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Research Article

Performance Optimization for Decode and Forward Cooperative Cognitive Radio Networks

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This paper considers the problem of optimizing the data rate of the cooperative cognitive system subject to the dual constraints of the interference threshold of primary users and power budget of secondary users. In particular, under a single constraint, the rate can reach its peak easily. But under the double restrictions, the peak rate problem becomes complicated and changeable. According to different interference conditions and power supplies, four scenarios are formulated: total interference threshold and total power budget, total interference threshold and separate power budget, separate interference threshold and total power budget, and separate interference threshold and separate power budget. Each scenario needs to be further divided into many situations for discussion due to the sheer particularity. Through careful comparison and classification, we summarize and formulate each situation one by one to achieve the optimal value of the rate. Extensive simulation results demonstrate that the proposed resource allocation policy represents the best compromise between enhancing the rate of the secondary users and satisfying the interference threshold requirements of the primary users.

1. Introduction

Spectrum sharing is one of the most significant features of cognitive radio technology, saving a lot of spectrum resources. On the other hand, cooperative technology establishes a communication bridge between transceivers that are far apart. Combining the advantages of cognitive radio and cooperative technologies is one of the current hot researches. A concept of greenhouse gas emission was proposed in cooperative cognitive radio networks in [1], where total rate maximization, gas emission minimization, and relay selection problems were achieved simultaneous by lexicographic multiobjective optimization methods. At the constraints of wireless transfer power and time, an outage probability optimization problem was studied in [2] for battery free secondary users by particle swarm algorithm. Taking into account of the spatial randomly distributed nodes, the relay forwarding time was decided the relay forwarding time according to the outage optimization problem in [3]. A joint power allocation and relay selection algorithm was investigated in [4] by carrier aggregation technology subject to the outage requirement of the primary users. In the context of primary interference and imperfect channel sate information, the power of secondary transmitters was established in [5] for underlay cooperative cognitive networks. In [6], the transmit power of the beacon and harvest to transmit ratio were optimized simultaneous subject to outage constraint in cognitive relay network. A energy efficient optimization problem in [7] in cooperative cognitive networks, where the secondary user can scavenge energy from the primary user's signal. Although this energy efficient problem is noncovex, the authors in [7] converted it into a biconvex problem by alternate convex search. An exhaustive search was imposed in [8] to determine the number of hops in underlay multihop cognitive radio networks. A problem of secondary rate maximization was formulated in [9] by considering feedback quantization due to imperfect channel state information. Under the constraint of primary quality of service, the particle swarm optimization algorithm was employed in [10] to derive the relay amplification matrices and bandwidths in two-way overlay cognitive radio networks. When secondary users had to harvest energy from their neighbor primary users and obey the regulation of outage probability constraint, an outage probability of a multihop relay-assisted underlay cognitive radio network was derived in [11]. An outage probability and an sum rate were studied in [12] when nonorthogonal multiple access was used in a spectrum sharing network. A comparison between nonorthogonal multiple access and time division multiple access for energy cooperation was conducted in [13] when a primary user harvests energy from its cognitive user. In a cognitive sensor network, the number of sensors was minimized subject to both detection probability and false alarm probability constraints, leading to a prolongation of network lifetime [14].

The above references solved an optimization problem under certain constraints. For example, the total power and total interference constraints were considered in [1, 4], while the power and time slot constraints were absorbed in [2]. Different constraints consider different actual scenarios, thereby defining different optimization problems. When a transmitter and a relay station are jointly scheduled by a central processor, then a total power constraint ensures a higher rate or throughput, because it can always allocate the optimal power between the transmitter and the relay station in a fluctuating channel. If a transmitter and a relay station are charged by an electric grid, then a total power constraint guarantees that the total power consumed by the network is limited [15]. But the transmitter and the relay station are independent entities, subject to different power supplies instead of joint power scheduling. Although the optimization problem under the total power constraint often provides an upper bound to the same problem under the separate power constraints, the latter takes into account the respective power budgets of the transmitter and the relay station when joint scheduling is not feasible. In short, different constraints reflect different actual scenarios. In previous works, only one or a few of them were studied, but we will explore all four scenarios in depth. On the other hand, most articles on the resource allocation of relay-assisted cognitive radio networks used the Lagrange multiplier method to obtain the optimal value of the objective function. The power distribution obtained by this method is often related to a dual variable, which cannot be known in advance through a closed formula, and its approximate value has to be obtained through multiple iterations. This iteration often consumes a lot of running time because the secondary user is limited by the double constraints of its own power peak and interference threshold. Our paper deeply analyzes the characteristics of cooperative cognitive radio networks, discusses different situations according to different constraints, and obtains the closed-form solution of optimal power allocation and peak rate. These optimal values avoid the instability of calculation results caused by multiple iterations.

The motivation of this paper is the emergence of stringent interference thresholds in cognitive radio networks over paid or licensed spectrum bands. Unlike [16–18], this paper considers the interaction between interference threshold constraint of the primary network and power constraint of the secondary network. On the surface, these two constraints are very simple, but the optimization problem constituted by these two constraints is extremely complicated. The contribution of this paper lies in the following aspects. (1) We optimize the data rate of the secondary network while preserving that the primary user's interference does not exceed a predetermined threshold level. Specifically, we formulate a rate minimum maximization problem. (2) In order to fully account for the impact of the two factors on the rate, without missing any possibilities, we have clarified four distinct scenarios: total interference threshold and total power budget, total interference threshold and separate power budget, separate interference threshold and total power budget, and separate interference threshold and separate power budget. (3) Although the feasible region of the considered optimization problem is the intersection of the two constraints, unfortunately, the optimal value of the problem is not the intersection of the maximum under the two separate constraints. In order not to miss any possible peaks and in the spirit of power saving and green energy, each scenario has to be further classified and discussed based on the characteristics of the two constraints.

2. System Model

Consider a primary network that shares a spectrum of bandwidth with the surrounding secondary network. The primary network comprises a primary source transmitter PS and a primary destination receiver PD. The secondary network consists of a secondary source SS, a secondary relay station SR, and a secondary destination SD. Assume that h_{sr}, h_{sd}, and h_{rd} denote the channel coefficients between source node SS and relay station SR, source node SS to destination node SD, and relay station SR to destination node SD, respectively. The interference channel coefficients caused by the secondary users SS and SR to the primary user PD are denoted as h_{sp} and h_{rp}, respectively. The transmission powers of SS, SR, and PS are denoted as p_s, p_r, and $p_{p,0}$, respectively. According to the rule of decode and forward (DF) protocol, the throughput of the secondary network is given by [19, 20]

$$R = \frac{1}{2}\log_2[1 + \max[\min(p_s a, p_s c + p_r b), p_s c]], \tag{1}$$

where

$$a = \frac{|h_{sr}|^2}{\sum_{i=0}^{I} p_{p,i}|h_{pr,i}|^2 + N_0},$$
$$b = \frac{|h_{rd}|^2}{\sum_{i=0}^{I} p_{p,i}|h_{pd,i}|^2 + N_0}, \tag{2}$$
$$c = \frac{|h_{sd}|^2}{\sum_{i=0}^{I} p_{p,i}|h_{pd,i}|^2 + N_0}.$$

Here, we assume that the relay station SR and the destination node SD suffer from distinct cochannel interferences. $p_{p,i}$ is the power of the cochannel interfering signal, and $h_{pr,i}$ and $h_{pd,i}$ are the channel coefficients from the interfering signals to the relay station SR and the destination SD, respectively ($i = 0$ corresponds to the primary user PS). N_0 is the noise variance.

3. Resource Allocation

In an actual environment, each transmitter has its own power constraints, and no transmitter always has unlimited energy. Power constraint is one of the most common constraints and appears in many optimization problems in communication fields. It is obvious that each transmitter in the transmitting behavior will be subject to a certain form of power constraint. Different constraints correspond to different scenarios. This paper is a comprehensive analysis of all possible scenarios, rather than only focusing on one or several scenarios as in previous work.

3.1. Total Power Budget and Separate Interference Threshold. In a traditional cooperative communication network, the data rate is only subject to a single power constraint, and the maximum rate in this scenario is easy to calculate. However, in the cooperative cognitive radio network, the secondary network is subject to double constraints. In this context, the problem of rate maximization problem becomes more complicated.

When the rate of secondary network is constrained by both the power budget and the interference threshold, this problem is mathematically expressed as

$$\begin{aligned} &\max_{\{p_s,p_r\}} \max\left[p_s c, \min\left(p_s a, p_s c + p_r b\right)\right], \\ &\quad \text{s.t.}\, p_s + p_r \le P_T, \\ &\quad p_s d \le Q_1, \\ &\quad p_r g \le Q_2, \end{aligned} \tag{3}$$

where $d = |h_{sp}|^2/N_0$, $g = |h_{rp}|^2/N_0$, P_T is the power budget of the secondary network, and Q_1 and Q_2 are the maximum tolerable interference thresholds of the primary network in the first and second phases, respectively, beyond which the primary network will seriously complain about the behavior of the secondary network. On the surface, this problem seems to be a very simple minimum maximization problem, but after careful observation and analysis, it actually turns out not to be the case. The rate of the secondary network is closely related to the channel gain of each link.

Towards the rate optimization problem, seven potential cases arise.

(1) When the following conditions are simultaneously satisfied

$$\begin{aligned} &\min(a,b) \ge c, \\ &\frac{bd}{a+b-c} \le \frac{Q_1}{P_T}, \\ &\frac{(a-c)g}{a+b-c} \le \frac{Q_2}{P_T}, \end{aligned} \tag{4}$$

then the optimal power allocation is given by

$$\begin{aligned} p_s &= \frac{bP_T}{a+b-c}, \\ p_r &= \frac{(a-c)P_T}{a+b-c} \end{aligned} \tag{5}$$

At this time, the data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left(1 + \frac{abP_T}{a+b-c}\right). \tag{6}$$

This situation is equivalent to that the primary user can tolerate enough interference, and relay assistance is more beneficial than direct transmission.

(2) When the following conditions are simultaneously satisfied

$$\begin{aligned} &\min(a,b) > c, \\ &\frac{bd}{a+b-c} > \frac{Q_1}{P_T}, \\ &\frac{(a-c)g}{a+b-c} < \frac{Q_2}{P_T}, \end{aligned} \tag{7}$$

then the optimal power allocation is given by

$$\begin{aligned} p_s &= \frac{Q_1}{d}, \\ p_r &= \frac{Q_1(a-c)}{bd} \end{aligned} \tag{8}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left(1 + \frac{Q_1 a}{d}\right). \tag{9}$$

This situation shows that the primary user cannot tolerate the interference from the source node SS but can accept the interference from the relay station SR, so the power depends on the interference threshold.

(3) When the following conditions are simultaneously satisfied

$$\begin{aligned} &\min(a,b) > c, \\ &\frac{bd}{a+b-c} > \frac{Q_1}{P_T}, \\ &\frac{(a-c)g}{a+b-c} > \frac{Q_2}{P_T}, \end{aligned} \tag{10}$$

then the optimal power allocation is given by

$$p_s = \frac{Q_1}{d},\quad p_r = \min\left[\frac{Q_1(a-c)}{bd}, \frac{Q_2}{g}\right] \tag{11}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \frac{Q_1 c}{d} + \min\left(\frac{Q_1(a-c)}{bd}, \frac{Q_2}{g}\right)b\right]. \tag{12}$$

This situation shows that the rate of the secondary network depends on the decoding capability of the destination node.

(4) When the following conditions are simultaneously satisfied

$$\min(a,b) > c,\quad \frac{bd}{a+b-c} < \frac{Q_1}{P_T},\quad \frac{(a-c)g}{a+b-c} > \frac{Q_2}{P_T}, \tag{13}$$

then the optimal power allocation is given by

$$p_s = \min\left[\frac{Q_1}{d}, P_T - \frac{Q_2}{g}\right],\quad p_r = \frac{Q_2}{g} \tag{14}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \min\left(\frac{Q_1}{d}, P_T - \frac{Q_2}{g}\right)c + \frac{Q_2 b}{g}\right]. \tag{15}$$

This situation also shows that the rate of the secondary network depends on the decoding capability of the destination node.

(5) When the following conditions are simultaneously satisfied

$$a > c > b,\quad d \le \frac{Q_1}{P_T}, \tag{16}$$

then the optimal power allocation is given by

$$p_s = P_T,\quad p_r = 0 \tag{17}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2(1 + P_T c). \tag{18}$$

This situation is equivalent to traditional peer to peer communications.

(6) When the following conditions are simultaneously satisfied

$$a > c > b,\quad d > \frac{Q_1}{P_T}, \tag{19}$$

then the optimal power allocation is given by

$$p_s = \frac{Q_1}{d},\quad p_r = \min\left[\frac{Q_1(a-c)}{bd}, \frac{Q_2}{g}, P_T - \frac{Q_1}{d}\right] \tag{20}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \frac{Q_1 c}{d} + \min\left(\frac{Q_1(a-c)}{bd}, \frac{Q_2}{g}, P_T - \frac{Q_1}{d}\right)b\right]. \tag{21}$$

In traditional cooperative communications, when $a > c > b$, the source node should choose the direct link for higher performance gain, but in cognitive radio, this is not the case. It can be seen from the above formula that the source node still needs to rely on relay assistance.

(7) When $c > a$ is satisfied, then the optimal power allocation is given by

$$p_s = \min\left(\frac{Q_1}{d}, P_T\right),\quad p_r = 0 \tag{22}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \min\left(\frac{Q_1}{d}, P_T\right)c\right]. \tag{23}$$

As can be seen from the above example, a seemingly simple problem needs to be classified into seven situations for discussion and analysis, which indeed illustrates the complexity and particularity of cooperative cognitive radio networks.

3.2. Separate Power Budgets and Separate Interference Thresholds. When the separate power budgets and separate interference thresholds are imposed on the cooperative cognitive radio network, this rate optimization problem is written as

$$\max_{\{p_s,p_r\}} \max\left[p_s c, \min\left(p_s a, p_s c + p_r b\right)\right], \quad \text{s.t.} p_s \le P_S, \quad p_r \le P_R, \quad p_s d \le Q_1, \quad p_r g \le Q_2, \tag{24}$$

where P_S and P_R are available power budgets on the SS and SR. Similar to the formality in the previous section, five potential situations arise.

(1) When $a \ge c$ is satisfied, then the optimal power allocation is given by

$$p_s = \min\left(P_S, \frac{Q_1}{d}\right), \quad p_r = \min\left[\min\left(P_S, \frac{Q_1}{d}\right)\frac{a-c}{b}, P_R, \frac{Q_2}{g}\right] \tag{25}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \min\left(P_S, \frac{Q_1}{d}\right)c + \min\left(\min\left(P_S, \frac{Q_1}{d}\right)\frac{a-c}{b}, P_R, \frac{Q_2}{g}\right)b\right]. \tag{26}$$

(2) When $a < c$ is satisfied, then the optimal power allocation is given by

$$p_s = \min\left(P_S, \frac{Q_1}{d}\right), \quad p_r = 0 \tag{27}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \min\left(P_S, \frac{Q_1}{d}\right)c\right]. \tag{28}$$

3.3. Separate Power Budgets and Total Interference Threshold. In this subsection, we shift our attention to separate power budgets and total interference threshold. This problem is given by

$$\max_{\{p_s,p_r\}} \max\left[p_s c, \min\left(p_s a, p_s c + p_r b\right)\right], \quad \text{s.t.} p_s \le P_S, \quad p_r \le P_R, \quad p_s d + p_r g \le Q_T, \tag{29}$$

where Q_T is the total interference threshold. Following a similar procedures, seven potential situations are discussed.

(1) When the following conditions are simultaneously satisfied

$$a \ge c, \quad bd \ge cg, \quad \frac{b}{ag + bd - cg} \le \frac{P_S}{Q_T}, \quad \frac{(a-c)}{ag + bd - cg} \le \frac{P_R}{Q_T}, \tag{30}$$

then the optimal power allocation is given by

$$p_s = \frac{bQ_T}{ag + bd - cg}, \quad p_r = \frac{(a-c)Q_T}{ag + bd - cg} \tag{31}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \frac{abQ_T}{ag + bd - cg}\right]. \tag{32}$$

(2) When the following conditions are simultaneously satisfied

$$a > c, \quad bd > cg, \quad \frac{b}{ag + bd - cg} > \frac{P_S}{Q_T}, \quad \frac{(a-c)}{ag + bd - cg} < \frac{P_R}{Q_T}, \tag{33}$$

then the optimal power allocation is given by

$$p_s = P_S, \quad p_r = \frac{P_S(a-c)}{b} \tag{34}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2(1 + P_S a). \tag{35}$$

(3) When the following conditions are simultaneously satisfied

$$a > c,\quad bd > cg,\quad \frac{b}{ag+bd-cg} > \frac{P_S}{Q_T},\quad \frac{(a-c)}{ag+bd-cg} > \frac{P_R}{Q_T}, \tag{36}$$

then the optimal power allocation is given by

$$p_s = P_S,\quad p_r = \min\left[\frac{P_S(a-c)}{b}, P_R\right] \tag{37}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + P_S c + \min\left(\frac{P_S(a-c)}{b}, P_R\right)b\right]. \tag{38}$$

(4) When the following conditions are simultaneously satisfied

$$a > c,\quad bd > cg,\quad \frac{b}{ag+bd-cg} < \frac{P_S}{Q_T},\quad \frac{(a-c)}{ag+bd-cg} > \frac{P_R}{Q_T}, \tag{39}$$

then the optimal power allocation is given by

$$p_s = \min\left[P_S, \frac{Q_T - P_R g}{d}\right],\quad p_r = P_R \tag{40}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \min\left(P_S, \frac{Q_T - P_R g}{d}\right)c + P_R b\right]. \tag{41}$$

(5) When the following conditions are simultaneously satisfied

$$a > c > \frac{bd}{g},\quad d \geq \frac{Q_T}{P_S}, \tag{42}$$

then the optimal power allocation is given by

$$p_s = \frac{Q_T}{d},\quad p_r = 0 \tag{43}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left(1 + \frac{Q_T c}{d}\right). \tag{44}$$

(6) When the following conditions are simultaneously satisfied

$$a > c > \frac{bd}{g},\quad d < \frac{Q_T}{P_S}, \tag{45}$$

then the optimal power allocation is given by

$$p_s = P_S,\quad p_r = \min\left[\frac{P_S(a-c)}{b}, P_R, \frac{Q_T - P_S d}{g}\right] \tag{46}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + P_S c + \min\left(\frac{P_S(a-c)}{b}, P_R, \frac{Q_T - P_S d}{g}\right)b\right]. \tag{47}$$

(7) When $c > a$ is satisfied, then the optimal power allocation is given by

$$p_s = \min\left(P_S, \frac{Q_T}{d}\right),\quad p_r = 0 \tag{48}$$

The data rate of the secondary network is given by

$$R = \frac{1}{2}\log_2\left[1 + \min\left(P_S, \frac{Q_T}{d}\right)c\right]. \tag{49}$$

3.4. Total Power Budget and Total Interference Threshold. When the cooperative cognitive radio is subject to total power budget and total interference threshold, the rate optimization is written by

$$\max_{\{p_s, p_r\}} \max\left[p_s c, \min\left(p_s a, p_s c + p_r b\right)\right]. \tag{50}$$

$$\text{s.t.} p_s + p_r \leq P_T, \quad (51)$$

$$p_s d + p_r g \leq Q_T. \quad (52)$$

In pursuance of solving equation (50), we delve into the relationship between these two constrains.

(1) When the following conditions are simultaneously satisfied

$$\begin{aligned} &\min (a, b) \geq c, \\ &\frac{bd + (a - c)g}{a + b - c} \leq \frac{Q_T}{P_T}, \end{aligned} \quad (53)$$

then the optimal power allocation is given by

$$\begin{aligned} p_s &= \frac{bP_T}{a + b - c}, \\ p_r &= \frac{(a - c)P_T}{a + b - c} \end{aligned} \quad (54)$$

As a double check, construct an inequality on p_s and p_r given by

$$\frac{bQ_T}{ag + bd - cg} + \frac{(a - c)Q_T}{ag + bd - cg} = \frac{[b + (a - c)]Q_T}{ag + bd - cg} \geq P_T. \quad (55)$$

The inequality shows that the power allocation is within the feasible region of the interference threshold constraint. The data rate of the secondary network is given by

$$R = \frac{1}{2} \log_2 \left(1 + \frac{abP_T}{a + b - c} \right). \quad (56)$$

(2) When the following conditions are simultaneously satisfied

$$\begin{aligned} &a > c, \\ &bd > cg, \\ &\frac{a + b - c}{ag + bd - cg} \leq \frac{P_T}{Q_T}, \end{aligned} \quad (57)$$

then the optimal power allocation is given by

$$\begin{aligned} p_s &= \frac{bQ_T}{ag + bd - cg}, \\ p_r &= \frac{(a - c)Q_T}{ag + bd - cg} \end{aligned} \quad (58)$$

The data rate of the secondary network is given by

$$R = \frac{1}{2} \log_2 \left(1 + \frac{abQ_T}{ag + bd - cg} \right). \quad (59)$$

(3) When the following conditions are simultaneously satisfied

$$\begin{aligned} &c > a or c > b, \\ &d \leq \frac{Q_T}{P_T}, \end{aligned} \quad (60)$$

then the optimal power allocation is given by

$$\begin{aligned} p_s &= P_T, \\ p_r &= 0 \end{aligned} \quad (61)$$

The data rate of the secondary network is given by

$$R = \frac{1}{2} \log_2 (1 + P_T c). \quad (62)$$

(4) When the following conditions are simultaneously satisfied

$$\begin{aligned} &c > a or cg > bd, \\ &d \geq \frac{Q_T}{P_T}, \end{aligned} \quad (63)$$

then the optimal power allocation is given by

$$\begin{aligned} p_s &= \frac{Q_T}{d}, \\ p_r &= 0 \end{aligned} \quad (64)$$

The data rate of the secondary network is given by

$$R = \frac{1}{2} \log_2 \left(1 + \frac{Q_T c}{d} \right). \quad (65)$$

(5) When the following conditions are simultaneously satisfied

$$
\begin{aligned}
&a > c > b,\\
&bd > cg,\\
&\frac{bd + (a - c)g}{a + b - c} < \frac{Q_T}{P_T},\\
&d > \frac{Q_T}{P_T},
\end{aligned} \tag{66}
$$

or

$$
\begin{aligned}
&\min(a, b) > c,\\
&cg > bd,\\
&\frac{bd + (a - c)g}{a + b - c} > \frac{Q_T}{P_T},\\
&d < \frac{Q_T}{P_T},
\end{aligned} \tag{67}
$$

then the optimal power allocation is given by

$$
\begin{aligned}
p_s &= \frac{Q_T - P_T g}{d - g},\\
p_r &= \frac{P_T d - Q_T}{d - g}
\end{aligned} \tag{68}
$$

The data rate of the secondary network is given by

$$
R = \frac{1}{2}\log_2\left(1 + \frac{P_T(bd - cg) + Q_T(c - b)}{d - g}\right). \tag{69}
$$

So far we have completed the analysis tasks of all four scenarios. This problem looks simple on the surface, but in fact, it has inherent complexity. The secondary user can seemingly obtain the maximum rate with the maximum allowable transmission power. But in fact, this will often cause energy waste, because the data rate of decode and forward cooperative system is the result of the coupling between direct transmission and relaying links. Blindly increasing power sometimes does not improve the rate. The difficulty of this optimization problem is classified discussion. There is no uniform formula that can cover all cases. On the other hand, some literature gives an iterative power allocation, which is often obtained according to the Lagrangian multiplier method. But the disadvantage of this method is that the dual variable itself cannot be determined in advance. In order to obtain the final power allocation, it is necessary to iterate continuously to reach the termination condition in terms of the rule of subgradient method. This undoubtedly slows down the running speed and increases the running time. Although this iterative method claims to eventually converge to the optimal value, it is still not as straightforward as our formulas, whose final results can be obtained by substituting the corresponding parameters.

3.5. A Comparison between Different Constraints. If all the scenes are compared in pairs, then a total of six comparisons are required, and the classification discussion of each scene aggravates the complexity of the comparison. As an example, we compare the data rate of direct transmission. When $c > a$, the data rates of these four scenes are, respectively, given by $R_1 = 1/2\log_2[1 + \min(Q_1/d, P_T)c]$ in total power budget and separate interference threshold; $R_2 = 1/2\log_2[1 + \min(P_S, Q_1/d)c]$ in separate power budgets and separate interference thresholds; $R_3 = 1/2\log_2[1 + \min(P_S, Q_T/d)c]$ in separate power budgets and total interference threshold; and $R_4 = 1/2\log_2[1 + \min(Q_T/d, P_T)c]$ in total power budget and total interference threshold. It is not difficult to find that the magnitude relationship among these rates is given by $R_4 \geq R_1$ and $R_3 \geq R_2$. Generally, the rate optimization problem under the total constraint is an upper bound of the same problem under the separation constraints because the source and the relay station can adjust the powers adaptively according to the fluctuating channel quality. This conclusion holds true for other cases as well.

4. Simulation Results

The secondary user performance in different scenarios is plotted in Figure 1, where the average signal to noise ratio (SNR) is defined as P_T/N_0. We always keep $P_S + P_R = P_T$ and $Q_1 + Q_2 = Q_T$ for fair comparison in distinct constraint conditions. It can be seen from Figure 1 that "total power and total interference" scenario reaches the highest rate because it can adaptively allocate power to the source node and the relay station. For example, at the average SNR of 14 dB, the rate of "total power and total interference" scenario is 18.88% higher than that of "total power and separate interference" scenario and 10.46% higher than that of "separate power and total interference" scenario. The rate gap caused by adaptive power allocation can be more clearly observed among the scenarios "total interference" and "separate interference" because the separate constraint faces more stringent condition.

In Figure 2, we draw the rate of secondary users subject to different interference levels which strictly limit the transmission behavior of the secondary users. As the tolerance of primary users increases, the rate of secondary users also increases. This indicates that the quality of service required by the primary user is not high, and the secondary user can take the opportunity to transmit their own data. When the interference level exceeds 15 dB, the rate reaches saturation because the power budget comes into play. This is the dual effect of power budget and interference level. This effect can also be seen from two scenarios. From Figure 2, at low interference levels, "separate power and total interference" is better than "total power and separate interference," but when the interference level exceeds about 10 dB, "total power and separate interference" overtakes "separate power and total interference" with a huge advantage. The reason is that at first, the power played a leading role in the rate optimization problem formulation, and then, the interference level dominates the rate.

Next, we turn our attention to how much power can be saved in the proposed optimization algorithm compared with the exhaustive search method. In the exhaustive search, the accurate transmission power cannot be predicted in advance, so the source node and the relay station have to turn on their transmitters to emit information with full

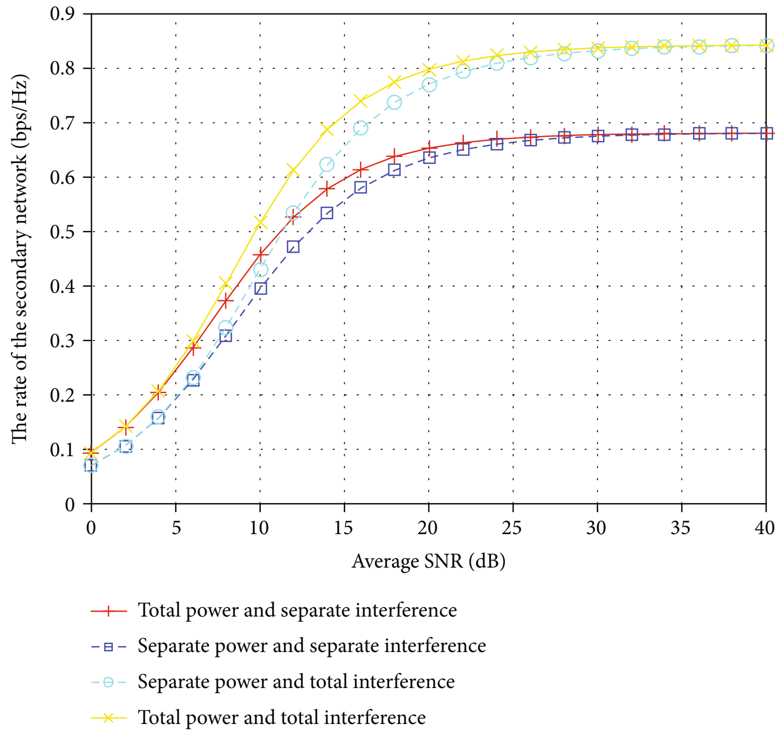

FIGURE 1: Comparison of the rate of the secondary network under different SNR values, where $Q_T = 10\,\text{dB}$

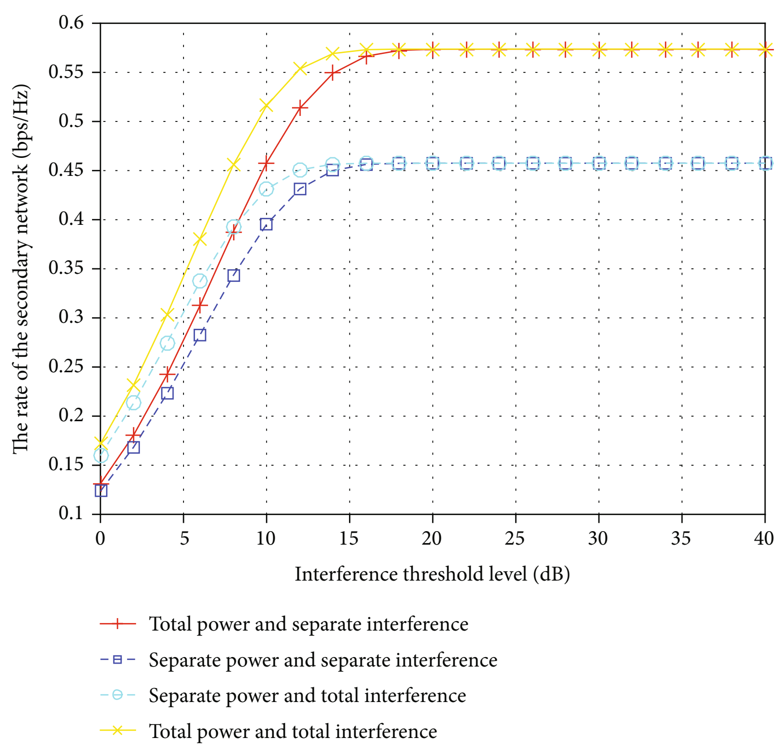

FIGURE 2: Comparison of the rate of the secondary network under different interference level values, where average SNR is 10 dB.

power in the feasible domain. In Figures 3 and 4, the ordinate represents the percentage of power saved by the proposed algorithm over exhaustive search in different scenarios. Except for the "total power and total interference," other scenarios can save power in varying degrees, thereby reducing the pressure on the primary user. This shows that the relay station can actually use less power to achieve the same effect of full power transmission.

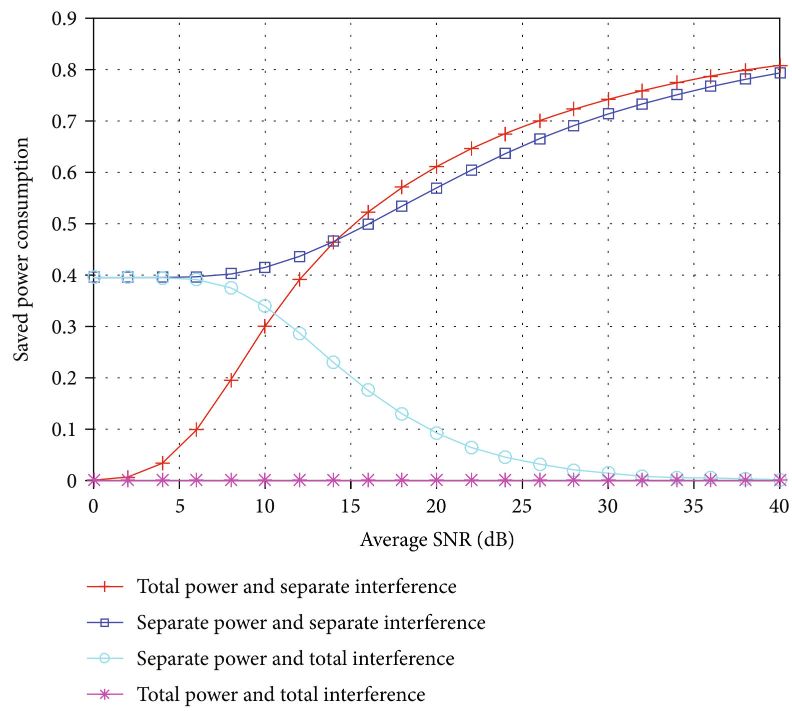

FIGURE 3: Comparison of saved power consumption of the secondary network under different SNR values.

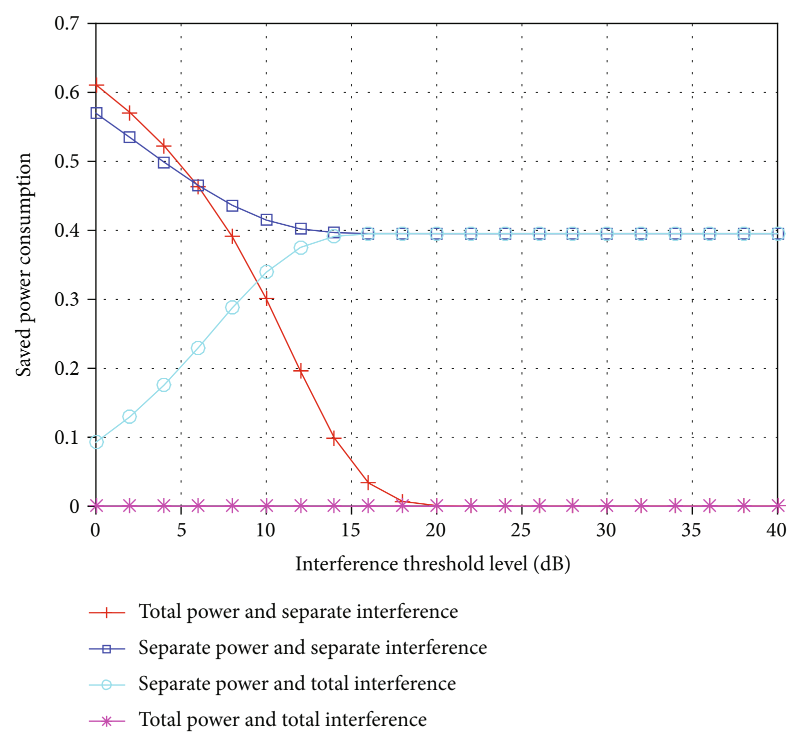

FIGURE 4: Comparison of saved power consumption of the secondary network under different interference level values.

5. Conclusion

This paper studies the rate optimization problem in DF cooperative cognitive networks subject to the joint constraints of power budget and interference threshold level. A seemingly simple problem is divided into many cases for discussion. This just illustrates the complexity of cognitive radio technology. The proposed algorithm guarantees the same rate of exhaustive search, saves power consumption, and reduces the interference to the primary network.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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