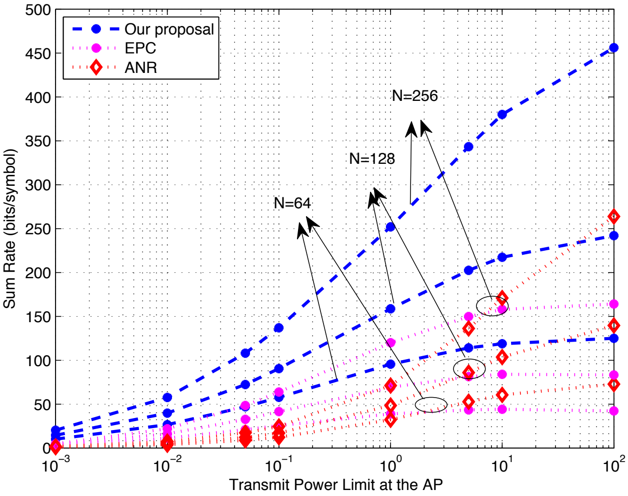


Fig. 5. Sum rate of all SUs as a function of the number of subchannels

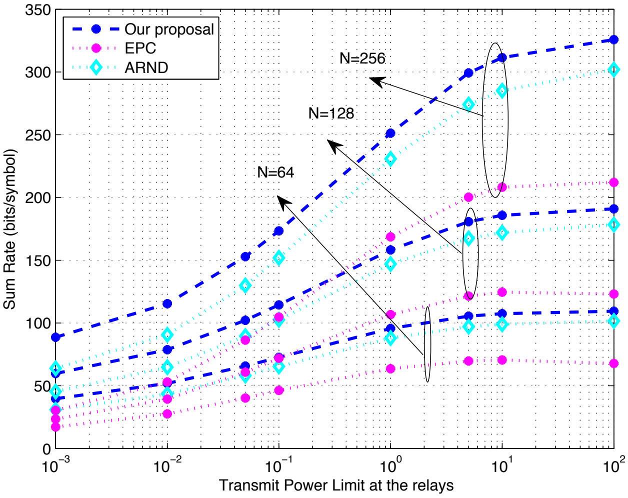


Fig. 6. Sum rate of all SUs as a function of the number of subchannels

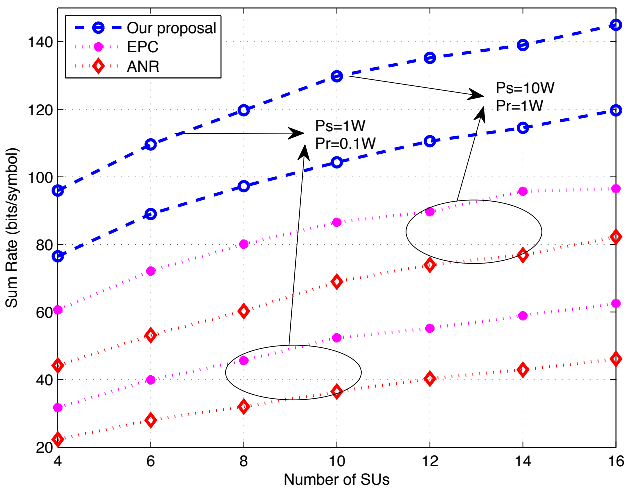


Fig. 7. Sum rate of all SUs as a function of the number of SUs

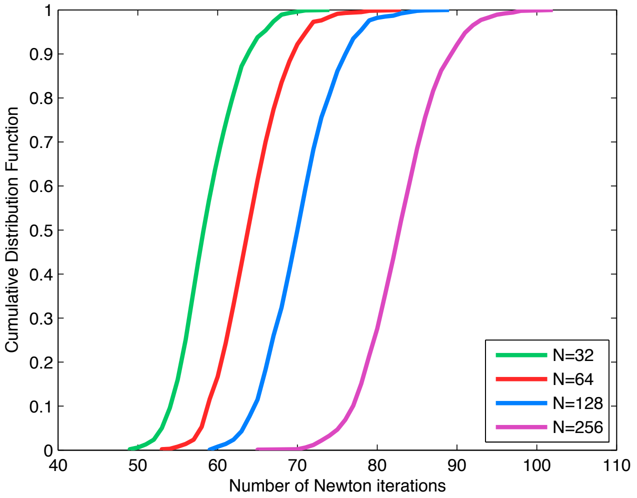


Fig. 8. Number of iterations for convergence

our proposal on average. As shown in Fig.5, the ANR scheme always obtains less than 50% rate of our proposed method, while the ARND achieves about 80% as in Fig.6.

We also investigate the multiuser diversity effect in Fig.7, where the number of subchannels is fixed to 64 and all PUs have the same interference threshold $10^{-13}W$. Two cases are considered: $P_S = 10W$, $P_R = 1W$ and $P_S = 1W$, $P_R = 0.1W$. The number of SUs varies from 4 to 16. As seen from Fig.7, when the SUs becomes more, the sum rate of the SUs increases for all schemes. It can be explained as follows: When there are more SUs, multiuser diversity makes a subchannel more possible to be assigned to an SU with high channel gain over it. Fig.7 shows our proposed scheme can always achieve more than 150% of the EPC, both of which outperform the ANR scheme.

The convergence performance of our proposed algorithm is shown in Fig.8. For power allocation, the computational load is mainly generated by the number of Newton iterations. Fig.8 shows the cumulative distribution function (CDF) of Newton iterations of the barrier method with a duality gap of less than $10^{-3}$. It can be observed that it requires more Newton iterations for the case of more subchannels. However, the number of Newton iterations varies in a narrow range with a given $N$, which validates the effectiveness and efficiency of our proposed power allocation algorithm.

Notice that the algorithm proposed in [29] adopts standard interior point method (Standard) to also work out the optimal power allocation. However, its time cost is high. Fig.9 shows the average time cost as a function of subchannels over 1000 instances. The elapsed time is counted by in-built *tic-toc* function in *Matlab*. From Fig.9 we can see the time cost of our proposed algorithm is much less than the standard technique employed in [29]. From the results shown in Fig.2-9, we can conservatively conclude that our proposed RA scheme is effective and efficient for applications in practical systems.

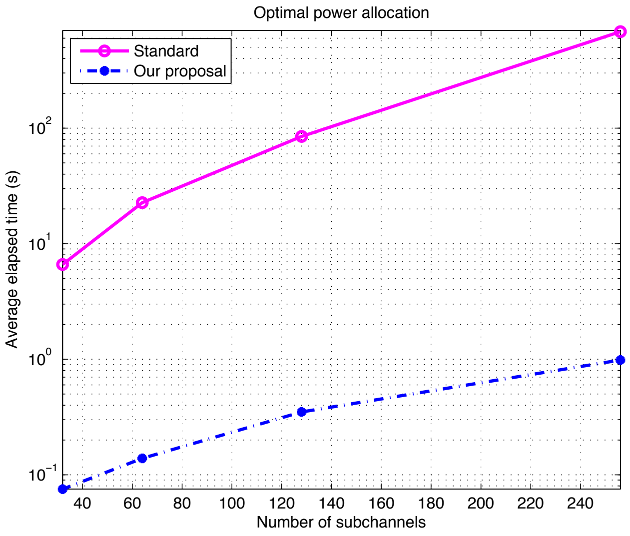


Fig. 9. Average time cost as a function of the number of subchannels.

## VI. CONCLUSION

In this paper, we studied the adaptive resource allocation problem in a multiuser OFDM-based CR system with cooperative relays. Since the formulated optimization problem is hard to solve because it involves integer variables, we firstly developed an efficient subchannel allocation to remove the frustrating integer constraints. Then we proposed a fast barrier method to work out the optimal power distribution at the source and relay node simultaneously by updating Newton step efficiently, which can reduce the computational complexity to a reasonable degree. Numerical simulations show that our proposed resource allocation scheme can achieve a significant capacity gain compared to others, indicating that relay technique is necessary to employ in CR systems. Moreover, our proposed algorithm converges quickly and stably. The result shown in this work is an upper bound because of the assumption of perfect channel state information. In future work, imperfect channel state information case should be investigated. In addition, more complex relay selection and subchannel pairing should be also studied to further improve the transmission efficiency.

## ACKNOWLEDGEMENT

The authors would like to thank the editors and the anonymous reviewers, whose invaluable comments helped improve the presentation of this paper substantially.

## REFERENCES

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[2] S. Huang, X. Liu, and Z. Ding, "Opportunistic spectrum access in cognitive radio networks," in *Proc. IEEE INFOCOM'08*, pp. 1427–1435.

[3] Federal Communications Commission, "Spectrum policy task force report," *FCC Report*, ET Docket 02-135, Nov. 2002.

[4] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Commun. Mag.*, vol. 42, no. 3, pp. 8–14, Mar. 2004.

[5] T. Cover and A. Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inf. Theory*, vol. 25, no. 5, pp. 572–584, Sep. 1979.

[6] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[7] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062 – 3080, dec. 2004.

[8] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. PartI: System description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[9] ——, "User cooperation diversity. Part II. Implementation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[10] S. Sadr, A. Anpalagan, and K. Raahemifar, "Radio resource allocation algorithms for the downlink of multiuser OFDM communication systems," *IEEE Commun. Surv. & Tutor.*, vol. 11, no. 3, pp. 92–106, Sep. 2009.

[11] S. Wang, "Efficient resource allocation algorithm for cognitive OFDM systems," *IEEE Commun. Lett.*, vol. 14, no. 8, pp. 725–727, Aug. 2010.

[12] S. Wang, F. Huang, and Z. Zhou, "Fast power allocation algorithm for cognitive radio networks," *IEEE Commun. Lett.*, vol. 15, no. 8, pp. 845–847, Aug. 2011.

[13] M. Ge and S. Wang, "Fast optimal resource allocation is possible for multiuser OFDM-based cognitive radio networks with heterogeneous services," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1500–1509, Apr. 2012.

[14] Y. Pei, Y.-C. Liang, K. C. Teh, and K. H. Li, "Energy-efficient design of sequential channel sensing in cognitive radio networks: Optimal sensing strategy, power allocation, and sensing order," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 8, pp. 1648–1659, Sep. 2011.

[15] R. Zhang, Y.-C. Liang, and S. Cui, "Dynamic resource allocation in cognitive radio networks," *IEEE Signal Process. Mag.*, vol. 27, no. 3, pp. 102–114, May 2010.

[16] S. Wang, Z.-H. Zhou, M. Ge, and C. Wang, "Resource allocation for heterogeneous cognitive radio networks with imperfect spectrum sensing," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 3, pp. 464–475, 2013.

[17] L. Vandendorpe, R. Duran, J. Louveaux, and A. Zaidi, "Power allocation for OFDM transmission with DF relaying," in *Proc. IEEE ICC'08*, pp. 3795–3800.

[18] C. Hsu, H. Su, and P. Lin, "Joint subcarrier pairing and power allocation for OFDM transmission with decode-and-forward relaying," *IEEE Trans. Signal Process.*, vol. 59, no. 1, pp. 399–414, Jan. 2011.

[19] M. Hajiaghayi, M. Dong, and B. Liang, "Optimal channel assignment and power allocation for dual-hop multi-channel multi-user relaying," in *Proc. IEEE INFOCOM'11*, pp. 76–80.

[20] T. Wang and L. Vandendorpe, "Sum rate maximized resource allocation in multiple DF relays aided OFDM transmission," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 8, pp. 1559–1571, Sep. 2011.

[21] ——, "WSR maximized resource allocation in multiple DF relays aided OFDMA downlink transmission," *IEEE Trans. Signal Process.*, vol. 59, no. 8, pp. 3964–3976, Aug. 2011.

[22] W. Dang, M. Tao, H. Mu, and J. Huang, "Subcarrier-pair based resource allocation for cooperative af multi-relay OFDM systems," in *Proc. IEEE Globecom'09*, pp. 1–6.

[23] W. Sun, L. Li, W. Yang, and L. Song, "Joint subcarrier pairing, relay selection and power allocation in OFDM relay systems," in *Proc. IEEE ICC'11*, pp. 1–5.

[24] Y. Shi and Y. Hou, "A distributed optimization algorithm for multi-hop cognitive radio networks," in *Proc. IEEE INFOCOM'08*, pp. 1292–1300.

[25] Q. Zhang, J. Jia, and J. Zhang, "Cooperative relay to improve diversity in cognitive radio networks," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 111–117, Feb. 2009.

[26] K. Letaief and W. Zhang, "Cooperative communications for cognitive radio networks," *Proc. IEEE*, vol. 97, no. 5, pp. 878–893, May 2009.

[27] M. Choi, J. Park, and S. Choi, "Simplified power allocation scheme for cognitive multi-node relay networks," *IEEE Trans. Wire. Commun.*, vol. 11, no. 6, pp. 2008–2012, June 2012.

[28] L. Li, X. Zhou, H. Xu, G. Li, D. Wang, and A. Soong, "Simplified relay selection and power allocation in cooperative cognitive radio systems," *IEEE Trans. Wireless Commun.*, vol. 10, no. 1, pp. 33–36, Jan. 2011.

[29] D. Bharadia, G. Bansal, P. Kaligineedi, and V. Bhargava, "Relay and power allocation schemes for OFDM-based cognitive radio systems," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 2812–2817, Sep. 2011.

[30] P. Ubaidulla and S. Aissa, "Optimal relay selection and power allocation for cognitive two-way relaying networks," *IEEE Wire. Commun. Lett.*, vol. 1, no. 3, pp. 225–228, June 2012.

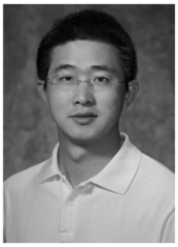
[31] M. Shaat and F. Bader, "Asymptotically optimal resource allocation in OFDM-Based cognitive networks with multiple relays," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 892–897, Mar. 2012.

[32] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[33] C. D. Meyer, *Matrix Analysis & Applied Linear Algebra*. SIAM Press, 2000.

**Shaowei Wang** (S'06-M'07-SM'13) received the BS, MS and PhD degrees in electronic engineering from Wuhan University, China, in 1997, 2003, and 2006, respectively (with honors). From 1997 to 2001, he was a research scientist of China Telecom, China. He joined the School of Electronic Science and Engineering of Nanjing University as an Assistant Professor, China, in 2006, where he has been an Associate Professor since 2008. From 2009 to 2011, He was also with LAMDA group, Nanjing University, China. From 2012 to 2013, he is/was also with Stanford University, CA, and The University of British Columbia, Canada, as a Visiting Scholar/Professor. His research interests are mainly in wireless communications and networks, optimization and machine learning. In these areas he has published more than 50 papers in leading journals and conference proceedings. He organized special issues for *IEEE Wireless Communications* on Enhancing Spectral Efficiency for LTE-Advanced, and Beyond Cellular Networks and *IEEE Communications Magazine* on Energy-Efficient Cognitive Radio Networks. He serves/served on the technical or executive committee of many reputable conferences in communications and networks.

**Mengyao Ge** received the BS degree in communication engineering from Nanjing University, Nanjing, China, in 2011. She is currently pursuing the M.S. degree at the School of Electronic Science and Engineering, Nanjing University, Nanjing, China. She won the Best Bachelor's Thesis Award from Nanjing University in 2011. Her research interests include wireless communications and convex optimization. Currently, her research focuses on resource allocation in wireless networks.



**Chonggang Wang** (SM'09) received the Ph.D. degree from Beijing University of Posts and Telecommunications (BUPT), China. He is currently with InterDigital Communications with focuses on Internet of Things (IoT) R&D activities including technology development and standardization. He (co-)authored more than 100 journal/conference articles and book chapters. He is the co-founder and the editor-in-chief of IEEE Internet of Things Journal (IoT-J). He is also on the editorial board for several journals including IEEE Communications Magazine, IEEE Wireless Communications Magazine, and IEEE Transactions on Network and Service Management. He organized and is co-organizing several special issues respectively for IEEE JSAC, IEEE Wireless Communications Magazine, IEEE Communications Magazine, IEEE Network Magazine, IEEE Communications Surveys and Tutorials, etc. He is a senior member of IEEE and the vice-chair of IEEE ComSoc Multimedia Technical Committee (MMTC).