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Cooperative Spectrum Sharing in Cognitive Radio Networks with Proactive Primary System

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Abstract—In this paper we investigate the cooperative spectrum sharing in cognitive radio networks with proactive primary system. In our scheme, Primary User (PU) is rewarded for sharing its licensed spectrum with Secondary Users (SUs) by charging their total throughput directly. The PU performs as the leader and chooses its interference-cap and transmit-power jointly to maximize its reward from spectrum-sharing with SUs. Meanwhile, the SUs perform as the followers and adapt their transmit-power according to the PU's decisions to maximize their net-utilities. We first explore the intrinsic property of this PU-SUs sharing problem and then utilize an efficient Simulated Annealing algorithm for the optimal solution. Our numerical results show that both the PU and the SUs gain from this spectrum-sharing cooperation and thus achieve a win-win situation. In addition, as its own transmission requirement increases, the PU limits the sharing of its channels gradually to maintain its own target quality of service. Correspondingly, both the net-profit of PU and the net-utility value of SUs decrease¹.

I. INTRODUCTION

The current congestion in radio spectrum is mainly due to conventional fixed spectrum allocation policies. To enable an efficient utilization of the licensed radio spectrum, Cognitive Radio (CR) appears as a promising technology, which allows the unlicensed Secondary Users (SUs) to share the licensed spectrum of Primary Users (PUs) opportunistically and flexibly. Preventing the SUs from causing harmful interference to the PUs' operations is one of the most important issues for CR, to which, radio resource allocations (e.g., the bandwidth and transmit-power) between the PUs and SUs play an important role. To deal with the problem, many studies have been carried out. In [1]-[3], the authors consider to utilize the power allocation, spectrum allocation, and sensing assignment etc., to improve the efficiency of the spectrum usage in CR networks. In these works, the PUs are assumed to be passive and unknown of the existence of SUs. In comparison, the PUs could be proactive and intentionally share its spectrum with SUs for additional reward [4]-[7]. In [4], the authors propose a framework of dynamic spectrum leasing, where the PU can lease its spectrum to the SUs to obtain certain compensation

from SUs. Specifically, the PU allows the SUs to access the leased spectrum by setting the limit on the tolerable interference. In [6], the authors considered the joint optimization of the pricing and transmit-power for CR networks where the PU charges the SUs according to the introduced interference. Further based on this interference-based charging, the authors investigate the optimal matching between PUs and SUs to maximize the network-welfare [7]. In this paper, motivated by these previous works, we propose a model of the cooperative spectrum sharing in CR networks with proactive PUs. In our model, the PU adjusts its transmit-power and interference-cap to provide opportunities for SUs' transmission while guaranteeing its own QoS. The PU's benefit from sharing its licensed spectrum is measured by the difference between charging the SUs and incurring cost due to its additional power allocation to combat the interference from SUs. The SUs, based on the PU's decisions, jointly allocate their transmit-power and bandwidth to maximize their net-utility.

Our key contributions in this paper can be summarized as follows. First, we identify the intrinsic property of the cooperative spectrum sharing between the PU and SUs, namely, it is always beneficial for SUs to fully exploit the interference-cap set by the PU. Based on this important property, the PU's net-profit optimization turns out to be a nonconvex optimization problem. Second, we propose an efficient algorithm to solve the PU's nonconvex optimization problem. Specifically, this algorithm has a layered structure, i.e., in the bottom layer, we obtain the optimal PU's power allocation in closed-form from convex optimization, and in the top-layer, we use the Simulated Annealing (SA) algorithm to determine the optimal PU's interference-cap efficiently.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model for Cooperative Spectrum-sharing

We consider a system that consists of a primary system and a CR network. As shown in Fig. 1, the primary system includes a set of BSs, denoted by $\{1, 2, \dots, K\}$, each with a licensed channel to access. The bandwidth associated with BS k (or channel k) is denoted by B^k . The PU has the freedom to allocate its traffic rate over the set of BSs, e.g., multi-homing. In addition, the PU also has the right to share its under-utilized

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channels with SUs in the CR network. Specifically, the SUs are allowed to access the set of PU-BSs (i.e., the corresponding set of channels) for their traffic delivery. As a compensation, the SUs have to pay the PU for their traffic delivery.

Fig. 1. The system model for cooperative spectrum-sharing

Let the set of SUs around BS k be denoted by $S_k = \{1, 2, \dots, S_k\}$. The channel power gain between SU s and BS k is denoted by g_s^k , and the channel gain between PU and BS k is denoted by g_0^k . We assume that all these channel power gains remain constant during the period of interest. In the cooperative spectrum-sharing, the PU allows the SUs to deliver their traffic via the same BSs (channels). Specifically, the PU sets its interference-cap Q^k to represent its tolerable interference level from the SUs. Due to the interference introduced by SUs, the PU has to increase its transmit-power p_0^k to combat the SUs' interference such that it ensures the QoS requirement, e.g., its total traffic rate over all BSs. Different from the previous works [4], [6], [7] which focused on charging the interference, our work proposes a new model in which the PU charges the SUs based on their achievable transmission rate. This is more practical, since the SUs deliver their traffic over the PU's BSs, and thus PU can measure the SUs traffic rates exactly instead of the interference. The PU's profit W is given by:

$$W = \omega \sum_k \sum_{s \in S_k} U_s^k, \quad (1)$$

where ω is the normalized price charged by PU, ranging from 0 to 1. Meanwhile, U_s^k denotes the utility SU s obtains by accessing the channel k . We assume that the SU s 's utility is represented by its achievable traffic rate as follows

$$U_s^k = b_s^k \log_2 \left(1 + \frac{g_s^k p_s^k}{b_s^k (n_0 + g_0^k p_0^k / B^k)} \right). \quad (2)$$

The transmit-power for SU s over channel k is denoted by p_s^k and the allocated bandwidth for SU s over channel k is denoted by b_s^k . n_0 is the power spectral density of the background additive Gaussian noise.

In CR networks, the SUs, as the followers, jointly optimize the bandwidth and transmit-power according to the PU's decision. Due to the charge of PU, the net-utility of secondary network is $(1 - \omega) \sum_k \sum_{s \in S_k} U_s^k$. Also, the realistic interference of SUs to the PU over channel k is denoted by I^k , and it

cannot exceed the interference threshold as follows²:

$$I^k = \sum_{s \in S_k} g_s^k p_s^k \leq Q^k \quad (3)$$

Due to the interference from the SUs, the PU has to increase the transmit-power to guarantee the successful data transmission over each base station. The cost for this additional power allocation is α per unit. Thus, the PU's total extra payment for the additional transmit-power is $\alpha(\sum_k p_0^k - \bar{p}_0)$, where $\bar{p}_0$ denotes the PU's initial transmit-power to achieve its target rate without allowing any interference from the SUs. As mentioned in [8], to guarantee the successful data transmission, the data rate over each channel has to meet

$$R_0^{k, \min} \leq B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + I^k} \right) \leq R_0^{k, \max}. \quad (4)$$

Besides, the PU's total rate over all the channels has to meet

$$\sum_k B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + I^k} \right) \geq R_0^{req}. \quad (5)$$

where $R_0^{k, \min}$ (or $R_0^{k, \max}$) is the minimum (or the maximum) data rate to make the transmission successful. Constraints (4) and (5) represent PU's QoS requirement.

B. Problem Formulation

To maximize its net-profit, the PU jointly allocates its transmit-power $\{p_0^k\}$ and the interference-cap $\{Q^k\}$ over channels to cooperate with SUs. Knowing the PU's decisions, the SUs determine their bandwidth allocation and the transmit-power to maximize their net-utilities. We illustrate these two aspects as follows.

i) The PU's net-profit maximization problem: The objective of PU is to maximize its net-profit from proactive spectrum-sharing. Thus its optimization problem is as follows:

$$(P1) : \max_{\{Q^k\}, \{p_0^k\}} W - \alpha \left(\sum_k p_0^k - \bar{p}_0 \right) \quad (6)$$

subject to :

$$R_0^{k, \min} \leq B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + \sum_{s \in S_k} g_s^k p_s^k} \right) \leq R_0^{k, \max} \quad (7)$$

$$\sum_k B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + \sum_{s \in S_k} g_s^k p_s^k} \right) \geq R_0^{req}. \quad (8)$$

Notice that the PU's profit W is given by eq. (1).

ii) The SUs' net-utility maximization problem: Knowing the PU's decisions, the SUs jointly determine their bandwidth allocations $\{b_s^k\}$ and transmit-power $\{p_s^k\}$ over channels to maximize its net-utility $(1 - \omega) \sum_k \sum_{s \in S_k} U_s^k$. Actually, this is equivalent to the following optimization problem,

$$(P2) : \max_{\{b_s^k\}, \{p_s^k\}} \sum_k \sum_{s \in S_k} R_s^k \quad (9)$$

²Besides the interference threshold, other more advanced performance metric could also be incorporated in our formulation, e.g., the received SNR as used in [5]. This is one of our future works to extend this paper.

$$\text{subject to: } \sum_{s \in S_k} b_s^k \leq B^k, \forall k \quad (10)$$

$$p_s^k \leq P_s^{\max}, \forall s, \forall k \quad (11)$$

$$\sum_{s \in S_k} g_s^k p_s^k \leq Q^k, \forall k \quad (12)$$

Constraint (10) represents that on each channel k , the total share of bandwidth among all SUs cannot exceed the bandwidth B^k . Constraint (11) shows that on each channel k , the SU's transmit-power is subject to an upper-bound $P_s^{\max}$. Also constraint (12) shows that on each channel k , the total interference from all SUs cannot exceed the PU's interference-cap.

III. ANALYSIS AND OPTIMAL ALGORITHM

Based on the leader-follower relationship between the PU and the SUs, we adopt the backward induction to solve the above PU's problem (P1) and the SUs' problem (P2). Specifically, we first solve the SUs' problem (P2) based on the fixed PUs' decisions. After that, using the SUs' *best response*, we solve the PU's problem (P1) and obtain the optimal PU-SUs cooperation. The details are illustrated as follows.

A. Analysis of SUs' Optimization Problem

Suppose that the PU's decisions are fixed. We analyze the SUs' optimization problem (P2) as follows. Specifically, for each feasible SUs' transmit-power $\{p_s^k\}$, the SUs' optimal bandwidth allocation should meet:

$$(P3): \max_{\{b_s^k\}} \sum_k \sum_{s \in S_k} b_s^k \log_2 \left(1 + \frac{g_s^k p_s^k}{b_s^k (n_0 + g_0^k p_0^k / B^k)} \right) \quad (13)$$

$$\text{subject to: } \sum_{s \in S_k} b_s^k \leq B^k, \forall k \quad (14)$$

The above problem is convex since the objective function is concave in $\{b_s^k\}$ and the constraint is linear. By relaxing the constraint (14) into the objective function with the Lagrangian multiplier $\{\lambda^k\}$, we can obtain the Lagrangian function $L_1(b_s^k, \lambda^k)$,

$$\begin{aligned} L_1(b_s^k, \lambda^k) = & \sum_k \sum_{s \in S_k} b_s^k \log_2 \left(1 + \frac{g_s^k p_s^k}{b_s^k (n_0 + g_0^k p_0^k / B^k)} \right) \\ & + \sum_k \lambda^k (B^k - \sum_{s \in S_k} b_s^k). \end{aligned} \quad (15)$$

According to the KKT conditions, we can obtain the optimal bandwidth allocation by setting $\frac{dL_1}{db_s^k} = 0$ (suppose that $b_s^{k*} > 0$), i.e.

$$\begin{aligned} & \log_2 \left(1 + \frac{g_s^k p_s^k}{b_s^{k*} (n_0 + g_0^k p_0^k / B^k)} \right) - \\ & \frac{1}{\ln 2} \frac{g_s^k p_s^k}{g_s^k p_s^k + b_s^{k*} (n_0 + g_0^k p_0^k / B^k)} - \lambda^k = 0. \end{aligned} \quad (16)$$

From the above, we can obtain that

$$f\left(\frac{g_s^k p_s^k}{b_s^{k*} (n_0 + g_0^k p_0^k / B^k)}\right) = \lambda^k, \forall s \in S_k, \quad (17)$$

where function $f(x) = \log_2(1+x) - \frac{1}{\ln 2} \left(\frac{x}{1+x} \right)$ is a monotonically increasing function in x . In other words, for two different SUs denoted by SU i and SU s , $i \neq s$, in the set S_k , their optimal bandwidth allocations should meet

$$\frac{g_s^k p_s^k}{b_s^{k*} (n_0 + g_0^k p_0^k / B^k)} = \frac{g_i^k p_i^k}{b_i^{k*} (n_0 + g_0^k p_0^k / B^k)}. \quad (18)$$

In addition, constraint (14) should be binding at the optimum, i.e. $\sum_{s \in S_k} b_s^{k*} = B^k$. Thus, the bandwidth allocation can be expressed in the term of p_s^k as follows:

$$b_s^k = B^k \frac{g_s^k p_s^k}{\sum_{s \in S_k} g_s^k p_s^k}. \quad (19)$$

Notice that the above result also captures the case when $p_s^k = 0$ and the similar results also appears in [9]. Knowing the above result, we can express the SU s 's achievable rate over channel k as a function of its transmit-power only as follows

$$R_s^k = \frac{g_s^k p_s^k}{I^k} B^k \log_2 \left(1 + \frac{I^k}{n_0 B^k + g_0^k p_0^k} \right), \quad (20)$$

where $I^k = \sum_{s \in S_k} g_s^k p_s^k$ denotes the SUs' aggregate interference on channel k . Therefore, the original SUs' optimization problem (P2) can be equivalently transformed as follows:

$$(P4): \max_{\{p_s^k\}} \sum_k B^k \log_2 \left(1 + \frac{I^k}{n_0 B^k + g_0^k p_0^k} \right) \quad (21)$$

$$\text{subject to: } I^k \leq Q^k, \forall k \quad (22)$$

$$p_s^k \leq P_s^{\max}, \forall s \in S_k. \quad (23)$$

Remark: The objective function of problem (P4) indicates that the SUs' net-utility increases in their aggregate interference to the PU, which is in general consistent with our intuition. Suppose that $\sum_{s \in S_k} g_s^k P_s^{\max} \geq Q^k$, i.e., the SUs have sufficient power capacities. Then, to solve (P4), we are only concerned with the aggregate interference $\{I^k\}$ from the SUs over channels. It is apparent that $I^k = Q^k, \forall k$ will yield the optimality for problem (P4), i.e., the SUs always reach the interference-limits over all the channels.

Notice that even though we know that the SUs' net-utility is maximized when their aggregate interference to the PU reach the limits over all channels, each SU's individual transmit-power is yet to be further determined, which could be based on the principle of fairness, for example. After knowing the optimal power allocation, the corresponding SU's bandwidth allocation can be obtained from eq. (19).

B. Analysis for PU's Optimization Problem

Knowing the result from the SUs' problem (P2) (or equivalent problem (P4)), we further solve the PU's problem (P1). By putting $\sum_{s \in S_k} R_s^k$ from eq. (20) into (P1), the PU's net-

profit can be expressed as function of Q^k and p_0^k (notice that we already use the result that $I^k = Q^k, \forall k$ from the previous subsection), and problem (P1) can be equivalently expressed as follows:

(P5):

$$\max_{\{p_0^k\}, \{Q^k\}} \omega \sum_k B^k \log_2 \left(1 + \frac{Q^k}{n_0 B^k + g_0^k p_0^k} \right) - \alpha \left(\sum_k p_0^k - \bar{p}_0 \right)$$

subject to :

$$R_0^{k, \min} \leq B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + Q^k} \right) \leq R_0^{k, \max}, \forall k \quad (24)$$

$$\sum_k B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + Q^k} \right) \geq R_0^{req}. \quad (25)$$

Problem (P5), however, is a non-convex problem, and thus is difficult to solve in general. To explore the intrinsic property of problem (P5), we introduce the auxiliary variable $R_0^k = B^k \log_2 \left(1 + \frac{g_0^k p_0^k}{n_0 B^k + Q^k} \right), \forall k$, which represents the PU's rate allocation over channel k . Therefore, the PU's interference-cap Q^k can be expressed in the terms of its rate allocation R_0^k and its transmit-power p_0^k as follows:

$$Q^k(R_0^k, p_0^k) = \frac{g_0^k p_0^k}{2^{R_0^k/B^k}} - n_0 B^k, \forall k$$

By substituting the above result into (P5), we obtain an equivalent problem to problem (P1) as follows:

(P6) :

$$\begin{aligned} \max_{\{p_0^k\}, \{R_0^k\}} & \sum_k \omega B^k \log_2 \frac{2^{R_0^k/B^k}}{(2^{R_0^k/B^k} - 1)} \\ & + \omega \sum_k B^k \log_2 \left(\frac{g_0^k p_0^k}{n_0 B^k + g_0^k p_0^k} \right) - \alpha \left(\sum_k p_0^k - \bar{p}_0 \right) \end{aligned} \quad (26)$$

$$\text{subject to: } R_0^{k, \min} \leq R_0^k \leq R_0^{k, \max}, \forall k \quad (27)$$

$$\sum_k R_0^k \geq R_0^{req}. \quad (28)$$

Nevertheless, problem (P6) is still nonconvex in $\{R_0^k, p_0^k\}$. We thus propose a *layered algorithm* to solve it as follows.

First, suppose that a feasible PU's rate allocation $\{R_0^k\}$ is given. Then, the PU's net-profit maximization problem over $\{p_0^k\}$ (i.e., a subproblem of (P6)) is as follows:

$$\text{(P6-Sub): } \max_{\{p_0^k\}} \omega \sum_k B^k \log_2 \frac{g_0^k p_0^k}{n_0 B^k + g_0^k p_0^k} - \alpha \left(\sum_k p_0^k - \bar{p}_0 \right) \quad (29)$$

$$\text{subject to: } g_0^k p_0^k \geq (2^{R_0^k/B^k} - 1) n_0 B^k, \forall k \quad (30)$$

where constraint (30) guarantees the interference-cap Q^k is nonnegative. More importantly, it can be identified that problem (P6-Sub) can be decomposed into each individual channel separately, which facilitates our following analysis. Problem (P6-Sub) is a concave optimization problem since the objective is a concave function and the constraint is linear (under the given R_0^k). Using the Lagrange multiplier λ^k to

relax the constraint (30) into the objective function, we obtain the corresponding Lagrangian function $L_2(p_0^k, \lambda^k)$ as follows:

$$\begin{aligned} L_2(p_0^k, \lambda^k) &= \omega B^k \log_2 \frac{g_0^k p_0^k}{n_0 B^k + g_0^k p_0^k} \\ &+ \lambda^k (g_0^k p_0^k - (2^{R_0^k/B^k} - 1) n_0 B^k) - \alpha p_0^k. \end{aligned} \quad (31)$$

According to the KKT conditions, the sets of primal and dual optimal solutions $\{(p_0^{k*}, \lambda^{k*})\}$ should meet

$$\lambda^{k*} (g_0^k p_0^{k*} - (2^{R_0^k/B^k} - 1) n_0 B^k) = 0, \quad (32)$$

$$\frac{\partial L_2}{\partial p_0^k} \Big|_{p_0^k = p_0^{k*}} = 0. \quad (33)$$

From eq.(33) we can obtain the optimal transmit-power as

$$p_0^{k*} = \frac{n_0 B^k}{2g_0^k} \left(\sqrt{1 + \frac{4\omega g_0^k}{\alpha n_0 \ln 2}} - 1 \right). \quad (34)$$

Based on the above result, we obtain the following two cases:

Case1: When $\lambda^* = 0$, then we have $p_0^{k*} = \frac{n_0 B^k}{2g_0^k} \left(\sqrt{1 + \frac{4\omega g_0^k}{\alpha n_0 \ln 2}} - 1 \right)$, which means that the optimal solution occurs within the feasible region strictly;

Case2: When $\lambda^* \neq 0$, then according to eq.(35), we have $p_0^{k*} = \frac{(2^{R_0^k/B^k} - 1) n_0 B^k}{g_0^k}$, which means the optimal solution occurs at the boundary of the feasible region.

It is apparent that on each channel k , the PU's transmit-power p_0^k should be lower bounded by $\frac{(2^{R_0^k/B^k} - 1) n_0 B^k}{g_0^k}$. In other words, if **Case1** holds, then $\frac{n_0 B^k}{2g_0^k} \left(\sqrt{1 + \frac{4\omega g_0^k}{\alpha n_0 \ln 2}} - 1 \right) > \frac{(2^{R_0^k/B^k} - 1) n_0 B^k}{g_0^k}$, which is equivalent to the situation that $R_0^k < \eta^k$ with $\eta^k = B^k (\log_2(1 + \sqrt{1 + \frac{4\omega g_0^k}{\alpha n_0 \ln 2}}) - 1)$. Otherwise, **Case2** will hold.

In summary, we obtain the optimal PU's transmit-power as a function of its rate allocation as follows:

$$p_0^{k*}(R_0^k) = \max \left\{ \frac{n_0 B^k}{2g_0^k} \left(\sqrt{1 + \frac{4\omega g_0^k}{\alpha n_0 \ln 2}} - 1 \right), \frac{(2^{R_0^k/B^k} - 1) n_0 B^k}{g_0^k} \right\}. \quad (35)$$

The above result shows that the optimal PU's transmit-power depends on its rate allocation.

Using the optimal power allocation (35), problem (P6) becomes the following top-problem (which depends on the set of PU's rate allocations $\{R_0^k\}$ only).

$$\text{(P6-Top): } \max_{\{R_0^k\}} F(\{R_0^k\}) \text{ subject to: constraints (27), (28)}$$

where the objective function $F(\{R_0^k\})$ is given by

$$\begin{aligned} F(\{R_0^k\}) &= \omega \sum_k B^k \log_2 \frac{2^{R_0^k/B^k}}{(2^{R_0^k/B^k} - 1)} - \alpha \sum_k p_0^{k*}(R_0^k) \\ &+ \omega \sum_k B^k \log_2 \left(1 - \frac{n_0 B^k}{n_0 B^k + g_0^k p_0^{k*}(R_0^k)} \right) \end{aligned} \quad (36)$$

C. Simulated Annealing based Algorithm for Top-Problem

Through the derivations in the above two subsections, the PU's net-profit maximization problem (P1) has been equivalently simplified into the top-problem (P6-Top), which only depends on the PU's rate allocation $\{R_0^k\}$. Nevertheless, (P6-Top) is still hard to solve since the objective function is not given analytically, and more importantly it is non-convex. Therefore, we design Algorithm (A1) to solve it based on the Simulated Annealing (SA). SA is a probabilistic approach for global optimization, which especially fits the complicated/nonconvex optimization problem like ours [10]. Compared to the original net-profit maximization problem (P1), the top-problem (P6-Top) has a significantly reduced search space, which facilitates us to get a satisfactory result through SA algorithm. Table I shows the details of Algorithm (A1). To escape from local optimum, Algorithm (A1) accepts non-improvement result with a certain probability depending on both the degradation in the PU's objective function and the current temperature as shown in Step 5. Meanwhile, the temperature gradually decreases such that the acceptance probability of non-improved solution decreases as shown in Step 8. It is worth emphasizing that SA can converge to the global optimality with probability equal to 1 when the cooling schedule is appropriately chosen [11]. Due to the space limitation, we skip the details of SA. Interested readers can refer to [10] for details.

Algorithm (A1) to solve Problem (P6-E)

Step 1: Initialize the temperature T , the initial solution $\{R_0^{k,ini}\}$ (which is feasible), and the number of iterations L for each temperature. Also set the index $n = 1$ for the temperature updating.

Step 2: Given the current temperature, If $n = 1$, then initialize $\{R_0^k\}$ as $\{R_0^{k,ini}\}$. Otherwise, initialize $\{R_0^k\} = \Omega_{n-1}$, which denotes the best solution from the previous temperature. Then, let $\theta_n = F(\{R_0^k\})$ denote the current best value for the n -th temperature, and let $\Omega_n = \{R_0^k\}$ denote the current best solution. Set $l = 0$, Then do the following Step 3 to Step 8 for local search.

Step 3: Set $l = l + 1$. Generate a new solution $\{R_0^{k'}\}$ randomly around $\{R_0^k\}$. If the new $\{R_0^{k'}\}$ fails to meet constraints (4) and (5), then set $F(\{R_0^{k'}\}) = 0$. Otherwise, evaluate $F(\{R_0^{k'}\})$ according to eq. (36).

Step 4: Evaluate $\Delta = F(\{R_0^{k'}\}) - F(\{R_0^k\})$.

Step 5: If $\Delta > 0$, then update the currently best solution within the current temperature as $\theta_n = F(\{R_0^{k'}\})$ and $\Omega_n = \{R_0^{k'}\}$, and also replace $\{R_0^k\}$ by $\{R_0^{k'}\}$. Otherwise, replace $\{R_0^k\}$ by $\{R_0^{k'}\}$ according to the probability $\exp(\Delta/T)$.

Step 6: If θ_n and Ω_n do not change for the consecutive $\tilde{L}$ iterations, then go to Step 8.

Step 7: If $l = L$, then go to Step 8, which means that the L rounds of local search are finished. Otherwise, go back to Step 3.

Step 8: Record the best solution Ω_n for n -th temperature and the corresponding best value θ_n . Update the temperature $T = \alpha T$ with $(0 < \alpha < 1)$. If $T < 0.0001$, then go to the next step. Otherwise, go back to Step 2.

Step 9: Compare the profile $\{\theta_n\}$ obtained. Output the largest one as the global optimum. Algorithm stops.

IV. NUMERICAL RESULTS

In this section, we show the numerical results regarding to our Algorithm (A1) and cooperative spectrum sharing model. Specifically, we consider a primary network with 1

PU and 3 BSs. The link gains between the PU and three BSs are $[g_0^1, g_0^2, g_0^3] = [0.9813, 0.4813, 0.0319]$. The bandwidth of each channel $[B^1, B^2, B^3] = [1, 1, 1]$. The power spectral density of the background noise n_0 is 0.001. In addition, the cost coefficient for extra power consumption α is 0.01. The normalized utility price over each channel ω is set to 0.1.

Fig. 2 shows the performance of our Algorithm (A1) to solve problem (P6-E), thus reaching the maximum PU's net-profit. The blue line represents the obtained PU's net-profit as the iteration goes, and the red line represents the maximum PU's net-profit via exhaustive search. The result shows that Algorithm (A1) can converge to the global optimum quickly.

Fig. 2. Performance of our Algorithm (A1)

Fig. 3 further shows the PU's net-profit and the SUs' aggregate net-utility from the cooperative spectrum-sharing. Specifically, both of the PU and SUs gain from the cooperation, i.e., achieving non-negative net-profit (or net-utility), which however, decrease when PU's rate requirement increases. This result in fact is consistent with our intuition, since the PU suffers a limited freedom to share its spectrum with SUs as its own QoS requirement becomes stringent. In addition, the cooperative spectrum sharing via Problem (P1) and Problem (P2) achieve much better results than the *average* scheme in which the PU first equally divides its rate over the three channels and then share them with the SUs.

Fig. 4 shows the PU's optimal decisions under its different rate requirements, which include the optimal interference-cap in the top-subfigure, the rate allocation in the middle subfigure and the corresponding transmit-power in the bottom subfigure. Specifically, in each subfigure, the line with star denotes the result on the channel with the largest PU-BS channel gain, and the line with square is the 2nd best, and the line with circle is the worst. The results in the top-subfigure indicates that as its rate requirement increases, the PU first reduces its interference-cap on the channel with the largest channel gain, i.e., limits its sharing with the SUs. As its rate requirement further increases, its interference-cap on the 2nd best channel decreases. Similar trend continues until the PU finds nonprofitable to tolerate any interference from SUs. This trend is also verified in the middle-subfigure, i.e., the PU tends to use its best channel to accommodate its rate requirement

Fig. 3. Benefit from cooperative spectrum-sharing. Top-subfigure: PU's net-profit; Bottom-subfigure: SU's net-utility

Fig. 4. The PU's optimal decisions. Top-subfigure: interference-cap; Middle-subfigure: rate allocation; Bottom-subfigure: transmit-power

first, then the 2nd best one and so on. The bottom-subfigure also verifies this trend through showing the corresponding PU's transmit-power. Specifically, as shown in eq. (35), it can be identified that if $R_0^k < \eta^k$ on channel k , then the PU's transmit power is fixed as $p_0^k = \frac{n_0 B^k}{2g_0^k} (\sqrt{1 + \frac{4\omega g_0^k}{\alpha n_0 \ln 2}} - 1)$. While, if $R_0^k \geq \eta^k$, then the PU's transmit-power shows the same trend as its rate allocation.

Fig. 5. The SU's net-utility versus different normalized price

Finally, Fig. 5 shows the SU's net-utility from the spectrum-sharing under different PU's normalized prices. It is apparent that as the follower in the cooperation, the SU's net-utility strongly depends on the PU's charge. A too small normalized price encourages the SU's access but discourages the PU's sharing. On the other hand, a too high normalized price discourages the SU's access but encourages the PU's sharing. Thus, the SU's net-utility suffers in both cases, i.e., when ω is either close to 0 or close to 1. Therefore, the PU should carefully choose its price to motivate the SU's cooperation and thus benefit both of them.

V. CONCLUSION

We propose a cooperative spectrum-sharing model between the PU and the CR network, which allows the PU to charge the traffic rate of CR network via the different PU BSs (or channels). We analyze this PU-SUs sharing problem in detail and propose an efficient algorithm for the PU's net-utility maximization via exploring its intrinsic property. Our results show that both PU and SUs benefit from the cooperative spectrum-sharing, which yields a win-win cooperation. In future work, we plan to incorporate the SU's freedom to choose different BSs (channels) for their own interests into our model, i.e., the SU can also choose different BSs to access based on the PU's decisions.

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