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Joint Power, Original Bandwidth and Detected Hole Bandwidth Allocation for Multi-Homing Heterogeneous Networks Based on Cognitive Radio

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***Abstract*—In this paper, we investigate a joint resource allocation problem based on cognitive radio (CR) techniques for user equipment (UE) with multi-homing capabilities. We consider a heterogeneous wireless medium where users in overlapping coverage areas simultaneously communicate with different base stations (BSs) and access points (APs). Currently, existing works assume that the working frequency bands of different networks are separated. Unlike these works, this paper focuses on the multi-homing networks which can share spectrum resources of each other to enhance the resource utilization efficiency. Based on spectrum sensing and spectrum sharing techniques in CR, we propose and then formulate an uplink joint original bandwidth, detected hole bandwidth and power allocation method. Specifically, the formulated optimization problem is a mixed integer nonlinear optimization problem. We adopt the continuity relaxation method to further transform it into a convex optimization problem and then solve it by Lagrange dual solution. A suboptimal method is further proposed with a reduced system overhead. Simulation results demonstrate the significantly improved performance of our proposed methods (both optimal and suboptimal) in terms of system throughput and energy efficiency over a joint resource allocation benchmark. Our results also indicate that the suboptimal strategy can indeed reduce the system overhead remarkably.**

***Index Terms*—Multi-homing heterogeneous network, cognitive radio, joint resource allocation, continuity relaxation method, spectrum sensing.**

I. Introduction

DURING the last decades, the wireless industry is pursuing for an astounding 1000-fold increase in terms of media applications [1]. Many conventional single-network technologies such as non-orthogonal multiple access [2] and dynamic spectrum management [3] have been proposed to increase the resource utilization efficiency to help enable such applications. In the meanwhile, the multi-homing framework [4] is considered as a promising technology to help achieve such target.

User equipments (UEs) with multi-homing capabilities maintain multiple connections with different base stations (BSs) and access points (APs) in a heterogeneous wireless network simultaneously and increase the data transmission rate by aggregating the bandwidth of these BSs/APs. The fifth generation (5G) wireless network [5-7] desires to create better user experience with limited resources for each individual user. As techniques constantly develop, the development space of single-network is getting smaller and smaller. Then the interworking among multiple networks is more promising to cater for users' increasing requirements for the high quality of service. Therefore, research works about multi-homing networks have attracted more and more attention recently. For instance, the cooperation between cellular networks and dedicated short-range communications (DSRC) networks was investigated in [8]. Authors of [9] integrated two kinds of networks, i.e., the vehicular ad-hoc network (VANET) and the third generation (3G) heterogeneous wireless network. Other examples for multi-homing heterogeneous networks include cellular/world interoperability for microwave access (WiMAX)/wireless local area network network (WLAN) [10-11], cellular/vehicle to everything (V2X) networks [8], long term evolution (LTE)/wireless fidelity (WiFi) [12], cellular/WLAN [13] and so on.

In the multi-homing medium, we regard resources of various networks as a whole and assign them to the most appropriate users. Compared with single networks, UEs with multi-homing capabilities have more options and thus they are likely to find more effective allocation results. Besides, femto-cells which are located near the bounds of macro-cells help avoid the frequent handovers between mobile UEs with BSs. That is to say multi-homing networks are capable of providing considerable benefits to the system performance.

However, compared with resource allocation in single networks, allocation methods for multi-homing networks are challenged by the following facts. First, the multi-homing feature leads to more resource parameters pending to be allocated. Also, the relationships among system variables are more complicated and so are the constraints. Therefore,

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the formulated resource allocation problem gets much more difficult to solve. Second, UEs need to spend additional power to activate multiple radio interfaces. So how to allocate the system resources for high utilization efficiency to make full use of the constrained resources such as the limited total available power at UEs and the limited bandwidth at BSs/APs is a significantly challenging task.

In the considered multi-homing heterogeneous network as shown in Fig. 1, user A and user B both have multi-homing access capabilities. However, user A is located only in the coverage area of the BS and thus it only sends data to the BS. In the meanwhile, user B communicates with both of the BS and the AP. Currently, all of the other researchers focus on the conventional scenario that the spectrum resources of different networks are separated and cannot be shared with each other. Such scheme makes these systems fail to further adequately utilize their radio resources. This paper smashes such constraint by enabling users to share the same spectrum bands at the same time. We define the inherent radio resources of each individual network as its original resources, and we regard the additional hole resources obtained from spectrum sensing [14-17] as detected hole resources which can be shared and reused. In this paper, we plan to jointly allocate these two kinds of resources to maximize the system throughput with the assistance of spectrum sensing and spectrum sharing which are both key techniques of cognitive radio (CR).

The four main contributions of our paper are outlined as follows.

- The uplink joint resource allocation problem based on CR is formulated into mathematical expressions to assign original resources and detected resources to UEs with multi-homing capabilities. This paper is the first to study the joint original and detected hole resource allocation problem in a multi-homing heterogeneous system where networks can share spectrum resources with each other.
- We find that the proposed CR-based joint resource allocation problem is formulated as a mixed integer nonlinear optimization problem. By the continuity relaxation method, it is then converted into a convex optimization problem which can be solved by the Lagrange dual solution. Based on the obtained solutions to the formulated problem, we propose an optimal method for original bandwidth, detected hole bandwidth and transmission power resource allocation.
- We further develop a suboptimal joint resource allocation method, which effectively reduces the system overhead.
- The performance of our proposed optimal and suboptimal methods is evaluated by comparing with a joint resource allocation benchmark. According to the simulation results, the performance of our two proposed methods is significantly superior in terms of the achieved throughput and energy efficiency. Moreover, simulation results also demonstrate that the suboptimal method indeed effectively reduces the system overhead.

The rest of this paper is organized as follows. The related work is reviewed in Section II. In Section III, we present the system model. In Section IV, the uplink joint resource allocation problem based on CR is formulated. Then the continuity relaxation method and the Lagrange dual solution are successively adopted to work out the optimal allocation results of original subcarriers, detected hole subcarriers and power resources regarding the formulated problem. In Section V, we further propose a suboptimal method to reduce the system overhead. The benchmark is then introduced for simulation comparison. Simulation results and discussions are presented in Section VI. Finally, conclusions are made in Section VII. Table I summarizes the important mathematical symbols in this paper.

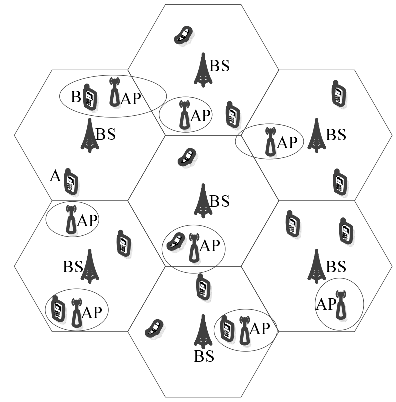

Fig. 1. The multi-homing heterogeneous network coverage areas.

II. RELATED WORK

Researchers have achieved some progress about resource allocation for multi-homing heterogeneous wireless networks. For example, authors of [18] investigated the resource optimization problem for such networks with orthogonal frequency division multiple access (OFDMA). A resource allocation method for heterogeneous wireless medium where both of the single-network and the multi-homing services simultaneously existed was investigated in [19]. Furthermore, a suboptimal decentralized resource allocation method was presented in a dynamic environment as an efficient manner [20]. A joint bandwidth and power allocation method was proposed in [21] for users with multi-homing capabilities in a battery-constrained uplink network. Afterwards, [21] presented a suboptimal method to reduce the system overhead.

However, all of the existing works about resource allocation in multi-homing heterogeneous networks assume that different networks must only work in their own separated frequency bands. In order to utilize the available network resources more adequately, we focus on how to execute the joint bandwidth and power resource allocation in multi-homing heterogeneous networks where the frequency bands of different networks can be reused and shared with each other. Furthermore, CR is able to further improve the spectrum efficiency and it is known as a key technology in 5G [22-23]. For the realization of our resource sharing scheme, CR techniques [24-27] such as the spectrum sensing and spectrum sharing techniques are introduced in this paper. Spectrum sensing technique identifies the spectrum holes which can be shared and reused in the

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbol	Definition
$\mathcal{N}$	Set of wireless networks in the considered geographical region
$\mathcal{S}_n$	Set of BSs/APs of network n
$\mathcal{M}$	Set of UEs in the considered geographical region
$\mathcal{M}_{ns}$	Subset of UEs in the coverage area of network n BS/AP s
$\mathcal{K}_{ns}$	Set of original subcarriers of network n BS/AP s
K_{ns}	Total number of original subcarriers of network n BS/AP s
B_0	Bandwidth of each subcarrier
N_0	One-sided noise power spectral density
x_{nsmk}	Binary original resource assignment variable regarding the subcarrier k at UE m to transmit messages to network n BS/AP s
P_{nsmk}	Transmission power allocated by UE m to the radio interface during communicating with network n BS/AP s by original subcarrier k
$P_{c,nsmk}$	Circuit power consumption of the transmission process between network n BS/AP s and UE m on the original subcarrier k
h_{nsmk}	Channel power gain between UE m and network n BS/AP s on subcarrier k
$D_{ns,k',n's'}$	Spectrum detection result by network n BS/AP s regarding subcarrier k', which is an original subcarrier of network n' BS/AP s'
$\mathcal{K}'_{n's'}$	Set of detected hole subcarriers which originally belong to network n' BS/AP s'
$\hat{x}_{nsmk'}$	Binary detected hole resource assignment variable regarding the hole subcarrier k' at UE m to transmit messages to network n BS/AP s
$\hat{P}_{nsmk'}$	Transmission power allocated by UE m to the radio interface during communicating with network n BS/AP s by the hole subcarrier k'
R_{nsmk}	Data transmission rate achieved by UE m during communicating via original subcarrier k with network n BS/AP s
$\hat{R}_{nsmk'}$	Data transmission rate obtained by UE m during communicating via hole subcarrier k' with network n BS/AP s
$\hat{h}_{nsmk'}$	Channel power gain on the hole subcarrier k' between network n BS/AP s and UE m
P_m	Total power consumed by UE m
$\hat{P}_{c,nsmk'}$	Circuit power consumption of the transmission process between network n BS/AP s and UE m on hole subcarrier k'
$P_{\max}$	Maximum boundary of available power at UE m
R_m	Achieved transmission rate of UE m
$R_{\min}$	Required minimum data rate of each UE
$h_{I_1,nsm'k'}$	Channel power gain between network n BS/AP s and UE m' on subcarrier k'
I_{th_1}	Spectrum detection threshold
I_{th_2}	Preset threshold of interference during spectrum sharing
$h_{I_2,n's'mk'}$	Channel power gain between network n' BS/AP s' and UE m via subcarrier k'
v_m	Lagrangian multiplier for the total power consumption constraint
φ_m	Lagrangian multiplier for the required data rate constraint
$\hat{\gamma}_{nsmk'}$	Lagrangian multiplier for the maximum interference during spectrum sharing constraint
L	Lagrangian function

proposed scheme. Spectrum sharing technique guarantees our resource sharing scheme will not cause harmful interference.

Research about cognitive heterogeneous multi-homing networks has attracted more and more attention where primary heterogeneous networks share the licensed band with cognitive heterogeneous networks as long as the interference at primary networks is within a proper interference level [28]. For instance, a spectrum allocation problem with multi-homing technology subject to constraints in the required transmission rate for heterogeneous constant bit rate and variable bit rate services was studied for cognitive heterogeneous networks in [29]. A spectrum pricing and allocation problem based on hierarchical game theory framework was further studied for cognitive multi-homing networks in [30]. Authors of [31] investigated the resource allocation problem to maximize the system capacity in heterogeneous cognitive radio networks with the coexistence of two types of users, i.e., multi-homing and single-network users. Reference [28] proposed an uplink power and bandwidth allocation problem for multiple services with multi-homing technology for cognitive heterogeneous networks. Constraints include system available bandwidth, interference power for primary base station, total power consumption for each secondary user and so on.

However, all of the above works about cognitive heterogeneous multi-homing networks only focus on the resource allocation process of the cognitive networks. They just investigate how the cognitive networks utilize the detected spectrum resources after spectrum sensing. These works cannot be counted as the same "spectrum sharing schemes" with ours since only the cognitive networks utilize the licensed resources of the primary networks. The reverse is not applicable. In fact, the above cognitive system model can be easily extended to the traditional heterogeneous wireless networks when the interference constraint is set to be infinite. There are no essential differences between cognitive heterogeneous multi-homing networks [28-31] and conventional ones [18-21]. The optimization problem of the former networks only has one more constraint about the interference on the primary networks than conventional heterogeneous wireless network resource optimization problem. They also fail to consider the resource sharing scheme among different networks and thus they lose the opportunity to further increase the utilization efficiency.

Our proposed joint method considers the entire process of original resource allocation, spectrum sensing and detected hole resource allocation. There exists a feedback link in our proposed strategy. Every time the resource allocation iteration procedure is completed, the BSs/APs will provide the allocation results and their associated Lagrange multipliers as feedback information for the original resource allocation stage. Then they will accordingly make appropriate adjustments on original resource allocation results and also allocate the detected hole resources again. This process proceeds circularly until the allocation results satisfy the iteration-stopping condition. The feedback information indicates the adjustment direction for the next iteration. In this way, limited resources can be adequately reused and shared among different networks, increasing the system throughput greatly. To the best of our knowledge, the CR-based joint original and detected hole resource allocation in multi-homing heterogeneous networks where spectrum resources are shared among them has never been investigated in other works.

In this paper, we propose a joint resource allocation method based on CR in a heterogeneous multi-homing wireless system where networks mutually share spectrum resources. Like [10] and [18], we also adopt OFDMA as the wireless access technology. That is the reason why bandwidth allocation in this paper is actually subcarrier assignment. Then we formulate the entire allocation problem. Through analysis, we find out that the established optimization problem is actually a mixed integer nonlinear optimization problem. So we employ the continuity relaxation method to transform it into a convex optimization problem and further solve it by Lagrange dual solution. Considering the high system overhead of loop iteration in the proposed optimal strategy, a suboptimal method is then proposed with a reduced system overhead. According to the simulation results, our proposed allocation method and its suboptimal strategy significantly improve the system performance in terms of throughput and energy efficiency, compared to the benchmark. Also, we verify that the suboptimal strategy can indeed greatly reduce the system overhead compared with the optimal strategy.

III. System Model

In this paper, we consider a geographical region where a set of wireless networks $\mathcal{N} = \{1, 2, \cdots, N\}$[1] is available, as shown in Fig. 1. Specifically, there exist cellular networks with different cell sizes (e.g., macro, pico and femto-cells) in the set $\mathcal{N}$ and exist overlapped coverage areas by those cells. Each network *n* ($n \in \mathcal{N}$) has a set of macro-cell BSs or femto-cell APs in the geographical region. We describe such set as $\mathcal{S}_n = \{1, 2, \cdots, S_n\}$. $\mathcal{M} = \{1, 2, \cdots, M\}$ is the set of UEs and they execute uplink multi-homing data transmission in the considered region. Let $\mathcal{M}_{ns} \subseteq \mathcal{M}$ be the subset of those UEs which are located in the coverage areas of network *n* BS/AP *s*. Each UE is capable of communicating with multiple BSs/APs simultaneously. According to OFDMA terminology, the resources in networks include subcarriers and transmission power. $\mathcal{K}_{ns}$ refers to the set of original subcarriers of network *n* BS/AP *s* before spectrum sensing process, and their total number is K_{ns}. k denotes one of the original subcarriers of network *n* BS/AP *s*, namely $k \in \mathcal{K}_{ns}$. B_0 represents the bandwidth of each subcarrier.

During the stage of original resource allocation, P_{nsmk} denotes the transmission power allocation result at UE *m* to the corresponding radio interface via subcarrier k when the UE is communicating with network *n* BS/AP *s*. Power consumption at each UE is made up of two components, namely the transmission power consumption and the circuit power consumption [21, 32-33]. Assume that the circuit power consumption of the transmission process between network *n* BS/AP *s* and UE *m* on original subcarrier k is $P_{c,nsmk}$. Then the total power consumption by each UE at each radio interface is $P_{t,nsmk} = P_{nsmk} + P_{c,nsmk}$ [32].

[1]In this work, $\mathcal{N}$ is used for the set, N is used as the total count, and n is used as an index for the parameter. Such definition is applicable to other variables as well.

h_{nsmk} is the channel power gain between UE *m* and network *n* BS/AP *s* on subcarrier k. d_{nsm} represents the distance between UE *m* and network *n* BS/AP *s*. The corresponding path loss is denoted by $d_{nsm}^{-\beta}$, where β refers to the path loss exponent. We assume that κ_{nsmk} is a Rayleigh random variable associated to the transmission link between UE *m* and network *n* BS/AP *s*. So the channel power gain can be written as $h_{nsmk} = \kappa_{nsmk} d_{nsm}^{-\beta}$. N_0 is used to represent the one-sided noise power spectral density.

IV. Joint Resource Allocation for Multi-Homing Heterogeneous Networks Based on CR

A. General Procedure of Joint CR-Based Allocation Method

The general procedure of our proposed CR-based joint resource allocation method for multi-homing heterogeneous networks is described as follows.

First, the original resource allocation stage. The original subcarriers of BSs/APs are assigned to each UE and in the meanwhile the transmission power at each UE is assigned to corresponding original subcarriers. Assume that the subcarrier and transmission power allocation results are respectively x_{nsmk} and P_{nsmk}. Binary variable x_{nsmk} is the indicator function and $x_{nsmk} = 1$ means that original subcarrier k of network *n* BS/AP s is assigned to UE *m*. Or otherwise, $x_{nsmk} = 0$.

Second, the spectrum sensing stage. In order to accurately identify spectrum holes which can be shared, spectrum sensing is indispensable. Spectrum sensing process is not our topic in this paper and here we adopt a common method, i.e., energy detection [34]. The threshold of energy detection is preset according to the threshold to noise power ratio in [35-38]. According to [39], the interference which is brought by spectrum resource sharing among networks can be regarded as noise and thus can be measured by the receivers of multi-homing users. Denote the spectrum detection result by network *n* BS/AP *s* regarding the subcarrier k' which originally belongs to network n' BS/AP s' as $D_{ns,k',n's'}$. $D_{ns,k',n's'} = 0$ means that according to the spectrum sensing result, the subcarrier k' is a spectrum hole subcarrier at the location of network *n* BS/AP s and thus can be reused by it. Or otherwise, $D_{ns,k',n's'} = 1$. Let $\mathcal{K}'_{n's'}$ ($k' \in \mathcal{K}'_{n's'}$) be the set of these hole subcarriers with the element number of $K'_{n's'}$.

Third, the detected spectrum hole resource allocation stage. We need to assign the detected hole subcarriers to UEs, and in the meanwhile assign corresponding transmission power to these subcarriers. A binary variable $\hat{x}_{nsmk'}$ is used to denote the indicator function of hole subcarrier assignment result and the corresponding power allocation result is $\hat{P}_{nsmk'}$. If x_{nsmk} or $\hat{x}_{nsmk'}$ is equal to 0, the corresponding power allocation results and Lagrange multipliers will be equal to 0 as well. The above three steps loop in turns until the iteration-stopping condition is satisfied.

B. CR-Based Joint Resource Allocation Method

1) Problem Formulation: The data transmission rate achieved by UE *m* ($m \in \mathcal{M}_{ns}$) during communicating through original subcarrier k with network *n* BS/AP *s* is

$$R_{nsmk} = x_{nsmk} B_0 \log_2 \left(1 + \frac{P_{nsmk} h_{nsmk}}{N_0 B_0}\right), \quad \forall n \in \mathcal{N},\ s \in \mathcal{S}_n,\ m \in \mathcal{M}_{ns},\ k \in \mathcal{K}_{ns} \tag{1}$$

based on Shannon formula. The detection result $D_{ns,k',n's'}$ is obtained from spectrum sensing. Afterwards, the transmission rate achieved by UE *m* on hole subcarrier k' is

$$\hat{R}_{nsmk'} = \hat{x}_{nsmk'} \bar{D}_{ns,k',n's'} B_0 \log_2 \left(1 + \frac{\hat{P}_{nsmk'} \hat{h}_{nsmk'}}{N_0 B_0}\right), \quad \forall n \in \mathcal{N},\ s \in \mathcal{S}_n,\ m \in \mathcal{M}_{ns},\ k' \in \mathcal{K}'_{n's'} \tag{2}$$

where $\hat{h}_{nsmk'}$ is the channel power gain on the reused hole subcarrier k' by UE *m* when communicating with network *n* BS/AP *s*. $\bar{D}_{ns,k',n's'}$ is the logical 'NOT' of $D_{ns,k',n's'}$. Hence, the total obtained data transmission rate of the system is given by

$$R = \sum_n \sum_s \sum_m \sum_k R_{nsmk} + \sum_n \sum_s \sum_m \sum_{n' \neq n} \sum_{s' \neq s} \sum_{k'} \hat{R}_{nsmk'}. \tag{3}$$

Since subcarriers of each BS/AP in each network are limited and they are allocated orthogonally, we have

$$\sum_{m \in \mathcal{M}_{ns}} x_{nsmk} \leq 1,\ x_{nsmk} \in \{0,1\}, \quad \forall n \in \mathcal{N},\ s \in \mathcal{S}_n,\ k \in \mathcal{K}_{ns}. \tag{4}$$

$$\sum_n \sum_s \sum_m \hat{x}_{nsmk'} \leq 1,\ \hat{x}_{nsmk'} \in \{0,1\}, \quad \forall n \in \mathcal{N},\ s \in \mathcal{S}_n,\ k' \in \mathcal{K}'_{ns}. \tag{5}$$

According to Section III, the total power consumed by UE *m* can be expressed as

$$P_m = \sum_n \sum_s \sum_k x_{nsmk} \left(P_{nsmk} + P_{c,nsmk}\right) + \sum_n \sum_s \sum_{n' \neq n} \sum_{s' \neq s} \sum_{k'} \hat{x}_{nsmk'} \left(\hat{P}_{nsmk'} + \hat{P}_{c,nsmk'}\right) \bar{D}_{ns,k',n's'}. \tag{6}$$

Considering practical hardware limitations, P_m is constrained by its maximum level $P_{\max}$, i.e.,

$$P_m \leq P_{\max},\ \forall m \in \mathcal{M}. \tag{7}$$

Moreover, considering the requirement of quality of services [13, 18, 40], transmission rate R_m of UE *m* is constrained by the minimum data rate $R_{\min}$. Therefore, we have

$$R_m \geq R_{\min},\ \forall m \in \mathcal{M} \tag{8}$$

where $R_m = \sum_n \sum_s \sum_k R_{nsmk} + \sum_n \sum_s \sum_{n' \neq n} \sum_{s' \neq s} \sum_{k'} \hat{R}_{nsmk'}$.

Our joint allocation purpose is to maximize the system throughput. Then the optimization problem can be formulated as follows.

$$\max_{\mathbf{x},\mathbf{P},\hat{\mathbf{x}}',\hat{\mathbf{P}}'} R \tag{9}$$

subject to (4), (5), (7) and (8),

$$\left(2D_{ns,k',n's'} - 1\right)\left(x_{n's'm'k'} P_{n's'm'k'} h_{I_1,nsm'k'} - I_{th_1}\right) \geq 0 \tag{10}$$

$$D_{ns,k',n's'} \in \{0,\ 1\} \tag{11}$$

$$\hat{x}_{nsmk'} \hat{P}_{nsmk'} h_{I_2,n's'mk'} \bar{D}_{ns,k',n's'} \leq I_{th_2} \tag{12}$$

$$\hat{P}_{nsmk'} \geq 0,\ P_{nsmk} \geq 0 \tag{13}$$

where $\mathbf{x}$, $\mathbf{P}$, $\hat{\mathbf{x}}'$ and $\hat{\mathbf{P}}'$ are respectively matrices made up of allocation results x_{nsmk}, P_{nsmk}, $\hat{x}_{nsmk'}$ and $\hat{P}_{nsmk'}$. We assume that the subcarrier k' belongs to network n' BS/AP s' and it is assigned to UE m' in the first stage. Assume that the channel power gain between network *n* BS/AP *s* and UE m' on subcarrier k' is $h_{I_1,nsm'k'}$. Moreover, when the subcarrier k' is reused by UE *m* during the third stage, the channel power gain between network n' BS/AP s' and UE *m* is written as $h_{I_2,n's'mk'}$. I_{th_1} represents the spectrum detection threshold. When UE m is reusing the subcarrier k' which originally belongs to network n' BS/AP s', it must ensure that the caused interference on network n' BS/AP s' won't exceed the preset threshold I_{th_2}, as expressed in (12). Such idea comes from the spectrum sharing technique in cognitive radio [35-38]. Constrains (10) and (11) are used to describe the spectrum sensing process and the detection result is $D_{ns,k',n's'}$. (13) refers to the transmission power constraints.

The formulated problem (4)-(13) is a mixed integer non-linear programming problem. This problem can be converted into a convex optimization problem through the continuity relaxation method, which can be further solved by Lagrange dual solution.

2) Continuity Relaxation Method: Binary variables x_{nsmk} and $\hat{x}_{nsmk'}$ can only be equal to 0 or 1. We first relax them to the continuous interval [0, 1], and then introduce the following two variables z_{nsmk} and $\hat{z}_{nsmk'}$.

$$z_{nsmk} = x_{nsmk} P_{nsmk}. \tag{14}$$

$$\hat{z}_{nsmk'} = \hat{x}_{nsmk'} \hat{P}_{nsmk'}. \tag{15}$$

Afterwards, we rewrite the problem (4)-(13) as

$$\max_{\mathbf{x},\mathbf{z},\hat{\mathbf{x}}',\hat{\mathbf{z}}'} \sum_m \sum_n \sum_s \sum_k x_{nsmk} B_0 \log_2 \left(1 + \frac{z_{nsmk} h_{nsmk}}{x_{nsmk} N_0 B_0}\right) + \sum_m \sum_n \sum_s \sum_{n' \neq n} \sum_{s' \neq s} \sum_{k'} \hat{x}_{nsmk'} \bar{D}_{ns,k',n's'} B_0 \cdot \log_2 \left(1 + \frac{\hat{z}_{nsmk'} \hat{h}_{nsmk'}}{\hat{x}_{nsmk'} N_0 B_0}\right) \tag{16}$$

subject to

$$\sum_{m \in \mathcal{M}_{ns}} x_{nsmk} \leq 1,\ x_{nsmk} \in [0,1] \tag{17}$$

$$\sum_n \sum_s \sum_m \hat{x}_{nsmk'} \leq 1,\ \hat{x}_{nsmk'} \in [0,1] \tag{18}$$

$$\sum_n \sum_s \sum_k \left(z_{nsmk} + x_{nsmk} P_{c,nsmk}\right) + \sum_n \sum_s \sum_{n' \neq n} \sum_{s' \neq s} \sum_{k'} \left(\hat{z}_{nsmk'} + \hat{x}_{nsmk'} \hat{P}_{c,nsmk'}\right) \bar{D}_{ns,k',n's'} \leq P_{\max} \tag{19}$$

$$\sum_n \sum_s \sum_k x_{nsmk} B_0 \log_2 \left(1 + \frac{z_{nsmk} h_{nsmk}}{x_{nsmk} N_0 B_0}\right) + \sum_n \sum_s \sum_{n' \neq n} \sum_{s' \neq s} \sum_{k'} \hat{x}_{nsmk'} \bar{D}_{ns,k',n's'} B_0 \cdot \log_2 \left(1 + \frac{\hat{z}_{nsmk'} \hat{h}_{nsmk'}}{\hat{x}_{nsmk'} N_0 B_0}\right) \geq R_{\min} \tag{20}$$

$$\left(2D_{ns,k',n's'}-1\right)\left(z_{n's'm'k'}h_{I_1,nsm'k'}-I_{th_1}\right)\geq 0 \quad (21)$$

$$D_{ns,k',n's'}\in\{0,\ 1\} \quad (22)$$

$$\hat{z}_{nsmk'}\bar{D}_{ns,k',n's'}\leq\frac{I_{th_2}}{h_{I_2,n's'mk'}} \quad (23)$$

$$\hat{z}_{nsmk'}\geq 0,\ z_{nsmk}\geq 0. \quad (24)$$

where $\mathbf{z}=[z_{nsmk}]_{K_{ns}\times M}$ and $\hat{\mathbf{z}}'=[\hat{z}_{nsmk'}]_{K'_{ns}\times M}$.

Proposition 1. *After the continuity relaxation process described in (16)-(24), the problem is converted into a convex optimization problem.*

Proof. See Appendix A. □

3) CR-Based Joint Resource Allocation Method: From Proposition 1, the optimization problem (16)-(24) can be solved based on Lagrange dual solution after the continuity relaxation process. We respectively relax the constraints (19), (20) and (23) by introducing Lagrange multiplier variables v_m, φ_m and $\hat{\gamma}_{nsmk'}$ and then obtain the Lagrange function (25), where matrices $\mathbf{v}=[v_m]_{1\times M}$, $\boldsymbol{\gamma}'=[\hat{\gamma}_{nsmk'}]_{K'_{ns}\times M}$ and $\boldsymbol{\varphi}=[\varphi_m]_{1\times M}$. According to Lagrange dual solution, the following theorem presents the allocation results of our proposed joint resource allocation method.

Theorem 1. *The allocation results of the original subcarriers and their corresponding transmission power are given by*

$$x^*_{nsmk}=\begin{cases}1, & m=\arg\max\limits_{m\in\mathcal{M}_{ns}}\{\Lambda_{nsmk}\}\\ 0, & \text{otherwise}\end{cases}, \quad (26)$$

$$P^*_{nsmk}=\left[\frac{(1+\varphi_m)B_0}{(\ln 2)v_m}-\frac{N_0B_0}{h_{nsmk}}\right]^+, \quad (27)$$

where $[x]^+=\max\{0,\ x\}$ *and*

$$\begin{aligned}\Lambda_{nsmk}&=(1+\varphi_m)B_0\log_2\left(1+\tfrac{P^*_{nsmk}h_{nsmk}}{N_0B_0}\right)\\&-v_m\left(P^*_{nsmk}+P_{c,nsmk}\right).\end{aligned} \quad (28)$$

The allocation results of the detected hole subcarriers and their corresponding transmission power are given by

$$\hat{x}^*_{nsmk'}=\begin{cases}1, & m=\arg\max\limits_{m\in\mathcal{M},\,m\notin\mathcal{M}_{n's'}}\left\{\hat{\Lambda}_{nsmk'}\right\}\\ 0, & \text{otherwise}\end{cases}, \quad (29)$$

$$\hat{P}^*_{nsmk'}=\left[\frac{(1+\varphi_m)B_0}{(\ln 2)\left(v_m+\hat{\gamma}_{nsmk'}\right)}-\frac{N_0B_0}{\hat{h}_{nsmk'}}\right]^+, \quad (30)$$

where

$$\begin{aligned}&\hat{\Lambda}_{nsmk'}\\&=(1+\varphi_m)\bar{D}_{ns,k',n's'}B_0\log_2\left(1+\tfrac{\hat{P}^*_{nsmk'}\hat{h}_{nsmk'}}{N_0B_0}\right)\\&-v_m\left(\hat{P}^*_{nsmk'}+\hat{P}_{c,nsmk'}\right)\bar{D}_{ns,k',n's'}\\&-\hat{\gamma}_{nsmk'}\hat{P}^*_{nsmk'}\bar{D}_{ns,k',n's'}.\end{aligned} \quad (31)$$

The optimal values of Lagrange multiplier matrices $\boldsymbol{\gamma}'$, $\mathbf{v}$ *and* $\boldsymbol{\varphi}$, *namely* $\boldsymbol{\gamma}'^*$, $\mathbf{v}^*$ *and* $\boldsymbol{\varphi}^*$, *are obtained by the following iteration equations.*

$$\begin{aligned}&\hat{\gamma}_{nsmk'}(i+1)=\\&\left[\hat{\gamma}_{nsmk'}(i)+\varepsilon_1\left(\hat{P}_{nsmk'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}-\tfrac{I_{th_2}}{h_{I_2,n's'mk'}}\right)\right]^+\end{aligned} \quad (32)$$

$$v_m(i+1)=\left[v_m(i)+\varepsilon_2\left(P_m-P_{\max}\right)\right]^+ \quad (33)$$

$$\varphi_m(i+1)=\left[\varphi_m(i)+\varepsilon_3\left(R_{\min}-\ R_m\right)\right]^+ \quad (34)$$

where the positive step sizes ε_1, ε_2 *and* ε_3 *are sufficiently small and* i *is the iteration index.*

Proof. The dual function of the optimization problem (16)-(24) is

$$h(\mathbf{v},\boldsymbol{\gamma}',\boldsymbol{\varphi})=\max_{\mathbf{x},\mathbf{z},\hat{\mathbf{x}}',\hat{\mathbf{z}}'}L\left(\mathbf{x},\mathbf{z},\hat{\mathbf{x}}',\hat{\mathbf{z}}',\mathbf{v},\boldsymbol{\gamma}',\boldsymbol{\varphi}\right) \quad (35)$$

subject to (17), (18) and (24). And then the dual problem of (16)-(24) can be written as

$$\min_{\mathbf{v}\geq 0,\boldsymbol{\gamma}'\geq 0,\boldsymbol{\varphi}\geq 0}h(\mathbf{v},\boldsymbol{\gamma}',\boldsymbol{\varphi}). \quad (36)$$

It is well known that the minimum value of (36) is equal to the maximum value of (16)-(24). First, we derive the original resource allocation results. That is to say we will solve (17), (18), (24), (35) and (36) for finding the optimum $\mathbf{x}$ and $\mathbf{z}$ first.

By using the Karush-Kuhn-Tucker (KKT) conditions on (16), we get

$$z_{nsmk}=\left[\frac{(1+\varphi_m)B_0}{(\ln 2)v_m}-\frac{N_0B_0}{h_{nsmk}}\right]^+x_{nsmk}. \quad (37)$$

According to (14) and (37), the power allocation result (27) is obtained.

Substitute (28) and (37) into (35), and then the optimization problem (35) can be written as (38). The equation (38) actually describes a linear assignment problem. Therefore, the optimal result x_{nsmk} can only be chosen among the extreme points of its constraint set, i.e., 0 or 1. So the optimal subcarrier allocation result is written as (26). It is noted that if Λ_{nsmk} has more than one maximum values during computing x_{nsmk} based on (26), we will assign the considered subcarrier k to the UE which owns the least allocated subcarriers for user fairness. Also, if all of the Λ_{nsmk}s corresponding to one particular subcarrier k are negative, that user must have terrible channel condition. Blindly accessing this channel will waste power resource. So we decide to abandon such subcarriers and save the transmission power for other better subcarriers.

As to the detected hole spectrum resource allocation results, we obtain (39) according to KKT conditions on (16).

$$\hat{z}_{nsmk'}=\left[\frac{(1+\varphi_m)B_0}{(\ln 2)\left(v_m+\hat{\gamma}_{nsmk'}\right)}-\frac{N_0B_0}{\hat{h}_{nsmk'}}\right]^+\hat{x}_{nsmk'}. \quad (39)$$

According to (15) and (39), the power allocation result (30) is obtained.

Substitute (31) and (39) into (38), and (38) can be written as

$$\begin{aligned}h(\mathbf{v},\boldsymbol{\gamma}',\boldsymbol{\varphi})&=\max_{\hat{\mathbf{x}}'}\sum_m\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{\Lambda}_{nsmk'}\hat{x}_{nsmk'}\\&+\sum_m\sum_n\sum_s\sum_k\Lambda_{nsmk}x_{nsmk}-\sum_m\varphi_mR_{\min}\\&+\sum_m v_mP_{\max}+\sum_m\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\frac{\hat{\gamma}_{nsmk'}I_{th_2}}{h_{I_2,n's'mk'}}.\end{aligned} \quad (40)$$

So the optimal allocation result $\hat{x}^*_{nsmk'}$ can also only be among the extreme points in the constraint set, i.e., 0 or 1. The optimal hole subcarrier allocation result is written as (29). As

$$
\begin{aligned}
&L\left(\mathbf{x},\mathbf{z},\hat{\mathbf{x}}',\hat{\mathbf{z}}',\mathbf{v},\boldsymbol{\gamma}',\boldsymbol{\varphi}\right)= \\
&\sum_m\sum_n\sum_s\sum_k x_{nsmk}B_0\log_2\left(1+\frac{z_{nsmk}h_{nsmk}}{x_{nsmk}N_0B_0}\right)+\sum_m\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}B_0\log_2\left(1+\frac{\hat{z}_{nsmk'}\hat{h}_{nsmk'}}{\hat{x}_{nsmk'}N_0B_0}\right) \\
&+\sum_m v_m\left(P_{\max}-\left(\sum_n\sum_s\sum_k\left(z_{nsmk}+x_{nsmk}P_{c,nsmk}\right)+\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\left(\hat{z}_{nsmk'}+\hat{x}_{nsmk'}\hat{P}_{c,nsmk'}\right)\bar{D}_{ns,k',n's'}\right)\right)+ \\
&\sum_m\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{\gamma}_{nsmk'}\left(\frac{I_{th_2}}{h_{I_2,n's'mk'}}-\hat{z}_{nsmk'}\bar{D}_{ns,k',n's'}\right)+\sum_m\varphi_m\left(\max_{\mathbf{x},\mathbf{z},\hat{\mathbf{x}}',\hat{\mathbf{z}}'}\sum_n\sum_s\sum_k x_{nsmk}B_0\log_2\left(1+\frac{z_{nsmk}h_{nsmk}}{x_{nsmk}N_0B_0}\right)\right. \\
&\left.+\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}B_0\log_2\left(1+\frac{\hat{z}_{nsmk'}\hat{h}_{nsmk'}}{\hat{x}_{nsmk'}N_0B_0}\right)-R_{\min}\right)
\end{aligned}
\tag{25}
$$

$$
\begin{aligned}
h\left(\mathbf{v},\boldsymbol{\gamma}',\boldsymbol{\varphi}\right)=&\max_{\mathbf{x}}\sum_m\sum_n\sum_s\sum_k\Lambda_{nsmk}x_{nsmk} \\
&+\sum_m\left(\left(1+\varphi_m\right)\left(\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}B_0\log_2\left(1+\frac{\hat{z}_{nsmk'}\hat{h}_{nsmk'}}{\hat{x}_{nsmk'}N_0B_0}\right)\right)-\varphi_mR_{\min}\right) \\
&+\sum_m v_m\left(P_{\max}-\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\left(\hat{z}_{nsmk'}+\hat{x}_{nsmk'}\hat{P}_{c,nsmk'}\right)\bar{D}_{ns,k',n's'}\right) \\
&+\sum_m\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{\gamma}_{nsmk'}\left(\frac{I_{th_2}}{h_{I_2,n's'mk'}}-\hat{z}_{nsmk'}\bar{D}_{ns,k',n's'}\right)
\end{aligned}
\tag{38}
$$

to responses to the situations that $\hat{\Lambda}_{nsmk'}$ has more than one maximum values when computing (29), and that all calculated $\hat{\Lambda}_{nsmk'}$s of one particular subcarrier k' are negative, please refer to the first allocation stage above. And these responses also apply to the following suboptimal method.

Based on the gradient descent method, the optimal values of Lagrange multiplier matrices $\boldsymbol{\gamma}'$, $\mathbf{v}$ and $\boldsymbol{\varphi}$, namely $\boldsymbol{\gamma}'^*$, $\mathbf{v}^*$ and $\boldsymbol{\varphi}^*$, are determined as shown in (32)–(34) by solving (36). Now the proof is completed. □

In conclusion, the proposed joint allocation method is presented in Algorithms 1 and 2 where F, F' and f refer to the loop-stopping indicators. j, j' and J denote the iteration indexes. T, T' and t are the maximum iteration times of corresponding loop iterations. The proposed method determines whether the current calculation results $x_{nsmk}\left(j'\right)$, $P_{nsmk}\left(j'\right)$, $\hat{x}_{nsmk'}\left(j'\right)$ and $\hat{P}_{nsmk'}\left(j'\right)$ satisfy the iteration-stopping condition given in Algorithm 1 or not every time the entire allocation process is completed. If so, stop iteration. Or otherwise, update Lagrange multipliers $v_m\left(j'\right)$ and $\varphi_m\left(j\right)$ based on current allocation results. These Lagrange multipliers and current allocation results are the so-called feedback information which are then provided for the first allocation stage. Our proposed method will determine the next iteration direction according to the feedback information and make appropriate adjustments on original and detected resource allocation results, and the associated Lagrange multipliers. For example, if current allocation results make the total power consumption of UE m larger than the upper boundary of available power $P_{\max}$, the gradient descent method in our algorithm will increase the corresponding Lagrange multiplier $v_m\left(j'\right)$ during iteration. Furthermore, larger $v_m\left(j'\right)$ results in smaller computed power values during the next iteration based on (27) and (30). Then the iteration loop is proceeding in the direction of decreasing the computed power values so they will not exceed $P_{\max}$. Such process proceeds circularly until the iteration-stopping condition in Algorithm 1 is satisfied.

V. Joint Suboptimal Resource Allocation Method Based on CR

Considering the complicated computation process of our proposed optimal strategy in Section IV, a suboptimal framework is further proposed to reduce the system overhead. Afterwards, a benchmark is introduced for comparison purpose.

A. Suboptimal Framework

The allocation results of our proposed optimal strategy in Section IV-B should be updated every time the channel state information (CSI) changes, leading to a large amount of data transmission and spectrum detection operation and thus high system overhead. In order to reduce the system overhead, we propose a three-step suboptimal allocation strategy which also jointly considers original subcarriers, detected hole subcarriers and transmission power. The first step is to allocate original resources and it is executed only once at the beginning of the entire allocation process. The allocation here is not based on instantaneous channel power gain, but on its expectation $\mathrm{E}\left[h_{nsmk}\right]$ which can generally reflect the long-term channel conditions of each UE. $\mathrm{E}\left[x\right]$ represents the expectation of x. The second step is spectrum sensing. And the third step is to allocate the detected hole resources, which should be executed every time CSI changes. Generally speaking, the difference between our optimal and suboptimal strategies is that the latter one allocates original resources based on long-term channel conditions instead of instantaneous conditions. In this way, although sometimes the allocation results may not be the optimal results to the current channel conditions, they are still reasonable in most of the time. Moreover, since the overall channel conditions are considered, the first step only

Algorithm 1 Joint Original Subcarriers, Detected Hole Subcarriers and Power Allocation Strategy in Multi-Homing Heterogeneous Networks Based on Cognitive Radio

Input: Preset thresholds I_{th_1} and I_{th_2}; minimum value of transmission rate $R_{\min}$; total power available at UE $P_{\max}$; the number of original subcarriers in network *n* BS/AP *s* K_{ns};
 Initialization: $\varphi_m(1) \geq 0,\ \forall m,\ j$=1, $F = 1$;
 while $F = 1$ and $j \leq T$ **do**
  Generate initial value $v_m(1) \geq 0,\ \forall m$. Let $j' = 1$ and $F' = 1$;
  while $F' = 1$ and $j' \leq T'$ **do**
   BSs/APs assign original resources to each UE according to the allocation results shown in (26) and (27). The allocation results are $x_{nsmk}(j')$ and $P_{nsmk}(j')$;
   BSs/APs detect spectrum bands with the results of $D_{ns,k',n's'}$;
   According to the detected results, BSs/APs calculate hole subcarriers and corresponding power resource allocation results $\hat{x}_{nsmk'}(j')$ and $\hat{P}_{nsmk'}(j')$ according to Algorithm 2;
   if $P_m \leq P_{\max}$ and $v_m(j') = 0$ **then**
    $F' = 0$;
   else if $P_m = P_{\max}$ and $v_m(j') > 0$ **then**
    $F' = 0$;
   else if $P_m < P_{\max}$ and $v_m(j') > 0$ **then**
    Decrease $v_m(j')$, according to (33);
   else
    Increase $v_m(j')$, according to (33);
   end if
   $j' \leftarrow j' + 1$;
  end while
  if $R_m \geq R_{\min}$ and $\varphi_m(j) = 0$ **then**
   $F = 0$;
  else if $R_m = R_{\min}$ and $\varphi_m(j) > 0$ **then**
   $F = 0$;
  else if $R_m > R_{\min}$ and $\varphi_m(j) > 0$ **then**
   Decrease $\varphi_m(j)$, according to (34);
  else
   Increase $\varphi_m(j)$, according to (34);
  end if
  $j \leftarrow j + 1$;
 end while
Output: $x^*_{nsmk},\ P^*_{nsmk},\ \hat{x}^*_{nsmk'},\ \hat{P}^*_{nsmk'},\ \forall n,\ s,\ m,\ k,\ k'$.

needs to be executed once. So the first step execution expenses are greatly saved through slightly sacrificing the system performance. Accordingly, the second step is executed only once as well, further reducing the system overhead. Moreover, although the hole resource allocation results of our suboptimal method keep updating as CSI changes, they are not required to be sent back to the first step as feedback information. That is to say the outermost loop of the optimal method is not needed in the suboptimal strategy, further reducing the system overhead.

We first present the step of original resource allocation.

Algorithm 2 Joint Allocation Method For Detected Hole Subcarriers and Transmission Power

Input: Spectrum detection result $D_{ns,k',n's'}$ and the threshold I_{th_2};
 Initialization: $\hat{\gamma}_{nsmk'}(1) \geq 0,\ J = 1,\ f = 1$;
 while $f = 1$ and $J \leq t$ **do**
  Calculate $\hat{\Lambda}_{nsmk'}$ based on (31);
  Obtain the hole subcarrier allocation result $\hat{x}^*_{nsmk'}(J)$ according to (29) and the computed $\hat{\Lambda}_{nsmk'}$ above. And then work out the corresponding power allocation result $\hat{P}^*_{nsmk'}(J)$ based on (30);
  if $\hat{P}_{nsmk'}(J) \leq \frac{I_{th_2}}{h_{I_2,n's'mk'}}$ and $\hat{\gamma}_{nsmk'}(J) = 0$ **then**
   $f = 0$;
  else if $\hat{P}_{nsmk'}(J) = \frac{I_{th_2}}{h_{I_2,n's'mk'}}$ and $\hat{\gamma}_{nsmk'}(J) > 0$ **then**
   $f = 0$;
  else if $\hat{P}_{nsmk'}(J) < \frac{I_{th_2}}{h_{I_2,n's'mk'}}$ and $\hat{\gamma}_{nsmk'}(J) > 0$ **then**
   Decrease $\hat{\gamma}_{nsmk'}(J)$, according to (32);
  else
   Increase $\hat{\gamma}_{nsmk'}(J)$, according to (32);
  end if
  $J \leftarrow J + 1$;
 end while
Output: $\hat{x}^*_{nsmk'},\ \hat{P}^*_{nsmk'},\ \forall n,\ s,\ m,\ k'$.

As above explained, the expectation of channel power gain $\mathrm{E}[h_{nsmk}]$ is adopted and correspondingly when it comes to the optimization objective function, the expectation of throughput should be considered. According to Section VI-B in [21] and Lemma 2.1 in [41], the optimization problem can be written as

$$\max_{\mathbf{x},\mathbf{P}} \sum_n \sum_s \sum_m \sum_k x_{nsmk} \frac{B_0}{2} \log_2 \left(1 + \frac{P_{nsmk} 2\mathrm{E}[h_{nsmk}]}{N_0 B_0}\right) \tag{41}$$

subject to (4),

$$\sum_n \sum_s \sum_k x_{nsmk}(P_{nsmk} + P_{c,nsmk}) \leq P_{1,\max},\ \forall m \in \mathcal{M} \tag{42}$$

$$P_{nsmk} \geq 0,\ \forall n \in \mathcal{N},\ s \in \mathcal{S}_n,\ m \in \mathcal{M}_{ns},\ k \in \mathcal{K}_{ns} \tag{43}$$

where $P_{1,\max} \leq P_{\max}$ and $P_{1,\max}$ denotes the upper boundary of available transmission power during the first step. $\frac{P_{1,\max}}{P_{\max}}$ is set to be the ratio of the number of subcarriers that the considered UE can possibly access during the first step to the number during the first and the third allocation steps in total. In this way, we assign more transmission power to the stage with more potential access opportunities. We work out the power allocation results of the optimization problem (41)-(43) according to a similar method as (14)-(40) in Section IV-B. The power allocation result is

$$P^*_{nsmk} = \left[\frac{B_0}{2(\ln 2) v_{1m}} - \frac{N_0 B_0}{2\mathrm{E}[h_{nsmk}]}\right]^+, \tag{44}$$

where v_{1m} is the Lagrange multiplier associated with the constraint (42). The subcarrier allocation result is

$$x_{nsmk}^{*}=\begin{cases}1, & m=\underset{m\in\mathcal{M}_{ns}}{\arg\max}\left\{\Lambda_{nsmk}\right\}\\ 0, & \text{otherwise}\end{cases}, \tag{45}$$

where

$$\Lambda_{nsmk}= \frac{B_0}{2}\log_2\left(1+\frac{2\mathrm{E}[h_{nsmk}]P_{nsmk}^{*}}{N_0B_0}\right)-v_{1m}\left(P_{nsmk}^{*}+P_{c,nsmk}\right). \tag{46}$$

According to the gradient descent method, the optimal values of Lagrange multiplier v_{1m} is obtained from the following iteration process.

$$v_{1m}(i+1)=\Big[v_{1m}(i)+ \varepsilon_4\left(\left(\sum_n\sum_s\sum_k x_{nsmk}\left(P_{nsmk}+P_{c,nsmk}\right)\right)-P_{1,\max}\right)\Big]^{+} \tag{47}$$

where ε_4 is a sufficiently small positive step size.

In the second step, BSs/APs execute the spectrum sensing operation to identify existing hole subcarriers.

Then during the third step, the allocation results of detected hole subcarriers and corresponding transmission power are calculated based on the instantaneous channel power gain. Therefore, this step should be executed every time CSI changes. The optimization objective is to maximize the system throughput. The optimization problem can be written as

$$\max_{\hat{\mathbf{x}}',\hat{\mathbf{P}}'}\sum_n\sum_s\sum_m\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}B_0 \times\log_2\left(1+\frac{\hat{P}_{nsmk'}\hat{h}_{nsmk'}}{N_0B_0}\right) \tag{48}$$

subject to (5),

$$\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\left(\hat{P}_{nsmk'}+\hat{P}_{c,nsmk'}\right)\bar{D}_{ns,k',n's'} \leq P_{\max}-P_{1,\max},\ \forall m\in\mathcal{M} \tag{49}$$

$$\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}B_0 \times\log_2\left(1+\frac{\hat{P}_{nsmk'}\hat{h}_{nsmk'}}{N_0B_0}\right)\geq R_{\min}-R_{1,m},\ \forall m\in\mathcal{M} \tag{50}$$

$$\hat{x}_{nsmk'}\hat{P}_{nsmk'}h_{I_2,n's'mk'}\bar{D}_{ns,k',n's'}\leq I_{th_2} \tag{51}$$

$$\hat{P}_{nsmk'}\geq 0 \tag{52}$$

where $R_{1,m}=\sum\limits_n\sum\limits_s\sum\limits_k x_{nsmk}^{*}B_0\log_2\left(1+\frac{P_{nsmk}^{*}h_{nsmk}}{N_0B_0}\right)$ and it refers to the achieved data transmission rate after the first step. After similar derivation process in Section IV, we get the power allocation result:

$$\hat{P}_{nsmk'}^{*}=\left[\frac{(1+\varphi_m)B_0}{(\ln 2)\left(v_{2m}+\hat{\gamma}_{nsmk'}\right)}-\frac{N_0B_0}{\hat{h}_{nsmk'}}\right]^{+} \tag{53}$$

where v_{2m} is the Lagrange multiplier associated with the constraint (49). The detected hole subcarrier allocation result is

$$\hat{x}_{nsmk'}^{*}=\begin{cases}1, & m=\underset{m\in\mathcal{M},\,m\notin\mathcal{M}_{n's'}}{\arg\max}\left\{\hat{\Lambda}_{nsmk'}\right\}\\ 0, & \text{otherwise}\end{cases}, \tag{54}$$

where

$$\begin{aligned}\hat{\Lambda}_{nsmk'} &=(1+\varphi_m)\bar{D}_{ns,k',n's'}B_0\log_2\left(1+\frac{\hat{P}_{nsmk'}^{*}\hat{h}_{nsmk'}}{N_0B_0}\right)\\ &-v_{2m}\left(\hat{P}_{nsmk'}^{*}+\hat{P}_{c,nsmk'}\right)\bar{D}_{ns,k',n's'}\\ &-\hat{\gamma}_{nsmk'}\hat{P}_{nsmk'}^{*}\bar{D}_{ns,k',n's'}.\end{aligned} \tag{55}$$

According to the gradient descent method, the optimal values of Lagrange multiplier matrices $\boldsymbol{\gamma}'$, $\mathbf{v}_2$ ($\mathbf{v}_2=[v_{2m}]_{1\times M}$) and $\boldsymbol{\varphi}$, i.e. $\boldsymbol{\gamma}'^{*}$, $\mathbf{v}_2^{*}$, and $\boldsymbol{\varphi}^{*}$, are obtained from the iteration processes as shown in (56), (57) and (58), where ε_5, ε_6 and ε_7 are sufficiently small positive step sizes. Now we have presented our proposed optimal and suboptimal strategies for jointly allocating both the original resources and the detected hole resources.

B. Benchmark

In this paper, we compare our optimal and suboptimal methods with the allocation method presented in [21] which is mentioned as benchmark. The reason why we choose this benchmark is that its system framework is the most similar with ours. Both are cellular networks with heterogeneous cell sizes (e.g., macro, pico, and femto-cells). Both are constrained by limited bandwidth, limited transmission power and minimum boundary of data transmission rate. To enhance the comparability of these methods, we assume that the objective function of the benchmark is the same with our paper and both papers adopt OFDMA scheme. However, just like other existing strategies, [21] also fails to share and reuse spectrum resources among networks which is the main difference between our methods and the benchmark. Then the comparison results, i.e., superior performance of our proposed methods, can verify the effectiveness of introducing cognitive radio techniques into our methods for realizing the resource sharing scheme.

VI. Simulation Results

This section compares the simulation results of the proposed optimal and the suboptimal methods for uplink joint bandwidth and power allocation based on CR with the benchmark [21] to illustrate the effectiveness of our methods, in a multi-homing heterogeneous wireless system. Simulation results also verify that the suboptimal method greatly reduces the system overhead compared with the optimal method in the premise that it still significantly improves the resource utilization efficiency compared to the benchmark. The simulation setting is shown in Fig. 2. It is noted that even if we add more BSs/APs, the principle of our proposed methods will still be applicable and effective. The BS in the macro-cell has a coverage area radius of 1000 m, and the AP in the femto-cell has a coverage area radius of 300 m. We assume that $B_0=1$ MHz, $N_0=-174$ dBm/Hz, $R_{\min}=5$ Mbps and $\beta=5$.

Figure 3 presents the comparison result of the proposed CR-based joint optimal allocation strategy (using Algorithm 1-2), the proposed suboptimal strategy and the benchmark with different circuit consumption power values, in terms of the

$$\hat{\gamma}_{nsmk'}\left(i+1\right)=\left[\hat{\gamma}_{nsmk'}\left(i\right)+\varepsilon_5\left(\hat{P}_{nsmk'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}-\frac{I_{th_2}}{h_{I_2,n's'mk'}}\right)\right]^{+} \tag{56}$$

$$v_{2m}\left(i+1\right)=\left[v_{2m}\left(i\right)+\varepsilon_6\left(\left(\sum_{n}\sum_{s}\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\left(\hat{P}_{nsmk'}+\hat{P}_{c,nsmk'}\right)\bar{D}_{ns,k',n's'}\right)-\left(P_{\max}-P_{1,\max}\right)\right)\right]^{+} \tag{57}$$

$$\varphi_m\left(i+1\right)=\left[\varphi_m\left(i\right)+\varepsilon_7\left(R_{\min}-R_{1,m}-\left(\sum_{n}\sum_{s}\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'}\bar{D}_{ns,k',n's'}B_0\log_2\left(1+\frac{\hat{P}_{nsmk'}\hat{h}_{nsmk'}}{N_0B_0}\right)\right)\right)\right]^{+} \tag{58}$$

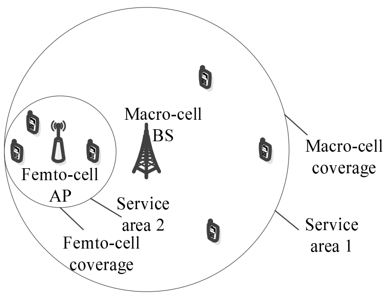

Fig. 2. The simulation setting.

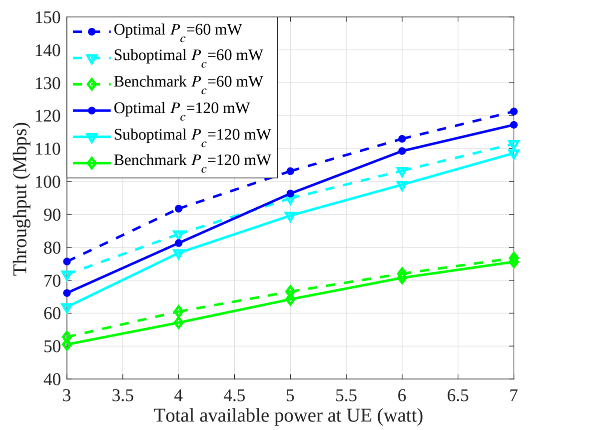

Fig. 3. The achieved system throughput by three allocation methods versus total available transmission power at each UE in systems with different circuit consumption power.

achieved system throughput for different available transmission power at UE. We assume that the circuit consumption power at each UE on each subcarrier of each BS/AP in each network is the same for simplicity and it can be denoted as P_c. Furthermore, we assume that the circuit consumption power $P_{c,nsmk}=\hat{P}_{c,nsmk'}=P_c$ is respectively 60 mW and 120 mW in Fig. 3. We vary the maximum available power at UEs on the *x*-axis. Assume that the number of original subcarriers in the macro-cell BS and that of the femto-cell AP are respectively $K_{11}=16$ and $K_{21}=8$. $M=6$. $I_{th_1}=I_{th_2}=0.1$. Under such simulation parameter assumptions, it is observed that the proposed optimal method always obtains the largest throughput, followed by our suboptimal method. Such simulation result benefits from the utilization of feedback information in the optimal method. Moreover, both of them achieve much larger throughput than the benchmark. This is because both of our methods utilize system resources more adequately and efficiently by sharing these resources. The results also illustrate that introducing the cognitive radio technique into our allocation process can indeed help achieve superior performance. For example, when $P_c=120$ mW and $P_{\max}=5$ watt, the obtained system throughput of our optimal and suboptimal strategies is respectively larger than the benchmark by 1.76 dB and 1.46 dB. Additionally, all of the three allocation methods provide larger system throughput as the *x*-axis variable $P_{\max}$ increases. Finally, we compare the performance of the three algorithms with different circuit power consumption. More circuit consumption makes less power be utilized for transmit data so correspondingly the system throughput will be less.

Figure 4 presents the system throughput of our proposed CR-based methods and the benchmark for different number of original subcarriers of the macro-cell BS K_{11}, when the UE number (*M*) is respectively equal to 6 and 8. We assume $P_{\max}=6$ watt. From Fig. 4, the proposed optimal strategy obtains the largest throughput under the above simulation assumptions, followed by the suboptimal method. They are both significantly superior to the benchmark. Also, larger K_{11} brings larger system throughput for all of the three methods since larger K_{11} obviously means more spectrum resources. Finally, we compare the throughput performance of the three methods with different *M*s and find that larger M leads to larger system throughput since the system total available power gets larger.

Figure 5 presents the energy efficiency of the proposed two CR-based strategies and the benchmark for different K_{11}s when the circuit consumption power is respectively equal to 60 mW and 120 mW. In this experiment, we assume that *M*=6 and $P_{\max}=6$ watt. It is observed in Fig. 5 that the proposed optimal method is able to achieve the largest energy efficiency under the above simulation assumptions, followed by the suboptimal method. Their energy efficiency values are both much larger than that of the benchmark. Moreover, as the *x*-axis variable K_{11} increases, energy efficiency values of the three methods get larger since there are more spectrum resources and thus larger throughput. According to the definition of energy efficiency, given the same transmission power consumption, larger achieved throughput results in larger

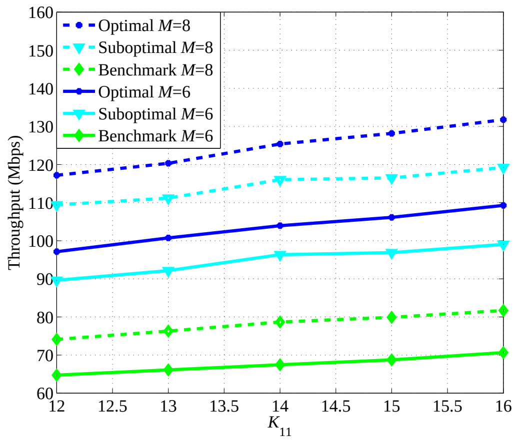

Fig. 4. The achieved system throughput by three allocation methods versus the number of original subcarriers of the macro-cell BS with different Ms.

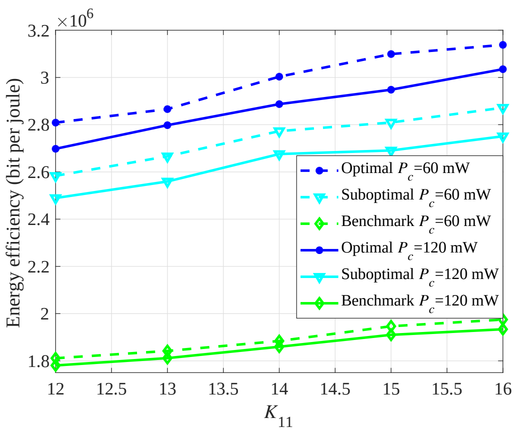

Fig. 5. The achieved energy efficiency by three allocation methods versus the number of original subcarriers in the macro-cell BS with different P_cs.

energy efficiency value. Finally, when comparing the energy efficiency performance in systems with different P_cs, we find that if P_c is larger, the transmission consumption power will be less since the total available power is limited. Thus, the system achieves less throughput and energy efficiency.

Figure 6 shows the system throughput of the three allocation methods for different preset thresholds when $P_{\max}$ is equal to 6 watt and 4 watt. In this experiment, we assume that $K_{21} = 16$, $M = 6$ and $P_c = 120$ mW. It is observed that the optimal method always obtain the largest throughput under the above simulation assumptions, followed by the suboptimal method and the benchmark successively. In addition, larger threshold brings more hole spectrum resources which can be shared and reused. Our two proposed CR-based methods will therefore tend to achieve larger throughput. But the benchmark dose not reuse the spectrum holes and thus its achieved throughput remains unchanged. At last, similar with the previous simulation result in Fig. 3, larger $P_{\max}$ leads to larger throughput.

Figure 7 is a comparison bar diagram about the three allocation methods, presenting the relationship between their total numbers of iteration calculations and the available power

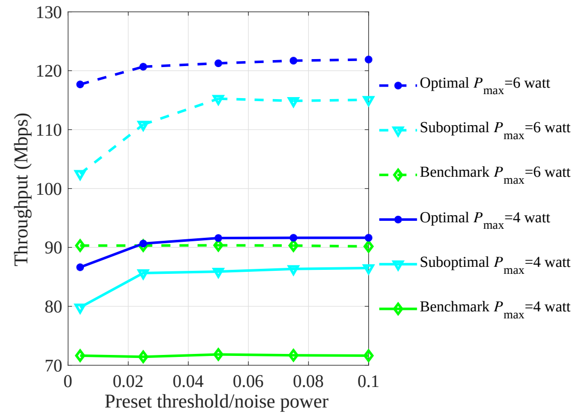

Fig. 6. The achieved system throughput by three allocation methods versus the ratio of the preset threshold to the noise power with different $P_{\max}$s.

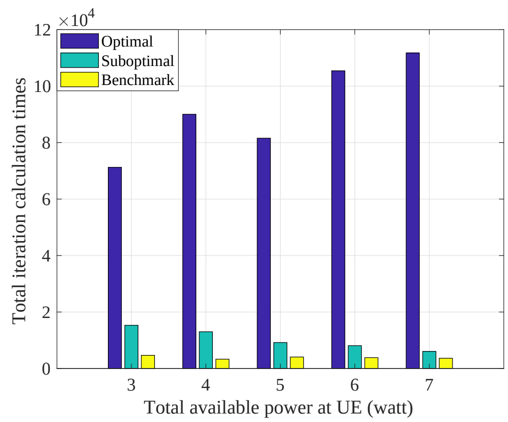

Fig. 7. The comparison bar diagram among the three allocation methods about their total iteration calculation times versus $P_{\max}$.

$P_{\max}$. We assume that $K_{11} = 16$, $K_{21} = 8$ and $P_c = 60$ mW. The number of iteration calculations in our paper includes the total required calculation times during the iteration process for all Lagrange multipliers and allocation results. It is observed from Fig. 7 that the number of iteration calculations in our proposed optimal method is much bigger than our suboptimal method under the above simulation assumptions, and the latter value is bigger than that of the benchmark. So it is verified that our proposed suboptimal strategy is able to greatly reduce the system overhead of the optimal method. In the meanwhile, the performance loss is quite slight according to the previous simulation results, which makes the suboptimal method more practicable.

VII. Conclusion

In this paper, we proposed an uplink joint resource allocation method for both the original and the detected resources to increase the resource utilization efficiency by adopting CR techniques in a multi-homing heterogeneous wireless medium. The proposed method allows various networks to share spectrum bands. According to the spectrum detection results, our proposed allocation method jointly assigned the limited transmission power, the original subcarriers and the detected hole subcarriers for each user to maximize the system throughput. To the best of our knowledge, this paper is the first to study the joint original and detected hole resource allocation problem in a heterogeneous system where networks share spectrum resources with each other. We first formulated this allocation problem as a mixed integer nonlinear optimization problem. Therefore, we employed the continuity relaxation method to convert it into a convex optimization problem and then obtained the optimal allocation results. A suboptimal method was also proposed to reduce the system overhead. Simulation results illustrated the improved performance of our proposed optimal and suboptimal methods over the benchmark in terms of system throughput and energy efficiency. We also verified that the suboptimal method significantly reduced the system overhead to address the practical challenge of real-time communication.

In the future, we will continue to focus on the resource allocation problem in multi-homing heterogeneous networks where spectrum resources can be shared and reused. We will focus on more practical but complicated optimization problems in multi-homing heterogeneous wireless networks based on cognitive radio with the consideration of realistic requirements of users and the objective features of networks. For example, in the integration heterogeneous network consisting of VANET and cellular networks, the safety message is transmitted among vehicles and the high-speed data stream is transmitted between vehicles and the macro base station. These services require distinct constraints and optimization objectives. The former service requires high reliability and thus the corresponding outage probability has an upper boundary. The latter service desires large data rate and thus the optimization objective should be to maximize the data transmission rate. Moreover, we plan to address other practical issues such as the resource allocation with the consideration of user fairness and the allocation problem with the coexistence of single-network and multi-homing services in heterogeneous wireless access medium.

Appendix A
Proof of Proposition 1

The objective function (16) is made up of two parts. Let the first part and the second part respectively be

$$R_1=\sum_m\sum_n\sum_s\sum_k x_{nsmk}B_0\log_2\left(1+\frac{z_{nsmk}h_{nsmk}}{x_{nsmk}N_0B_0}\right), \tag{59}$$

$$R_2=\sum_m\sum_n\sum_s\sum_{n'\neq n}\sum_{s'\neq s}\sum_{k'}\hat{x}_{nsmk'} \times \bar{D}_{ns,k',n's'}B_0\log_2\left(1+\frac{\hat{z}_{nsmk'}\hat{h}_{nsmk'}}{\hat{x}_{nsmk'}N_0B_0}\right). \tag{60}$$

First, we need to prove that the Hessian matrix $\mathbf{H}=\begin{bmatrix} H_{11} & H_{12}\\ H_{21} & H_{22}\end{bmatrix}$ of R_1 is a negative semidefinite matrix. There are two resource allocation variables in R_1 in total, namely x_{nsmk} and z_{nsmk}. We work out each element in the Hessian matrix as follows.

$$H_{11}=\frac{B_0}{(\ln 2)\,x_{nsmk}}\frac{-(z_{nsmk}h_{nsmk})^2}{(x_{nsmk}N_0B_0+z_{nsmk}h_{nsmk})^2}, \tag{61}$$

$$H_{12}=H_{21}=\frac{B_0}{\ln 2}\frac{z_{nsmk}{h_{nsmk}}^2}{(x_{nsmk}N_0B_0+z_{nsmk}h_{nsmk})^2}, \tag{62}$$

$$H_{22}=\frac{x_{nsmk}B_0}{\ln 2}\frac{-(h_{nsmk})^2}{(x_{nsmk}N_0B_0+z_{nsmk}h_{nsmk})^2}. \tag{63}$$

Accordingly, the diagonal elements of $\mathbf{H}$ are negative and the second principal minor of $\mathbf{H}$ is 0. So $\mathbf{H}$ is negative semidefinite [42]. Thus, R_1 is actually a concave function regarding variables x_{nsmk} and z_{nsmk}. Similarly, it can be also proved that the Hessian matrix of R_2 is $\begin{bmatrix} H'_{11} & H'_{12}\\ H'_{21} & H'_{22}\end{bmatrix}$, where

$$H'_{11}=\frac{B_0\bar{D}_{ns,k',n's'}}{(\ln 2)\hat{x}_{nsmk'}}\frac{-\left(\hat{z}_{nsmk'}\hat{h}_{nsmk'}\right)^2}{\left(\hat{x}_{nsmk'}N_0B_0+\hat{z}_{nsmk'}\hat{h}_{nsmk'}\right)^2}, \tag{64}$$

$$H'_{12}=H'_{21}=\frac{B_0\bar{D}_{ns,k',n's'}}{\ln 2}\frac{\hat{z}_{nsmk'}{\hat{h}_{nsmk'}}^2}{\left(\hat{x}_{nsmk'}N_0B_0+\hat{z}_{nsmk'}\hat{h}_{nsmk'}\right)^2}, \tag{65}$$

$$H'_{22}=\frac{\hat{x}_{nsmk'}B_0\bar{D}_{ns,k',n's'}}{\ln 2}\frac{-\left(\hat{h}_{nsmk'}\right)^2}{\left(\hat{x}_{nsmk'}N_0B_0+\hat{z}_{nsmk'}\hat{h}_{nsmk'}\right)^2}. \tag{66}$$

According to such derivation results, R_2 is a concave function regarding variables $\hat{x}_{nsmk'}$ and $\hat{z}_{nsmk'}$ as well. So the objective function (16) is the sum of two concave functions and thus it is a concave function [42]. It is also noted that the feasible sets of constraints (17)-(24) are linear or concave sets. That is to say the problem (16)-(24) is already converted into a convex optimization problem after the continuity relaxation process and can be solved by Lagrange dual solution.

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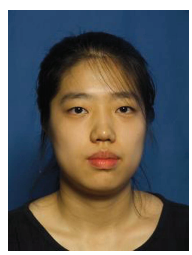

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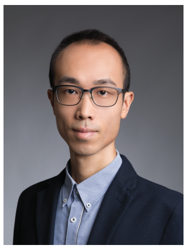

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