Energy Minimization of Multi-cell Cognitive Capacity Harvesting Networks with Neighbor Resource Sharing

Shijun Lin, *Member, IEEE*, Haichuan Ding, Liqun Fu, *Senior Member, IEEE*, Yuguang Fang, *Fellow, IEEE*, Jianghong Shi

***Abstract*—In this paper, we investigate the energy minimization problem for a cognitive capacity harvesting network (CCHN), where secondary users (SUs) without cognitive radio (CR) capability communicate with CR routers via device-to-device (D2D) transmissions, and CR routers connect with base stations (BSs) via CR links. Different from traditional D2D networks that D2D transmissions share the resource of cellular transmissions in the same cell, we consider the scenario that D2D transmissions share the uplink cellular frequency bands (CFBs) of neighbor cells. To ensure that the transmissions from SUs do not affect the transmissions for the cellular users (CUs) in the neighbor cells, an inter-cell handshake process is proposed. We formulate the energy minimization problem for SUs as a mixed integer non-linear programming (MINLP). To solve this problem, we decompose it into two nested subproblems: a transmit power optimization subproblem and a CR router and uplink CFB selection subproblem. For the first subproblem, it is proved to be convex, and thus can be efficiently solved. For the second subproblem, we propose a two-level nested game theoretic approach to findind its solution. Simulation results show that the proposed algorithms can significantly improve the performance. With the help of CR routers/the neighbor resource sharing, the energy consumption for SUs can be saved around 30%-37% on average.**

***Index Terms*—Cognitive capacity harvesting network, Energy minimization, Neighbor resource sharing.**

I. INTRODUCTION

As smart mobile phones become popular, mobile data traffic increases dramatically in recent years. According to the Cisco Visual Networking Index, the mobile data traffic will grow at a compound annual growth rate of 46 percent between 2017 and 2022, reaching 77.5 exabytes per month by 2022 [1]. This dramatic increase in mobile data traffic aggravates the congestion in the existing telecommunication systems. To increase the capacity of telecommunication systems, cognitive radio (CR) [2] and the corresponding cognitive radio networks (CRNs) [3] are proposed, and they are then used to handle congestion problems [4]. With CRs, the secondary users (SUs) can actively sense the unused licensed spectrum and opportunistically utilize it to conduct communications when the transmissions of the primary users (PUs) are not affected.

In the literature, CRNs have been widely investigated under various network architectures, i.e., [5]–[9]. In [5], Fu et al. investigated the energy-efficient communications in the one-hop infrastructure-based CRNs with multiple-input multiple-output (MIMO) techniques. In [6], Wang et al. proposed a frequency-domain cooperative sensing and multi-channel contention protocol for the cognitive radio ad-hoc networks (CRANs); while in [7], Qu et al. studied the problem of network-coding-based multicast in CRANs considering both channel uncertainty and node mobility. In [8], [9], the authors studied the throughput maximization of SUs in the cooperative CRNs where the SUs access primary resource by helping PUs relay packets in one-hop and multi-hop manners. However, in traditional architectures of CRNs, one common drawback is that the SUs, including the light-weighted hand-held end users, should have CR capability, which indeed brings many design challenges in implementation. In particular, the SUs should be equipped with a reconfigurable antenna for data transmissions and a dedicated antenna for spectrum monitoring/sensing, keep monitoring/sensing the spectrum, and frequently switch between different available frequency channels, which will complicate the hardware design and consume a significant amount of computational resources and energy [10]–[12]. Furthermore, in traditional CRNs, it is difficult to establish a common control channel (CCC) for the exchange of control messages due to the uncertainty of the harvested spectrum and the spatial variation of PUs' activities [4]. To enable the SUs without CR capabilities to benefit from CRN and effectively and efficiently manage the resource harvesting and allocation processes in CRN, a new CRN architecture, namely, cognitive capacity harvesting network (CCHN), is proposed [4]. In CCHN, the SUs simply connect with nearby CR routers via the non-CR accessing technologies, while the CR routers communicate with each other or with the base station (BS) via single-hop/multi-hop CR transmissions. Furthermore, a secondary service provider (SSP) is introduced to manage CRN in a centralized manner via reliable licensed control channels.

The existing works about CCHN mainly focus on how to utilize the sensed spectrum effectively through the coor-

The work of S. Lin and J. Shi was partially supported by the National Natural Science Foundation of China under Grant 61401380 and the Specialized Research Fund for the Doctoral Program of Higher Education under Grant 20110121120019. The work of L. Fu was partially supported by the National Natural Science Foundation of China under Grant 61771017. The work of Y. Fang and H. Ding was partially supported by the US National Science Foundation under Grant CNS-1717736. (Corresponding author: Liqun Fu.)

S. Lin, L. Fu, and J. Shi are with the Department of Communication Engineering, Xiamen University, Xiamen 361000, China, e-mail: linsj@xmu.edu.cn, liqun@xmu.edu.cn, shijh@xmu.edu.cn.

H. Ding is with the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109 USA, e-mail: dhcbit@gmail.com.

Y. Fang is with the Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611 USA, e-mail: fang@ece.ufl.edu.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TWC.2020.2971194, IEEE Transactions on Wireless Communications

dination of the centralized SSP [13]–[17]. In [13], Pan et al. investigated the joint routing and frequency scheduling problem for CR routers under uncertain spectrum supply by introducing the parameters of targeted confidence level for the availability of the required spectrum resource, and the targeted quality of CR communications. In [14] and [15], Pan et al. proposed a session-based spectrum trading system for CCHN. They exploited the licensed band vacancy statistics and attempted to obtain the optimal spectrum trading under multiple constraints such as the spectrum availability, the competition among different CR sessions, link scheduling constraints, and flow routing constraints. In [16], Ding et al. proposed vehicular CCHN architecture where CR router enabled vehicles are employed to transport the data of SUs to intended locations via storage of on-board CR routers and harvested spectrum resources. In [17], Ding et al. further developed a Markov-decision-process based spectrum aware data transportation scheme for the vehicular CCHNs. To the best of our knowledge, none of the existing works investigates the design of the access network for CCHNs. However, if the access network is inefficient, the entire CCHN cannot obtain good user experience even when its core CR network is optimally designed.

Considering that the traffic traversed across the CCHN is usually with low-priority, it is reasonable to access the CCHN with device-to-device (D2D) technology [18]–[21]. That is, the SUs connect with the CR routers via D2D transmissions, and share the spectrum of cellular users (CUs) under the premise that the quality-of-service (QoS) of CU transmissions is guaranteed. In this case, to improve the performance of the D2D access network to the CCHN, we should consider not only the resource sharing between D2D transmissions and cellular transmissions, but also the selection of the accessed CR routers, which is different from the existing works on pure resource allocation in the D2D networks [22]–[24].

In this paper, we focus on the energy minimization problem for the SUs in the CCHN, where they communicate with the CR routers via D2D transmissions. Different from the existing D2D studies in which the resource sharing is performed in the same cell [25], [26], we consider the scenario that the D2D transmissions from SUs to CR routers share the uplink cellular frequency bands (CFBs) of neighbor cells. Since for each cell, there are many CR routers and multiple neighbor cells operated on different CFBs, we need to jointly consider the CR router selection, the uplink CFB selection, and the transmit power adjustment for SUs. The main contributions in this paper are summarized as follows:

1) We propose an inter-cell handshake process to ensure that the transmissions of SUs do not affect the transmissions of the CUs in the neighbor cells. We formulate the energy minimization problem for SUs while satisfying their rate requirements as a mixed integer non-linear programming (MINLP).
2) Given the CR router and uplink CFB selections, we show that by changing the variable from “transmit power” to “transmission time”, the formulated energy minimization is a convex optimization problem, and thus can be efficiently solved by typical optimization methods.
3) We further propose a two-level game theoretic approach to improving the CR router and uplink CFB selections. We conduct extensive simulations and show that the proposed algorithms could achieve significantly better performance, i.e., the energy consumption for SUs can be saved 30%-37% on average and the CCHN can accommodate more SUs with higher transmission rates.

The rest of this paper is organized as follows. Section II presents the network and power model, and proposes the inter-cell handshake process. In Section III, we formulate the energy minimization for SUs while satisfying their rate requirements. In Section IV, we optimize the transmit power of SUs when the CR router and uplink CFB selections are given. In Section V, we propose a two-level game theoretic approach to improve the CR router and uplink CFB selections. In section VI, we carry out simulations to evaluate the performance of the proposed algorithms. Section VII concludes this paper.

II. System description

A. Multi-cell CCHNs

In this paper, the considered CCHN is built based on traditional multi-cell cellular network by randomly placing a set of CR routers in each cell and introducing a centralized controller “SSP”, as shown in Fig. 1. In each cell, there is a BS, a set of CR routers, and two kinds of users: CUs and SUs. Each CU communicates with the BS via a dedicated cellular channel; while each SU connects with a nearby CR router by D2D transmission, which shares one of the dedicated uplink CFBs of the neighbor cells[1]. The CR routers in each cell communicate with the BS in the same cell by using the harvested cognitive spectrums, which are allocated by the centralized controller “SSP” through reliable control channels. In this paper, we focus on the energy minimization of the access network of the considered CCHN. Thus, we assume that the transmission capacity from each CR router to the BS is known. The data transmissions of the SUs are delay-tolerant but do have average rate requirements.

Obviously, the SUs that share different CFBs of the neighbor cells will not interfere with each other since they use different frequency spectrums. For the SUs that share the same CFB of the neighbor cells, we adopt time-division multiple access (TDMA) mechanism to avoid mutual interference. To minimize the energy consumption, the time periods allocated to different SUs are dynamically adjusted according to their average rate requirements.

Furthermore, according to the above descriptions, each SU should select one of the CFBs of the neighbor cells to share. Since the devices that occupy different CFBs have different locations and transmit powers, the interference will be different when different CFBs are selected. Thus, when

[1]In traditional cellular networks, the adjacent cells are usually allocated different dedicated CFBs to avoid severe mutual interference among licensed CUs according to the setting of spatial reuse factor [27]. The CFB allocation example when the spatial reuse factor equals 4 is given in Fig. 1. More CFB allocation details with other spatial reuse factors can be found in [27]. In each cell, the allocated CFB is further divided into orthogonal channels, and each CU will occupy one orthogonal channel, which is also called “cellular channel”.

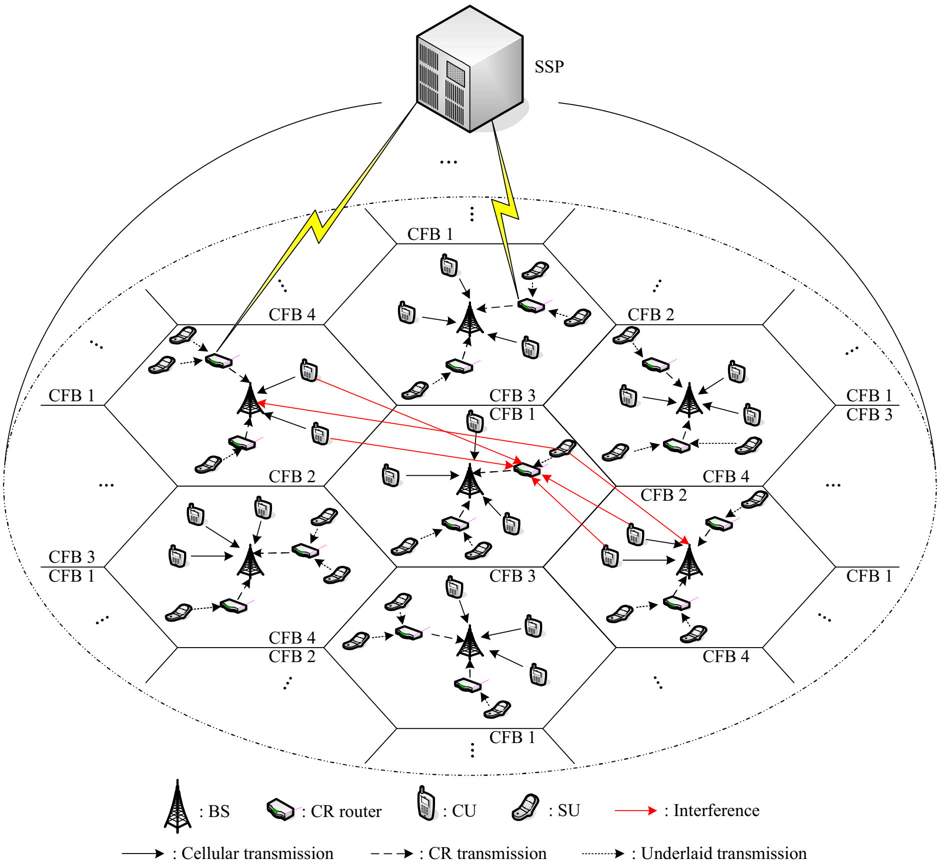


Fig. 1. The considered multi-cell CCHN with a spatial reuse factor of 4.

an SU selects a CFB for its transmission, it would be more likely to select the CFB in which the occupied devices have the smallest interference to its destination. In this paper, we consider the uplink transmissions of SUs. Thus, the SUs connected with the same CR router have the same destination. That is, they would be more likely to select the same CFB in which the occupied devices have the smallest interference to the common connected CR router. Therefore, we assume that the SUs connected with the same CR router select the same CFB of neighbor cells. In fact, this assumption will result in two additional advantages. First, under this assumption, when a CR router receives packets, it does not need to frequently switch between different CFBs, which significantly reduces the energy consumption [11]. Second, the computational complexity of the solution for the considered problem will be greatly reduced since the optimization space is greatly reduced. The benefit of this assumption on the system performance is also evaluated through simulations (See Section VI-C).

B. The inter-cell handshake process

To make sure that the uplink data transmissions of the CUs are not affected, we need a handshake process if the SUs in one cell want to share the uplink CFB of the neighbor cells, as shown in Fig. 2. Let $\mathcal{C}_i^{nb} = \left\{c_j^i, 1 \leq j \leq 6\right\}$ denote the set of neighbor cells of cell c_i. Let BS_i and BS_j^i denote the BS of cell c_i and c_j^i, respectively. When the SUs in cell c_i have data to transmit, they send transmission requests to BS_i via the

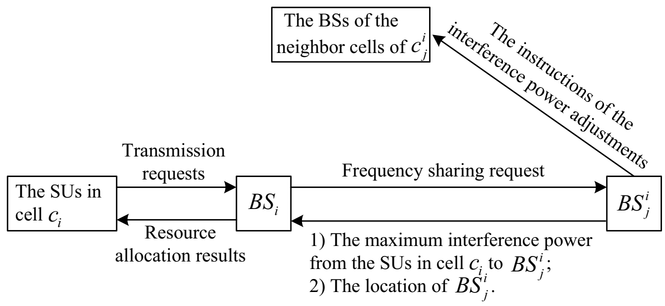


Fig. 2. The inter-cell hand shake process.

control channel. Then, BS_i sends frequency sharing request to all the neighbor BSs ($BS_j^i, 1 \leq j \leq 6$). After receiving the frequency sharing request from BS_i, the neighbor BS (i.e. BS_j^i) deals with the request as follows. Let $N_{BS_j^i}^{cur}$ denote the number of cells that have been allowed by BS_j^i to share the uplink CFB of cell c_j^i. Let $P_{Int}^{bg}\left(BS_j^i\right)$, $P_{Int}^{cur}\left(BS_j^i\right)$ and $P_{Int}^{\max}\left(BS_j^i\right)$ respectively denote the maximum background interference at BS_j^i when $N_{BS_j^i}^{cur} = 0$, the current maximum interference power at BS_j^i, and the maximum interference power at BS_j^i under which all the transmissions of the CUs are not affected. Obviously, when $N_{BS_j^i}^{cur} = 0$, we have $P_{Int}^{cur}\left(BS_j^i\right) = P_{Int}^{bg}\left(BS_j^i\right)$. Then, if $N_{BS_j^i}^{cur} = 0$, BS_j^i tells BS_i the following information by sending back a response: 1) the maximum interference power from the SUs in cell c_i to BS_j^i, which is $\left(P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{cur}\left(BS_j^i\right)\right)$; 2) the location of BS_j^i. If $N_{BS_j^i}^{cur}\geq 1$, there are two cases. When $P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{cur}\left(BS_j^i\right)\geq\frac{1}{N_{BS_j^i}^{cur}+1}\left(P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{bg}\left(BS_j^i\right)\right)$, BS_j^i tells BS_i the same information as those in the case $N_{BS_j^i}^{cur}=0$ by sending back a response. When $P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{cur}\left(BS_j^i\right)<\frac{1}{N_{BS_j^i}^{cur}+1}\left(P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{bg}\left(BS_j^i\right)\right)$, BS_j^i first tells the BS(s) of the cell(s) that currently has(have) SUs sharing the uplink CFB of cell c_j^i to reduce their interference powers to BS_j^i. The maximum interference power to BS_j^i from each cell is limited by $\frac{1}{N_{BS_j^i}^{cur}+1}\left(P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{bg}\left(BS_j^i\right)\right)$. Then, BS_j^i tells BS_i the following information by sending back a response: 1) the maximum interference power from the SUs in cell c_i to BS_j^i, which is $\frac{1}{N_{BS_j^i}^{cur}+1}\left(P_{Int}^{\max}\left(BS_j^i\right)-P_{Int}^{bg}\left(BS_j^i\right)\right)$; 2) the location of BS_j^i. After receiving the response from all the neighbor BSs, BS_i can allocate proper time resource, and select proper CR router and uplink CFB for the SUs.

TABLE I
NOTATION SUMMARY

Notation	Physical Meaning
c_i	the considered cell
BS_i	the BS of cell c_i
c_j^i	the j^{th} neighbor cell of c_i
BS_j^i	the BS of cell c_j^i
u_k^i	the k^{th} SU in cell c_i
r_h^i	the h^{th} CR router in cell c_i
f_s^i	the s^{th} uplink CFB used in neighbor cells of c_i
$y_{k,h}^1$	the indicator denoting whether SU u_k^i connects with CR router r_h^i
$y_{h,s}^2$	the indicator denoting whether the group of SUs connected with CR router r_h^i share the uplink CFB f_s^i
$Q_{u_k^i}$	the average rate requirement of SU u_k^i
$P_{tr}^{u_k^i}$	the transmit power of SU u_k^i
$P_c^{u_k^i}$	the circuit power consumption of SU u_k^i
$P_{id}^{u_k^i}$	the idle power consumption of SU u_k^i
θ	the drain efficiency of PA
$g_{v_1}^{v_2}$	the channel gain from device v_1 to device v_2
$P_{IN}^{f_s^i,r_h^i}$	the maximum level of interference and noise power at CR router r_h^i when uplink CFB f_s^i is selected

* Device v_1 and device v_2 can be any device, i.e. SU, CU, CR router, and BS.

C. The power model of SUs

Since we consider uplink transmissions, the power consumption of an SU contains two parts:

1) The power consumption of the power amplifier (PA) P_{PA}, which is determined by the output power of the transmitter P_{tr} and the drain efficiency of PA θ. Specifically, $P_{PA}=\frac{P_{tr}}{\theta}$.
2) Circuit power consumption P_c, which is the power consumption of the other circuit blocks except for the PA.

When an SU does not transmit, it turns off all the circuit blocks and only consumes a small amount of energy due to the leakage currents [28]. We call this power consumption "idle power consumption", denoted by P_{id}. The main notations of this paper are summarized in Table I.

III. PROBLEM FORMULATION

In this section, we formulate the energy minimization problem of the SUs in cell c_i when they share the uplink CFBs of the neighbor cells c_j^i $(1\leq j\leq 6)$. Let $\mathcal{U}_i=\left\{u_k^i,1\leq k\leq|\mathcal{U}_i|\right\}$ and $\mathcal{R}_i=\left\{r_h^i,1\leq h\leq|\mathcal{R}_i|\right\}$ denote the set of SUs and CR routers in cell c_i, respectively. Let $\mathcal{F}_i=\left\{f_s^i,1\leq s\leq|\mathcal{F}_i|\right\}$ denote the set of uplink CFBs used by the neighbor cells of c_i. Without loss of generality, we assume that f_s^i is used by cell $c_{s+b|\mathcal{F}_i|}^i$, where b is an integer in the range $\left[0,\frac{6}{|\mathcal{F}_i|}-1\right]$. We define two variables $y_{k,h}^1\in\{0,1\}$ and $y_{h,s}^2\in\{0,1\}$ which indicate whether SU u_k^i connects with CR router r_h^i, and whether the group of SUs connected with CR router r_h^i share the uplink CFB f_s^i, respectively. As shown in Section II-A, each SU connects with one CR router, and each group of SUs that connect with one CR router select one uplink CFB of neighbor cells to share. Thus, we have $\sum\limits_{r_h^i\in\mathcal{R}_i}y_{k,h}^1=1,\forall u_k^i\in\mathcal{U}_i$ and $\sum\limits_{f_s^i\in\mathcal{F}_i}y_{h,s}^2=1,\forall r_h^i\in\mathcal{R}_i$.

The energy consumption of each SU is determined by the power consumption and the time fraction for transmission, both of which are closely related to the transmission rate of SU. In the following, we calculate the transmission rate of SU u_k^i when it connects with CR router r_h^i and shares the uplink CFB f_s^i, $x_{u_k^i}\left(r_h^i,f_s^i\right)$. Let $g_{v_1}^{v_2}$ denote the channel gain from device v_1 to device v_2, where device v_1 and device v_2 can be any device, i.e. SU, CU, CR router, and BS. According to the Shannon's capacity formula, $x_{u_k^i}\left(r_h^i,f_s^i\right)$ equals

$$x_{u_k^i}\left(r_h^i,f_s^i\right)=W\log\left(1+\frac{P_{tr}^{u_k^i}g_{u_k^i}^{r_h^i}}{P_{IN}^{f_s^i,r_h^i}}\right). \quad (1)$$

Here, $P_{IN}^{f_s^i,r_h^i}$ is the maximum level of interference and noise power at CR router r_h^i when uplink CFB f_s^i is selected; W and $P_{tr}^{u_k^i}$ are the bandwidth of an uplink CFB, and the transmit power of SU u_k^i, respectively. Since the selected uplink CFB is not only used by the neighbor cells, but also the cells far away, the interference comes from the devices in all the related cells that use the uplink CFB f_s^i [29]. Considering that it is difficult to obtain the necessary information for interference calculations from all the related cells, in this paper, we propose to obtain $P_{IN}^{f_s^i,r_h^i}$ by measuring it at r_h^i during the inter-cell handshake process. Furthermore, the natural logarithm is adopted, thus the unit of $x_{u_k^i}\left(r_h^i,f_s^i\right)$ is "nats/s".

Let $Q_{u_k^i}$ denote the average rate requirement of SU u_k^i. Then, the fraction of time needed to satisfy $Q_{u_k^i}$ when SU u_k^i connects with CR router r_h^i and shares the uplink CFB f_s^i, $t_{u_k^i}\left(r_h^i,f_s^i\right)$, equals

$$t_{u_k^i}\left(r_h^i,f_s^i\right)=\frac{Q_{u_k^i}}{x_{u_k^i}\left(r_h^i,f_s^i\right)}. \quad (2)$$

As shown in Section II-A, when SU u_k^i transmits, the other SUs that share the same spectrum do not transmit.

Then, during the time $t_{u_k^i}\left(r_h^i, f_s^i\right)$, the energy consumption of the SUs that share the uplink CFB f_s^i, $E_{f_s^i}^{t_{u_k^i}\left(r_h^i,f_s^i\right)}$, can be calculated as follows:

$$E_{f_s^i}^{t_{u_k^i}\left(r_h^i,f_s^i\right)} = t_{u_k^i}\left(r_h^i, f_s^i\right) \times \left(\frac{P_{tr}^{u_k^i}}{\theta} + P_c^{u_k^i} + \sum_{u_{k'}^i \in \mathcal{U}_i \setminus \left\{u_k^i\right\}} \sum_{r_{h'}^i \in \mathcal{R}_i} y_{h',s}^2 y_{k',h'}^1 P_{id}^{u_{k'}^i}\right), \tag{3}$$

where $P_c^{u_k^i}$ and $P_{id}^{u_k^i}$ is the circuit power consumption and idle power consumption of SU u_k^i.

Let $T_{f_s^i}^{idle}$ denote the fraction of time during which all the SUs that share the uplink CFB f_s^i are idle. That is,

$$T_{f_s^i}^{idle} = 1 - \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 t_{u_k^i}\left(r_h^i, f_s^i\right). \tag{4}$$

The energy consumption of the SUs that share the uplink CFB f_s^i during the time $T_{f_s^i}^{idle}$, $E_{f_s^i}^{idle}$, can be calculated by

$$E_{f_s^i}^{idle} = T_{f_s^i}^{idle}\left(\sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 P_{id}^{u_k^i}\right). \tag{5}$$

Thus, the total energy consumption of the SUs that share the uplink CFB f_s^i, $E_{f_s^i}^{total}$, can be calculated as follows:

$$E_{f_s^i}^{total} = \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 E_{f_s^i}^{t_{u_k^i}\left(r_h^i,f_s^i\right)} + E_{f_s^i}^{idle}. \tag{6}$$

Therefore, the total energy consumption of all the SUs in cell c_i, $E_{c_i}^{total}$, equals

$$\begin{aligned} E_{c_i}^{total} &= \sum_{f_s^i \in \mathcal{F}_i} E_{f_s^i}^{total} \\ &= \sum_{f_s^i \in \mathcal{F}_i}\left(\sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 E_{f_s^i}^{t_{u_k^i}\left(r_h^i,f_s^i\right)} + E_{f_s^i}^{idle}\right). \end{aligned} \tag{7}$$

Applying equations (1)-(6), after some simplifications, equation (7) can be expressed as

$$\begin{aligned} E_{c_i}^{total} = &\sum_{f_s^i \in \mathcal{F}_i} \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i}\left(\frac{y_{h,s}^2 y_{k,h}^1 Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_h^i}}{P_{IN}^{f_s^i,r_h^i}}\right)} \times \right. \\ &\left.\left(\frac{P_{tr}^{u_k^i}}{\theta} + P_c^{u_k^i} - P_{id}^{u_k^i}\left(\sum_{r_{h'}^i \in \mathcal{R}_i} y_{h',s}^2 y_{k,h'}^1\right)\right)\right) \\ &+ \sum_{f_s^i \in \mathcal{F}_i} \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 P_{id}^{u_k^i}. \end{aligned} \tag{8}$$

Since $\sum_{r_h^i \in \mathcal{R}_i} y_{k,h}^1 = 1$ and $\sum_{f_s^i \in \mathcal{F}_i} y_{h,s}^2 = 1$, we have

$$\begin{aligned} &\sum_{f_s^i \in \mathcal{F}_i} \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 P_{id}^{u_k^i} \\ &= \sum_{u_k^i \in \mathcal{U}_i}\left(P_{id}^{u_k^i} \sum_{r_h^i \in \mathcal{R}_i}\left(y_{k,h}^1 \sum_{f_s^i \in \mathcal{F}_i} y_{h,s}^2\right)\right) = \sum_{u_k^i \in \mathcal{U}_i} P_{id}^{u_k^i}. \end{aligned} \tag{9}$$

Furthermore, we have

$$\begin{aligned} &y_{h,s}^2 y_{k,h}^1\left(\sum_{r_{h'}^i \in \mathcal{R}_i} y_{h',s}^2 y_{k,h'}^1\right) \\ &= \left(y_{h,s}^2 y_{k,h}^1\right)^2 + \sum_{r_{h'}^i \in \mathcal{R}_i \setminus \left\{r_h^i\right\}} y_{h,s}^2 y_{k,h}^1 y_{h',s}^2 y_{k,h'}^1. \end{aligned} \tag{10}$$

Since $\sum_{r_h^i \in \mathcal{R}_i} y_{k,h}^1$ equals 1, $y_{k,h}^1$ and $y_{k,h'}^1$ cannot both equal 1 when $h \neq h'$. That is, $\sum_{r_{h'}^i \in \mathcal{R}_i \setminus \left\{r_h^i\right\}} y_{h,s}^2 y_{k,h}^1 y_{h',s}^2 y_{k,h'}^1 = 0$. Considering that $\left(y_{h,s}^2 y_{k,h}^1\right)^2 = 0$ if $y_{h,s}^2 y_{k,h}^1 = 0$, and $\left(y_{h,s}^2 y_{k,h}^1\right)^2 = 1$ if $y_{h,s}^2 y_{k,h}^1 = 1$, we have $\left(y_{h,s}^2 y_{k,h}^1\right)^2 = y_{h,s}^2 y_{k,h}^1$. Then, equation (10) can be simplified to

$$y_{h,s}^2 y_{k,h}^1\left(\sum_{r_{h'}^i \in \mathcal{R}_i} y_{h',s}^2 y_{k,h'}^1\right) = y_{h,s}^2 y_{k,h}^1. \tag{11}$$

Thus, equation (8) can be simplified to

$$\begin{aligned} E_{c_i}^{total} = &\sum_{f_s^i \in \mathcal{F}_i} \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i}\left(\frac{y_{h,s}^2 y_{k,h}^1 Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_h^i}}{P_{IN}^{f_s^i,r_h^i}}\right)} \times \right. \\ &\left.\left(\frac{P_{tr}^{u_k^i}}{\theta} + P_c^{u_k^i} - P_{id}^{u_k^i}\right)\right) + \sum_{u_k^i \in \mathcal{U}_i} P_{id}^{u_k^i}. \end{aligned} \tag{12}$$

Next, we discuss the constraints of the considered energy minimization problem. The first constraint is that the interference from the SUs in cell c_i to the BS of each neighbor cell should not be higher than the value given in the handshake process. Since f_s^i is used by cell $c_{s+b|\mathcal{F}_i|}^i$, we know that cell c_j^i uses the uplink CFB $f_{((j-1) \bmod |\mathcal{F}_i|)+1}^i$. Let $P_{Int}^{c_i,BS_j^i}$ denote the maximum allowed interference from the SUs in cell c_i to the BS of neighbor cell c_j^i. Then, this constraint can be expressed as follows:

$$\begin{aligned} &y_{h,((j-1) \bmod |\mathcal{F}_i|)+1}^2 y_{k,h}^1 P_{tr}^{u_k^i} g_{u_k^i}^{BS_j^i} \leq P_{Int}^{c_i,BS_j^i}, \\ &\forall u_k^i \in \mathcal{U}_i, \forall r_h^i \in \mathcal{R}_i, \forall j \in [1,6]. \end{aligned} \tag{13}$$

The second constraint is that the transmit power of SUs should not be larger than the given maximum transmit power $P_{tr}^{\max}$, that is,

$$P_{tr}^{u_k^i} \leq P_{tr}^{\max}, \forall u_k^i \in \mathcal{U}_i. \tag{14}$$

The third constraint is that the total average rate requirement of the SUs connected with each CR router should not be larger than the given average data rate from each CR router to the BS. Let A_h^i denote the given average data rate from CR router r_h^i to BS_i. Then, this constraint can be expressed as

$$\sum_{u_k^i \in \mathcal{U}} y_{k,h}^1 Q_{u_k^i} \leq A_h^i, \forall r_h^i \in \mathcal{R}_i. \tag{15}$$

The fourth constraint is that the total time fraction of the SUs that share the same uplink CFB should be no more than 1. That is,

$$\sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} y_{h,s}^2 y_{k,h}^1 t_{u_k^i}\left(r_h^i, f_s^i\right) \leq 1, \forall f_s^i \in \mathcal{F}_i. \tag{16}$$

Applying (1) and (2), equation (16) can be expressed as

$$\sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} \frac{y_{h,s}^2 y_{k,h}^1 Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_h^i}}{P_{IN}^{f_s^i, r_h^i}}\right)} \leq 1, \forall f_s^i \in \mathcal{F}_i. \tag{17}$$

Then, the energy minimization problem of the SUs in cell c_i when they share the uplink CFBs of neighbor cells can be formulated as follows:

$$\min \sum_{f_s^i \in \mathcal{F}_i} \sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} \left(\frac{y_{h,s}^2 y_{k,h}^1 Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_h^i}}{P_{IN}^{f_s^i, r_h^i}}\right)} \times \left(\frac{P_{tr}^{u_k^i}}{\theta} + P_c^{u_k^i} - P_{id}^{u_k^i}\right)\right) + \sum_{u_k^i \in \mathcal{U}_i} P_{id}^{u_k^i},$$

$$\text{s.t.} \sum_{r_h^i \in \mathcal{R}_i} y_{k,h}^1 = 1, \forall u_k^i \in \mathcal{U}_i, \tag{18a}$$

$$\sum_{f_s^i \in \mathcal{F}_i} y_{h,s}^2 = 1, \forall r_h^i \in \mathcal{R}_i, \tag{18b}$$

$$y_{h,((j-1) \bmod |\mathcal{F}_i|)+1}^2 y_{k,h}^1 P_{tr}^{u_k^i} g_{u_k^i}^{BS_j^i} \leq P_{Int}^{c_i, BS_j^i}, \forall u_k^i \in \mathcal{U}_i, \forall r_h^i \in \mathcal{R}_i, \forall j \in [1,6], \tag{18c}$$

$$P_{tr}^{u_k^i} \leq P_{tr}^{\max}, \forall u_k^i \in \mathcal{U}_i, \tag{18d}$$

$$\sum_{u_k^i \in \mathcal{U}_i} y_{k,h}^1 Q_{u_k^i} \leq A_h^i, \forall r_h^i \in \mathcal{R}_i, \tag{18e}$$

$$\sum_{u_k^i \in \mathcal{U}_i} \sum_{r_h^i \in \mathcal{R}_i} \frac{y_{h,s}^2 y_{k,h}^1 Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_h^i}}{P_{IN}^{f_s^i, r_h^i}}\right)} \leq 1, \forall f_s^i \in \mathcal{F}_i, \tag{18f}$$

$$\text{var.}\ y_{k,h}^1 \in \{0,1\}, \forall u_k^i \in \mathcal{U}_i, \forall r_h^i \in \mathcal{R}_i, \quad y_{h,s}^2 \in \{0,1\}, \forall r_h^i \in \mathcal{R}_i, \forall f_s^i \in \mathcal{F}_i, \quad P_{tr}^{u_k^i} > 0, \forall u_k^i \in \mathcal{U}_i.$$

Obviously, Problem (18) is an MINLP, which is difficult to solve in general. To solve Problem (18), we decompose it into two nested subproblems: a transmit power optimization subproblem and a CR router and uplink CFB selection subproblem. Then, we solve these two subproblems iteratively. In particular, given the CR router and uplink CFB selections, we optimize the transmit power of the SUs. Then, based on the solution to the transmit power optimization subproblem, a two-level nested game theoretic approach is proposed to improve the CR router and uplink CFB selections iteratively. The proposed solution is indeed not globally optimal but effective. We will evaluate its performance in Section VI.

IV. Transmit power optimization given CR router and CFB selections

When the selections of CR router and uplink CFB are given, we know the CR router and uplink CFB selection of each SU. Let $r_{h(u_k^i)}^i$ and $f_{s(u_k^i)}^i$ denote the connected CR router and the selected uplink CFB of SU u_k^i, respectively. Let $\mathcal{U}_i^{f_s^i}$ denote the set of SUs in cell c_i that use uplink CFB f_s^i. Then, Problem (18) can be simplified as

$$\min \sum_{u_k^i \in \mathcal{U}_i} \left(\frac{Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_{h(u_k^i)}^i}}{P_{IN}^{f_{s(u_k^i)}^i, r_{h(u_k^i)}^i}}\right)} \times \left(\frac{P_{tr}^{u_k^i}}{\theta} + P_c^{u_k^i} - P_{id}^{u_k^i}\right)\right) + \sum_{u_k^i \in \mathcal{U}_i} P_{id}^{u_k^i},$$

$$\text{s.t.}\ P_{tr}^{u_k^i} g_{u_k^i}^{BS_{s(u_k^i)+b|\mathcal{F}_i|}^i} \leq P_{Int}^{c_i, BS_{s(u_k^i)+b|\mathcal{F}_i|}^i}, \forall u_k^i \in \mathcal{U}_i, \forall b \in \left[0, \frac{6}{|\mathcal{F}_i|}-1\right], \tag{19a}$$

$$P_{tr}^{u_k^i} \leq P_{tr}^{\max}, \forall u_k^i \in \mathcal{U}_i, \tag{19b}$$

$$\sum_{u_k^i \in \mathcal{U}_i^{f_s^i}} \frac{Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_{h(u_k^i)}^i}}{P_{IN}^{f_{s(u_k^i)}^i, r_{h(u_k^i)}^i}}\right)} \leq 1, \forall f_s^i \in \mathcal{F}_i, \tag{19c}$$

$$\text{var.}\ P_{tr}^{u_k^i} > 0, \forall u_k^i \in \mathcal{U}_i.$$

To simplify the optimization process, we change the variable from $P_{tr}^{u_k^i}$ to $t\left(P_{tr}^{u_k^i}\right)$ as follows. Since

$$t\left(P_{tr}^{u_k^i}\right) \triangleq \frac{Q_{u_k^i}}{W \log\left(1+\frac{P_{tr}^{u_k^i} g_{u_k^i}^{r_{h(u_k^i)}^i}}{P_{IN}^{f_{s(u_k^i)}^i, r_{h(u_k^i)}^i}}\right)}, \tag{20}$$

we have

$$P_{tr}^{u_k^i} = \frac{P_{IN}^{f_{s(u_k^i)}^i, r_{h(u_k^i)}^i}}{g_{u_k^i}^{r_{h(u_k^i)}^i}} \left(\exp\left(\frac{Q_{u_k^i}}{W t\left(P_{tr}^{u_k^i}\right)}\right) - 1\right). \tag{21}$$

From equation (20), we know that $t\left(P_{tr}^{u_k^i}\right)$ is a decreasing function of $P_{tr}^{u_k^i}$. Then, Constraints (19a) and (19b) can be

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TWC.2020.2971194, IEEE Transactions on Wireless Communications

expressed as

$$t\left(P_{tr}^{u_k^i}\right) \geq \frac{Q_{u_k^i}}{W\log\left(1+\frac{P_{Int}{}^{c_i,BS^i}_{s\left(u_k^i\right)+b|\mathcal{F}_i|}\, g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)}}{g_{u_k^i}{}^{BS^i}_{s\left(u_k^i\right)+b|\mathcal{F}_i|}\, P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}}}\right)}, \tag{22}$$
$$\forall u_k^i \in \mathcal{U}_i, \forall b \in \left[0, \frac{6}{|\mathcal{F}_i|}-1\right],$$

and

$$t\left(P_{tr}^{u_k^i}\right) \geq \frac{Q_{u_k^i}}{W\log\left(1+\frac{P_{tr}^{\max} g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)}}{P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}}}\right)}, \forall u_k^i \in \mathcal{U}_i. \tag{23}$$

Combining inequalities (22) and (23), we have

$$t\left(P_{tr}^{u_k^i}\right) \geq \alpha_{u_k^i}, \forall u_k^i \in \mathcal{U}_i, \tag{24}$$

where $\alpha_{u_k^i}$ equals

$$\frac{Q_{u_k^i}}{W\log\left(1+\frac{\min\left(\min\limits_{0\le b\le\frac{6}{|\mathcal{F}_i|}-1}\left(\frac{P_{Int}{}^{c_i,BS^i}_{s\left(u_k^i\right)+b|\mathcal{F}_i|}}{g_{u_k^i}{}^{BS^i}_{s\left(u_k^i\right)+b|\mathcal{F}_i|}}\right), P_{tr}^{\max}\right) g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)}}{P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}}}\right)}.$$

Applying (21), Problem (19) can be recast to

$$\min \sum_{u_k^i\in\mathcal{U}_i}\left(t\left(P_{tr}^{u_k^i}\right)\left(\frac{P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}}}{\theta g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)}}\left(\exp\left(\frac{Q_{u_k^i}}{Wt\left(P_{tr}^{u_k^i}\right)}\right)\right.\right.\right.$$
$$\left.\left.\left.-1\right)+P_c^{u_k^i}-P_{id}^{u_k^i}\right)\right)+\sum_{u_k^i\in\mathcal{U}_i} P_{id}^{u_k^i},$$
$$\text{s.t. } t\left(P_{tr}^{u_k^i}\right) \geq \alpha_{u_k^i}, \forall u_k^i \in \mathcal{U}_i, \tag{25a}$$
$$\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}} t\left(P_{tr}^{u_k^i}\right) \leq 1, \forall f_s^i \in \mathcal{F}_i, \tag{25b}$$
$$\text{var. } t\left(P_{tr}^{u_k^i}\right), \forall u_k^i \in \mathcal{U}_i.$$

From Problem (25), we can easily find that the optimization processes of the SUs that use different uplink CFBs are independent of each other. Thus, Problem (25) can be divided into $|\mathcal{F}_i|$ separate subproblems, and solved in a parallel manner. For the SUs that use uplink CFB f_s^i, the energy minimization problem can be expressed as follows:

$$\min \sum_{u_k^i\in\mathcal{U}_i^{f_s^i}}\left(t\left(P_{tr}^{u_k^i}\right)\left(\frac{P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}}}{\theta g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)}}\left(\exp\left(\frac{Q_{u_k^i}}{Wt\left(P_{tr}^{u_k^i}\right)}\right)\right.\right.\right.$$
$$\left.\left.\left.-1\right)+P_c^{u_k^i}-P_{id}^{u_k^i}\right)\right)+\sum_{u_k^i\in\mathcal{U}_i} P_{id}^{u_k^i},$$
$$\text{s.t. } t\left(P_{tr}^{u_k^i}\right) \geq \alpha_{u_k^i}, \forall u_k^i \in \mathcal{U}_i^{f_s^i}, \tag{26a}$$
$$\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}} t\left(P_{tr}^{u_k^i}\right) \leq 1, \tag{26b}$$
$$\text{var. } t\left(P_{tr}^{u_k^i}\right), \forall u_k^i \in \mathcal{U}_i^{f_s^i}.$$

Theorem 1: Problem (26) is a convex optimization problem.

Proof: Obviously, the constraint set of Problem (26) is a convex set. The second-order derivative of the objective function of Problem (26) with respect to $t\left(P_{tr}^{u_k^i}\right)$, equals

$$\frac{P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}} Q_{u_k^i}^2}{\theta g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)} W^2\left(t\left(P_{tr}^{u_k^i}\right)\right)^3}\exp\left(\frac{Q_{u_k^i}}{Wt\left(P_{tr}^{u_k^i}\right)}\right), \tag{27}$$

which is always positive. Therefore, the object function of Problem (26) is convex and Problem (26) is a convex optimization problem. ∎

Based on Theorem 1, we can solve the convex optimization problem (26) using the Lagrangian method. Let $\left\{\eta_{u_k^i}, u_k^i \in \mathcal{U}_i^{f_s^i}\right\}$ and λ denote the Lagrangian multipliers of the constraints (26a) and (26b), respectively. The Lagrangian function can then be expressed as

$$L\left(\mathbf{t},\boldsymbol{\eta},\lambda\right) =$$
$$\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}}\left(t\left(P_{tr}^{u_k^i}\right)\left(\frac{P_{IN}{}^{f^i_{s\left(u_k^i\right)},r^i_{h\left(u_k^i\right)}}\left(\exp\left(\frac{Q_{u_k^i}}{Wt\left(P_{tr}^{u_k^i}\right)}\right)-1\right)}{\theta g_{u_k^i}{}^{r^i}_{h\left(u_k^i\right)}}\right.\right.$$
$$\left.\left.+P_c^{u_k^i}-P_{id}^{u_k^i}\right)\right)+\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}} P_{id}^{u_k^i}+\lambda\left(\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}} t\left(P_{tr}^{u_k^i}\right)-1\right)$$
$$+\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}}\eta_{u_k^i}\left(\alpha_{u_k^i}-t\left(P_{tr}^{u_k^i}\right)\right),$$

where $\mathbf{t}$ and $\boldsymbol{\eta}$ are the vectors whose elements are $t\left(P_{tr}^{u_k^i}\right)$ and $\eta_{u_k^i}$, respectively. Since Problem (26) is convex, the necessary and sufficient conditions for optimality are given by Karush-Kuhn-Tucker (KKT) conditions [30], i.e., for all $u_k^i \in \mathcal{U}_i^{f_s^i}$,

$$\frac{\partial L}{\partial t^*\left(P_{tr}^{u_k^i}\right)}=0,\ \eta_{u_k^i}^*\left(\alpha_{u_k^i}-t^*\left(P_{tr}^{u_k^i}\right)\right)=0,$$
$$\text{and } \lambda^*\left(\sum_{u_k^i\in\mathcal{U}_i^{f_s^i}} t^*\left(P_{tr}^{u_k^i}\right)-1\right)=0, \tag{28}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TWC.2020.2971194, IEEE Transactions on Wireless Communications

where $t^*\left(P_{tr}^{u_k^i}\right)$, $\eta_{u_k^i}^*$, and λ^* are the optimal $t\left(P_{tr}^{u_k^i}\right)$, $\eta_{u_k^i}$, and λ, respectively. The optimal Lagrangian multipliers $\eta_{u_k^i}^*$ and λ^* can be computed by the interior point method, as shown in Chapter 11 of the book [30][2]. After obtaining the optimal Lagrangian multipliers, $t^*\left(P_{tr}^{u_k^i}\right)$ can be calculated by applying $\eta_{u_k^i}^*$ to equation $\eta_{u_k^i}^*\left(\alpha_{u_k^i} - t^*\left(P_{tr}^{u_k^i}\right)\right) = 0$. The optimal value of $P_{tr}^{u_k^i}$ when $y_{k,h}^1$ and $y_{h,s}^2$ are given can then be obtained accordingly.

V. Two-level game theoretic approach for CR router and CFB selections

In this section, we propose two nesting coalition games to improve the CR router and uplink CFB selections, respectively. In the outer level, a CFB selection coalition game is used to determine the uplink CFB selection for the group of SUs that connect with each CR router, $y_{h,s}^2$. In each step of the CFB selection coalition game, $y_{h,s}^2$ is given, and a CR router selection coalition game is adopted to determine the CR router selection of the SUs, $y_{k,h}^1$. Next, we present the details of these two nesting coalition games.

A. CR router selection coalition game

In the CR router selection coalition game, the SUs in cell c_i are treated as players. They form $|\mathcal{R}_i|$ coalitions to minimize the system utility. Let $\mathcal{Z} = \left\{\mathcal{Z}_1, \mathcal{Z}_2, ..., \mathcal{Z}_h, ..., \mathcal{Z}_{|\mathcal{R}_i|}\right\}$ denote the $|\mathcal{R}_i|$ coalitions of SUs. Without loss of generality, we assume that CR router r_h^i is connected with the SU(s) in coalition $\mathcal{Z}_h$. If $\mathcal{Z}_h = \emptyset$, CR router r_h^i is not connected with any SU. Obviously, we have $\mathcal{Z}_h \cap \mathcal{Z}_{h'} = \emptyset$ for any $h \neq h'$, and $\bigcup_{r_h^i \in \mathcal{R}_i} \mathcal{Z}_h = \mathcal{U}_i$. Since $y_{h,s}^2$ is given, we can obtain $\mathcal{U}_i^{f_s^i}$ according to the coalition partition of the SUs, $\mathcal{Z}$. Then, the transferable utility of the SUs in $\mathcal{U}_i^{f_s^i}$ under the coalition partition $\mathcal{Z}$, $\varphi_{f_s^i}(\mathcal{Z})$, can be defined as the minimum energy consumption of the SUs in $\mathcal{U}_i^{f_s^i}$, which can be obtained by solving Problem (26). If the solution of Problem (26) does not exist, $\varphi_{f_s^i}(\mathcal{Z})$ is set to "$+\infty$". Let $\mathcal{F}_i^{r_h^i, r_{h'}^i}$ denote the set of uplink CFBs used by the SUs connected with r_h^i and $r_{h'}^i$. The Nash-stable coalition partition of SUs in CR router selection coalition game can be defined as follows.

Definition 1: In the CR router selection coalition game, a coalition partition $\mathcal{Z}$ is Nash-stable if $\forall u_k^i \in \mathcal{Z}_h \in \mathcal{Z}$, for all $\mathcal{Z}_{h'} \in \mathcal{Z} \backslash \{\mathcal{Z}_h\}$, the following conditions cannot be both satisfied:

$$\sum_{f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}} \varphi_{f_s^i}(\mathcal{Z}) > \sum_{f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}} \varphi_{f_s^i}(\mathcal{Z}_{temp1}), \tag{29}$$

$$\sum_{u_k^i \in \mathcal{Z}_{h''}} Q_{u_k^i} \leq A_{h''}^i, \forall \mathcal{Z}_{h''} \in \mathcal{Z}_{temp1}, \tag{30}$$

where $\mathcal{Z}_{temp1} = (\mathcal{Z} \backslash \{\mathcal{Z}_h, \mathcal{Z}_{h'}\}) \cup \left\{\mathcal{Z}_h \backslash \left\{u_k^i\right\}, \mathcal{Z}_{h'} \cup \left\{u_k^i\right\}\right\}$.

[2]Considering that the interior point method is not the key contribution of this paper, and due to the space limitation, we omit its details here. For the readers that are interested in this method, we propose to read Chapter 11 of the book [30] for more details.

Algorithm 1: The algorithm of the CR router selection coalition game

```
Initialization: Generate a random coalition partition of SUs Z_ini that satisfies Σ_{u_k^i ∈ Z_h} Q_{u_k^i} ≤ A_h^i, ∀Z_h ∈ Z_ini;
Set the current coalition partition of SUs Z_cur as Z_ini;
while The coalition partition of SUs does not converge to the final Nash-stable partition Z_final do
    Randomly select an SU (i.e. u_k^i) in a coalition (i.e. Z_h);
    Randomly select a coalition (i.e. Z_h') in Z_cur \ {Z_h};
    Let Z_nex denote the coalition partition when u_k^i is moved from coalition Z_h to Z_h', which equals (Z_cur \ {Z_h, Z_h'}) ∪ {Z_h \ {u_k^i}, Z_h' ∪ {u_k^i}};
    For ∀f_s^i ∈ F_i^{r_h^i, r_h'^i}, calculate φ_{f_s^i}(Z_cur) and φ_{f_s^i}(Z_nex) by solving Problem (26);
    if Σ_{f_s^i ∈ F_i^{r_h^i, r_h'^i}} φ_{f_s^i}(Z_nex) < Σ_{f_s^i ∈ F_i^{r_h^i, r_h'^i}} φ_{f_s^i}(Z_cur) and Σ_{u_k^i ∈ Z_h} Q_{u_k^i} ≤ A_h^i, ∀Z_h ∈ Z_nex then
        Move SU u_k^i from Z_h to Z_h';
        Update the current partition set Z_cur to Z_nex;
Output the final Nash-stable partition Z_final and the corresponding minimum energy consumption under the given y_{h,s}^2.
```

The detailed process of the CR router selection coalition game is described as follows, as shown in Algorithm 1. It contains two sub-processes: the initial sub-process and the adjusting sub-process. In the initial sub-process, we generate a random coalition partition $\mathcal{Z}_{ini}$ that satisfies $\sum_{u_k^i \in \mathcal{Z}_h} Q_{u_k^i} \leq A_h^i, \forall \mathcal{Z}_h \in \mathcal{Z}_{ini}$. In the adjusting sub-process, the current coalition partition $\mathcal{Z}_{cur}$ is first set to $\mathcal{Z}_{ini}$. In each round, we randomly select an SU $u_k^i \in \mathcal{Z}_h$, and a coalition $\mathcal{Z}_{h'} \in \mathcal{Z}_{cur} \backslash \{\mathcal{Z}_h\}$. Let $\mathcal{Z}_{nex}$ denote the coalition partition when u_k^i is moved from coalition $\mathcal{Z}_h$ to $\mathcal{Z}_{h'}$, which equals $(\mathcal{Z}_{cur} \backslash \{\mathcal{Z}_h, \mathcal{Z}_{h'}\}) \cup \left\{\mathcal{Z}_h \backslash \left\{u_k^i\right\}, \mathcal{Z}_{h'} \cup \left\{u_k^i\right\}\right\}$. Then, for $\forall f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}$, we calculate $\varphi_{f_s^i}(\mathcal{Z}_{cur})$ and $\varphi_{f_s^i}(\mathcal{Z}_{nex})$ by solving Problem (26). If

$$\sum_{f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}} \varphi_{f_s^i}(\mathcal{Z}_{nex}) < \sum_{f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}} \varphi_{f_s^i}(\mathcal{Z}_{cur}), \tag{31}$$

and

$$\sum_{u_k^i \in \mathcal{Z}_h} Q_{u_k^i} \leq A_h^i, \forall \mathcal{Z}_h \in \mathcal{Z}_{nex}, \tag{32}$$

then, u_k^i is moved from coalition $\mathcal{Z}_h$ to $\mathcal{Z}_{h'}$, and $\mathcal{Z}_{cur}$ is updated to $\mathcal{Z}_{nex}$. Otherwise, the movement is not executed. After a limited number of iterations, the coalition partition $\mathcal{Z}_{cur}$ converges to the final Nash-stable partition $\mathcal{Z}_{final}$.

The convergence and stability of the CR router selection coalition game is given in Theorem 2.

Theorem 2: Algorithm 1 converges to the Nash-stable partition $\mathcal{Z}_{final}$ in finite time with probability 1.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TWC.2020.2971194, IEEE Transactions on Wireless Communications

Proof: Suppose that the final coalition partition $\mathcal{Z}_{final}$ obtained from Algorithm 1 is not Nash-stable. According to Definition 1, we can find a $u_k^i \in \mathcal{Z}_h \in \mathcal{Z}_{final}$, a $\mathcal{Z}_{h'} \in \mathcal{Z}_{final} \backslash \{\mathcal{Z}_h\}$, and a $\mathcal{Z}_{temp2} = (\mathcal{Z}_{final} \backslash \{\mathcal{Z}_h, \mathcal{Z}_{h'}\}) \cup \{\mathcal{Z}_h \backslash \{u_k^i\}, \mathcal{Z}_{h'} \cup \{u_k^i\}\}$, which satisfy

$$\sum_{f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}} \varphi_{f_s^i}(\mathcal{Z}_{final}) > \sum_{f_s^i \in \mathcal{F}_i^{r_h^i, r_{h'}^i}} \varphi_{f_s^i}(\mathcal{Z}_{temp2}), \tag{33}$$

and

$$\sum_{u_k^i \in \mathcal{Z}_{h''}} Q_{u_k^i} \le A_{h''}^i, \forall \mathcal{Z}_{h''} \in \mathcal{Z}_{temp2}. \tag{34}$$

In this case, we can move u_k^i from coalition $\mathcal{Z}_h$ to $\mathcal{Z}_{h'}$ to further reduce the system utility, which contradicts to the supposition that $\mathcal{Z}_{final}$ is the final coalition partition. Thus, Algorithm 1 converges to the Nash-stable partition $\mathcal{Z}_{final}$ with probability 1. Furthermore, since the number of coalitions in the CR router selection coalition game is $|\mathcal{R}_i|$, the number of possible coalition partitions is the Bell number [31]. Therefore, Algorithm 1 converges in finite time. ∎

B. The CFB selection coalition game

In the CFB selection coalition game, the CR routers are treated as players. They form $|\mathcal{F}_i|$ coalitions to minimize the system utility. Let $\mathcal{D} = \{\mathcal{D}_1, \mathcal{D}_2, ..., \mathcal{D}_s, ..., \mathcal{D}_{|\mathcal{F}_i|}\}$ denote the $|\mathcal{F}_i|$ coalitions of CR routers. Without loss of generality, we assume that the uplink CFB f_s^i is used by the SUs that connect with the CR router(s) in coalition $\mathcal{D}_s$. If $\mathcal{D}_s = \emptyset$, the uplink CFB f_s^i is not used by any SU. Obviously, we have $\mathcal{D}_s \cap \mathcal{D}_{s'} = \emptyset$ for any $s \neq s'$, and $\bigcup_{f_s^i \in \mathcal{F}} \mathcal{D}_s = \mathcal{R}_i$. The transferable utility of all the SUs under the coalition partition $\mathcal{D}$, $\varphi_{total}(\mathcal{D})$, is defined as the minimum energy consumption of all the SUs after the CR router selection, which can be obtained by executing the CR router selection coalition game in Section V-A. We further define the Nash-stable coalition partition in the CFB selection coalition game as follows.

Definition 2: In the CFB selection coalition game, a coalition partition $\mathcal{D}$ is Nash-stable if $\forall r_h^i \in \mathcal{D}_s \in \mathcal{D}$, for all $\mathcal{D}_{s'} \in \mathcal{D} \backslash \{\mathcal{D}_s\}$, we have

$$\varphi_{total}(\mathcal{D}) \le \varphi_{total}(\mathcal{D}_{temp}), \tag{35}$$

where $\mathcal{D}_{temp} = (\mathcal{D} \backslash \{\mathcal{D}_s, \mathcal{D}_{s'}\}) \cup \{\mathcal{D}_s \backslash \{r_h^i\}, \mathcal{D}_{s'} \cup \{r_h^i\}\}$.

Similarly, the CFB selection coalition game contains two sub-processes: the initial sub-process and the adjusting sub-process, as shown in Algorithm 2. In the initial sub-process, the random coalition partition of the CR routers $\mathcal{D}_{ini}$ is generated. In the adjusting sub-process, the current coalition partition of the CR routers, $\mathcal{D}_{cur}$, is first set to $\mathcal{D}_{ini}$. In each round, we try to move a CR router from one coalition to another coalition to further reduce the system transferable utility. Specifically, we randomly select a CR router (i.e. r_h^i) from a coalition (i.e. $\mathcal{D}_s$), and a coalition (i.e. $\mathcal{D}_{s'}$) in $\mathcal{D}_{cur} \backslash \{\mathcal{D}_s\}$. Let $\mathcal{D}_{nex}$ denote the coalition partition when r_h^i is moved from coalition $\mathcal{D}_s$ to $\mathcal{D}_{s'}$, which equals $(\mathcal{D}_{cur} \backslash \{\mathcal{D}_s, \mathcal{D}_{s'}\}) \cup \{\mathcal{D}_s \backslash \{r_h^i\}, \mathcal{D}_{s'} \cup \{r_h^i\}\}$. Then, we calculate $\varphi_{total}(\mathcal{D}_{cur})$ and $\varphi_{total}(\mathcal{D}_{nex})$ by executing the CR router selection coalition game in Section V-A. If

$$\varphi_{total}(\mathcal{D}_{nex}) < \varphi_{total}(\mathcal{D}_{cur}), \tag{36}$$

Algorithm 2: The algorithm of the CFB selection coalition game

```
Initialization: Generate a random coalition partition of
  the CR routers D_ini;
Set the current coalition partition of the CR routers D_cur
  as D_ini;
while The coalition partition of the CR routers does not
  converge to the final Nash-stable partition D_final do
    Randomly select a CR router (i.e. r_h^i) in a coalition
      (i.e. D_s);
    Randomly select a coalition (i.e. D_s') in D_cur\{D_s};
    Let D_nex denote the coalition partition when r_h^i is
      moved from coalition D_s to D_s', which equals
      (D_cur\{D_s, D_s'}) ∪ {D_s\{r_h^i}, D_s' ∪ {r_h^i}};
    Calculate φ_total(D_cur) and φ_total(D_nex) by
      executing the CR router selection coalition game in
      Section V-A;
    if φ_total(D_nex) < φ_total(D_cur) then
        Move CR router r_h^i from coalition D_s to D_s';
        Update the current partition set D_cur to D_nex;
Output the final Nash-stable partition of CR routers
  D_final, the Nash-stable partition of SUs Z_final under the
  Nash-stable partition of CR routers D_final, the transmit
  powers of all the SUs, and the corresponding minimum
  energy consumption of all the SUs.
```

then, we move r_h^i from coalition $\mathcal{D}_s$ to $\mathcal{D}_{s'}$, and update $\mathcal{D}_{cur}$ to $\mathcal{D}_{nex}$. Otherwise, we do not execute the movement. After a limited number of iterations, the coalition partition $\mathcal{D}_{cur}$ converges to the final Nash-stable partition $\mathcal{D}_{final}$.

The convergence and stability of the CFB selection coalition game is given in Theorem 3.

Theorem 3: Algorithm 2 converges to the Nash-stable partition $\mathcal{D}_{final}$ in finite time with probability 1.

The proof of Theorem 3 is similar to the proof of Theorem 2 and thus is omitted here.

VI. Performance evaluation

In this section, we carry out simulations to evaluate the performance of the proposed algorithms and the performance gains brought by the CR router and neighbor resource sharing. In the simulation, the multi-cell CCHN contains one central cell surrounded by six neighbor cells. The frequency reuse factor is set to 7. The radius of each cell is 500 m. The BS locates at the center of each cell, and the CUs, SUs, and the CR routers are uniformly distributed in each cell. We adopt the same power parameters as [28] and [32] such that the circuit power consumption, the idle power consumption, and the drain efficiency of PA are set to 106.4 mW, 25 mW, and 0.2, respectively. The channel gain is obtained from the log-distance path-loss model with a path-loss exponent of 4. The number of CUs in each cell, the maximum transmit power of SUs, the noise power density, and the bandwidth of an uplink CFB are set to 20, 23 dBm, -174 dBm/Hz, and 1 MHz, respectively. The average data rate from each CR router

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TWC.2020.2971194, IEEE Transactions on Wireless Communications

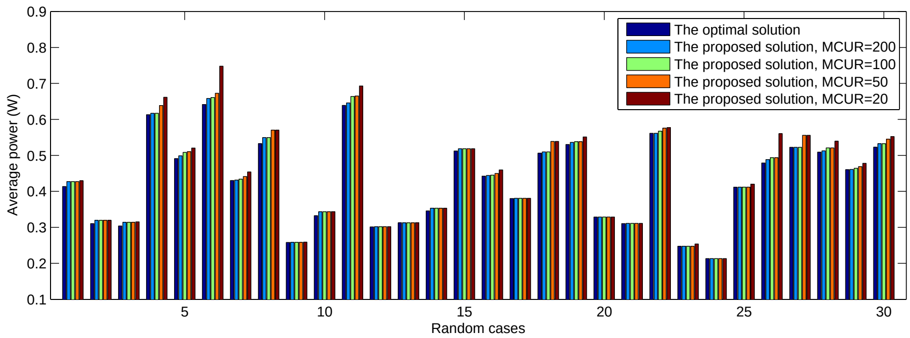


Fig. 3. Comparison with the optimal solution.

to the BS is set to 10 Mnats/s. The transmit power and the rate requirement of CUs are respectively set to 23 dBm and 200 knats/s, which can be used to calculate the maximum allowed interference power at each BS. In the process of a game, a round is called “an unsuccessful round” if the movement of players is not executed. To facilitate simulation, we use the maximum number of consecutive unsuccessful rounds (MCUR) to approximate the Nash-stable state. That is, if the number of consecutive unsuccessful rounds is greater than the given MCUR, the current state of the considered game is treated as Nash-stable state, and the game is terminated. Furthermore, since in this paper, the time resource is normalized to “1”, the energy consumption in a unit time is equivalent to the average power consumption.

A. Comparison with the optimal solution

Fig. 3 shows the energy comparison of the proposed algorithm with the optimal solution obtained from exhaustive search. Since the computational complexity of the exhaustive search method increases exponentially with the network size, we can only obtain the solution for a small network with seven SUs and three CR routers. We consider 30 random cases, and in each random case, the rate requirement of SUs is randomly set in the range of [100 knats/s, 1700 knats/s]. From Fig. 3, we can see that the energy consumption of the proposed algorithm is close to the optimal solution when the MCUR is no less than 50.

B. Comparison with other policies

Fig. 4 shows the energy comparison of the proposed optimal power transmission policy and the maximum power transmission policy under different rate requirements and different numbers of SUs when given a random CR router and uplink CFB selection. In the maximum power transmission policy, the transmit power of each SU is set to the maximum value that satisfies constraints (19a) and (19b). The reason that we select the maximum power transmission policy as the benchmark is as follows. The maximum power transmission policy is indeed a fixed power policy. Considering that the left-hand side of constraint (19c) is minimized when the transmit power of each SU is maximized, in the maximum power transmission policy, constraint (19c) will be satisfied if the solution exists. That is, the maximum power transmission policy can accommodate the maximum number of SUs and allow the maximum rate requirements. In order to cover all the configurations of simulation parameters, we select the maximum power transmission policy as the benchmark to represent the fixed power policy. We want to show in this simulation how much gain we can obtain by dynamically adjusting the transmit power, compared with the fixed power policy. In the first subfigure, the rate requirement of SUs varies from 100 knats/s to 1100 knats/s when the number of SUs is set to 20; while in the second subfigure, the number of SUs varies from 10 to 30 when the rate requirement of SUs is set to 600 knats/s. The number of CR routers in both subfigures is set to 10. From Fig. 4, we can see that compared with the maximum power transmission policy, the optimal power transmission policy can at most save 87%-88% of the energy consumption.

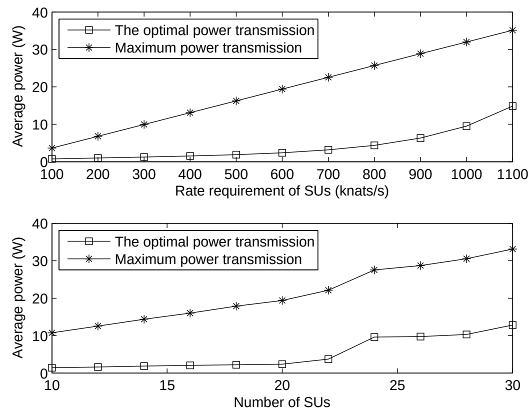


Fig. 4. The optimal transmit power setting versus the maximum power transmission policy.

Fig. 5 and Fig. 6 show the energy consumption of the CR router selection coalition game (CG) versus the nearest-first (NF), the farthest-first (FF), and the random-selection (RS) policies under the optimal transmit power setting when given a random uplink CFB selection. In NF, FF, and RS policy of CR router selection, each SU connects with the nearest, the farthest, and a random-selected CR router that satisfies constraint (15), respectively. In Fig. 5, the rate requirement of SUs varies from 100 knats/s to 1000 knats/s when the number of SUs equals 20; while in Fig. 6, the number of SUs varies from 12 to 45 when the rate requirement of SUs equals 430 knats/s. The number of CR routers and the MCUR in both figures are set to 10 and 200, respectively. In FF and RS policies, some points are not provided because the solution in these settings does not exist. From Fig. 5 and Fig. 6, we can see that the proposed CR router selection CG policy outperforms the NF, FF, and RS policies. The maximum energy saving ratio reaches 81%-94%. Another observation from these two figures is that compared with the NF, FF, and RS policies, the proposed CG policy is more likely to achieve a bigger energy saving ratio when the rate requirement or the number of the SUs is large. The reasons are as follows. Since the uplink CFB selection is given, the selection of CR router is indeed equivalent to the selection of CFB. When the rate requirement or the number of the SUs is small, the time resource of each CFB is abundant. Thus, the effect of CR router selection on the system energy consumption is small. However, when the rate requirement or the number of the SUs is large, the time resource of each CFB is insufficient. In this case, we need to carefully select the CR router for the SUs to make sure that each CFB has similar traffic load. Thus, the proposed CG policy can achieve a bigger energy saving ratio.

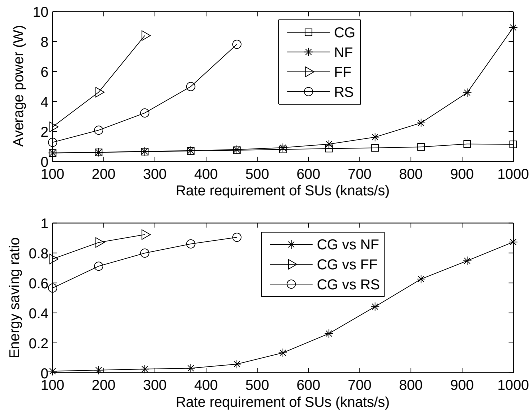


Fig. 5. The performance of CR router selection coalition game under different rate requirement of SUs.

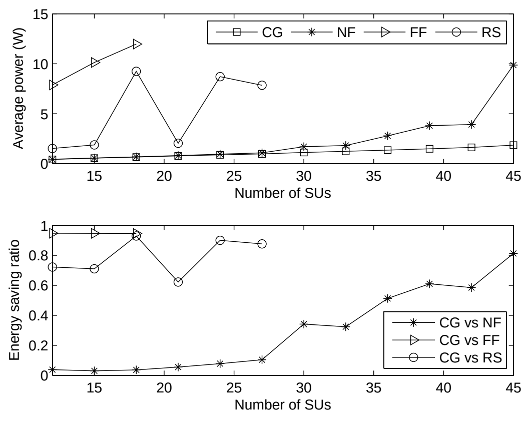


Fig. 6. The performance of CR router selection coalition game under different number of SUs.

Fig. 7 and Fig. 8 show the energy consumption of the CFB selection CG versus the NF, the FF, and the RS policies under the optimal transmit power setting and the CR router selection CG policy. In NF and FF policy of CFB selection, the group of SUs that connect with each CR router selects the CFB that is used by the nearest and farthest BS from the CR router, respectively; in RS policy of CFB selection, the group of SUs that connect with each CR router selects a random CFB. In Fig. 7, the rate requirement of SUs varies from 700 knats/s to 1700 knats/s when the number of SUs equals 20; while in Fig. 8, the number of SUs varies from 18 to 45 when the rate requirement of SUs equals 770 knats/s. The number of CR routers and MCUR in both figures are set to 20 and 200, respectively. In NF and RS policies, some points are not provided because the solution in these settings does not exist. From Fig. 7 and Fig. 8, we can see that on the whole, the energy saving ratio of the CFB selection CG versus the NF, the FF, and the RS policies increases with the rate requirement or the number of the SUs. The maximum energy saving ratio reaches 27%-61%. The reasons are similar to those discussed in Fig. 5 and Fig. 6.

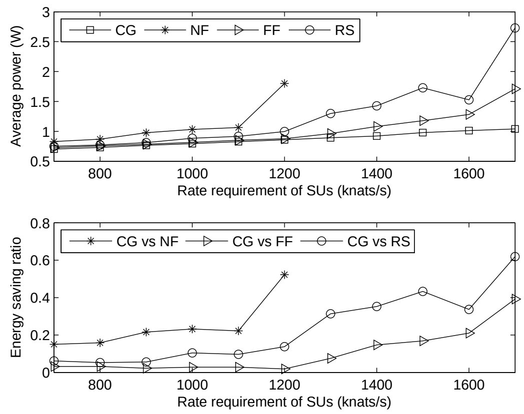


Fig. 7. The performance of CFB selection coalition game under different rate requirement of SUs.

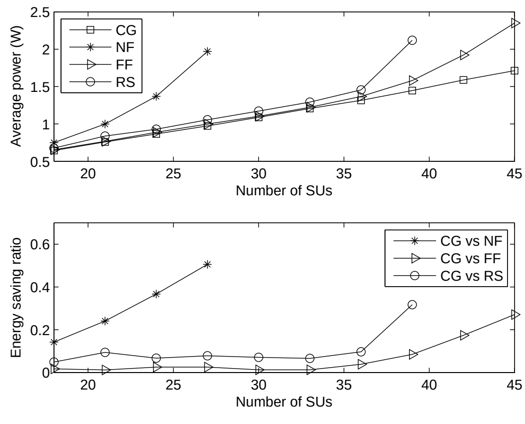


Fig. 8. The performance of CFB selection coalition game under different number of SUs.

C. Some other discussions

Fig. 9 shows the energy consumption of the SUs versus the number of CR routers under different configurations of the rate requirement and the number of SUs when the MCUR is set to 200. From Fig. 9, we can see that under all configuration parameters, the energy consumption of the SUs decreases as the number of CR routers increases. This is because that when the number of CR routers increases, the SUs have a bigger CR router selection space and they can select more proper CR routers to reduce their energy consumption.

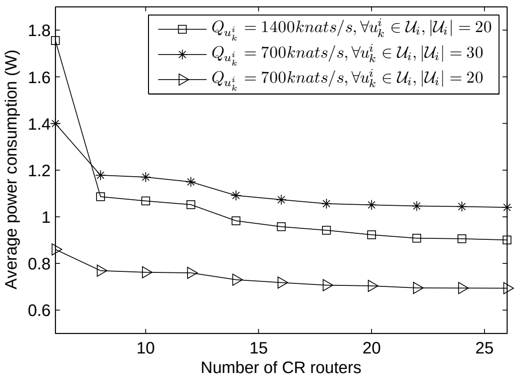


Fig. 9. The effect of the number of CR routers.

Fig. 10 shows the effect of the setting of MCUR on the energy consumption of the SUs and the computational complexity of the proposed solution. We consider 30 random cases, and in each random case, the number of SUs, the rate requirement of each SU, and the number of CR routers are randomly selected in the ranges of [20, 40], [100 knats/s, 500 knats/s], and [10, 25], respectively. From Fig. 10, we can see that the energy consumption of SUs has a big decrease when the value of MCUR changes from 20 to 50, but only decreases a little when the value of MCUR increases from 50 to 200. Furthermore, the computational complexity of the proposed solution increases quickly as the MCUR increases. In practice, we can select a proper MCUR according to the characteristics of the application scenario.

Fig. 11 compares the energy consumption and computational complexity with and without the assumption that the SUs connected with the same CR router select the same CFB of neighbor cells in the same random cases considered in Fig. 10. The MCUR is set to 100. From Fig. 11, we can see that the energy consumption of SUs with the assumption is close to the case without the assumption. That is, the performance cannot be improved by allowing the SUs connected with the same CR router to select different CFBs of the neighbor cells. However, the computational complexity with the assumption is much lower than the case without the assumption. The reason is that without the assumption, the convergence rate becomes much lower since the optimization space is greatly increased.

D. Performance comparison with and without CR routers

Fig. 12 and Fig. 13 show the energy consumption of the SUs and the network capacity under different rate requirements and different numbers of SUs with and without CR routers, respectively. When the CR routers are not used, the SUs connect with the BS directly. When the CR routers are used, the number of CR routers is set to 10. In the first subfigure of Fig. 12, the number of SUs is set to 20 while the rate requirement of SUs varies from 100 knats/s to 700 knats/s; in the second subfigure of Fig. 12, the rate requirement of SUs is set to 400 knats/s while the number of SUs varies from 10 to 30. The ranges of rate requirement and the number of SUs in Fig. 13 are the same as those in Fig. 12. The MCUR in both figures is set to 200. From these two figures, we can see that, 1) by using the CR routers, the energy consumption of the SUs can be saved at a ratio of around 30% on average; 2) when the rate requirement of the SUs is given, the cellular network with the CR routers can at most accommodate more SUs than the case without the CR routers by 6.6 times; 3) when the number of SUs is given, the maximum allowed rate requirement of the SUs in the case with the CR routers is at most 6.2 times bigger than the case without the CR routers.

E. Performance comparison with and without neighbor resource sharing

Fig. 14 and Fig. 15 show the energy consumption of the SUs and the network capacity under different rate requirements and different numbers of SUs with and without neighbor resource sharing, respectively. When the neighbor resource sharing is not adopted, the SUs share the resource of the CUs in their own cell. The number of CR routers is set to 10. In the first subfigure of Fig. 14, the number of SUs is set to 10 while the rate requirement of SUs varies from 30 knats/s to 130 knats/s; in the second subfigure of Fig. 14, the rate requirement of SUs is set to 60 knats/s while the number of SUs varies from 8 to 18. The ranges of rate requirement and the number of SUs in Fig. 15 are the same as those in Fig. 14. The MCUR in both figures is set to 200. From these two figures, we can see that, 1) with neighbor resource sharing, the energy consumption of the SUs can be saved at a ratio of 20%-47%; 2) when the rate requirement of the SUs is given, the cellular network with neighbor resource sharing can at most accommodate more SUs than the case without neighbor resource sharing by 71 times; 3) when the number of SUs is given, the maximum allowed rate requirement of the SUs in the case with neighbor resource sharing is at most 42 times bigger than the case without neighbor resource sharing.

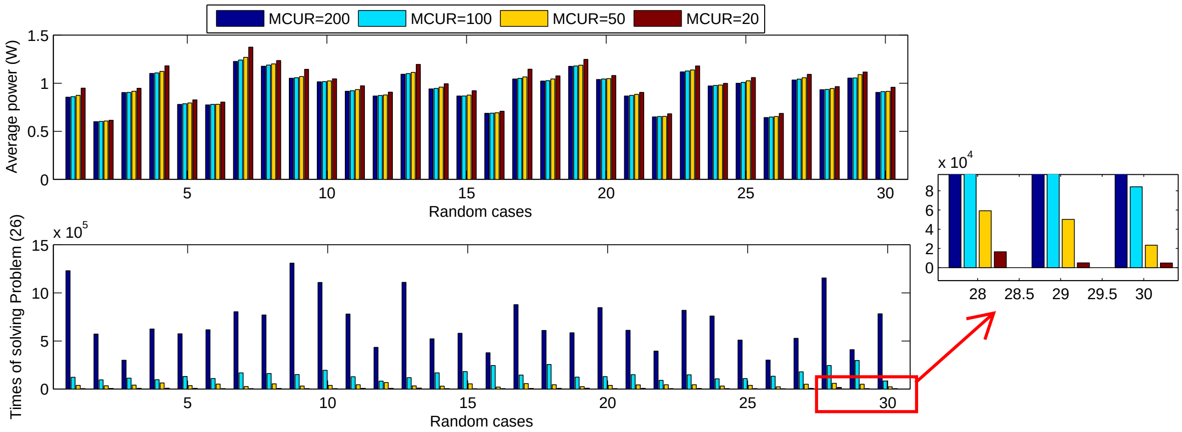


Fig. 10. The effect of the setting of MCUR.

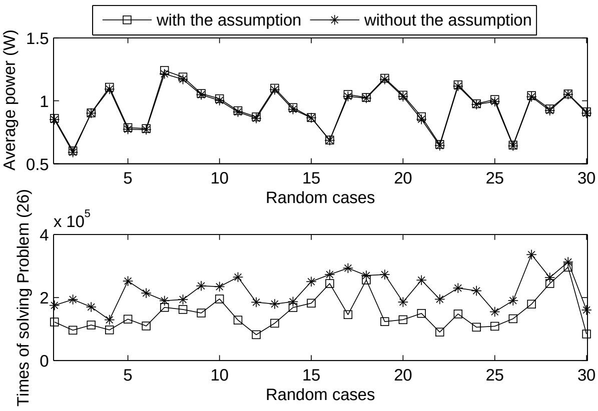


Fig. 11. The energy consumption and computational complexity with and without the assumption that the SUs connected with the same CR router select the same CFB of neighbor cells.

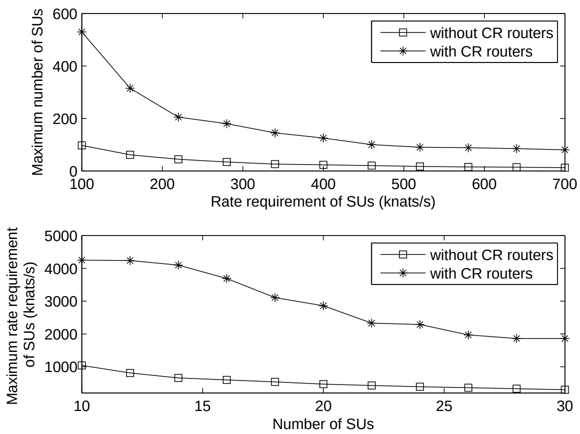


Fig. 13. Network capacity with and without CR routers.

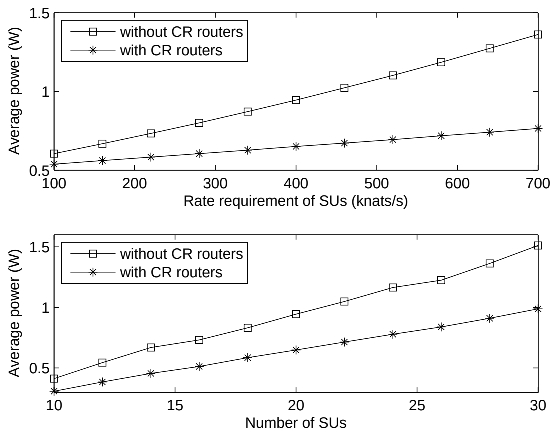


Fig. 12. Energy consumption with and without CR routers.

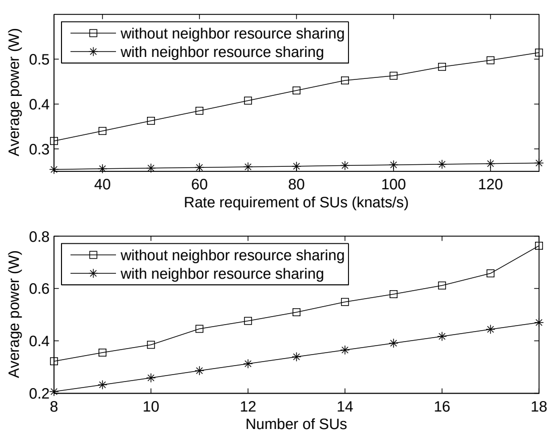


Fig. 14. Energy consumption with and without neighbor resource sharing.

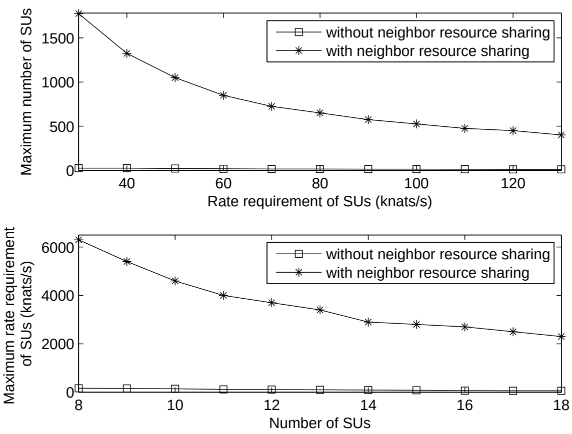


Fig. 15. Network capacity with and without neighbor resource sharing.

VII. Conclusions

In this paper, we investigated the energy minimization problem of the SUs in the CCHN when they share the unlink resource of the CUs in the neighbor cells. We jointly considered the transmit power optimization, CR router selection and CFB selection. We proposed an inter-cell hank shake process to ensure that the transmissions of SUs do not affect the transmissions of the CUs in neighbor cells, and formulated the energy minimization problem as an MINLP. To solve this problem, we decomposed it into a transmit power optimization problem, and a CR router and CFB selection problem. In particular, given the CR router and CFB selections, we showed that the transmit power optimization problem is convex and thus can be efficiently solved by typical methods. We further proposed a two-level game theoretic approach to improve the CR router and CFB selections. Simulation results show that the proposed algorithms that utilize the CR routers or the neighbor resource sharing, have significantly better performance. The average energy saving ratio can reach up to 30%-37%. Furthermore, when the rate requirement of the SUs is given, the cellular network with CR routers/neighbor resource sharing can accommodate more SUs than the case without CR routers/neighbor resource sharing by 6.6 times/71 times. When the number of SUs is given, the maximum allowed rate requirement of the SUs in the case with CR routers/neighbor resource sharing is up to 6.2 times/42 times bigger than the case without CR routers/neighbor resource sharing.

In this paper, we mainly focused on the resource allocation from the pure communication aspect in a centralized CCHN architecture. In the future work, one interesting direction is to consider the joint optimization of the communication, computation, and caching (3C) resource by applying the mobile edge computing to the CCHN architecture. In this case, the optimization problem will become much more complicated and we need to develop more effective algorithms for finding the solution.

References

[1] Cisco, “Cisco Visual Networking Index: Forecast and Trends, 2017ÍC2022,” White Paper, Feb. 2019.

[2] J. Mitola, and G. Q. Maguire, “Cognitive radio: making software radios more personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13-18, Aug. 1999.

[3] R. W. Thomas, D. H. Friend, L. A. Dasilva, and A. B. Mackenzie, “Cognitive networks: adaptation and learning to achieve end-to-end performance objectives,” *IEEE Communications Magazine*, vol. 44, no. 12, pp. 51-57, Dec. 2006.

[4] H. Ding, Y. Fang, X. Huang, M. Pan, P. Li, and S. Glisic, “Cognitive capacity harvesting networks: architectural evolution towards future cognitive radio networks,” *IEEE Communications Surveys & Tutorials*, vol.19, no. 3, pp. 1902-1923, Mar. 2017.

[5] L. Fu, M. Johansson, and M. Bengtsson , “Energy Efficient Transmissions in Cognitive MIMO Systems with Multiple Data Streams,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 9, pp. 5171-5184, Sept. 2015.

[6] L. Wang, K. Wu, J. Xiao, and M. Hamdi, “Harnessing frequency domain for cooperative sensing and multi-channel contention in CRAHNs,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 440-449, Jan. 2014.

[7] Y. Qu, C. Dong, S. Guo, S. Tang, H. Wang, and C. Tian, “Spectrum-Aware Network Coded Multicast in Mobile Cognitive Radio Ad Hoc Networks,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 6, pp. 5340-5350, Jun. 2017.

[8] Y. Long, H. Li, H. Yue, M. Pan, and Y. Fang, “SUM: spectrum utilization maximization in energy-constrained cooperative cognitive radio networks,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 11, pp. 2105-2116, Nov. 2014.

[9] A. H. Bastami, and P. Kazemi, “Cognitive Multi-Hop Multi-Branch Relaying: Spectrum Leasing and Optimal Power Allocation,” *IEEE Transactions on Wireless Communications*, to appear.

[10] A. M. Wyglinski, M. Nekovee, and T. Hou, “Cognitive radio communications and networks: principles and practice,” Academic Press, San Diego, 2010.

[11] S. Wang, F. Tosato, and J. P. Coon, “Reliable energy-efficient spectrum management and optimization in cognitive radio networks: how often should we switch,” *IEEE Wireless Communications Magazine*, vol. 20, no. 6, pp. 14-20, Dec. 2013.

[12] Y. Tawk, J. Costantine, and C. G. Christodoulou, “Cognitive-radio and antenna functionalities: a tutorial,” *IEEE Antennas and Propagation Magazine*, vol. 56, no. 1, pp. 231-243, Feb. 2014.

[13] M. Pan, C. Zhang, P. Li, and Y. Fang, “Spectrum harvesting and sharing in multi-hop crns under uncertain spectrum supply,” *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 2, pp. 369-378, Feb. 2012.

[14] M. Pan, P. Li, Y. Song, Y. Fang, P. Lin, and S. Glisic, “When spectrum meets clouds: optimal session based spectrum trading under spectrum uncertainty,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 3, pp. 615-627, Mar. 2014.

[15] M. Pan, P. Li, Y. Song, Y. Fang, and P. Lin, “Spectrum clouds: a session based spectrum trading system for multi-hop cognitive radio networks,” *IEEE INFOCOM*, Orlando, Florida, USA, pp. 1557-1565, Mar. 2012.

[16] H. Ding, C. Zhang, Y. Cai, and Y. Fang, “Smart cities on wheels: A newly emerging vehicular cognitive capability harvesting network for data transportation,” *IEEE Wireless Communications*, vol. 25, no. 2, pp. 160ÍC169, Apr. 2018.

[17] H. Ding, X. Li, Y. Cai, B. Lorenzo, Y. Fang, “Intelligent Data Transportation in Smart Cities: A Spectrum-Aware Approach,” *IEEE/ACM Transactions on Networking*, vol. 26, no. 6, pp. 2598-2611, Dec. 2018.

[18] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, “Device-to-device communication as an underlay to LTE-advanced networks,” *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42-49, Dec. 2009.

[19] J. Liu, N. Kato, J. Ma, and N. Kadowaki, “Device-to-device communication in LTE-advanced networks: a survey,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1923-1940, 2015.

[20] J. Liu, S. Zhang, N. Kato, H. Ujikawa, and K. Suzuki, "Device-to-Device Communications for Enhancing Quality of Experience in Software Defined Multi-Tier LTE-A Networks," *IEEE Network Magazine*, vol. 29, no. 4, pp. 46-52, Jul. 2015.

[21] J. Liu, Y. Kawamoto, H. Nishiyama, N. Kato, and N. Kadowaki, "Device-to-Device Communications Achieve Efficient Load Balancing in LTE-Advanced Networks," *IEEE Wireless Communications Magazine*, vol. 21, no. 2, pp.57-65, Apr. 2014.

[22] Y. Li, D. Jin, J. Yuan, and Z. Han, “Coalitional games for resource allocation in the device-to-device uplink underlaying cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3965-3977, Jul. 2014.

[23] J. Liu, H. Nishiyama, N. Kato, and J. Guo, "On the Outage Probability of Device-to-Device Communication Enabled Multi-Channel Cellular Networks: A RSS Threshold-Based Perspective," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 1, pp. 163-175, Jan. 2016.

[24] J. Dai, J. Liu, Y. Shi, S. Zhang, and J. Ma, "Analytical Modeling of Resource Allocation in D2D Overlaying Multi-hop Multi-channel Uplink Cellular Networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 8, pp. 6633-6644, Aug. 2017.

[25] N. Sawyer, and D. B. Smith, “Flexible Resource Allocation in Device-to-Device Communications Using Stackelberg Game Theory,” *IEEE Transactions on Communications*, vol. 67, no. 1, pp. 653-667, Jan. 2019.

[26] C. Sergio, and V. Tralli, “QoS-Aware Admission Control and Resource Allocation for D2D Communications Underlaying Cellular Networks,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 8, pp. 5256-5269, Aug. 2018.

[27] T. S. Rappaport, “Wireless Communications: Principles and Practice,” Prentice Hall, 2002.

[28] H. Kim, G. D. Veciana, “Leveraging dynamic spare capacity in wireless systems to conserve mobile terminalsąŕ energy,” *IEEE/ACM Transactions on Networking*, vol. 18, no. 3, pp. 802-815, Jun. 2010.

[29] L. Fu, S. C. Liew, and J. Huang, “Effective Carrier Sensing in CSMA Networks under Cumulative Interference,” *IEEE Transactions on Mobile Computing*, vol. 12, no. 4, pp. 748-760, Apr. 2013.

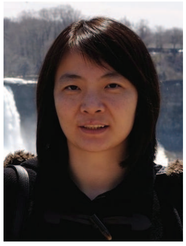
[30] S. Boyd, L. Vandenberghe, “Convex Optimization," Cambridge university press, Cambridge, United Kingdom, 2004.

[31] W. Saad, Z. Han, M. Debbah, A. Hjorungnes, and T. Basar, “Coalitional game theory for communication networks,” *IEEE Signal Processing Magazine*, Special Issue on Game Theory, pp. 77-97, Sept. 2009.

[32] Y. Li, M. Reisslein, C. Chakrabarti, “Energy-efficient video transmission over a wireless link,” *IEEE Transactions on Vehicular Technology*, vol. 58, no. 3, pp. 1229-1244, Mar. 2009.

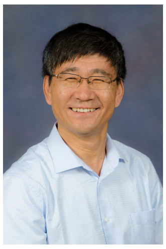
Shijun Lin (M’12) is currently an Associate Professor with the Department of Communication Engineering at Xiamen University (Xiamen, China). He received the B.S. degree (honors) in Electrical Engineering from Xiamen University in 2005, and the Ph.D. Degree in Electrical Engineering from Tsinghua University (Beijing, China) in 2010. From 2016 to 2017, he was a visiting scholar with the Department of Electrical and Computer Engineering, University of Florida. His current research interests are in the area of wireless communications and networking, with focus on cognitive radio network, physical-layer network coding, Device-to-Device communication, wireless greening, resource allocation, and distributed protocol design. He has served as TPC Chair/TPC Member for several international conferences such as ICC, Globecom, ICCC, MLICOM. He is also on the editorial board of KSII Transactions on Internet and Information Systems.

Haichuan Ding received the B.Eng. and M.S. degrees in electrical engineering from Beijing Institute of Technology (BIT), Beijing, China, in 2011 and 2014, and the Ph.D. degree in electrical and computer engineering from the University of Florida, Gainesville, FL, USA, in 2018. From 2012 to 2014, he was with the Department of Electrical and Computer Engineering, the University of Macau, as a visiting student. Since 2019, he has been a postdoctoral research fellow with the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor, MI, USA. His current research interests include mmWave and V2X communications.



Liqun Fu (S’08-M’11-SM’17) is a Full Professor of the School of Informatics at Xiamen University, China. She received her Ph.D. Degree in Information Engineering from The Chinese University of Hong Kong in 2010. She was a post-doctoral research fellow with the Institute of Network Coding of The Chinese University of Hong Kong, and the ACCESS Linnaeus Centre of KTH Royal Institute of Technology during 2011-2013 and 2013-2015, respectively. She was with ShanghaiTech University as an Assistant Professor during 2015-2016.

Her research interests are mainly in communication theory, optimization theory, and learning theory, with applications in wireless networks. She is on the editorial board of IEEE Access and the Journal of Communications and Information Networks (JCIN). She served as the Technical Program Co-Chair of the GCCCN Workshop of the IEEE INFOCOM 2014, the Publicity Co-Chair of the GSNC Workshop of the IEEE INFOCOM 2016, and the Web Chair of the IEEE WiOpt 2018. She also serves as a TPC member for many leading conferences in communications and networking, such as the IEEE INFOCOM, ICC, and GLOBECOM.



Yuguang Fang (F’08) received an MS degree from Qufu Normal University, Shandong, China in 1987, a PhD degree from Case Western Reserve University in 1994, and a PhD degree from Boston University in 1997. He joined the Department of Electrical and Computer Engineering at University of Florida in 2000 as an assistant professor, then was promoted to an associate professor in 2003 and a full professor in 2005, and has been a distinguished professor since 2019. He holds a University of Florida Foundation Preeminence Term Professorship (2019-2022), a University of Florida Foundation Professorship (2017-2020, 2006-2009), a University of Florida Term Professorship (2017-2019, 2019-2021).

Dr. Fang received the US NSF Career Award in 2001, the US ONR Young Investigator Award in 2002, the 2018 IEEE Vehicular Technology Outstanding Service Award, the 2015 IEEE Communications Society CISTC Technical Recognition Award, the 2014 IEEE Communications Society WTC Recognition Award, the Best Paper Award from IEEE ICNP (2006), and a 2010-2011 UF Doctoral Dissertation Advisor/Mentoring Award. He was the Editor-in-Chief of IEEE Transactions on Vehicular Technology (2013-2017) and IEEE Wireless Communications (2009-2012), and serves/served on several editorial boards of premier journals. He also served as the Technical Program Co-Chair of IEEE INFOCOM’2014. He is a fellow of IEEE and AAAS.

Jianghong Shi received his Ph.D. from Xiamen University, China, in 2002. He is currently a professor in the School of Information Science and Technology, Xiamen University. He is also the director of the West Straits Communications Engineering Center, Fujian Province, China. His research interests include wireless communication networks and satellite navigation.