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MULTI-RELAY SELECTION AND POWER ALLOCATION FOR TWO-WAY DF COGNITIVE RADIO NETWORKS

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Abstract. *In this letter, the problem of multi-relay selection and power allocation in decode-and-forward (DF) two-way relaying cognitive radio networks using half duplex is investigated. We aim at maximizing the capacity of system under the individual power constraints of source and relays while the interference introduced to the primary users should be kept below a certain limit. Via converting the power of two end nodes into that of relays, an implement algorithm of low complexity is proposed, which can achieve the capacity of system from the maximum sum* SNR_m *(signal to noise radio of* m_{th} *relay). Simulation results show the superior performance of the proposed algorithm.*
Keywords: Cognitive radio, Multi-relay selection, Power allocation, DF

1. **Introduction.** With rapid development of wireless technology, the spectrum scarcity problem becomes serious. The relay communication in cognitive radio (CR) networks can improve usage of the ratio spectrum and the capacity of system [1]. According to the data flow direction, the network with relays in cognitive radio can be divided into two main categories: one-way and two-way relaying network. The two-way relaying transmission attracts more attention due to its higher system capacity comparing to one-way relaying system [2].

Relay selection and power allocation in relay communication networks have been extensively discussed in literature. In [3], Shaat and Bader studied the joint power and sub-carrier allocation in OFDM (orthogonal frequency division multiplexing) based on cognitive one-way relaying network. Then Shaat and Bader added relay selection in one-way multi-relay network [4]. Li et al. studied the problem of joint relay assignment and channel allocation for cooperative communications in single relay and multiple source-destination pairs network [5]. In [6] Vu and Kong studied the optimal power allocation in non-cognitive two-way DF OFDM relay network. The capacity of the system in [3, 4, 5, 6] is very low due to one-way, non-cognitive two-way system and single relay selection. Therefore in [7], Abrar et al. jointed sub-carrier paring and power allocation and used dual decomposition method to maximize the capacity of system based on two-way relaying cognitive radio networks. To simplify the problem of the network, Alsharoa et al. proposed an iterative quantization algorithm with discrete number of power levels with one relay selection in the two-way relaying cognitive radio networks on the assumption that the power of two cognitive terminals is the same [8]. However, the assumption is unreasonable. In [9], Alsharoa et al. quantized the power of both cognitive terminals with one relay selection improving the solution. However, these three methods in [7, 8, 9] have high computational complexity.

We propose an algorithm to improve the capacity of system with low complexity. In this algorithm, firstly, we convert the power of two end nodes into that of relays based on a certain criterion so that constraint conditions of optimization problem are reduced. Then we calculate the SNR_m of each relay and search out the maximum sum SNR_m of partial relays selection, which satisfies the interference constraints. The simulation results show that the proposed algorithm not only improves the capacity but also simplifies the power allocation and reduces the complexity.

The rest of this paper is organized as follows. Section 2 introduces the system model and problem formulation. Section 3 gives the algorithm of relay selection and power allocation, and some simulation results are presented in Section 4. Finally, some conclusions are made in Section 5.

2. System Model and Problem Formulation.

2.1. System model. The cognitive system consists of a primary user (PU), a secondary User (SU), a cognitive base station (CB), and M cognitive relays (RSs). It is assumed that there is no direct link between the two terminals, and L ($L \leq M$) relays are selected to transmit signals. In this system, two time slots are considered. During the first time slot, SU and CB transmit their signals to the relays simultaneously, and their power are denoted as P_S and P_{CB} respectively. This slot causes two interferences to the PU from SU and CB respectively. In the second time slot, the selected RSs broadcast their signals with power denoted as P_{Rm}, where $m = 1, \ldots, M$. This slot also causes interference to the PU from the RS.

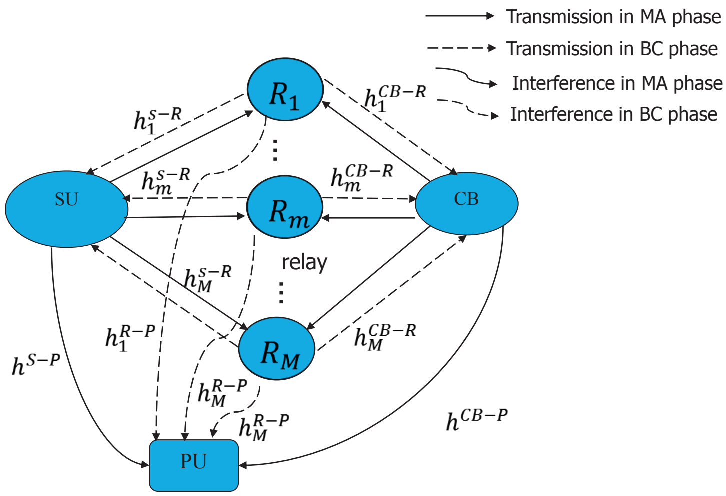


FIGURE 1. System model of the cooperative two relaying cognitive radio system

Half duplex channel case is considered as illustrated in Figure 1. We assume that all the channel gains are perfectly known at the communication nodes, which can be adopted by assuming channel reciprocity and classical channel estimation approaches [7]. Also, we assume that the Primary Network (PN) and Secondary Network (SN) access the spectrum at the same time. Furthermore, the selection strategy of DF protocol is applied in order to achieve the maximum capacity of the SN without affecting the QoS of the PU of which the interference threshold is denoted as I_{th}. Finally, without loss of generality, all the noise variances are assumed to be σ_n^2.

2.2. Problem formulation. Multi-relay selection is considered in this letter. We formulate the problem and calculate the capacity of system from the sum SNR_m of partial relays selection. The details are as below.

The transmission rate of the m_{th} relay is indicated as R_{DF_m}. With DF protocol, R_{DF_m} can be written as [10]:

$$R_{DF_m} = \frac{1}{2}\min\left(\min\{R_1, R_3\} + \min\{R_2, R_4\}, R_5\right) \tag{1}$$

where $R_1 = \log_2\left(1 + \frac{P_S g_2}{\sigma_n^2}\right)$, $R_2 = \log_2\left(1 + \frac{P_{CB} g_1}{\sigma_n^2}\right)$ denote the rate from the SU and the CB to the relay in the first time slot, respectively. $R_3 = \log_2\left(1 + \frac{P_{R_m} g_1}{\sigma_n^2}\right)$, $R_4 = \log_2\left(1 + \frac{P_{R_m} g_2}{\sigma_n^2}\right)$ denote the rate from the relay to the CB and to the SU in the second time slot, respectively, and $R_5 = \log_2\left(1 + \frac{P_{CB} g_1 + P_S g_2}{\sigma_n^2}\right)$ denotes that the max capacity can be achieved in both time slots.

According to Shannon Theorem, R_{DF_m} can also be written as:

$$R_{DF_m} = \frac{1}{2}\log_2(1 + SNR_m). \tag{2}$$

From Equations (1) and (2), we have the following equation:

$$SNR_m = 2^{\min(\min\{R_1,R_3\}+\min\{R_2,R_4\},R_5)} - 1. \tag{3}$$

Let R_{DF} denote the the capacity of two-way relaying CR system, which is written as:

$$R_{DF} = \frac{1}{2}\log_2\left(1 + \sum_{m=1}^{M} \epsilon_m * SNR_m\right) \tag{4}$$

where $\epsilon_m \in \{0, 1\}$ is relay assignment indicator. $\epsilon_m = 1$ if the m_{th} relay is assigned and zero otherwise.

Our objective is to maximize the capacity of the CR system while satisfying the transmission power and interference constraints. We formulate the following Optimization Problem1 (OP1) with multi-relay selection:

$$\max_{P_S, P_{CB}, P_{R_m}, \epsilon_m} \quad R_{DF} = \frac{1}{2}\log_2\left(1 + \sum_{m=1}^{M} \epsilon_m * SNR_m\right) \tag{5}$$

$$\text{s.t.} \quad 0 \le P_S \le \overline{P_S}, \tag{6}$$

$$0 \le P_{CB} \le \overline{P_{CB}}, \tag{7}$$

$$0 \le P_{R_m} \le \overline{P_R},\ \forall m = 1, \ldots, M, \tag{8}$$

$$P_S g_3 + P_{CB} g_4 \le I_{th}, \tag{9}$$

$$\sum_{m=1}^{M} \epsilon_m g_5 P_{R_m} \le I_{th}, \tag{10}$$

$$\epsilon_m \in \{0, 1\},\ \forall m = 1, \ldots, M \tag{11}$$

where $\overline{P_S}$, $\overline{P_{CB}}$, $\overline{P_R}$ are the peak transmit power of the secondary SU, CB, and m_{th} RS, respectively. I_{th} is the interference constraint of PU. Formulas (6), (7), (8) indicate that

TABLE 1. Symbol notation

Symbol	Notation	Complex channel gain between
g_1	$\lvert h_m^{(CB-R)}\rvert^2$	CB and RS m
g_2	$\lvert h_m^{(S-R)}\rvert^2$	SU and RS m
g_3	$\lvert h^{(S-P)}\rvert^2$	SU and PU m
g_4	$\lvert h^{(CB-P)}\rvert^2$	CB and PU m
g_5	$\lvert h_m^{(R-P)}\rvert^2$	RS m and PU m

the powers of SU, CB and m_{th} relay respectively should be below the power constraint; similarly formulas (9), (10) indicate that the interference to PU from SU, CB in the first slot and from L relays in the second slot should be below interference constraint.

3. **Proposed Algorithm.** The purpose of allocation resource is to maximize the capacity of system by implementing the power allocation of SU, CB, and RS under the conditions of power and interference constraint. To solve the optimization problem effectively, we simplify the power allocation via converting the power of P_S and P_{CB} into that of P_{R_m} when the data rates of symmetrical transmitting links are equal, and obtain capacity from the maximum *SNR* which is searched out from the sum SNR_m of partial relays selected. The details are as follows:

First, we simplify the power.

According to [12], the maximum rate of R_{DF_m} is got when $R_1 = R_3$, $R_2 = R_4$. Equations (1) and (3) can be written respectively as

$$R_{DF_m} = \frac{1}{2}\min(R_3 + R_4, R_5) \tag{12}$$

$$SNR_m = 2^{\min(R_3+R_4,R_5)} - 1 \tag{13}$$

and $P_S g_2 = P_R g_1$, $P_{CB} g_1 = P_R g_2$. Thus $P_S = \frac{P_{R_m} g_1}{g_2}$, $P_{CB} = \frac{P_{R_m} g_2}{g_1}$, and $R_5 = \log_2\left(1 + \frac{P_{R_m} g_1 + P_{R_m} g_2}{\sigma_n^2}\right)$. Formulas (6), (7), (9) can be transformed as $\frac{P_{R_m} g_1}{g_2} \le \overline{P_S}$, $\frac{P_{R_m} g_2}{g_1} \le \overline{P_{CB}}$, $\frac{P_{R_m} g_1 g_3}{g_2} + \frac{P_{R_m} g_2 g_4}{g_1} \le I_{th}$, then

$$P_{R_m} \le \frac{\overline{P_S} g_2}{g_1}, P_{R_m} \le \frac{\overline{P_{CB}} g_1}{g_2}, P_{R_m} \le \frac{I_{th}}{\frac{g_1 g_3}{g_2} + \frac{g_2 g_4}{g_1}}. \tag{14}$$

From (8) and (14) we can get

$$P_{R_m} = \min\left(\frac{\overline{P_S} g_2}{g_1}, \frac{\overline{P_{CB}} g_1}{g_2}, \frac{I_{th}}{\frac{g_1 g_3}{g_2} + \frac{g_2 g_4}{g_1}}, \overline{P_R}\right). \tag{15}$$

Based on the above results, four variables are transformed into one variable in OP1. In this way, we form the following Optimization Problem2 (OP2):

$$\max_{\epsilon_m} R_{DF} = \frac{1}{2}\log_2\left(1 + \sum_{m=1}^{M} \epsilon_m * SNR_m\right)$$
$$\text{s.t.}\ (10), (11), (15).$$

Second, we deal with the relay selection and capacity of system.

There are C_M^1 options of relays and combinations sum of SNR_m when one relay is selected, and C_M^2 options of relays and combinations sum of SNR_m when two relays are selected, and so on. So there are $\sum_{i=1}^{M} C_M^i = 2^M - 1$ combinations sum of SNR_m ($m = 1, 2, \ldots, M$). This group is denoted as $\boldsymbol{G}$.

Therefore, the OP2 is transformed as follows:

$$\max_{SNR \in \boldsymbol{G}} R_{DF} = \frac{1}{2}\log_2(1 + SNR)$$
$$\text{s.t.}\ (10), (11)$$

where SNR is one element of $\boldsymbol{G}$. Search out the maximal sum $SNR_{\max}$ from all the options of *SNR*. Then the power of relays selected and corresponding relays can also be searched out, which can be expressed as:

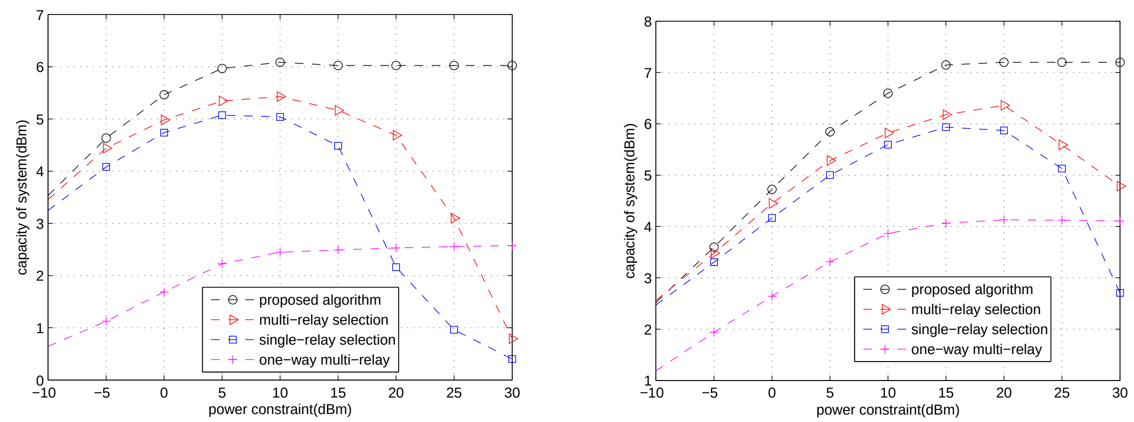
$$SNR_{\max} = \max(SNR), \quad (P_{R_m}, m_{th}^*) = \arg\max(SNR).$$

If the interference constraint (10) is satisfied, $SNR_{\max}$ is the optimal capacity; otherwise find the next $SNR_{\max}$ until interference constraint (10) is satisfied. Thus the capacity of system is obtained, so are the selected relays, and power of selected relays, SU, and CB, respectively.

4. **Simulation Results.** In this section, simulation results show the benefits of the proposed methods. A single cell subject to a small scale Rayleigh fading, consisting of one PU and an SN constituted by one CB, one SU, and $M = 4$ relays is assumed. The variance σ_n^2 is assumed to be 10^{-4}. We also assume that the transmit peak power constraint of SU, CB and each RS are $\bar{P}$.

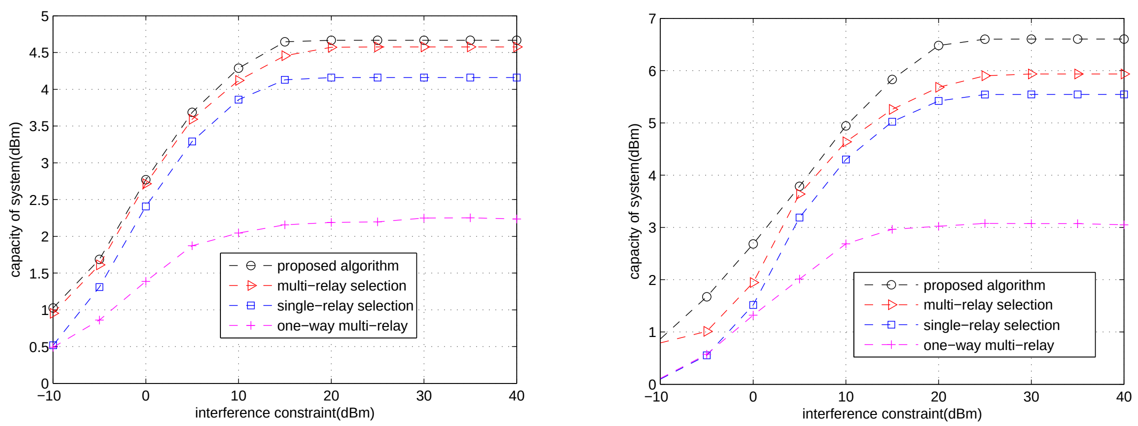
To evaluate the performance, the proposed algorithm is compared with the multi-relay selection based on GA (genetic algorithm) in [9], the single relay selection based on GA in [8] and one-way multi-relay selection with sub-carrier paring in [4].

Figure 2(a) and 2(b) show the capacities of system versus power constraint when the interference constraints are fixed as $I_{th} = 10$dBm and 20dBm respectively. From Figure 2 we find that the capacities increase before a certain power constraint and then remain unchanged for one-way multi-relay and the proposed algorithms; The capacities increase before a certain power constraint and then decrease in the other two algorithms. The results show that the proposed algorithm has the best performance among the four algorithms.



(a) $I_{th} = 10$dBm (b) $I_{th} = 20$dBm

FIGURE 2. The achieved SR of suboptimal solutions varying with $\bar{P}$



(a) $\bar{P} = 20$dBm (b) $\bar{P} = 25$dBm

FIGURE 3. The achieved SR of suboptimal solutions varying with I_{th}

Figure 3(a) and 3(b) show that capacities of system versus interference constraint when the power constraints are fixed as $\bar{P} = 20$dBm and 25dBm respectively. From Figure 3, we find that the capacities increase before a certain power constraint and then remain unchanged for the four algorithms. Furthermore, the figures also show that the performance of the proposed algorithm is better than the other three algorithms.

These figures verify that the proposed algorithm offers better performance over the other three algorithms.

Complexity analysis: In Section 3, the computation complexity of the proposed method for solving the Optimization Problem2 depends on M (M the number of relays), in which there are $5M$ operations to calculate P_{R_m} in the first section and $2^M - 1$ operations to calculate $SNR_{\max}$ in the second section. Therefore, the complexity of the algorithm is $O(2^M)$. The complexity of the algorithm is $O(M2^{2k_1})$ (2^{k_1} the number of quantization level) in [8], $O\left((2k_1)^M\right)$ in [9], and $O\left(M2^{2k_2}\right)$ (2^{k_2} the number of sub-carriers) in [4]. Generally, the number of relays (M) is much smaller than $2k_1, 2k_2$. By comparison, the complexity of the proposed algorithm is lower.

5. **Conclusions.** In this letter, we propose an algorithm to allocate power and relays in cognitive radio networks. The good performance of the capacity is achieved in the proposed algorithm and the proposed algorithm is of lower complexity. The proposed algorithm in this letter considers one SU and one CB; how to extend these results to several SUs or CBs will be studied in the future.

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