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COOPERATIVE MULTI-RELAY RESOURCE ALLOCATION ALGORITHM IN COGNITIVE RADIO NETWORKS

Shibing Zhang[1,2], Xin Guo[1], Zhihua Bao[1,2] and Xiaoge Zhang[1]

[1]School of Electronics and Information
Nantong University
No. 9, Seyuan Road, Nantong 226019, P. R. China
{ zhangshbntu; xiangzhang1043 }@163.com; { bao.zh; zxg }@ntu.edu.cn

[2]Nantong Research Institute for Advanced Communication Technologies
Nantong 226019, P. R. China

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Abstract. *Cognitive radio (CR) is an effective way to improve the utilization of spectrum resource. This paper focuses on the resource allocation in cooperative multi-relay cognitive radio networks and proposes a cooperative multi-relay transmission algorithm. In the algorithm, secondary users (SUs) work as the relays of a primary user (PU) to cooperate PU transmitting its data. The transmission slot is divided into two sub-slots. In the first slot, the PU chooses suitable SUs and sub-channels to relay PU's data, and then the SUs who have been chosen as the relays, select the remaining idle sub-channels to transmit their own data. In the second slot, the SUs who work as the relays forward PU's data by decode-and-forward (DF) protocol; meanwhile, all SUs who want to access the network select the remaining idle sub-channels to transmit their own data. It would accelerate the data transmission of the PU and achieve higher throughput of the CR network, especially when the channel between primary transmitter (PT) and primary receiver (PR) is weak. Simulation results show that the cooperative multi-relay would improve the throughput of the CR network obviously compared with the single relay.*
Keywords: Wireless networks, Cognitive radio, Network optimization, Cooperation, Multi-relay, Throughput

1. **Introduction.** With the rapid development of communication traffic, the demand for spectrum has been on the increase. It is difficult to find vacant bands for the new wireless communication systems. The conflict between the increasing demand for spectrum and the available spectrum has become deeper [1]. Cognitive radio (CR) is an effective way to improve the utilization of the spectrum and relieve the pressure of spectrum [2,3].

Cooperative relay is introduced first in 1979. It may reduce the transmitted power, extend the battery lives, cut down the level of interference and improve the throughput of wireless networks, especially when the channel is bad [4-6]. There is much work on cooperative relay networks. A power allocation of two hops orthogonal frequency division multiplexing (OFDM) system with/without diversity is proposed to maximize the channel capacity [7]. They used a sub-channel pairing strategy based on instantaneous channel state information (ICSI) to improve the system performance. Taken the transmitting power and relay location into consideration, a power efficient allocation algorithm is proposed to reduce the average bit error rate of the network [8]. Nadkar et al. have given a power loading and bits allocation to achieve an optimal secondary system [9,10]. In an decode-and-forward (DF) cognitive cooperative relay network, a suitable power allocation would maximize the capacity of cognitive systems [11], and a suboptimal relay and power allocation would also improve the capacity of multi-relay cognitive radio networks [12].

SUs could also work as relays of PUs to speed up the data transmission of PUs when the channel between the primary transmitter (PT) and primary receiver (PR) is poor.

It would save the transmitting time and let SUs have more opportunities to access the spectrum. Lu et al. proposed an opportunistic spectrum sharing protocol in which the SUs work as the relay of PUs [13,14]. They use an optimal sub-channels and power allocation to cooperate the PU to achieve the target rate in single relay cognitive networks. However, there is little work on the cooperative multi-relay cognitive radio networks as far as we know.

In this paper, we focus on the cooperative multi-relay cognitive radio networks. We propose a cooperative multi-relay resource allocation algorithm, in which SUs can play as relays of PUs. It would accelerate the data transmission of the PUs and SUs, and achieve higher throughput of the CR network, especially when the channel between primary transmitter (PT) and primary receiver (PR) is weak. As a reward, SUs would occupy more spectrums and more time to transmit data than the single relay. Simulation results show that the cooperative multi-relay resource allocation would increase the throughput of the CR network obviously compared with the single relay.

The remainder of the paper is organized as follows. Section 2 gives the cooperative multi-relay model. Section 3 describes the optimization objective of the resource allocation in networks. The resource allocation algorithm is proposed in Section 4. Simulation results are shown in Section 5. Finally, Section 6 gives some conclusions.

2. **System Model.**

We consider a cooperative multi-relay cognitive radio network with bandwidth B, in which the channel between PT and PR is weak. The PU agrees to cooperate with SUs to accelerate its data transmission and is willing to contribute extra spectrum for SUs to transmit their data. For the sake of simplicity, we assume there are one primary user pair (one PT and one PR), L second user pairs (L second transmitters (STs) and L second receivers (SRs)), as shown in Figure 1. The transmission of the PU may be assisted by one or more SUs to relay with the DF protocol.

The data transmission slot is divided into two sub-slots. First, the PU transmits its data from the PT to relays on the selected sub-channels while SUs who have been selected as relays transmit their own data on the remaining sub-channels. Then, the relays forward the PU's data to the PR while SUs select remaining sub-channels to transmit their own data.

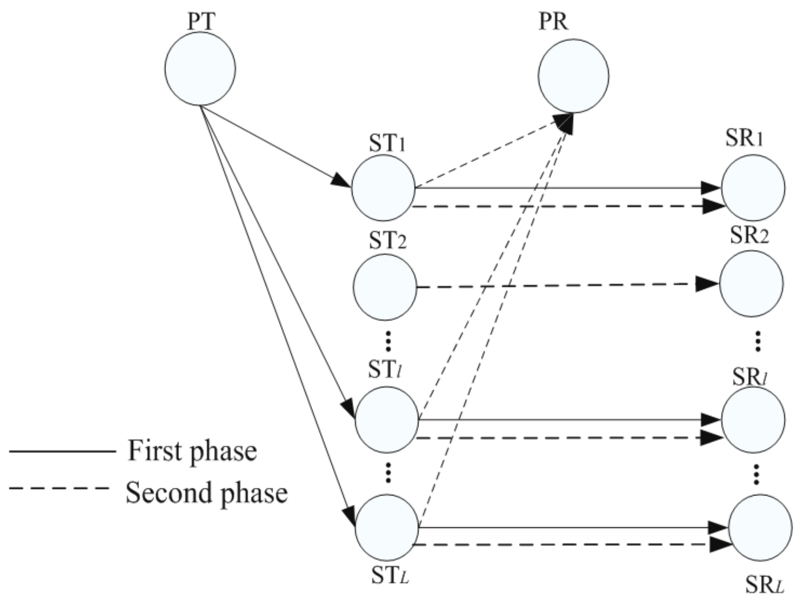

FIGURE 1. System model of cognitive radio network

3. **Problem Description.** Suppose there are N sub-channels in the band, the bandwidth of sub-channel is B_0, $B_0 = B/N$. Let $h_{p,l}^n$, $h_{l,p}^n$ and $h_{l,l}^n$ denote the n-th sub-channel gain from PT to ST_l, ST_l to PR, ST_l to SR_l; $P_{l,1}^n$ and $P_{l,2}^n$ denote the transmitted power of ST_l in the first slot and second slot over the n-th channel respectively, $l \in L$, $n \in N$, where $\mathbf{L} = \{1, 2, \ldots, L\}$ and $\mathbf{N} = \{1, 2, \ldots, N\}$ are the sets of L SUs and N sub-channels. The noises in corresponding sub-channels are assumed to be AWGN with zero mean and variance of $\sigma_{p,l}^2$, $\sigma_{l,p}^2$, $\sigma_{l,l}^2$ respectively. The channel allocation index $\rho_{p,l}^n$ is a binary variable, $\rho_{p,l}^n \in \{0, 1\}$. If the n-th channel is allocated to the PU and ST_l, $\rho_{p,l}^n$ is equal to one; otherwise, $\rho_{p,l}^n$ is equal to zero. $\rho_{l,p}^n$, $\rho_{l,1}^n$ and $\rho_{l,2}^n$ represent the allocation indexes between ST_l and PR, ST_l to SR_l in the first slot and second slot over the n-th channel respectively. Their values are defined as the same as $\rho_{p,l}^n$. In each slot, a sub-channel can only be allocated to one user (PU or SU). Therefore, index $\rho_{p,l}^n$ should be satisfied with the constraint as follows

$$\begin{cases} \rho_{p,l}^n + \rho_{l,1}^n \le 1, \\ \rho_{l,p}^n + \rho_{l,2}^n \le 1, \end{cases} \quad \forall n \tag{1}$$

The transmission rate between the PT and relay ST_l over the n-th sub-channel is given by

$$R_{p,l}^n = \frac{B_0}{2} \log_2^{\left(1 + \frac{P_{pu} \left|h_{p,l}^n\right|^2}{\sigma_{p,l}^2}\right)} \tag{2}$$

If the data rate of the PU is R_p, the relays rate R_T should be satisfied as follows

$$R_T = \min\left(\sum_{n=1}^{N}\sum_{l=1}^{L} \rho_{p,l}^n R_{p,l}^n, \sum_{n=1}^{N}\sum_{l=1}^{L} \rho_{l,p}^n R_{l,p}^n\right) \ge R_P \tag{3}$$

and the transmitted power of each SU, P_{su} must be satisfied as follows

$$\begin{cases} P_{su} \ge \sum\limits_{n=1}^{N}\sum\limits_{l=1}^{L} \rho_{l,1}^n P_{l,1}^n, & \text{first slot} \\ P_{su} \ge \sum\limits_{n=1}^{N}\sum\limits_{l=1}^{L} \left(\rho_{l,p}^n P_{l,p}^n + \rho_{l,2}^n P_{l,2}^n\right), & \text{second slot} \end{cases} \tag{4}$$

When ST_l is selected as the relay on the n-th sub-channel, the transmitted power of ST_l is

$$P_{l,p}^{n'} = \frac{P_{su} \left|h_{p,l}^n\right|^2 \sigma_{l,p}^2}{\left|h_{l,p}^{n'}\right|^2 \sigma_{p,l}^2} \tag{5}$$

Then, the data rate of SUs in the two slots can be formulated by

$$R_i = \frac{B_0}{2} \sum_{n=1}^{N}\sum_{l=1}^{L} \rho_{l,i}^n \log_2^{\left(1 + \frac{P_{l,i}^n \left|h_{l,l}^2\right|^2}{\sigma_{l,l}^2}\right)} \qquad i \in \{1, 2\} \tag{6}$$

The optimization objective of the resource allocation in the networks is to maximize the data rate of second system (CR network) as follows

$$\max \sum_{i=1}^{2} R_i \quad \text{s.t. } (1), (2), (3)\ i \in \{1, 2\} \tag{7}$$

where (1), (3) and (4) mean the constraints in the expressions of (1), (3) and Equation (4).

4. Resource Allocation.

4.1. Sub-channel and power allocation in the first slot. When the PU wants SUs to relay its data, it has the priority in selecting the relay sub-channels. The selection of sub-channels can be described as the optimization as follows

$$\min \sum_{n=1}^{N}\sum_{l=1}^{L}\rho_{p,l}^{n} \qquad \text{s.t.} \ \sum_{n=1}^{N}\sum_{l=1}^{L}\rho_{p,l}^{n}R_{p,l}^{n} \geq R_T \tag{8}$$

Define the transmission efficiency of the relay sub-channel as follows

$$\beta_{p,l}^{n} = \frac{R_{p,l}^{n}}{R_T} \tag{9}$$

and construct the efficiency matrix as follows

$$\boldsymbol{\beta} = \begin{bmatrix} \beta_{p,1}^{1} & \beta_{p,1}^{2} & \cdots & \beta_{p,1}^{N} \\ \beta_{p,2}^{1} & \beta_{p,2}^{2} & \cdots & \beta_{p,2}^{N} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{p,L}^{1} & \beta_{p,L}^{2} & \cdots & \beta_{p,L}^{N} \end{bmatrix}_{L\times N} \tag{10}$$

The optimization in (8) can be simplified to find the largest efficiency $\beta_{p,l^*}^{n^*}$ as follows

$$[l^*, n^*] = \max_{l\in\mathbf{L}, n\in\mathbf{N}}(\boldsymbol{\beta}) \tag{11}$$

where $\max(\mathbf{X})$ means to find the largest value in the set $\mathbf{X}$.

Now, the n^*-th sub-channel and the l^*-th ST cannot be selected any more, the channel allocation index $\rho_{p,l}^{n}$ and the transmission efficiency matrix $\boldsymbol{\beta}$ should be renewed as follows

$$\rho_{p,l^*}^{n^*} = 1 \tag{12}$$

and

$$\boldsymbol{\beta}^{n^*} = \begin{bmatrix} \beta_{p,1}^{n^*} & \beta_{p,2}^{n^*} & \cdots & \beta_{p,l}^{n^*} \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & \cdots & 0 \end{bmatrix}^T \tag{13}$$

where "T" denotes the matrix transpose. We continue the selection until

$$\sum_{n^*\in\mathbf{N}^*}\sum_{l^*\in\mathbf{L}^*}\rho_{p,l^*}^{n^*}\beta_{p,l^*}^{n^*} \geq 1 \tag{14}$$

is satisfied, where $\mathbf{N}^*$ is the set of relay sub-channels selected, and $\mathbf{L}^*$ is the set of relays selected.

In order to embody the attributes of fairness between SUs, only the SUs who have been selected as the relays can occupy the rest of sub-channels. Suppose there are $\overline{N}$ residual sub-channels, which structure the set of residual sub-channels $\overline{\mathbf{N}}$ $\left(\overline{\mathbf{N}} = \mathbf{N} - \mathbf{N}^*\right)$, and there are L^* SUs selected to be the relays, which structure the set of relays $\mathbf{L}^*$. Then, the optimization in (7) can be formulated as a one-to-one matching optimization as follows

$$\max\ R_1, \quad \text{s.t.} \ \sum_{l^*=1}^{L^*}\rho_{l^*,1}^{\overline{n}} \leq 1 \text{ and } \sum_{\overline{n}=1}^{\overline{N}}\sum_{l^*=1}^{L^*}\rho_{l^*,1}^{\overline{n}}P_{l^*,1}^{\overline{n}} \leq P_{su} \tag{15}$$

The sub-channel gain matrix of the relay SUs in $\mathbf{L}^*$ over the sub-channel $\overline{\mathbf{N}}$ can be given by

$$\mathbf{H}_1 = \begin{bmatrix} h_{1,1}^{1} & h_{1,1}^{2} & \cdots & h_{1,1}^{\overline{N}} \\ h_{2,2}^{1} & h_{2,2}^{2} & \cdots & h_{2,2}^{\overline{N}} \\ \vdots & \vdots & \ddots & \vdots \\ h_{L^*,L^*}^{1} & h_{L^*,L^*}^{2} & \cdots & h_{L^*,L^*}^{\overline{N}} \end{bmatrix}_{L^*\times\overline{N}} \tag{16}$$

Then, we can structure the coefficient matrix of the sub-channels as follows

$$w_{l^*,l^*}^{\bar{n}} = \left(h_{l^*,l^*}^{\bar{n}}\right)^2 - \left(\max_{l^* \in \mathbf{L}^*, \bar{n} \in \overline{\mathbf{N}}} (\mathbf{H}_1)\right)^2 \tag{17}$$

The optimal sub-channels assignment in Equation (15) can be achieved by applying the Hungarian algorithm [15] according to the coefficients matrix $\mathbf{W}$. However, when $\overline{N} \neq L^*$, we should restructure a square matrix from $\mathbf{W}$. When $\overline{N} < L^*$, we need add $L^* - \overline{N}$ virtual sub-channels and restructure the coefficient matrix; when $\overline{N} > L^*$, an SU can occupy more than one but no more than $\overline{N} - L^* + 1$ sub-channels to transmit its data.

Finally, the transmitted powers of SUs are assigned according to their contribution to PU as follows

$$P_{l^*} = \frac{\sum\limits_{n=1}^{N} \rho_{p,l^*}^n}{\sum\limits_{n=1}^{N} \sum\limits_{l=1}^{L} \rho_{p,l}^n} P_{su} \tag{18}$$

Then, we use the Water-Filling algorithm [16] to allocate the power of each SU, which has been selected as relay, to each sub-channel.

4.2. **Sub-channel and power allocation in the second slot.** In the second slot, the relays forward the PU's data by DF protocol. Note that the number of sub-channels used to forward is the same as that of sub-channels occupied by the PU in the first slot, but the sub-channels in the two slots may not be the same.

In this case, the sub-channel gain of the relays in L^* over sub-channels N is given by

$$\mathbf{H}_2 = \begin{bmatrix} h_{1,p}^1 & h_{1,p}^2 & \cdots & h_{1,p}^N \\ h_{2,p}^1 & h_{2,p}^2 & \cdots & h_{2,p}^N \\ \vdots & \vdots & \cdots & \vdots \\ h_{L^*,p}^1 & h_{L^*,p}^2 & \cdots & h_{L^*,p}^N \end{bmatrix}_{L^* \times N} \tag{19}$$

In order to maximize the efficiency of each sub-channel, the relay sub-channels should be selected to find the largest sub-channel gain $h_{l',p}^{n'}$ among $\mathbf{H}_2$ as follows

$$[l', n'] = \max_{l^* \in \mathbf{L}^*, n \in \mathbf{N}} (\mathbf{H}_2) \tag{20}$$

The transmitted power of the relays can be allocated according to Equation (5).

For the sub-channels selection, the rest sub-channels are allocated to all SUs with the Hungarian algorithm as the same as in the first slot. According to the contribution to the relay network, the total transmitted power of the l''-th SU is allocated as follows

$$P_{l''} = \frac{\sum\limits_{n=1}^{N} \rho_{l',2}^n}{\sum\limits_{n=1}^{N} \sum\limits_{l=1}^{L} \rho_{l,2}^n} \left(P_{su} - \sum_{n=1}^{N} \sum_{l=1}^{L} P_{l,p}^n\right) \tag{21}$$

Then, the transmitted power of the l''-th SU on the sub-channel is allocated by Water-Filling algorithm.

5. **Simulation Results and Analyses.** In this section, we present some simulation results to demonstrate the performance of the cooperative multi-relay cognitive radio network proposed. We simulate the network 1000 times using Monte Carlo simulation. We consider a 160 MHz bandwidth cognitive radio system with 1 pair of PU and 4 pairs of SUs over a frequency-selective Rayleigh fading channel. The system is divided into 16 sub-channels, and each of bandwidth is 10 MHz. In the simulations, the transmitted

power of PT in each sub-channel is set to 20 mW. Each sub-channel has the same noise power.

Figure 2 gives the relationship between non-cooperative probability and the transmitted power of the second system. It shows that the non-cooperative probability is inversely proportional to the transmitted power. When the transmitted power is very low, it is too small to relay the data of PU. At this moment, the cooperative relay mode cannot be adopted, and the non-cooperative probability is near to 1. When the power is large enough, the SUs could cooperate with PU, and the non-cooperative probability is near to 0.

Figure 3 compares the achieved rates in cooperative multi-relay second systems with the one in cooperative single-relay second systems [14]. With the increase of the power of second systems, the SUs have more power after cooperating with PU, so the throughput

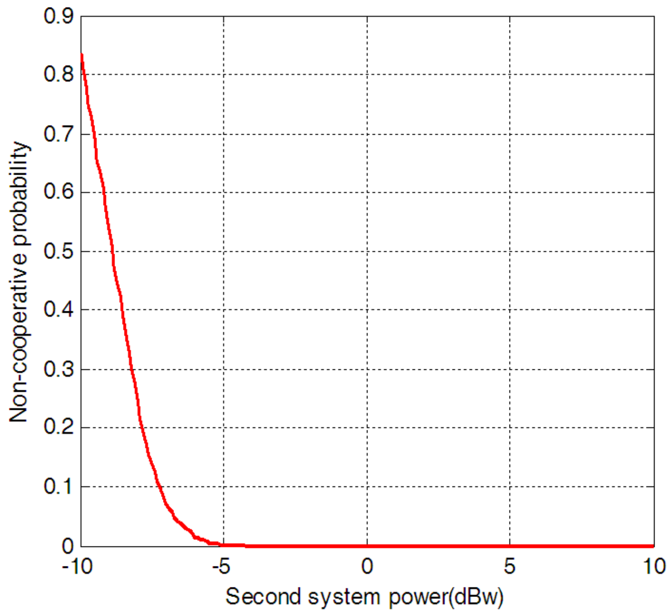

FIGURE 2. Non-cooperative probability with transmitted power of the second system

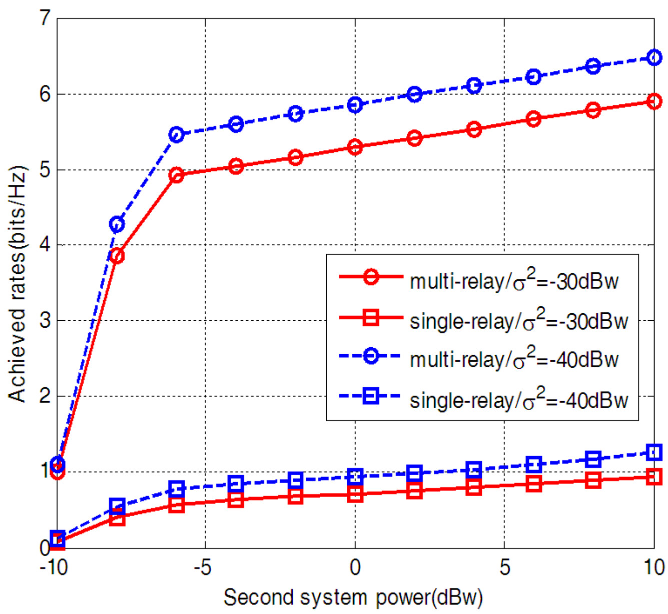

FIGURE 3. Comparison of achieved rates under different transmitted powers

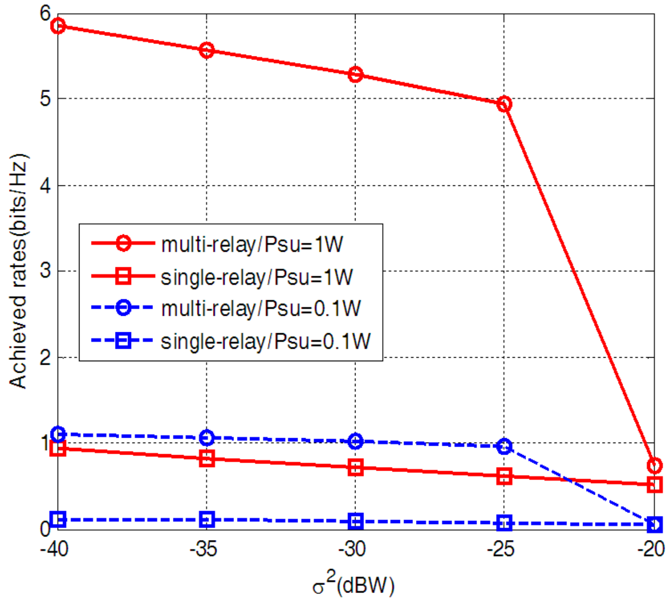

FIGURE 4. Comparison of achieved rates under different noise powers

of the two networks is both increased. However, the achieved rates of second systems with multi-relay is much more than the one with single-relay.

Figure 4 illustrates the achieved rates with multi-relay and single-relay under different noise powers. It shows that the noise power in the sub-channel affects the throughput a lot. However, the achieved rates in multi-relay networks are always higher than the one in single-relay networks.

6. **Conclusions.** In this paper, we have investigated the cooperative multi-relay CR network and propose a resource allocation algorithm, in which a part of SUs may work as the relays of PU when the channel between PT and PR is poor. As a reward, SUs could occupy the spectrum to transmit their own data. It could achieve a higher throughout because the relays accelerate data transmission of PU. Simulations show that the system proposed is suitable for the weak channel gain between PT and PR. And the cooperative multi-relay model proposed can increase the throughput of SU system obviously compared with the single relay model. In the further work, we will design a joint optimal allocation scheme, which can not only guarantee the low computational complexity, but also improve the throughput.

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