Power and Bandwidth Allocation for Cognitive Heterogeneous Multi-homing Networks

Lei Xu IEEE Member, A. Nallanathan IEEE Fellow, Jian Yang, and Wenhe Liao

Abstract

In this work, an uplink power and bandwidth allocation problem for multiple services with multihoming technology is formulated for cognitive heterogeneous networks. The joint power and bandwidth allocation with multiple services is subject to constraints in system available bandwidth, proportional fairness transmission rate for non-real-time secondary mobile terminals (MTs), minimum required transmission rate for real-time secondary MTs, interference power for primary base station (BS), and total power consumption for each secondary MT. The joint power and bandwidth allocation problem with multiple services based on risk-return model is formulated as a bargaining game framework, firstly. Then, an optimal power and bandwidth allocation algorithm utilizing a dual decomposition method is proposed to obtain Nash bargaining solution. Finally, a heuristic algorithm is proposed to reduce computational complexity. Simulation results demonstrate the optimal and heuristic algorithms not only improve the spectrum efficiency, but also guarantee the fairness for secondary MTs with non-real-time service.

Index Terms

Cognitive heterogeneous networks, multiple services, multi-homing technology, bargaining game, dual decomposition method.

I. INTRODUCTION

Wireless communication networks become a heterogeneous environment with various wireless networks. Different wireless networks have different characteristics. For example, in cellular

Lei Xu and Jian Yang are at the School of Computer Science and Engineering, Nanjing University of Science and Technology, Nanjing, China. Wenhe Liao is at the School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China. (E-mail: xulei_marcus@126.com).

A. Nallanathan is at Department of Informatics, King's College London, London WC2R 2LS, U.K. (nallanathan@ieee.org).

network, macro network supports low-to-medium rate service, but it has a large coverage area. On the other hand, femto network supports high rate service, but it is only deployed in hotspot areas. Consequently, integrating macro network and femto network can help to provide various classes of services for MTs [1, 2]. Cognitive radio can further improve the spectrum efficiency by accessing the licensed spectrum opportunistically, which is known as the key technology in 5G. In cognitive radio network, secondary MT can transmit over the licensed band, as long as the interference at primary network is controlled within a proper interference level [3–7]. In order to improve spectrum utilization efficiency, many international standardization organizations, e.g., IEEE 802.11af, 802.19 TG, and IEEE 802.22, develop standards for further development of cognitive networks [8]. Additionally, multiple cognitive wireless networks overlap with each other to constitute cognitive heterogeneous networks.

Existing studies in resource allocation for cognitive radio network can be divided into two categories [9–20]. The first category is resource allocation for cognitive homogeneous network [9–15]. The objective optimization of resource allocation in cognitive homogeneous network can be spectrum efficiency [9–11], energy efficiency [12, 13] or user fairness [14, 15]. The second category is resource allocation in cognitive heterogeneous networks [16–20]. They can be further divided into resource allocation with single access [16–18] and resource allocation with multi-homing technology [19, 20].

In cognitive homogeneous network, a resource allocation problem for relay-aided cognitive radio network is investigated to maximize spectrum efficiency [9]. Further, an adaptive resource allocation problem for multiuser orthogonal frequency division multiplexing (OFDM)-based cognitive radio network with cooperative relays is studied in [10]. In [11], imperfect spectral sensing is considered, and optimal resource allocation strategy is investigated to maximize the ergodic throughput under the rate loss constraint for primary users. Different from [9–11], an energy-efficient power allocation algorithm for single-user cognitive OFDM network is proposed in [12]. An energy-efficient resource allocation problem based on risk-return model for multiuser cognitive OFDM network is investigated in [13]. Considering the worst energy efficiency and average energy efficiency, the energy efficient opportunistic spectrum access strategies for multiuser cognitive OFDM network are studied in [14]. For guaranteeing user's fairness, a game theory resource allocation framework is developed in [15].

In cognitive heterogeneous femtocell networks, a packet scheduling framework considering

the user's priority is proposed to support the real-time and non-real-time services [16]. In order to maximize the capacity while avoiding cross-tier interferences, a joint power and bandwidth allocation algorithm is proposed in [17]. Further, a distributed joint power and bandwidth allocation algorithm for cognitive heterogeneous femtocell networks is proposed in [18]. Existing resource allocation mechanisms for cognitive heterogeneous femtocell networks mainly limit to secondary MT to communicate with one secondary BS. However, in order to improve user's experience in cognitive heterogeneous networks, multi-homing capability can be carried out, where the data stream from a secondary MT is split into multiple sub-streams and transmitted over multiple secondary base stations (BSs) by different radio interfaces simultaneously¹. In [19], a call admission control algorithm based on inter-network cooperation is proposed via a Stackelberg game framework for cognitive heterogeneous networks with multi-homing technology. In [20], a video packet scheduling framework with stochastic quality of service (QoS) is proposed for cognitive heterogeneous networks cooperation is investigated.

So far, existing power and bandwidth allocation algorithms in cognitive radio network focus on the resource allocation in cognitive radio network with single access [9–18]. Due to the scarcity of spectrum resource in cognitive radio network, the QoS requirement of secondary MTs can not be guaranteed. Additionally, cognitive heterogeneous networks is an important scenario in 5G. Consequently, how to aggregate the spectrum resources in cognitive heterogeneous networks to satisfy the QoS requirement of secondary MTs is an important problem. In order to solve this problem, we introduce the multi-homing technology to cognitive heterogeneous networks, and investigate the efficient resource allocation for cognitive heterogeneous networks with multihoming technology. Specially, we summarize our contributions as follows: (i) A novel network architecture is proposed to aggregate the spectrum resources from different cognitive radio networks, i.e., cognitive heterogeneous networks with multi-homing technology (ii) An uplink resource allocation problem with the multi-homing technology for the real-time service and nonreal-time service is formulated to jointly allocate power and bandwidth resources to different radio interfaces at each secondary MT; (iii) The uplink joint power and bandwidth is modeled as a bargaining game framework, and an optimal power and bandwidth allocation algorithm based

¹In multi-homing scenario, each secondary MT can communicate with multiple secondary BSs. However, each secondary MT can only communicate with one secondary BS in the classic cognitive wireless network. Consequently, multi-homing technology increases the network diversity to improve the QoS of secondary MTs.

on the dual decomposition method is proposed, and a heuristic algorithm is developed to reduce the computational complexity. Simulation results demonstrate that the proposed algorithms not only improve the spectrum efficiency, but also guarantee QoS for secondary MTs.

The rest of this work is organized as follows. The system model and cooperative game framework are described in Section II and Section III, respectively. Section IV presents the optimal joint power and bandwidth allocation solutions. The heuristic algorithm and computational complexity analysis are given in Section V. Finally, performance evaluation and conclusions are given in Sections VI and VII, respectively.

II. SYSTEM MODEL

In this section, the system model is described firstly. Then, the power consumption model is presented.

A. System Description

There is a set, $\mathcal{N} = \{1, 2, \dots, N\}$, of cognitive radio networks, which are operated by different service providers². In cognitive radio network *n*, there is a set, $S_n = \{1, 2, \dots, S_n\}$, of secondary BSs and a set, $S_{n_1}^* = \{1, 2, \dots, S_{n_1}^*\}$, of primary BSs in the geographical region. Since the coverage of secondary BSs for each cognitive radio network is different from those of other networks and different cognitive radio networks have overlapped coverage in some areas, the geographical region can be partitioned into multiple service areas, as shown in Fig. 1. There is a set, $\mathcal{M} = \{1, 2, \dots, M\}$, of secondary MTs in the geographical region and $\mathcal{M}_{n,s} = \{1, 2, \dots, M\}$, is a subset of secondary MTs, which lie in the coverage area of cognitive network *n* BS *s*. In the same cognitive network, interference mitigation is achieved by interference management schemes [21, 22]. There are two types of secondary MTs, i.e., secondary MTs with the real-time non-real-time service is \mathcal{M}_{RT} , and the number of real-time service is \mathcal{M}_{RT} , and the number of that is M_{NRT} . In the set \mathcal{M} , secondary MTs from 1 to \mathcal{M}_{NRT} are secondary MTs with the non-real-time service. Cooperative spectrum sensing algorithms can be used

²In this work, \mathcal{X} is used for the set, X is used as the total count, and x is used as an index for the parameter.



Figure 1: Cognitive heterogeneous networks.

for cognitive radio networks based on machine learning techniques, e.g., support vector machine [23–25]. In this work, we adopt the underlay mode for cognitive heterogeneous networks [26]. Using this spectrum sensing mode, primary networks and secondary networks utilize the same bandwidth. In order to protect the communication quality of primary networks, the interference power at primary BS should be controlled according to the interference temperature model [27]. Using multi-homing mechanism and multiple radio interfaces, each secondary MT is able to communicate with multiple secondary BSs simultaneously.

B. Power Consumption Model

The total consumed power at each interface for each secondary MT includes two components. The first part, $Q_{n,s,m}^F$, is a consumed power of fixed circuit for each secondary MT's interface. The second part is a dynamic part referring to the consumed power of digital circuit, i.e., $Q_{n,s,m}^D = Q_D^{\text{ref}} + \sigma_{n,s,m} B_{n,s,m} / B_{\text{ref}}$. Q_D^{ref} is the power consumption of digital circuit for a reference bandwidth, B_{ref} , and $\sigma_{n,s,m}$ is a proportional constant. For $m \notin \mathcal{M}_{n,s}$, $P_{n,s,m} = Q_{n,s,m}^F = Q_{n,s,m}^D = 0$. Denote $Q_{n,s,m} = Q_{n,s,m}^F + Q_D^{\text{ref}}$ and $\zeta_{n,s,m} = \sigma_{n,s,m} / B_{\text{ref}}$. Consequently, the total power consumption for each interface of secondary MT is [28, 29]

$$P_{n,s,m}^{\rm T} = \frac{P_{n,s,m}}{\rho_{n,s,m}} + Q_{n,s,m} + \zeta_{n,s,m} B_{n,s,m}$$
(1)

where $B_{n,s,m}$ is the bandwidth for cognitive network n BS s to communicate with secondary MT m, $\rho_{n,s,m}$ is the power amplifier efficiency for cognitive network n BS s MT m, and $P_{n,s,m}$ is the power for cognitive network n BS s MT m.

III. COOPERATIVE GAME FRAMEWORK

In cognitive heterogeneous networks, secondary MTs are able to cooperate in power and bandwidth allocation to achieve the better performance. Additionally, secondary MTs aggregate the offered bandwidth resources from different cognitive radio networks. In order to increase the spectrum efficiency among secondary MTs, Nash bargaining game offers a cooperation incentive power and bandwidth allocation³.

The allocated bandwidth resource by cognitive network n BS s is not larger than the total bandwidth resource, i.e.,

$$\sum_{n \in \mathcal{M}_{n,s}} B_{n,s,m} \le B_{n,s} \tag{2}$$

where $B_{n,s}$ is the total available bandwidth at cognitive network n BS s.

n

The power consumption, $P_m = \sum_{n \in \mathcal{N}} \sum_{s \in \mathcal{S}_n} P_{n,s,m}^T$, for secondary MT *m* should satisfy the maximum power constraint, i.e.,

$$P_m \le P_m^{\mathrm{T}} \tag{3}$$

where P_m^T is the total available power at secondary MT m.

The achieved transmission rate by secondary MT m to communicate with cognitive network n BS s is

$$R_{n,s,m} = B_{n,s,m} \log_2 \left(1 + \frac{P_{n,s,m} h_{n,s,m}^{\text{CBS}}}{n_0 B_{n,s,m} + I_{n_1,s}^{\text{Pri}}} \right)$$
(4)

where n_0 is noise power spectral density, $I_{n_1,s}^{\text{Pri}}$ is the interference power caused by all primary MTs at primary network n_1 BS s, and $h_{n,s,m}^{\text{CBS}}$ is the channel gain for cognitive network n BS s to communicate with secondary MT m.

In the geographical area, the distances between secondary MTs and secondary BSs are different. Hence, the transmission path loss for different secondary MTs are different. For example,

³There exist many cooperative game models that can be used to solve this problem, e.g., coalition formation theory, and bargaining game theory. Since the following cooperation incentive power and bandwidth allocation can be transformed into a convex optimization problem, we adopt the bargaining game theory to obtain the global optimal power and bandwidth allocation solution.

the secondary MT close to secondary BS can obtain the higher transmission capacity, while the secondary MT far away from secondary BS can only obtain the less transmission capacity. This phenomenon leads to the hunger throughput for the secondary MT far away from secondary BS. To guarantee the proportional fair transmission rate with the non-real time service in the geographical area, we have

$$\frac{R_{m+1}}{R_m} = \frac{\varphi_{m+1}}{\varphi_m}, m = 1, \cdots, M_{\text{NRT}}$$
(5)

where $R_m = \sum_{n \in \mathcal{N}} \sum_{s \in S_n} R_{n,s,m}$ is the total achieved transmission rate for secondary MT m, and φ_m is the fairness weight for secondary MT m.

Since there are M_{NRT} secondary MTs with the non-real service, constraint (5) includes $M_{\text{NRT}} - 1$ independent equalities [30]. Additionally, they can be transformed into M_{NRT} dependent inequalities, i.e.,

$$\frac{R_{\lfloor m+1 \rfloor_{M_{\text{NRT}}}}}{R_m} \le \frac{\varphi_{\lfloor m+1 \rfloor_{M_{\text{NRT}}}}}{\varphi_m}, m = 1, \cdots, M_{\text{NRT}}$$
(6)

where $\lfloor \bullet \rfloor_{M_{\text{NRT}}}$ is the modulus based on M_{NRT} with $1 \leq \lfloor \bullet \rfloor_{M_{\text{NRT}}} \leq M_{\text{NRT}}$, e.g., $\lfloor 0 \rfloor_{M_{\text{NRT}}} = M_{\text{NRT}}$ and $\lfloor M_{\text{NRT}} + 1 \rfloor_{M_{\text{NRT}}} = 1$.

Constraint (6) can be rewritten as

$$\varphi_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}} R_m - \varphi_m R_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}} \ge 0, m = 1, \cdots, M_{\mathrm{NRT}}.$$
(7)

The total achieved transmission rate with the real-time service should satisfy the required minimum transmission rate using (8), e.g., video traffic⁴.

$$R_m \ge R_m^{\min}, m = M_{\text{NRT}} + 1, \cdots, M.$$
(8)

The interference at primary BS is

$$\sum_{m \in \mathcal{M}_{n,s}} P_{n,s,m} h_{n_1,s,m}^{\text{PBS}} \le I_{n_1,s}^{\text{Thd}}.$$
(9)

where $I_{n_1,s}^{\text{Thd}}$ is the interference threshold for primary network n_1 BS s, and $h_{n_1,s,m}^{\text{PBS}}$ is the channel gain between primary network n_1 BS s and secondary MT m.

The space of the radio power and bandwidth allocation, Υ , is

$$\Upsilon = \{ (P_{n,s,m}, B_{n,s,m}) \mid (2), (3), (7) - (9), P_{n,s,m} \ge 0, B_{n,s,m} \ge 0 \}.$$
(10)

⁴In order to improve the multiview video coding efficiency, variable block-size motion estimation, disparity estimation, and multiple reference frames selection are adopted [31–33].

Proposition 1. The space of the radio power and bandwidth allocation, Υ , is convex.

Proof. Since Appendix A proves that R_m is concave in $B_{n,s,m}$ and $P_{n,s,m}$, the (2),(3),(7)-(9) are concave. As Υ is described by linear and concave constraints, it is a concave set.

In this work, the general risk-return model is adopted [13]. The allocated power and bandwidth for secondary MT is considered as an investment. In cognitive heterogeneous networks, loss of useful power can be represented as a rate loss of primary MT. Additionally, define a real-valued increasing, concave and normalized loss function, $L(P_m)$, for a power P_m . Consequently, the utility function for secondary MT m is

$$U_m = R_m - L\left(P_m\right) \tag{11}$$

where a linear rate loss function is $L(P_m) = C_m P_m$, and C_m is normalized average cost per unit power for secondary MT to allocate resources. In this utility function about the bandwidth and power, only the power consumption is considered as a part of costs. This is due to the fact that the underlay model for cognitive wireless networks is adopted in this work. All the bandwidth can be used by secondary MTs, and the power should be controlled to guarantee the interference level at the primary BSs.

Since Nash Equilibrium (NE) in a non-cooperative game is not always efficient, we resort to cooperative bargaining games. The space of the radio power and bandwidth allocation, Υ , is closed and convex, and is the set of feasible power and bandwidth allocation when secondary MTs cooperate. In this work, a *M*-players bargaining game is constructed, and a Pareto efficient point is defined, where a secondary MT can not find another point that improves the utility of all the secondary MTs simultaneously.

Definition 1. A point is Pareto optimal if and only if no other power and bandwidth allocation solution, U_m^* , exists to make $U_m^* \ge U_m$ without causing inferior performance for other secondary *MTs*, i.e., there is no other power and bandwidth allocation to achieve superior performance for some secondary *MTs* [34].

According to definition 1, an infinite number of Pareto optimal points may exist in a game for secondary MTs. Therefore, how to select a Pareto point for a cooperative bargaining game is an important question, and a possible criterion is the fairness of power and bandwidth allocation, i.e., Nash bargaining solution. As asymmetric Nash bargaining game enables different secondary

MTs to have different bargaining power and bandwidth allocation in the game. For example, if one secondary MT has higher capacity and less interference to primary network, the secondary MT can have more influence on the cooperative bargaining game outcome [35].

Proposition 2. For the cooperative power and bandwidth allocation problem (12), there exists a bargaining point⁵.

$$\max_{\substack{B_{n,s,m}^*, P_{n,s,m}^* \\ n \in \mathcal{M}^*}} \prod_{m \in \mathcal{M}^*} U_m$$

$$S.t.: P_{n,s,m}^*, B_{n,s,m}^* \in \Upsilon, \forall n \in \mathcal{N}, s \in \mathcal{S}_n.$$
(12)

where \mathcal{M}^* is a nonempty subset of secondary MTs achieving strictly superior performance via cooperation.

Proof. Since Υ is bounded and closed, and it is compact, there exists a bargaining point for the cooperative power and bandwidth allocation problem (12).

The equivalent form of (12) is given by

$$\max_{\substack{B_{n,s,m}^*, P_{n,s,m}^* \\ m \in \mathcal{M}^*}} \sum_{m \in \mathcal{M}^*} \log_2\left(U_m\right)$$

$$S.t.: P_{n,s,m}^*, B_{n,s,m}^* \in \Upsilon, \forall n \in \mathcal{N}, s \in \mathcal{S}_n.$$
(13)

Proposition 3. Problem (13) is a convex optimization problem.

Proof: Similar to proposition 1, we can prove the concavity of the objective function. Since Υ is a concave set in $B_{n,s,m}^*$ and $P_{n,s,m}^*$, (13) is a convex programming problem.

IV. BARGAINING POWER AND BANDWIDTH ALLOCATION SOLUTIONS

In this section, we solve the convex power and bandwidth allocation problem (13) based on the multi-homing technology for cognitive heterogeneous networks. Since problem (13) is a convex optimization problem, we adopt the dual decomposition method to obtain the bargaining resource allocation solution and an optimal power and bandwidth allocation algorithm for multiple classes of services is proposed.

⁵The objection function for the cooperative bargaining game is the product of all the U_m instead of the classical sum function. This is because the product objection function can make secondary MTs to influence with each other and the fairness can be guaranteed among different secondary MTs. Hence, the cooperative bargaining game can be applied to this case. Additionally, we choose the disagreement point to be all zeros which correspond to maximizing the proportional fair sum of utilities.

A. Solution of the Cooperative Resource Allocation Game

As problem (13) is a convex optimization problem, it is appropriate to solve (13) via the dual decomposition method. The Lagrangian function for problem (13) is

$$f\left(\alpha_{n,s}, \gamma_{m}, u_{m}, v_{m}, \delta_{n,s}, B_{n,s,m}^{*}, P_{n,s,m}^{*}\right) = \sum_{m \in \mathcal{M}^{*}} \log_{2}\left(U_{m}\right)$$

$$+ \sum_{m \in \mathcal{M}_{\mathrm{RT}}} \gamma_{m}\left(R_{m} - R_{m}^{\mathrm{min}}\right) + \sum_{n \in \mathcal{N}} \sum_{s \in \mathcal{S}_{n}} \delta_{n,s}\left(I_{n,s}^{\mathrm{Thd}} - \sum_{m \in \mathcal{M}_{n,s}} P_{n,s,m}^{*}h_{n,s,m}^{\mathrm{PBS}}\right)$$

$$+ \sum_{m \in \mathcal{M}_{\mathrm{NRT}}} u_{m}\left(\varphi_{\lfloor m+1 \rfloor_{\mathcal{M}_{\mathrm{NRT}}}} R_{m} - \varphi_{m}R_{\lfloor m+1 \rfloor_{\mathcal{M}_{\mathrm{NRT}}}}\right) + \sum_{m \in \mathcal{M}_{n,s}} v_{m}\left(P_{m}^{\mathrm{T}} - P_{m}\right)$$

$$+ \sum_{n \in \mathcal{N}} \sum_{s \in \mathcal{S}_{n}} \alpha_{n,s}\left(B_{n,s} - \sum_{m \in \mathcal{M}^{*}} B_{n,s,m}^{*}\right)$$

$$(14)$$

where $\alpha_{n,s}$, γ_m , u_m , v_m and $\delta_{n,s}$ are Lagrangian multipliers.

Based on (14), the dual function, $h(\alpha_{n,s}, \gamma_m, u_m, v_m, \delta_{n,s})$, is

$$h(\alpha_{n,s}, \gamma_m, u_m, v_m, \delta_{n,s}) = \begin{cases} \max_{\substack{B_{n,s,m}^*, P_{n,s,m}^* \\ B_{n,s,m}, P_{n,s,m}^* \\ S.t. : B_{n,s,m}^* \ge 0, P_{n,s,m}^* \ge 0. \end{cases}$$
(15)

Additionally, the dual problem is

$$\min_{\substack{u_m, v_{n,s} \\ \alpha_m, \gamma_m, \delta_{n,s}}} h\left(\alpha_{n,s}, \gamma_m, u_m, v_m, \delta_{n,s}\right) S.t.: u_m \ge 0, v_m \ge 0, \gamma_m \ge 0, \alpha_{n,s} \ge 0, \delta_{n,s} \ge 0.$$
(16)

Problem (16) can be simplified to

$$f_m = \log_2 \left(R_m - L\left(P_m\right) \right) - \sum_{n \in \mathcal{N}} \sum_{s \in \mathcal{S}_n} \alpha_{n,s} B^*_{n,s,m} + \gamma_m R_m$$

$$-P_m v_m + R_m L_m - \sum_{n \in \mathcal{N}} \sum_{s \in \mathcal{S}_n} \delta_{n,s} P^*_{n,s,m} h^{\text{PBS}}_{n_1,s,m}$$
(17)

and

$$L_m = u_m \varphi_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}} - u_{[m-1]_{M_{\mathrm{NRT}}}} \varphi_{[m-1]_{M_{\mathrm{NRT}}}}.$$
(18)

Consequently, each MT can solve its own utility maximization problem, i.e.,

$$\max_{\substack{B_{n,s,m}^{*},P_{n,s,m}^{*}}} f_{m}$$

$$S.t.: B_{n,s,m}^{*} \ge 0, P_{n,s,m}^{*} \ge 0.$$
(19)

The optimal bandwidth allocation $B_{n,s,m}^*$ for the fixed values $P_{n,s,m}^*$, $\alpha_{n,s}$, γ_m , u_m , v_m and $\delta_{n,s}$ can be calculated with (21) by applying Karush-Kuhn-Tucker (KKT) condition on (19).

$$\frac{\partial f_m}{\partial B^*_{n,s,m}} = 0. \tag{20}$$

From (20), we can obtain

$$\frac{\partial R_{n,s,m}}{\partial B_{n,s,m}^*} = \begin{cases} \frac{[C_m \omega(L(P_m)) + \lambda_m] \zeta_{n,s,m} + \alpha_{n,s}}{\omega(L(P_m)) + \gamma_m}, m \in \mathcal{M}_{\mathrm{RT}} \\ \frac{[C_m \omega(L(P_m)) + \lambda_m] \zeta_{n,s,m} + \alpha_{n,s}}{\omega(L(P_m)) + L_m}, m \in \mathcal{M}_{\mathrm{NRT}} \end{cases}$$
(21)

$$\omega\left(x\right) = \frac{1}{\ln 2\left(R_m - x\right)}\tag{22}$$

and

$$\lambda_m = v_m + \delta_{n,s} h_{n_1,s,m}^{\text{PBS}}.$$
(23)

Using the Newton's method on (21)-(23), the optimal bandwidth solution is

$$B_{n,s,m}^* = \left[g_B^*\left(P_{n,s,m}^*, \alpha_{n,s}, \gamma_m, u_m, v_m, \delta_{n,s}\right)\right]^+$$
(24)

where $[\bullet]^+$ is a projection on the positive orthant to account for $B^*_{n,s,m}$, and $g^*_B(\bullet)$ is a mapping function which satisfies (20).

The optimal power allocation $P_{n,s,m}^*$ for the fixed values $B_{n,s,m}^*$, $\alpha_{n,s}$, γ_m , u_m , v_m and $\delta_{n,s}$ can be calculated with (25) by applying KKT condition on (19).

$$\frac{\partial f_m}{\partial P^*_{n,s,m}} = 0. \tag{25}$$

From (25), we can obtain

$$P_{n,s,m}^{*} = \begin{cases} \kappa_{n,s,m} \left[\omega \left(L \left(P_{m} \right) \right) + \gamma_{m} \right] - y_{n,s,m}, m \in \mathcal{M}_{\mathrm{RT}} \\ \kappa_{n,s,m} \left[\omega \left(L \left(P_{m} \right) \right) + L_{m} \right] - y_{n,s,m}, m \in \mathcal{M}_{\mathrm{NRT}} \end{cases}$$
(26)

$$y_{n,s,m} = \frac{n_0 B_{n,s,m}^* + I_{n,s,m}}{h_{n,s,m}^{\text{CBS}}}$$
(27)

and

$$\kappa_{n,s,m} = \frac{\rho_{n,s,m} B_{n,s,m}^*}{\left[C_m \omega \left(L\left(P_m\right)\right) + \lambda_m\right] \ln 2}.$$
(28)

B. Update the Dual Variables

The optimum values $\alpha_{n,s}$, γ_m , u_m , v_m and $\delta_{n,s}$ can be calculated by solving the dual problem (16). For a fixed $B^*_{n,s,m}$ and $P^*_{n,s,m}$, the dual problem (16) can be simplified to

$$\min\left\{\sum_{n\in\mathcal{N}}\sum_{s\in\mathcal{S}_{n}}\alpha_{n,s}\left(B_{n,s}-\sum_{m\in\mathcal{M}_{n,s}}B_{n,s,m}^{*}\right)\right\}$$

+
$$\min\left\{\sum_{n\in\mathcal{N}}\sum_{s\in\mathcal{S}_{n}}\delta_{n,s}\left(I_{n,s}^{\mathrm{Thd}}-\sum_{m\in\mathcal{M}_{n,s}}P_{n,s,m}^{*}h_{n_{1},s,m}^{\mathrm{PBS}}\right)\right\}$$

+
$$\min\left\{\sum_{m\in\mathcal{M}_{\mathrm{NRT}}}u_{m}\left(\varphi_{\lfloor m+1\rfloor_{M_{\mathrm{NRT}}}}R_{m}-\varphi_{m}R_{\lfloor m+1\rfloor_{M_{\mathrm{NRT}}}}\right)\right\}$$

+
$$\min\left\{\sum_{m\in\mathcal{M}_{\mathrm{RT}}}\gamma_{m}\left(R_{m}-R_{m}^{\mathrm{min}}\right)\right\}+\min\left\{\sum_{m\in\mathcal{M}_{n,s}}v_{m}\left(P_{m}^{\mathrm{T}}-P_{m}\right)\right\}.$$
(29)

For a differentiable dual function (29), a gradient descent method can be applied to calculate the optimal values for $\alpha_{n,s}$, γ_m , u_m , v_m and $\delta_{n,s}$, and we can obtain

$$\alpha_{n,s}\left(i+1\right) = \left[\alpha_{n,s}\left(i\right) - \Delta\varepsilon_{1}\left(B_{n,s} - \sum_{m \in \mathcal{M}_{n,s}} B_{n,s,m}^{*}\right)\right]^{+}$$
(30)

$$\delta_{n,s}\left(i+1\right) = \left[\delta_{n,s}\left(i\right) - \Delta\varepsilon_{2}\left(I_{n,s}^{\text{Thd}} - \sum_{m \in \mathcal{M}_{n,s}} P_{n,s,m}^{*}h_{n_{1},s,m}^{\text{PBS}}\right)\right]^{+}$$
(31)

$$u_{m}\left(i+1\right) = \left[u_{m}\left(i\right) - \Delta\varepsilon_{3}\left(\varphi_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}}R_{m} - \varphi_{m}R_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}}\right)\right]^{+}, \forall m \in \mathcal{M}_{\mathrm{NRT}}$$
(32)

$$\gamma_m \left(i+1 \right) = \left[\gamma_m \left(i \right) - \Delta \varepsilon_4 \left(R_m - R_m^{\min} \right) \right]^+, \forall m \in \mathcal{M}_{\mathrm{RT}}$$
(33)

and

$$v_m(i+1) = \left[v_m(i) - \Delta\varepsilon_5 \left(P_m^{\mathrm{T}} - P_m\right)\right]^+$$
(34)

where *i* is the iteration index and $\Delta \varepsilon_j$, $j = 1, \dots, 5$, is a small step size. Since the gradient of problem (29) satisfies the Lipchitz continuity condition, the convergence towards the optimum solution is guaranteed by (30)-(34) with an appropriate step size [36]. Consequently, the power and bandwidth allocation solutions in (24) and (26) converges to the optimum solution.

C. Cooperative Bargaining Resource Allocation Algorithm

Although (24) and (26) give solutions to the power and bandwidth allocation, it still needs to design the optimal power and bandwidth allocation algorithm to provide the execution structure. Consequently, we propose the cooperative bargaining power and bandwidth allocation algorithm, which guarantees convergence by using the subgradient method. In the cooperative bargaining power and bandwidth allocation algorithm, ε_p is an arbitrarily small positive number. ϑ (i - 1), and ϑ (i) are the variable values at the (i - 1) iteration and the *i* iteration. $\alpha_{n,s}(i)$, $\gamma_m(i)$, $u_m(i)$, $v_m(i)$, and $\delta_{n,s}(i)$ are the Lagrangian multipliers at the *i* iteration. $\alpha_{n,s}(i + 1)$, $\gamma_m(i + 1)$, $u_m(i + 1)$, $v_m(i + 1)$, and $\delta_{n,s}(i + 1)$ are the Lagrangian multipliers at the (i + 1) iteration. In algorithm 1, $R_{n,s,m}$, $B^*_{n,s,m}$, $u_m(i + 1)$, $\gamma_m(i + 1)$, and $v_m(i + 1)$ are calculated in each secondary MT. $P^*_{n,s,m}h^{\text{PBS}}_{n,s,m}$, $B^*_{n,s,m}$, and ϑ (i) are exchanged between the secondary BS via the wireline backbone.

V. HEURISTIC ALGORITHM AND COMPLEXITY ANALYSIS

Although the cooperative bargaining power and bandwidth allocation algorithm can obtain the optimal power and bandwidth, it has enormous computational complexity. This motives us to develop the heuristic algorithm. In this section, we first propose the heuristic power and bandwidth allocation algorithm. Then, the computational complexities for optimal and heuristic algorithms are analyzed, respectively.

A. Heuristic Power and Bandwidth Allocation Algorithm

In this subsection, we propose the heuristic power and bandwidth allocation algorithm via the greedy algorithm [37], which has two stages. In the first stage, the power and bandwidth are allocated to secondary MT $m^* \in \mathcal{M}_{RT}$ with the minimum utility function. Additionally, the radio interface of secondary MT $m^* \in \mathcal{M}_{RT}$ with the highest transmission rate obtains the resource. The resource allocation procedure is repeated until all secondary MTs with the real-time service meet the required minimum transmission rate. In the second stage, the power and bandwidth are allocated to secondary MT $m^* \in \mathcal{M}_{NRT}$ with minimum normalized utility function and the radio interface of secondary MT $m^* \in \mathcal{M}_{NRT}$ with the highest transmission rate obtains the resource.

Algorithm 1 Cooperative Bargaining Power and Bandwidth Allocation.

Require: $B_{n,s}$, $P_{n,s}^{\max}$, P_m^{T} , φ_m , $B_{n,s}$, R_m^{\min} and $I_{n,s}^{\mathrm{Thd}}$.

Ensure: $B_{n,s,m}^*$ and $P_{n,s,m}^*$.

1: Initialize $\alpha_{n,s}(i)$, $\gamma_m(i)$, $u_m(i)$, $v_m(i)$, $\delta_{n,s}(i)$, $P^*_{n,s,m}$, $B^*_{n,s,m}$, $\vartheta(i) = \sum_{m \in \mathcal{M}^*} \log_2(U_m(i))$ and i = 1.

2: repeat

- 3: Each secondary MT calculates $R_{n,s,m}$, $B_{n,s,m}^*$, and $P_{n,s,m}^*$. Update $u_m(i+1)$, $\gamma_m(i+1)$, and $v_m(i+1)$. Additionally, broadcast its $R_{n,s,m}$, $P_{n,s,m}^*h_{n_1,s,m}^{\text{PBS}}$ and $B_{n,s,m}^*$ to all its serving secondary BSs.
- 4: Each secondary BS updates $\delta_{n,s}$ (i + 1), and broadcasts it to all its serving secondary MTs.
- 5: **if** $R_m \ge R_m^{\min}$, $m \in \mathcal{M}_{\mathrm{RT}}$ and $\varphi_m R_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}} \ge \varphi_{\lfloor m+1 \rfloor_{M_{\mathrm{NRT}}}} R_m$, $m \in \mathcal{M}_{\mathrm{NRT}}$ and $\sum_{\substack{m \in \mathcal{M}_{n,s}}} P_{n,s,m}^* h_{n_1,s,m}^{\mathrm{PBS}} \le I_{n,s}^{\mathrm{Thd}}$ and $|\vartheta(i) - \vartheta(i-1)| \le \varepsilon_p$ then 6: Go to step 10. 7: **else** 8: Set i = i + 1, and go to step 3.
- 9: **end if**
- 10: **until**
- 11: Output $B_{n,s,m}^*$ and $P_{n,s,m}^*$.

are not enough to be allocated. In heuristic power and bandwidth allocation algorithm, $B_{n,s,m}^t$ is the temporary bandwidth allocation variable for cognitive network n BS s MT m, $R_{n,s,m}^t$ is the temporary transmission rate variable for cognitive network n BS s MT m, ΔB is the bandwidth allocation increment, $B_{n,s}^r$ is the remaining bandwidth for cognitive network n BS s, β_m is the allocated power at unit bandwidth, η_m is the normalized utility function for secondary MT m, and η_m^t is the temporary normalized utility function for secondary MT m. Since the heuristic power and bandwidth allocation is designed via greedy algorithm, the convergence can be guaranteed [38].

Require: $B_{n,s}$, P_m^{T} , φ_m , R_m^{\min} and $I_{n,s}^{\mathrm{Thd}}$.
Ensure: $B_{n,s,m}$ and $P_{n,s,m}$.
1: Initialize $B_{n,s,m} = \Delta B$, $B_{n,s,m}^t$, $R_{n,s,m}^t$ and $\beta_m = P_m^T / \sum_{n \in \mathcal{N}} \sum_{n \in \mathcal{N}} B_{n,s}$.
2: repeat $7 \text{ here } s \in S_n$
3: Find $m^* = \min_{m \in \mathcal{M}_{\mathrm{BT}}} \log_2(U_m)$, and update $B_{n,s,m^*}^t = B_{n,s,m^*} + \Delta B$ and R_{n,s,m^*}^t .
4: Select $(n^*, s^*) = \max_{(n,s) \in \mathcal{N}, S_n} R_{n,s,m^*}^t, B_{n^*,s^*,m^*}$, and update $P_{n^*,s^*,m^*} = \beta_{m^*} B_{n^*,s^*,m^*}$.
5: if $\sum_{m \in \mathcal{M}} P_{n^*,s^*,m} h_{n_1,s,m}^{\text{PBS}} < I_{n^*,s^*}$ and $R_m \ge R_m^{\min}$ then
6: Find $\eta_m = \log_2(U_m) / \varphi_m$ $m \in \mathcal{M}_{\text{NRT}}$, and $m^* = \min_{m \in \mathcal{M}_{\text{NRT}}} \eta_m$.
7: Calculate B_{n,s,m^*}^t , R_{n,s,m^*}^t , $(n^*, s^*) = \max_{(n,s)\in\mathcal{N},\mathcal{S}_n} R_{n,s,m^*}^t$, $\eta_{m^*}^t$, and $B_{n^*,s^*}^r = B_{n^*,s^*} - B_{n^*,s^*}$
$\sum_{m \in \mathcal{M}} B_{n^*,s^*,m}.$
8: if $B^{r}_{n^{*},s^{*}} > \Delta B$ and $\sum_{m \in \mathcal{M}} P_{n^{*},s^{*},m} h^{\text{PBS}}_{n_{1},s,m} < I_{n^{*},s^{*}}$ then
9: Update B_{n^*,s^*,m^*} and $P_{n^*,s^*,m^*} = \beta_{m^*}B_{n^*,s^*,m^*}$, and go to step 3.
10: else
11: Go to step 15.
12: end if
13: end if
14: until
15: Output $B_{n,s,m}$ and $P_{n,s,m}$.

B. Computational Complexity

Like reference [39], we have analyzed the computational complexity for the proposed algorithms. In the cooperative bargaining power and bandwidth allocation algorithm, the computational complexity of the gradient method is polynomial with the number of dual variables [36]. Therefore, the computational complexity is $O(O_I M^2 \sum_{n \in \mathcal{N}} S_n)$, and O_I is the number of iterations required for the optimal algorithm. Since optimal algorithm needs to update four Lagrangian multipliers in an iterative manner, O_I is a large number and the online computational complexity is high. Therefore, it is infeasible for optimal algorithm to run in each time slot. In heuristic algorithm, the computational complexity is $O(BP_I \sum_{n \in \mathcal{N}} \sum_{s \in S_n} M_{n,s})$, and BP_I is the number of iterations for power and bandwidth allocation.

VI. PERFORMANCE EVALUATION

This section presents the simulation results for optimal and heuristic algorithms for cognitive heterogeneous networks. A geographical region covered by one cognitive macrocell and one cognitive microcell is considered. The radius of a coverage area at cognitive macrocell is 400 m, while the radius of a coverage area at cognitive microcell 200 m. Due to the overlapped coverage between cognitive macrocell and cognitive microcell, secondary MTs can get service from both secondary macrocell BS and secondary microcell BS. The path loss exponent is 4, and the amplitude of multipath fading is Rayleigh. The noise power is 10^{-19} watts/Hz, and $I_{n,s,m}$ follows Gaussian distribution with zero mean and variance 1×10^{-20} watts. The number of secondary MTs with the non-real-time service in the secondary macrocell and secondary microcell are [2, 3, 1]. The other simulation parameters are $\rho_{n,s,m} = 0.35$, $Q_{n,s,m} = 100$ mW and $\zeta_{n,s,m} = 20 \times 10^{-9}$ watts/Hz [28, 40]. In order to compare with proposed optimal and heuristic algorithms, Tang's algorithm is adopted, which is the fairness resource allocation for cognitive radio network [41].

We evaluate the impact of the interference power threshold on the throughput of non-real time service for different algorithms in Fig. 2, and the throughput for each secondary MT at macrocell vs. the secondary MT index at macrocell for different algorithms in Fig. 3. In Fig. 2, the number of secondary MTs with the real-time service in the secondary macrocell and secondary microcell is 2. The required minimum transmission rate for each secondary MT with the real-time service is 1 Mbps. The bandwidths of macrocell and microcell have two cases, i.e., $B_{n,s} = 5$ MHz and $B_{n,s} = 10$ MHz. In Fig. 3, $B_{n,s} = 5$ MHz and $I_{n,s}^{\text{Thd}} = 1 \times 10^{-9}$ watts. The other simulation parameters in Fig. 3 are the same as Fig. 2. From Fig. 2, we observe that the throughput of non-real time service increases with the interference power threshold for three algorithms. This is because increasing the interference power threshold results in the fact that the available power at each secondary MT grows. Additionally, we can see that increasing the available bandwidth enhances the throughput of non-real time service significantly, which benefits from the relationship of the bandwidth and the power based on the Shannon capacity formulation. The throughput of optimal and heuristic algorithms outperforms that of Tang algorithm. This



Figure 2: The throughput of non-real time service vs. the interference threshold.

is due to the fact optimal and heuristic algorithms utilize the multi-homing technology. Multihoming technology can integrate the vacant bandwidth resource from different cognitive wireless networks. The increasing bandwidth resource can improve the throughput for secondary MTs with non-real-time traffic. However, Tang algorithm only utilizes the resource from single wireless network. In Fig. 3, it can be seen that the throughput of heuristic algorithm for each secondary MT is very close to that of optimal algorithm. Moreover, the throughput of optimal and heuristic algorithms for different secondary MTs satisfy the proportional fairness constraint very well. However, Tang algorithm can not satisfy the proportional fairness constraint for secondary MTs with the non-real-time service. This is because Tang algorithm is designed for max-min fairness, which is the special case of proportional fairness constraint.

We evaluate the impact of the required minimum rate on the throughput of non-real-time service in Fig. 4, and the throughput for each secondary MT at microcell vs. the secondary MT index at microcell in Fig. 5. Additionally, we evaluate the impact of the required minimum rate on Jain fairness index in Fig. 6. The number of secondary MTs with the real-time service in the secondary macrocell and secondary microcell is 3. The bandwidth of macrocell and microcell is



Figure 3: The throughput for each secondary MT at macrocell vs. the secondary MT index at macrocell.

15 MHz. In Fig. 5, the required minimum transmission rate is 0.2 Mbps. The other simulation parameters are the same as Fig. 4. In Fig. 6, the other simulation parameters are the same as Fig. 4. The interference power thresholds of primary macrocell and microcell have two cases, i.e., $I_{n,s}^{\text{Thd}} = 1 \times 10^{-11}$ watts and $I_{n,s}^{\text{Thd}} = 1 \times 10^{-10}$ watts. As can be seen in Fig. 4, the throughputs of non-real time service for optimal and heuristic algorithms decrease along with the required minimum transmission rate. The higher the required minimum rate is, the more power and bandwidth resource secondary MT with the real-time service obtains. Consequently, the sum throughput for secondary MTs with the non-real-time service decreases. It can be also observed that the higher the interference power threshold is, the more the sum throughput for secondary MTs with the non-real-time service more consumption at secondary MT increases. It is shown in Fig. 5 that the throughput of non-real-time service for heuristic algorithm has a slight loss compared with optimal algorithm, and they can both guarantee the secondary MT's fairness very well. Although heuristic algorithm has a slight



Figure 4: The throughput of non-real time service vs. the required minimum transmission rate.

loss on the throughput, it reduces the computational complexity. From Fig. 6, we can observe that Jain fairness index for the optimal and heuristic algorithms are almost close to 1, which means the optimal and heuristic algorithms can guarantee the fairness among secondary MTs with non-real-time traffic very well. Compared with optimal algorithm, Jain fairness index for heuristic algorithm is decreased slightly. However, the loss is very small. This can prove the proposed heuristic algorithm reduce the computational complexity at the cost of a little system performance.

We evaluate the impact of the number of secondary MTs with the real-time service on satisfaction index in Fig. 7. The satisfaction index captures the ability of the power and bandwidth allocation framework to satisfy the required minimum transmission rate of the secondary MTs with the real-time service, the satisfaction index is

$$SI = E\left\{ \mathbb{I}_{R_m \ge R_m^{\min}} + \mathbb{I}_{R_m < R_m^{\min}} \frac{R_m}{R_m^{\min}} \right\}$$
(35)

where $\mathbb{I}_a = 1$ if a is satisfied, and 0 otherwise [29].

The bandwidth of macrocell and microcell is 5 MHz. The interference power threshold of primary macrocell and microcell is $I_{n,s}^{\text{Thd}} = 5 \times 10^{-11}$ watts. The required minimum transmission



Figure 5: The throughput for each secondary MT at microcell vs. the secondary MT index at microcell.



Figure 6: Jain Fairness Index vs. the required minimum transmission rate.



Figure 7: Satisfaction index vs. the number of secondary MTs with the real-time service.

rates for each secondary MT with the real-time service have two cases, i.e., $R_m^{\min} = 1$ Mbps and $R_m^{\min} = 1.2$ Mbps. Fig. 7 depicts the satisfaction index vs. the number of secondary MTs with the real-time service. In Fig. 7, we observe that the satisfaction index for optimal and heuristic algorithms decrease with the number of secondary MTs for the real-time service. The reason is that the more the number of secondary MTs with the real-time service is, the more frequently secondary MTs exhaust the power and bandwidth resources, and aggregating bandwidth resources can not afford the burden of heavy service load. Compared with the curves of two cases, we observe that the satisfaction index is smaller with the required minimum transmission rate. This phenomenon can be explained that increasing the required minimum transmission rate consumes more power and bandwidth resources. Consequently, increasing the secondary MTs with the real-time service leads to higher outage probability.

From Fig. 2 to Fig. 7, it can be concluded that optimal and heuristic algorithms not only improve the throughput of non-real time service, but also guarantee the required minimum transmission rate for secondary MTs with the real-time service, and the proportional fairness for secondary MTs with the non-real-time service. Although heuristic algorithm has a little

performance loss compared with optimal algorithm, it achieves the tradeoff between system performance and computational complexity.

VII. CONCLUSIONS

In this work, we study the uplink power and bandwidth allocation problem for multiple classes of services based on the multi-homing technology for cognitive heterogeneous networks. The objective function maximizes the total utility function to satisfy the real-time service and nonreal-time service for secondary MTs. In order to solve the above joint power and bandwidth allocation problem, we adopt the risk-return model to design the utility function and model it as a cooperative game firstly. Then, the dual decomposition method is utilized to obtain the Nash bargaining solution. Finally, the heuristic algorithm is proposed to reduce the computational complexity. Simulation results demonstrate proposed algorithms not only improve the spectrum efficiency for cognitive heterogeneous networks, but also guarantee the fairness for secondary MTs with the non-real-time service.

APPENDIX A

PROOF OF PROPOSITION 1

Proof. First, we prove Υ is concave and compact. From (12), Υ is bounded and closed. Consequently, it is compact. It is obviously that the first, second and third constraints in (12) are concave. Then, we prove the concavity of R_m for the resource allocation variables $B_{n,s,m}^*$ and $P_{n,s,m}^*$. The Hessian matrix, \mathcal{H}_R , of R_m is

$$\mathcal{H}_{R} = \begin{bmatrix} \frac{\partial^{2} R_{m}}{\partial B_{n,s,m}^{*}^{2}} & \frac{\partial^{2} R_{m}}{\partial B_{n,s,m}^{*} \partial P_{n,s,m}^{*}} \\ \frac{\partial^{2} R_{m}}{\partial P_{n,s,m}^{*} \partial B_{n,s,m}^{*}} & \frac{\partial^{2} R_{m}}{\partial P_{n,s,m}^{*}^{*}} \end{bmatrix}$$
(36)

$$\frac{\partial^2 R_m}{\partial B_{n,s,m}^*}^2 = -\frac{\left(P_{n,s,m}^* h_{n,s,m}^{\text{CBS}}\right)^2}{B_{n,s,m}^* \left(B_{n,s,m}^* n_0 + I_{n,s,m} + P_{n,s,m}^* h_{n,s,m}^{\text{CBS}}\right)^2 \ln 2} \le 0$$
(37)

$$\frac{\partial^2 R_m}{\partial P_{n,s,m}^*}^2 = -\frac{\left(h_{n,s,m}^{\text{CBS}}\right)^2 B_{n,s,m}^*}{\left(B_{n,s,m}^* n_0 + I_{n,s,m} + P_{n,s,m}^* h_{n,s,m}^{\text{CBS}}\right)^2 \ln 2} \le 0$$
(38)

$$\frac{\partial^2 R_m}{\partial B^*_{n,s,m} \partial P^*_{n,s,m}} = \frac{h_{n,s,m}^{\text{CBS}\ ^2} P^*_{n,s,m}}{\left(B^*_{n,s,m} n_0 + I_{n,s,m} + P^*_{n,s,m} h_{n,s,m}^{\text{CBS}}\right)^2 \ln 2}$$
(39)

and

$$\frac{\partial^2 R_m}{\partial P_{n,s,m}^* \partial B_{n,s,m}^*} = \frac{h_{n,s,m}^{\text{CBS}\ 2} P_{n,s,m}^*}{\left(B_{n,s,m}^* n_0 + I_{n,s,m} + P_{n,s,m}^* h_{n,s,m}^{\text{CBS}}\right)^2 \ln 2}.$$
(40)

Since the secondary principal minor of \mathcal{H}_R is 0, \mathcal{H}_R is negative semidefinite [36]. Additionally, R_m is concave in $B^*_{n,s,m}$ and $P^*_{n,s,m}$ according to (36)-(40). Therefore, the third and fourth constraints in (12) are concave. Consequently, Υ constitutes a concave set.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (no. 61301108, No. 61671244), and the Project of Jiangsu Provincial Six Talent Peaks (no.XYDXXJS-033).

REFERENCES

- M. Ismail, A. Abdrabou, and W. Zhuang, "Cooperative decentralized resource allocation in heterogeneous wireless access medium," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 714–724, Feb. 2013.
- [2] X. Ge, S. Tu, G. Mao, C. X. Wang, and T. Han, "5G ultra-dense cellular networks," *IEEE Wireless Commun.*, vol. 23, no. 1, pp. 72–79, Feb. 2016.
- [3] S. Mallick, R. Devarajan, R. Loodaricheh, and V. Bhargava, "Robust resource optimization for cooperative cognitive radio networks with imperfect CSI," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 907–920, Feb. 2015.
- [4] A. C. Cirik, R. Wang, Y. Rong, and Y. Hua, "MSE-based transceiver designs for full-duplex MIMO cognitive radios," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2056–2070, Jun. 2015.
- [5] M. Soysa, P. C. Cosman, and L. B. Milstein, "Disruptive attacks on video tactical cognitive radio downlinks," *IEEE Trans. Commun.*, vol. 64, no. 4, pp. 1411–1422, Apr. 2016.
- [6] T. E. Bogale, L. Vandendorpe, and L. B. Le, "Wide-band sensing and optimization for cognitive radio networks with noise variance uncertainty," *IEEE Trans. Commun.*, vol. 63, no. 4, pp. 1091–1105, Apr. 2015.
- [7] M. G. Song, Y. J. Kim, E. Y. Park, and G. H. Im, "Rate adaptation and power allocation for cognitive radio networks with HARQ-based primary system," *IEEE Trans. Commun.*, vol. 62, no. 4, pp. 1178–1187, Apr. 2014.
- [8] C. Ghosh, S. Roy, and D. Cavalcanti, "Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces," *IEEE Wireless Commun.*, vol. 18, no. 4, pp. 22–31, Aug. 2011.
- [9] G. Sidhu, F. Gao, W. Wang, and W. Chen, "Resource allocation in relay-aided OFDM cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3700–3710, Oct. 2013.
- [10] S. Wang, M. Ge, and C. Wang, "Efficient resource allocation for cognitive radio networks with cooperative relays," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2432–2441, Nov. 2013.
- [11] B. Ning, S. Yang, L. Liu, and Y. Lu, "Resource allocation for OFDM cognitive radio with enhanced primary transmission protection," *IEEE Commun. Lett.*, vol. 18, no. 11, pp. 2027–2030, Nov. 2014.
- [12] Y. Wang, W. Xu, K. Yang, and J. Lin, "Optimal energy-efficient power allocation for OFDM-based cognitive radio networks," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1420–1423, Sep. 2012.

- [13] Z. Hasan, G. Bansal, E. Hossain, and V. Bhargava, "Energy-efficient power allocation in OFDM-based cognitive radio systems: A risk-return model," *IEEE Trans. Wireless Commun.*, vol. 8, no. 12, pp. 6078–6088, Dec. 2009.
- [14] C. Xiong, L. Lu, and G. Li, "Energy-efficient spectrum access in cognitive radios," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 3, pp. 550–562, Mar. 2014.
- [15] A. Attar, M. Nakhai, and A. Aghvami, "Cognitive radio game for secondary spectrum access problem," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 2121–2131, Apr. 2009.
- [16] K. Sethom, A. Salem, F. Mhiri, and R. Bouallegue, "Resource management mechanism for femtocell enterprise networks," in *Proc.2012 IEEE WIAD*, Jun. 2012, pp. 74–78.
- [17] F. Khan and Y.-J. Choi, "Joint subcarrier and power allocations in OFDMA-based cognitive femtocell networks," in *Proc.2012 IEEE APCC*, Oct. 2012, pp. 812–817.
- [18] C. C. Chai, "Distributed subcarrier and power allocation for OFDMA-based cognitive femtocell radio uplink," in *Proc.2013 IEEE PIMRC*, Sep. 2013, pp. 2876–2880.
- [19] L. Xu, P. Wang, Q. Li, and Y. Jiang, "Call admission control with inter-network cooperation for cognitive heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1963–1973, Mar. 2017.
- [20] L. Xu, N. Arumugam, and Y. Yang, "Video packet scheduling with stochastic QoS for cognitive heterogeneous networks," *IEEE Trans. Veh. Technology*, vol. PP, no. 99, pp. 1–1, 2017.
- [21] N. Saquib, E. Hossain, L. B. Le, and D. I. Kim, "Interference management in OFDMA femtocell networks: issues and approaches," *IEEE Wireless Commun.*, vol. 19, no. 3, pp. 86–95, Jun. 2012.
- [22] P. Liu, X. Wang, and J. Li, "Uplink co-tier interference management in femtocell networks with successive group decoding," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 4797–4809, Sep. 2015.
- [23] B. Gu and V. S. Sheng, "A robust regularization path algorithm for nu -support vector classification," IEEE Trans. Neural Networks and Learning Systems, vol. 28, no. 5, pp. 1241–1248, May. 2017.
- [24] B. Gu, X. Sun, and V. S. Sheng, "Structural minimax probability machine," *IEEE Trans. Neural Networks and Learning Systems*, vol. PP, no. 99, pp. 1–11, 2016.
- [25] B. Gu, V. S. Sheng, K. Y. Tay, W. Romano, and S. Li, "Incremental support vector learning for ordinal regression," *IEEE Trans. Neural Networks and Learning Systems*, vol. 26, no. 7, pp. 1403–1416, Jul. 2015.
- [26] L. Xu and A. Nallanathan, "Energy-efficient chance-constrained resource allocation for multicast cognitive OFDM network," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1298–1306, May. 2016.
- [27] J. S. Pang, G. Scutari, D. P. Palomar, and F. Facchinei, "Design of cognitive radio systems under temperature-interference constraints: A variational inequality approach," *IEEE Trans. Signal Process.*, vol. 58, no. 6, pp. 3251–3271, Jun. 2010.
- [28] G. Lim and L. J. Cimini, "Energy-efficient cooperative relaying in heterogeneous radio access networks," *IEEE Wireless Commun. Lett.*, vol. 1, no. 5, pp. 476–479, Oct. 2012.
- [29] M. Ismail, A. T. Gamage, W. Zhuang, X. Shen, E. Serpedin, and K. Qaraqe, "Uplink decentralized joint bandwidth and power allocation for energy-efficient operation in a heterogeneous wireless medium," *IEEE Trans. Commun.*, vol. 63, no. 4, pp. 1483–1495, Apr. 2015.
- [30] W. L. Huang, K. B. Letaief, and Y. J. Zhang, "Cross-layer multi-packet reception based medium access control and resource allocation for space-time coded MIMO/OFDM," *IEEE Trans. Wireless Commun.*, vol. 7, no. 9, pp. 3372–3384, Sep. 2008.
- [31] Z. Pan, Y. Zhang, and S. Kwong, "Efficient motion and disparity estimation optimization for low complexity multiview video coding," *IEEE Trans. Broadcasting*, vol. 61, no. 2, pp. 166–176, Jun. 2015.

- [32] Z. Pan, J. Lei, Y. Zhang, X. Sun, and S. Kwong, "Fast motion estimation based on content property for low-complexity H.265/HEVC encoder," *IEEE Trans. Broadcasting*, vol. 62, no. 3, pp. 675–684, Sep. 2016.
- [33] Z. Pan, P. Jin, J. Lei, Y. Zhang, X. Sun, and S. Kwong, "Fast reference frame selection based on content similarity for low complexity HEVC encoder," *Journal of Visual Communication and Image Representation*, vol. 40, no. B, pp. 516–524, Oct. 2016.
- [34] D. Fudenberg and J.Tirole., Game Theory. MIT Press, 1993.
- [35] R. Langar, S. Secci, R. Boutaba, and G. Pujolle, "An operations research game approach for resource and power allocation in cooperative femtocell networks," *IEEE Trans. Mob. Comput.*, vol. 14, no. 4, pp. 675–687, Apr. 2015.
- [36] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge University Press, 2004.
- [37] J. Shi and L. L. Yang, "Bidirectional worst subchannel avoiding versus best subchannel seeking subcarrier-allocation in downlink OFDMA systems," *IEEE Trans. Veh. Tech.*, vol. 65, no. 9, pp. 7160–7172, Sep. 2016.
- [38] A. ParandehGheibi, A. Eryilmaz, A. Ozdaglar, and M. Medard, "On resource allocation in fading multiple-access channels an efficient approximate projection approach," *IEEE Trans. Information Theory*, vol. 56, no. 9, pp. 4417–4437, Sep. 2010.
- [39] M. Ismail, K. Qaraqe, and E. Serpedin, "Cooperation incentives and downlink radio resource allocation for green communications in a heterogeneous wireless environment," *IEEE Trans. Veh. Tech.*, vol. 65, no. 3, pp. 1627–1638, Mar. 2016.
- [40] G. Miao, "Energy-efficient uplink multi-user MIMO," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2302–2313, May. 2013.
- [41] L. Tang, H. Wang, and Q. Chen, "Power allocation with max-min fairness for cognitive radio networks," in *Proc. 2010 IEEE GMC*, Oct. 2010, pp. 1–5.