IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 1, 2018, accepted May 1, 2018, date of publication May 11, 2018, date of current version June 5, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2835568

Power Allocation for Downlink NOMA Heterogeneous Networks

DADONG NI[1], (Student Member, IEEE), LI HAO[1], (Member, IEEE), QUANG THANH TRAN[1,2], AND XIAOMIN QIAN[1]

[1]Key Laboratory of Information Coding and Transmission, Southwest Jiaotong University, Chengdu 610031, China
[2]Faculty of Electrical and Electronic Engineering, University of Transport and Communications, Hanoi 112345, Vietnam

Corresponding author: Dadong Ni (dadongni@hotmail.com)

This work was supported by the National Natural Science Foundation of China Project under Grant 61271245.

ABSTRACT Non-orthogonal multiple access (NOMA) and heterogeneous network (HetNet) are two significant and promising enabling techniques to further improve overall system performance for next-generation mobile communication systems. In this paper, we develop a novel NOMA HetNet through applying NOMA technique to both macrocell and small-cell of conventional HetNet, which improves the spectral efficiency whereas results in a more complex interference environment. To tackle this complicated interference problem and maximize the overall throughput of this NOMA HetNet, meanwhile ensure the desired quality of service (QoS) of each user, we mathematically formulate a power allocation problem which proves to be an NP-hard problem. Then, to deal with this optimization problem, we propose a users scheduling scheme and an iterative distributed power control algorithm. The simulation results demonstrate that compared with the conventional orthogonal multiple access (OMA) HetNet systems and single-tier NOMA networks, the combination of OMA technique and HetNet with the proposed algorithm can greatly improve the system performance in terms of spectral efficiency and outage performance.

INDEX TERMS Non-orthogonal multiple access, heterogeneous networks, user scheduling scheme, distributed power allocation algorithm.

I. INTRODUCTION

With the explosive growth of smart devices and rapid arising of various media services, the deep longings for extremely higher aggregate data rate, better coverage and higher spectral efficiency (SE) increase and become more intensive [1]. To cope with these issues, the technologies of HetNet and NOMA, which exploit respectively spatial diversity and multi-user diversity, are enabling and attract much attention. Consisting of various base stations with vastly different transmit power and coverage area, the basic framework of a heterogeneous network was provided in the provisions of the fourth generation (4G) mobile system long ago [2]–[6]. On the other hand, as a promising technique for future radio access(FRA), NOMA was proposed by NTT DOCOMO [7] to enable multiple users to share the identical radio resource at the same time, which should be distinguished through different power levels [7]–[10]. To successfully retrieve the desired information from the overlapped signals, successive interference cancelation (SIC) technique is utilized at the receivers in NOMA networks [7].

Due to the scarcity of spectrum resource, the co-channel deployment scenario between macrocell and small-cell prefers to be employed [5]. While in HetNet the co-channel deployment of small and macro-cells can improve the spectral efficiency, the unavoidable cross-tire interference would occur. Thus, Lopez-Perez *et al.* [4], Saquib *et al.* [11], and Zahir *et al.* [12] discussed diverse advanced interference mitigation and resource management approaches for orthogonal-frequency-division multiple-access (OFDMA) HetNet. The work in [13] presented some cooperative distributed radio resource management algorithms for the scene of hyper-dense small-cell deployment. To eliminate the cross-tier interference of downlink OFDMA HetNet, a dynamic power allocation scheme was proposed in [14], in which the transmit power of each small-cell base station (BS) was controlled dynamically upon the feedback from macro-tier. To optimize the sum rate and energy efficiency of small-tier simultaneously, a multi-objective optimization problem was formulated in [15] to jointly allocate the subchannel and power in the uplink and downlink of a two-tier OFDMA HetNet. In [16], a throughput maximization problem of OFDMA HetNet was studied under the QoS and per-tier minimum sum-rate constraints.

In general, it is unlikely to constantly improve the spectral efficiency only through the orthogonal multiple access technique. As a result, NOMA technique dramatically attracts the attention of the academic community. The basic concepts of uplink and downlink NOMA networks were exploited in [7] and [17], and various challenges for NOMA networks involving power allocation and user scheduling were discussed in [17]. Power allocation therein plays a significant role in enhancing the system performance of NOMA networks since the signals of multiple users are superposed under certain power partitions, and thereby attracts a lot of research attention. For instance, the closed-form formulae of outage probability and ergodic sum-rate were derived for two-user static power allocation NOMA system in [18]. Yang *et al.* [19] analyzed the drawbacks of fixed power allocation in NOMA network and proposed a general two-user power allocation scheme. On the other hand, the influence of power allocation on fairness performance of NOMA network was investigated in [20], and the power allocation algorithms for two users NOMA networks were investigated under sum rate maximization and proportional fairness criteria in [21]. To further improve the system performance, the work in [22] proposed a MIMO collaborative communication scheme with NOMA technique to accommodate two users in each stream and designed a novel precoder to suppress the inter-stream interference of MIMO-NOMA multicell networks.

Since the most transmit power are consumed by the cell-edge users who always experience the worst channel conditions according to NOMA protocol, it will hinder the performance improvement of NOMA networks. To deal with this problem, Zeng *et al.* [23] firstly proposed a strategy that combines HetNet and NOMA, and indicated that this cooperative scheme could enhance the spectral efficiency. In [24], the energy efficiency optimization scheme of NOMA HetNet was investigated, in which only small-cells employed NOMA technique, meanwhile the cellular network utilized MIMO technique. Similarly, in [25], the resource allocation problem was focused in which macrocell networks employed OMA protocol and small-cells served two users on single subcarrier through NOMA principle without taking the user QoS constraints into account. Instead, to make full use of the advantage of NOMA technique, as shown in Fig.1, we develop a NOMA heterogeneous network, where the NOMA protocol is applied to both macrocells and small cells. As a result, the interference environment becomes more complicated due to the multi-user interference and cross-tier interference. Therefore, the existing interference management approaches are not applicable, and more advanced interference management is required to further improve the system performance of this NOMA HetNet.

In this paper, we formulate a resource allocation problem to maximize the sum-rate of NOMA HetNet under the constraints of total transmit power and users QoS requirement,

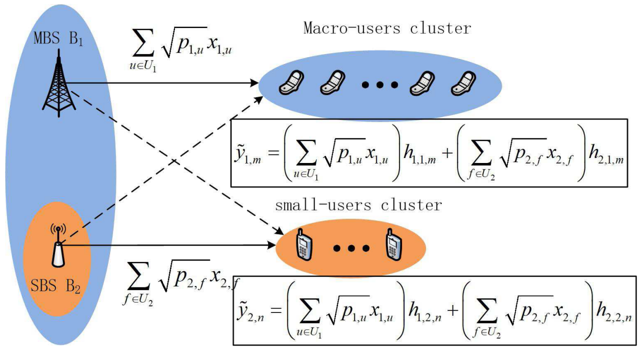

FIGURE 1. The architecture of NOMA HetNet.

which proves to be NP-hard. As depicted in [7], the optimal decoding order of SIC is along with the ascending sequence of channel gain normalized by the inter-cell interference and noise power. It means that the user decode order in NOMA HetNet is closely intertwined with the power allocation in each cell which increases the difficulty greatly of solving the resource allocation problem. Consequently, to solve the resource allocation problem in NOMA HetNet, we first propose a user scheduling scheme to determine the maximum users set subjected to the systems service capability, then upon which we develop an iterative distributed power control algorithm to obtain the total transmit power of each cell. The simulation results demonstrate that the proposed NOMA HetNet can provide greater improvement in spectral efficiency (SE) and lower outage performance compared with conventional OMA HetNet and single-tier NOMA network.

The remainder of this paper is organized as follows. In Section II, we introduce the NOMA HetNet system model. Section III formulates a power allocation problem and provides the solution of this optimization problem. The numerical results and analysis are presented in Section V. Finally, the conclusions are given in Section VI.

II. SYSTEM MODEL

As shown in Fig.1, we consider a downlink NOMA heterogeneous network, involving one macro base station (MBS) located at the center of the macrocell and one overlaid small BS (SBS) deployed at the edge of the macrocell. For notation convenience, we use BS-i to denote the two BSs, where $i = 1$ stands for MBS and $i = 2$ for SBS. There are U_1 macrocell users (MUE) distributed randomly in the macrocell and U_2 small-cell users (SUE) distributed randomly in small-cell, respectively. Let $\mathcal{U}_i \triangleq \{1, 2, \cdots, U_i\}$ be the set of users connected with BS-i. All the devices and BSs are assumed to equip with single antenna scenario.

In this paper, BSs are supposed to deliver the superposed signals to their own users via NOMA principle. Accordingly, each user receives not only the desired signals from its serving BS, but also interfering signals from the cross-tier BS. We assume that the users are capable of utilizing SIC technique to retrieve its desired signals. Let UE-(i, k) represent the kth user in U_i and BS-j, $j \neq i$ be the interfering BS. Hence, the received signal at UE-(i, k) is

$$y_{i,k} = \sum_{n=1}^{U_i} \sqrt{\rho_{i,n} P_i} h_{i,i,k} + \sum_{m=1}^{U_j} \sqrt{\rho_{j,m} P_j} h_{j,i,k} + n_{i,k}, \quad i = 1, 2 \text{ and } i \neq j, \tag{1}$$

where $h_{j,i,k}$ denotes the channel fading coefficient between BS-j and UE-(i, k) which accounts for both large- and small-scale channel fading, P_i represents the total power consumption of BS-i, $\rho_{i,n}$ is the power allocation fraction for UE-(i, n), and $n_{i,k} \sim \mathcal{CN}(0, \sigma^2)$ stands for the corresponding additive white Gaussian noise (AWGN) with noise variance σ^2.

As described in [7], the optimal decode order is in the ascending order of normalized channel gain which is represented as the channel gain-to-the noise and inter-cell interference power ratio. Thereby, the normalized channel gain of UE-(i, k) is formulated as:

$$g_{i,k} = \frac{|h_{i,i,k}|^2}{\sum_{n \in \mathcal{U}_j} \rho_{j,n} P_j |h_{j,i,k}|^2 + \sigma^2}. \tag{2}$$

For simplicity, let $g_{i,1} \geq g_{i,2} \geq \cdots \geq g_{i,U_i}$. According to SIC protocol, UE-$\{i, k\}$ can decode the signals from the user set $\{\text{UE-}(i, k+1), \text{UE-}(i, k+1), \ldots, \text{UE-}(i, U_i)\}$ successively. By subtracting these signals from the received signals, UE-$\{i, k\}$ finally obtains its desired signals through treating the signals of the remaining users as noise. Therefore, the received signal to interference plus noise ratio (SINR) of UE-(i, k) is given by [7]

$$\gamma_{i,k} = \frac{\rho_{i,k} P_i g_{i,k}}{\sum_{u=1}^{k-1} \rho_{i,u} P_i g_{i,k} + 1}. \tag{3}$$

Denote $R_{i,k} = W \log_2(1+\gamma_{i,k})$ as the data rate of UE-(i, k), where W represents the total bandwidth. The achievable sum rate of this NOMA HetNet system is

$$C = \sum_{i \in \{1,2\}} \sum_{k \in \mathcal{U}_i} R_{i,k}. \tag{4}$$

On the other hand, to perform efficient SIC, the decoded signals should be accurately distinguished with the remaining undetectable signals as shown in the expression below,

$$\left(\rho_{i,k'} - \sum_{u=k+1}^{k'-1} \rho_{i,u} \right) g_{i,k} P_i \geq P_{diff}, \quad \forall k \in \{2, \cdots, U_i\}, \tag{5}$$

where P_{diff} stands for the required minimum power difference between the decoded and undetectable signals. Following this representation, a necessary condition for the power allocation in each cell was introduced in [26] as

$$\left(\rho_{i,k} - \sum_{u=1}^{k-1} \rho_{i,u} \right) P_i g_{i,k-1} \geq P_{diff}, \quad i \in \{1, 2\}, \ k \in \mathcal{U}_i/\{1\}, \tag{6}$$

which will be considered in the following resource management for NOMA HetNet to guarantee the system performance.

III. POWER ALLOCATION FOR DOWNLINK NOMA HetNet

In the previous section, the system model of NOMA HetNet has been presented, from which we can observe that the interference environment becomes more complicated due to the multi-user interference and cross-tier interference. Thus, an advanced resource management is called for to mitigate the interference and ensure the system performance improvement, which is the focus of this section.

A. PROBLEM FORMULATION

Denoting the power allocation vector in cell i as $\boldsymbol{\rho}_i = \{\rho_{i,1}, \rho_{i,2}, \cdots, \rho_{i,U_i}\}$, $i = 1, 2$, to maximize the sum rate, the power allocation problem for NOMA HetNet is mathematically formulated as

$$\text{(P1)} \quad \max_{\boldsymbol{\rho}_1, \boldsymbol{\rho}_2} \left\{ C = \sum_{i \in \{1,2\}} \sum_{k \in \mathcal{U}_i} R_{i,k} \right\} \tag{7}$$

$$\text{subject to} \quad \sum_{k \in \mathcal{U}_i} \rho_{i,k} \leq 1, \quad i \in \{1, 2\}, \tag{C7.1}$$

$$\rho_{i,k} \geq 0, \quad i \in \{1, 2\}, \ k \in \mathcal{U}_i, \tag{C7.2}$$

$$\left(\rho_{i,k} - \sum_{u=1}^{k-1} \rho_{i,u} \right) P_i g_{i,k-1} \geq P_{diff}, \quad i \in \{1, 2\}, \quad k \in \mathcal{U}_i/\{1\}, \tag{C7.3}$$

$$R_{i,k} \geq R_{i,k}^{th}, \quad i \in \{1, 2\}, \ k \in \mathcal{U}_i, \tag{C7.4}$$

where $R_{i,k}^{th}$ represents the data rate requirement of UE-(i, k). Then (C7.1) denotes the total power constraint for each BS, (C7.2) ensures that the power allocation for each user is nonnegative, (C7.3) guarantees the effective SIC as discussed in Section II, and (C7.4) supports the data rate requirement of every user.

As shown in (2) and (3), the increased transmit power of BS-i is beneficial for the sum rate of cell i while does harm to that of cell j. Thus, it is difficult to distinguish the convexity of above optimization problem (C7.1), and the optimization problem (C7.1) is a NP-hard problem. To deal with this situation, we replace (C7.4) by following linear form

$$\rho_{i,k} P_i g_{i,k} - I_{i,k}^{th} \left(\sum_{u=1}^{k-1} \rho_{i,u} P_i g_{i,k} + 1 \right) \geq 0, \tag{8}$$

where $I_{i,k}^{th} = 2^{R_{i,k}^{th}/W} - 1$ represents the desired minimum SINR for UE-(i, k).

Theorem 1: As the global optimization of previous optimization problem (C7.1) is achieved, for any given user $k \in \{2, 3, \cdots, U_i\}$, at least one of the two inequalities (C7.3) and (8) is an equation.

Proof: See **Appendix A**.

An necessary condition for the global optimization of (C7.1) is provided by **Theorem 1**. Some insights into the power allocation for user $k, k \in \{2, 3, \cdots, U_i\}$ are also obtained. We suppose that the total power consumption of BS-i, $i \in \{1, 2\}$ is $\tilde{P}_i$ where $\tilde{P}_i \leq P_i$. Thus, we can rewrite aforementioned optimization problem (P1) as:

$$\text{(P2)} \max_{\rho_1,\rho_2} \left\{ C = \sum_{i\in\{1,2\}} \sum_{k\in\mathcal{U}_i} R_{i,k} \right\} \tag{9}$$

$$\text{subject to} \sum_{k\in\mathcal{U}_i} \rho_{i,k} = 1, \quad i \in \{1, 2\}, \tag{C9.1}$$

$$\rho_{i,k} \geq 0, \quad i \in \{1, 2\},\ k \in \mathcal{U}_i, \tag{C9.2}$$

$$\left(\rho_{i,k} - \sum_{u=1}^{k-1} \rho_{i,u} \right) \tilde{P}_i g_{i,k-1} \geq P_{diff}, \quad i \in \{1, 2\}, \quad k \in \mathcal{U}_i/\{1\}, \tag{C9.3}$$

$$\rho_{i,k} \tilde{P}_i g_{i,k} \geq I_{i,k}^{th} \left(\sum_{u=1}^{k-1} \rho_{i,u} \tilde{P}_i g_{i,k} + 1 \right), \quad i \in \{1, 2\}, \quad k \in \mathcal{U}_i, \tag{C9.4}$$

$$\tilde{P}_i \leq P_i, \quad i \in \{1, 2\}. \tag{C9.5}$$

Obviously, above optimization problem (P2) is equivalent to the original optimization problem (P1). Once $\tilde{P}_i$ is confirmed, the optimal decoding order in each cell can be determined as well. Note that the decoding order in cell i should be updated in real time as the consumption power of BS-j, $j \neq i$ changes, which greatly increases the difficulty of solving the optimization problem (P2). However, the optimal power allocations for all users except the last decoding user are given in following theorem.

Theorem 2: With the fixed $\tilde{P}_i$, $i \in \{1, 2\}$, to guarantee the QoS demand of user k, $k \in \{2, 3, \cdots, U_i\}$, the optimal power allocation for user k is

$$\rho_{i,k} = \frac{1}{2} \left(\frac{P_{diff}}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{j=k+1}^{U_i} \rho_{i,j} \right), \tag{10}$$

if and only if

$$I_{i,k}^{th} \leq \frac{\left(\frac{P_{diff}}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{u=k+1}^{U_i} \rho_{i,u} \right)}{\left(\frac{2}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{u=k+1}^{U_i} \rho_{i,u} - \frac{P_{diff}}{\tilde{P}_i g_{i,k}} \right)}; \tag{11}$$

Otherwise,

$$\rho_{i,k} = \frac{I_{i,k}^{th}}{1 + I_{i,k}^{th}} \left(1 - \sum_{j=k+1}^{U_i} \rho_{i,j} + \frac{1}{\tilde{P}_i g_{i,k}} \right). \tag{12}$$

Proof: See **Appendix B**.

Based on **Theorem 2**, with known total power consumption of all BSs, the power allocation in cell i can be calculated by

$$\rho_{i,k} = \begin{cases} \left[\frac{1}{2} \left(\frac{P_{diff}}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{j=k+1}^{|\mathcal{U}_i|} \rho_{i,j} \right) \right]^+, & k \in \Phi, \\ \left[\frac{I_{i,k}^{th}}{1 + I_{i,k}^{th}} \left(1 - \sum_{j=k+1}^{|\mathcal{U}_i|} \rho_{i,j} + \frac{1}{\tilde{P}_i g_{i,k}} \right) \right]^+, & k \in \Phi', \\ \left[1 - \sum_{j=2}^{|\mathcal{U}_i|} \rho_{i,j} \right]^+, & k = 1, \end{cases} \tag{13}$$

where $[\bullet]^+ = \max\{0, \bullet\}$. Φ denotes the set of user conforming to (11) and Φ' is the complementary set of Φ.

B. USER SCHEDULING SCHEME

Note that the user with better channel condition has a higher priority over the user with worse channel condition, due to the fact that the user with better channel condition can contribute more capacity in NOMA HetNet but only consumes less power. However, as we can see in (13), the power allocation for all users are estimated in the inverse order of their normalized channel gain. To guarantee the QoS requirement of users with better channel condition, the maximum connection capability of each cell would like to be determined firstly with the known transmit power of each BS.

Thus, in this section, we propose a user scheduling scheme to determine the connection capability of NOMA HetNet with fixed maximum transmit power of each BS. The proposed user scheduling scheme is described detailedly as following:

1) *Initialization:* The maximum transmit power of BSs are set to be $\tilde{P}_i = P_i$, $i \in \{1, 2\}$, respectively. Denote $\mathcal{U}_i$, $i \in \{1, 2\}$ the set of users in cell i.
2) *Main loop (iteration):*

Step 1. With fixed $\tilde{P}_i$ and $\mathcal{U}_i$, $i \in \{1, 2\}$, the decoding order in each cell is confirmed firstly, and then the power allocation $\boldsymbol{\rho}_i$, $i \in \{1, 2\}$ can be estimated through the formulation (13). Afterward, $\boldsymbol{\rho}_i$, $i \in \{1, 2\}$ should be validated as follows.

Step 2. If the constraints of all users in each cell can be met, break out of the loop. If the constraints of some users with higher priority are not met in every cell, the user in this NOMA HetNet system with worst channel condition should be eliminated, and then go to **Step 1**.

Step 3. If the constraints of some users with higher priority are not fulfilled only in cell t, we should identify whether the constraints of all users in cell t can be satisfied by controlling the transmit power of BS-t', $t' \neq t$. The needed minimum transmit power of BS t', $P_{t'}^{\min}$, can be evaluated by following **Theorem 3** with fixed transmit power $\tilde{P}_t$. Let $\tilde{P}_{t''} = P_{t'}^{\min}$ and recalculate the power allocation $\boldsymbol{\rho}_i$, $i \in \{1, 2\}$. If the constraints of some users in cell t cannot be satisfied as usual, the user in cell t

with worst channel condition should be eliminated, and then go to **Step 1**; Otherwise, break out of the loop.

3) *Output:* The connection capability of each cell is obtained and return $\mathcal{U}_i$, $i \in \{1, 2\}$.

Theorem 3: With the given transmit power of BS-j, $\tilde{P}_j$ and fixed serving users of BS-i, $\mathcal{U}_i$, $i \neq j$, the needed minimum transmit power of BS-i is calculated by $P_i^{min} = \sum_{k=1}^{\mathcal{U}_i} p_{i,k}^{\min}$, where

$$\begin{cases} p_{i,1}^{\min} = \dfrac{I_{i,1}^{th}}{g_{i,1}} \\ p_{i,k}^{\min} = \max\left\{ I_{i,k}^{th}\left(\sum_{u=1}^{k-1} p_{i,u}^{\min} + \dfrac{1}{g_{i,k}}\right), \dfrac{P_{diff}}{g_{i,k-1}} + \sum_{u=1}^{k-1} p_{i,u}^{\min} \right\}, \\ \qquad k \neq 1. \end{cases} \tag{14}$$

Proof: See **Appendix C**.

C. ITERATIVE DISTRIBUTED POWER ALLOCATION

Once the users set is determined, the aforementioned optimization problem (P2) can be cast as:

$$\text{(P3)} \quad \max_{\tilde{P}_1, \tilde{P}_2} \left\{ \sum_{i \in \{1,2\}} \sum_{k \in \mathcal{U}_i} R_{i,k} \right\} \tag{15}$$

$$\text{subject to} \sum_{k \in \mathcal{U}_i} \rho_{i,k} = 1, \quad i \in \{1, 2\}, \tag{C15.1}$$

$$\rho_{i,k} > 0, \quad i \in \{1, 2\},\ k \in \mathcal{U}_i, \tag{C15.2}$$

$$P_i \leq P_i, \quad i \in \{1, 2\}, \tag{C15.3}$$

where $\boldsymbol{\rho}_i$ can be estimated according to (13).

Obviously, (P3) also has the same optimal solution as (P1), but greatly reduces the dimension of optimization problems. Fixed the transmit power of one BS, the suboptimal transmit power of another BS with the potential of being a global optimum can be obtained through Fibonacci method, which is depicted in **Algorithm 1**. The computational complexity of **Algorithm 1** is $O(\ln(\epsilon/L)/\ln(2/3))$ where ϵ is the arithmetic precision and L is the length of the feasible region of the variable.

Finally, the suboptimal total power consumption for each BS can be estimated alternately by utilizing the Algorithm 1 until the algorithm converges.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we demonstrate the system performance of downlink NOMA HetNet with the proposed resource management scheme through Monte Carlo simulations. We consider a two-tier cellular network involving one small-cell deployed at the edge of the macrocell, where the NOMA principle is employed in both macrocell and small-cell, and the users are distributed randomly. We suppose that each user can perfectly retrieve their intended information by using the technique of SIC. The modified Hata urban propagation model [27] is adopted here and some significant simulation parameters are provided in Table 1.

Algorithm 1 Obtain Optimal Transmit P_i With Fixed P_j

Input: $P_i^{\max}$, P_j, $\epsilon > 0$;
Calculate $P_i^{\min}$ according to **Theorem 3**;
while $|P_i^{\max} - P_i^{\min}| \leq \epsilon$ **do**
  Let $P_i' = P_i^{min} + \frac{P_i^{max} - P_i^{min}}{3}$, $P_i'' = P_i^{min} + \frac{2(P_i^{max} - P_i^{min})}{3}$;
  Estimate $\{\boldsymbol{\rho}_i', \boldsymbol{\rho}_j'\}$ and $\{\boldsymbol{\rho}_i'', \boldsymbol{\rho}_j''\}$;
  Calculate $C'(\boldsymbol{\rho}_i', \boldsymbol{\rho}_j')$ and $C''(\boldsymbol{\rho}_i'', \boldsymbol{\rho}_j'')$;
  if $C' < C''$ **then**
    $P_i^{min} = P_i'$.
  else
    $P_i^{max} = P_i''$.
  end if
end while
return $P_i = \frac{P_i^{\max} + P_i^{\min}}{2}$.

TABLE 1. System parameters.

Noise power spectrum density	-174dBm/Hz
Noise figure	9dB
Number of sub-channel	8
Bandwidth of sub-channel	180kHz
Radius of macrocell	250m
Radius of small-cell	30m
Transmit power of CBS $\{P_C\}$	20W
Transmit power of SBS $\{P_S\}$	10dBm $\sim$ 30dBm

The performance of the proposed NOMA HetNet is compared with that of one-tier NOMA system (termed as NOMA system) as well as conventional OMA HetNet [28]. To ensure a fair comparison, the bandwidth and total power consumption in three systems are identical, i.e. all spectral resource is utilized to multiplex the users in NOMA HetNet and one-tier NOMA system, and the transmit power of BS in one-tier NOMA network is set to be the sum power of all base station in a heterogeneous network.

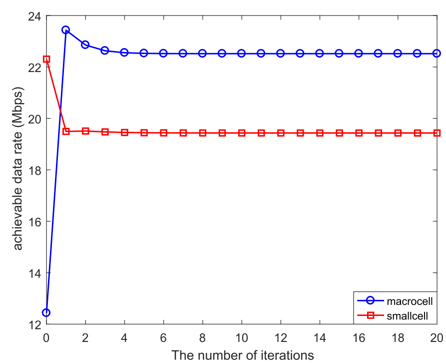

FIGURE 2. Convergence of the proposed Algorithm 1.

Fig.2 illustrates the convergence performance of the proposed Algorithm 1, where the numbers of users distributed in macrocell and small-cell are set to be 5 and 3, respectively.

We assume the data rate requirement of each user is 2Mbit/s, and the maximum transmit power of MBS and SBS are set to be 20W and 1W. It can be seen that our proposed Algorithm 1 can converges quickly with finite iterations.

Fig.3 depicts the curves of the outage probability and spectral efficiency (SE) versus user data rate requirement. It clearly points out that NOMA HetNet outperforms one-tier NOMA as well as OMA HetNet from Fig.3(a) and Fig.3(b) in terms of both outage performance and spectral efficiency. The main reason is that NOMA HetNet combines the advantages of NOMA technique and heterogeneous networks, which can not only improve the spectral efficiency by using non-orthogonal access manner, but also reduce the outage probability by offloading overfull users to the small cell. Compared with one-tier NOMA network, OMA HetNet system improves the spectral efficiency by shortening the distance between transmitter and receivers, but at the cost of worse outage performance due to the introduction of inter-tier interference. Besides, as shown in Fig.3(c), the outage performances of MUE and SUE decline gradually with the increase of data rate requirement for both NOMA HetNet and OMA HetNet. While the outage performance of MUE in NOMA HetNet always outperforms that in OMA one, the outage performance of SUE behaves worse in NOMA as 0.856Mbit/s $\leq R^{th} \leq$ 2Mbit/s because OMA can provide adequate resources in this region. Further, as shown in Fig.3(d), NOMA HetNet acquires much higher SE compared with OMA both for macrocell and small-cell. Note that for the macrocell, the SE remains unchanged as $R^{th} <$ 1.5Mbit/s and deteriorates significantly when $R^{th} >$ 1.5Mbit/s, which makes sense since some users have to be abandoned as the data rate user data rate requirement is higher due to the limited radio resources.

With the increase of the transmit power of SBS, the system performance of one-tier NOMA network is almost unchange as illustrated in Fig.4(a) and Fig.4(b), since the transmit power of SBS is extremely small compared with that of MBS. The influences of the increasing transmit power of SBS on heterogeneous networks are represented detailedly in Fig.4(c) and Fig.4(d). As illustrated in Fig.4(c), the outage

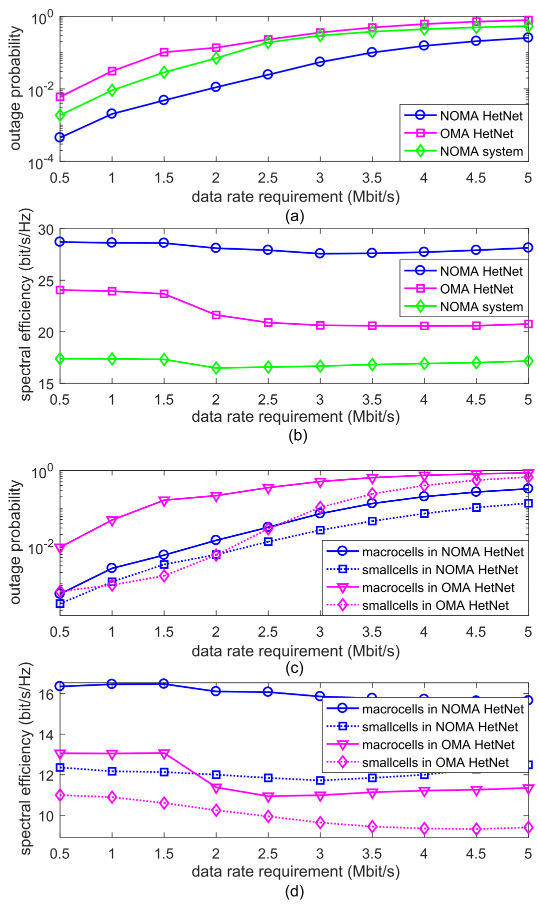

FIGURE 3. Illustration of the outage probability and spectral efficiency as P_1 = 20W, P_2 = 0.1W, U_1 = 5 and U_2 = 3. (a) and (b) respectively illustrate the influence of varying data rate requirements on the overall performance of three systems in term of outage probability and spectral efficiency; (c) and (d) detailedly explore the outage performance and spectral efficiency for different cell in heterogeneous network versus the data rate requirement of users, respectively.

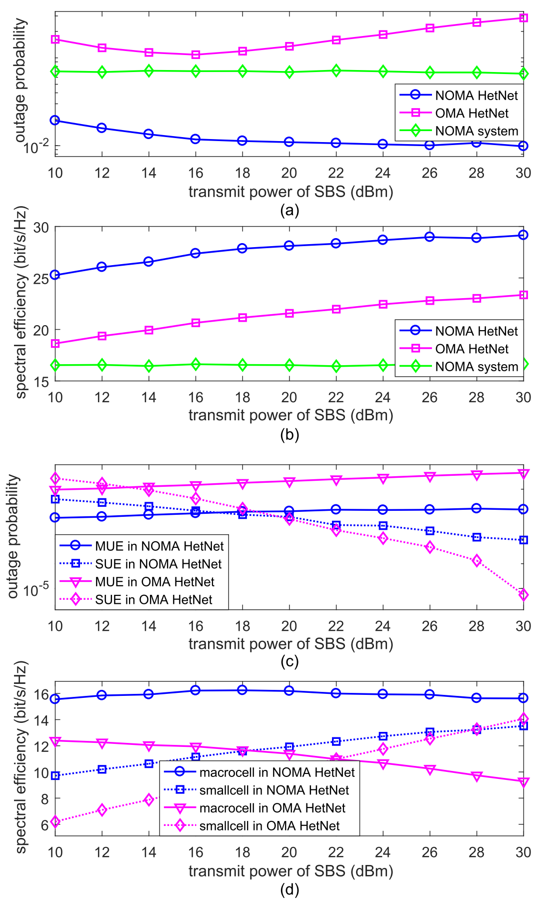

FIGURE 4. As P_1 = 20dB, U_1 = 5, U_2 = 3 and R^{th} = 2Mbit/s, (a) and (b) respectively explore the influence of varying transmit power of SBS on the overall performance in term of outage probability and spectral efficiency; (c) and (d) detailedly show the curves of outage probability and spectral efficiency for different cell versus transmit power of SBS, respectively.

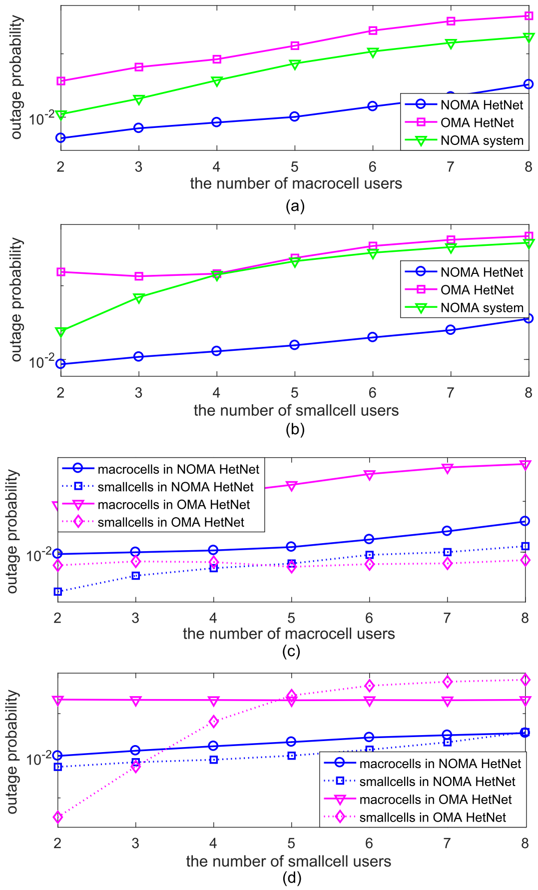

FIGURE 5. Outage probability comparison of three systems with varying number of users as $P_1 = 20$W, $P_2 = 0.1$W and $R^{th} = 2$Mbit/s. (a) and (c) reveal the influence of varying number of macrocell users on the outage probability with $U_2 = 3$; (b) and (d) show the curves of outage probability versus the varying number of small users with $U_1 = 5$.

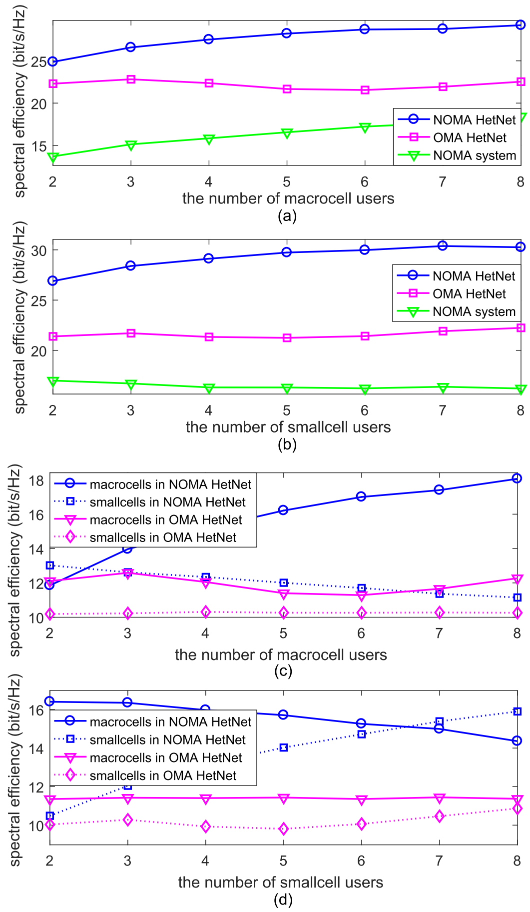

FIGURE 6. Spectral efficiency comparison with varying number of users as $P_1 = 20$W, $P_2 = 0.1$W and $R^{th} = 2$Mbit/s. (a) and (c) illustrate the spectral efficiency versus varying number of macrocell users as $U_2 = 3$; (b) and (d) represent the curves of spectral efficiency with the varying number of smallcell users as $U_1 = 5$.

probability of MUE increases gradually with the growing SBS transmit power in both systems, while NOMA HetNet performs much better than OMA HetNet. Meanwhile, the outage performance of SUE improves with the increase of SBS transmit power in both NOMA and OMA HetNet. Obviously, the slope of the curve of SUE in OMA HetNet is greater than that of MUE in OMA HetNet, which can provide a perfect explanation of the cause of saturation point in Fig.4(a). Besides, the outage performance of SUE in OMA HetNet outperforms that in NOMA HetNet when the SBS transmit power is greater than 20dBm. In particular, as shown in Fig.4(d), the SE of small-cell in OMA HetNet is also superior to that of NOMA HetNet as $P_2 \geq 28$dBm, which means that the influence of SBS transmit power on SE of NOMA HetNet exerts less due to the fact that more wide bandwidth is utilized in NOMA HetNet.

The outage probability comparison of three systems with the varying user number is depicted in Fig.5. It is easy to observe that with the increasing number of MUEs or SUEs, the outage performances of three systems gradually decline as illustrated in Fig.5(a) and Fig.5(b). In particular, as shown in Fig.5(c) and Fig.5(d), the outage performances of both MUE and SUE decline gradually as NOMA scenario is employed since more power would be consumed to support the growing number of users but bring about serious inter-tier interference. Further, while NOMA HetNet always performs better than OMA HetNet in terms of the MUE outage performance as shown in Fig.5(c), its outage performance of small-cell user can only surpass that of OMA when the number of MUE is less than 4 due to the multi-user interference. In Fig.5(d) where $U_1 = 5$, with the growing SUE number, the outage probability of SUE increases sharply and that of MUE declines slightly in OMA HetNet. However, for NOMA HetNet, the outage performances of both MUE and SUE decrease slightly as the SUE number increases, and the outage performance of SUE in NOMA HetNet cannot outperform OMA one until $U_2 \geq 3$.

Fig.6 shows the spectral efficiency with varying number of users. As shown in Fig.6(a) and Fig.6(b), the spectral efficiency of one-tier NOMA network increases gradually with the increasing number of MUEs, but declines with the increasing number of SUEs. The essential reason is that the

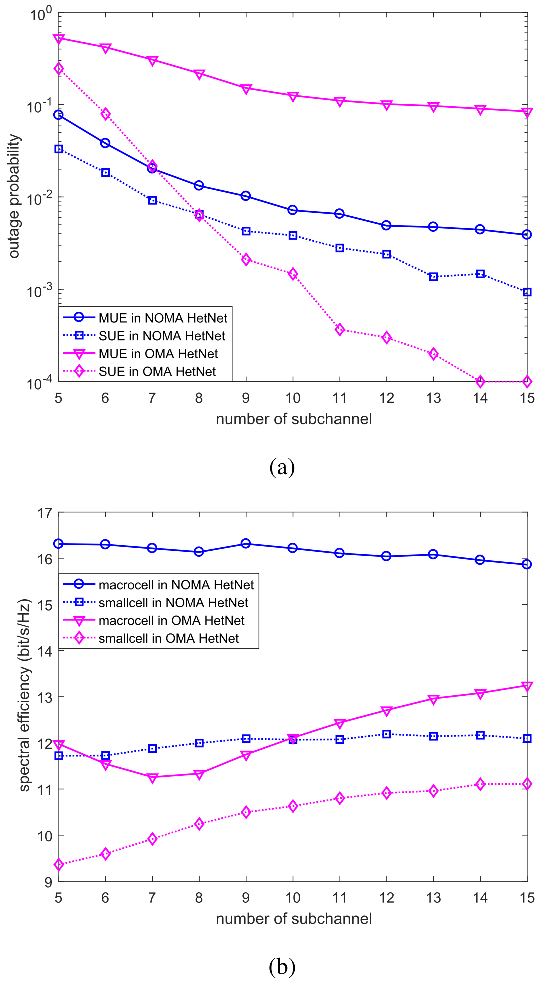

FIGURE 7. Illustration of the outage probability and spectral efficiency with varying number of sub-channel as $P_1 = 20$W, $P_2 = 0.1$W, $U_1 = 5$ and $U_2 = 3$ and $R^{th} = 2$Mbit/s. (a) outage probability versus varying number of sub-channel; (b) spectral efficiency versus varying number of sub-channel.

edge users (smallcell users) always require more transmit power but produce less data rate, instead the inner users (macrocell users) consume less transmit power but can bring more data rate. Besides, from Fig.6(c) and Fig.6(d), we can see that in OMA HetNet, with the increase of the user number in one cell, its SE would fluctuate while that of the other cell would remain constant. The main reason is that the users with worse channel condition are interrupted sequentially due to the restriction of transmit power and spectrum resource. In general, the NOMA HetNet possesses a greater spectral efficiency compared with OMA HetNet because NOMA principle could make full use of the spectrum resource.

The outage performance and SE versus varying sub-channel number are depicted in Fig.7. Because all sub-channels are utilized to accommodate multiple users, the available bandwidth in NOMA HetNet linearly increases with the growth of sub-channel number. As we can see from Fig.7(a), with the increasing number of sub-channels, the outage performances of MUE and SUE in both NOMA and OMA HetNet can be improved. Specifically, as the number of sub-channel is greater than 8, the outage performance of SUE in OMA HetNet surpasses that of NOMA HetNet. As shown in Fig.7(b), regardless of which transmission principle is adopt in heterogeneous network, the spectral efficiency of small-cell gradually increases with the growing number of sub-channels. However, the influence of sub-channel number on the spectral efficiency of macrocell in NOMA HetNet is extremely finite which brings about a slight reduction in spectral efficiency of macrocell with the increasing number of sub-channels. Similarly, the curve of spectral efficiency of macrocell in OMA HetNet declines firstly to a saddle point, and then gradually increases. The main reason is that as the number of sub-channels is more, the interference experienced by each sub-channel becomes smaller so that the spectral efficiency of macrocell will be improved gradually with the increasing number of sub-channels.

V. CONCLUSIONS

By exploiting spatial diversity and multi-user diversity respectively, heterogeneous networks and NOMA technique are two essential strategies to enhance the spectral efficiency and improve the overall system performance for next-generation wireless communication networks. In this paper, we develop a novel heterogeneous network in which NOMA technology is employed at macrocell and small-cell. To mitigate the more complicated interference and maximize the overall throughput of this NOMA HetNet subjected to the constraints of the user QoS demand and total transmit power of BSs, we formulate a power allocation problem which proves to be an NP-hard problem. To deal with this optimization problem, we propose a user scheduling scheme and iterative power control algorithm to capture a suboptimal solution. Simulation results demonstrate that compared with conventional OMA HetNet and one-tier NOMA network, the system performance of NOMA HetNet with the proposed radio resource management scheme performs much better in terms of outage performance and spectral efficiency.

APPENDIX A
VERIFICATIONS OF THEOREM 1

The **Theorem 1** will be demonstrated by contradiction. Firstly, we assume $\boldsymbol{\rho}'_i = \{\rho'_{i,1}, \rho'_{i,2}, \cdots, \rho'_{i,U_i}\}$ is the optimal solution of optimization problem (P1) and the following strict inequalities exist for UE-(i, k).

$$\left(\rho'_{i,k} - \sum_{u=1}^{k-1} \rho'_{i,u}\right) P_i g_{i,k-1} > P_{\text{diff}}, \tag{16}$$

and

$$\rho'_{i,k} P_i g_{i,k} - I_{i,k}^{th} \left(\sum_{u=1}^{k-1} \rho'_{i,u} P_i g_{i,k} + 1\right) > 0. \tag{17}$$

Hence, the sum rate of users from UE-(i, 1) to UE-(i, k) can be formulated as

$$\begin{aligned} T_k(\boldsymbol{\rho}_i') &= \sum_{m=1}^{k} R_{i,m} \\ &= \log_2\left(1+\rho_{i,1}'P_ig_{i,1}\right)+\log_2\left(1+\frac{\rho_{i,2}'P_ig_{i,2}}{\rho_{i,1}'P_ig_{i,2}+1}\right) \\ &\quad+\cdots+\log_2\left(1+\frac{\rho_{i,k}'P_ig_{i,k}}{\sum\limits_{u=1}^{k-1}\rho_{i,j}'P_ig_{i,k}+1}\right) \\ &= \log_2\left(\frac{\rho_{i,1}'P_ig_{i,1}+1}{\rho_{i,1}'P_ig_{i,2}+1}\right)+\log_2\left[\frac{\left(\rho_{i,1}'+\rho_{i,2}'\right)P_ig_{i,2}+1}{\left(\rho_{i,1}'+\rho_{i,2}'\right)P_ig_{i,3}+1}\right] \\ &\quad+\cdots+\log_2\left[\frac{\left(\sum\limits_{u=1}^{k-1}\rho_{i,j}'\right)P_ig_{i,k-1}+1}{\left(\sum\limits_{u=1}^{k-1}\rho_{i,j}'\right)P_ig_{i,k}+1}\right] \\ &\quad+\log_2\left[\left(\sum_{u=1}^{k}\rho_{i,j}'\right)P_ig_{i,k}+1\right]. \end{aligned} \tag{18}$$

Let $\boldsymbol{\rho}_i'' = \{\rho_{i,1}', \cdots, \rho_{i,k-2}', \rho_{i,k-1}'', \rho_{i,k}'', \rho_{i,k+1}', \cdots, \rho_{i,U_i}'\}$ be a feasible solution of optimization problem (P1) where $\rho_{i,k}'' = \rho_{i,k}' - \Delta$, $\rho_{i,k-1}'' = \rho_{i,k-1}' + \Delta$ which makes at least one equality of (C7.3) and (8) hold.

Then we can get the increment of sum rate as

$$\begin{aligned} T_k(\boldsymbol{\rho}_i'')-T_k(\boldsymbol{\rho}_i') &= \log_2\left\{\frac{\left(\sum\limits_{j=1}^{k-1}\rho_{i,j}'+\Delta\right)P_ig_{i,k-1}+1}{\left(\sum\limits_{j=1}^{k-1}\rho_{i,j}'+\Delta\right)P_ig_{i,k}+1}\right\} \\ &\quad-\log_2\left\{\frac{\left(\sum\limits_{j=1}^{k-1}\rho_{i,j}'\right)P_ig_{i,k-1}+1}{\left(\sum\limits_{j=1}^{k-1}\rho_{i,j}'\right)P_ig_{i,k}+1}\right\} \\ &= \log_2\left\{\frac{\lambda+\Delta P_ig_{i,k-1}}{\lambda+\Delta P_ig_{i,k}}\right\}, \end{aligned} \tag{19}$$

where $\lambda = [\sum_{j=1}^{k-1}\rho_{i,j}'P_ig_{i,k-1}+1][\sum_{j=1}^{k-1}\rho_{i,j}'P_ig_{i,k}+1] + \Delta P_ig_{i,k-1}\sum_{j=1}^{k-1}\rho_{i,j}'P_ig_{i,k}$. Due to $\Delta P_ig_{i,k-1} > \Delta P_ig_{i,k}$, we can get

$$T_k(\boldsymbol{\rho}_i'') - T_k(\boldsymbol{\rho}_i') > 0. \tag{20}$$

Additionally, since the total transmit power of BS i is unchange, it would not affect the performance of another cell $j, j \neq i$. Therefore we can see that the achievable throughput $T_k(\boldsymbol{\rho}_i')$ is not maximum, which is contradictory with the original assumption. Then the Theorem 1 is proved.

APPENDIX B
VERIFICATIONS OF THEOREM 2

According to **Theorem 1**, for any user k, $k \in \{2, 3, \cdots, U_i\}$, at least one equality holds between the two inequalities (C9.3) and (8). If the inequality (C9.3) is equation, i.e.,

$$\left(\rho_{i,k} - \sum_{u=1}^{k-1}\rho_{i,u}\right)P_ig_{i,k-1} = P_{\text{diff}}. \tag{21}$$

After some algebraic operations, the power allocation $\rho_{i,k}^{(1)}$ is expressed as:

$$\rho_{i,k}^{(1)} = \frac{1}{2}\left(\frac{P_{diff}}{\tilde{P}_ig_{i,k-1}} + 1 - \sum_{u=k+1}^{U_i}\rho_{i,u}\right). \tag{22}$$

Similarly, as the inequality (8) is equation, the power allocation $\rho_{i,k}^{(2)}$ is given by:

$$\rho_{i,k}^{(2)} = \frac{I_{i,k}^{th}}{1+I_{i,k}^{th}}\left(1 - \sum_{u=k+1}^{U_i}\rho_{i,u} + \frac{1}{\tilde{P}_ig_{i,k}}\right). \tag{23}$$

Due to the constraints (C9.3) and (8) should be satisfied simultaneously, the optimal power allocation for user k, $k \in \{2, 3, \cdots, U_i\}$ is $\rho_{i,k}^* = \max\{\rho_{i,k}^{(1)}, \rho_{i,k}^{(2)}\}$. Therefore, if $\rho_{i,k}^* = \rho_{i,k}^{(1)}$, we can get

$$\frac{I_{i,k}^{th}}{1+I_{i,k}^{th}}\left(1-\sum_{u=k+1}^{U_i}\rho_{i,u}+\frac{1}{\tilde{P}_ig_{i,k}}\right) \leq \frac{1}{2}\left(\frac{P_{diff}}{\tilde{P}_ig_{i,k-1}}+1-\sum_{u=k+1}^{U_i}\rho_{i,u}\right). \tag{24}$$

After some algebraic operations, above inequality (24) can be further simplified to

$$I_{i,k}^{th} \leq \frac{\left(\frac{P_{diff}}{P_ig_{i,k-1}} + 1 - \sum\limits_{u=k+1}^{U_i}\rho_{i,u}\right)}{\left(\frac{2}{P_ig_{i,k-1}} + 1 - \sum\limits_{u=k+1}^{U_i}\rho_{i,u} - \frac{P_{diff}}{P_ig_{i,k}}\right)}. \tag{25}$$

Thus, we can get that $\rho_{i,k}^* = \rho_{i,k}^{(1)}$ if and only if the inequality (25) holds, otherwise $\rho_{i,k}^* = \rho_{i,k}^{(2)}$.

APPENDIX C
VERIFICATIONS OF THEOREM 3

The users with better channel condition should be satisfied firstly since they have the higher priority. Therefore, to fulfill the SINR requirement of UE-(i, 1) with fixed transmit power $P_j, j \neq i$, the minimum power allocation $p_{i,1}^{\min}$ is given by:

$$p_{i,1}^{\min} = \frac{I_{i,1}^{th}}{g_{i,1}}. \tag{26}$$

However, for the user k, $k \in \{2, 3, \cdots, U_i\}$, at least one equality holds between the two inequalities (C9.3) and (8) according to **Theorem 1**. If the inequality (C9.3) is equation, i.e.,

$$\left(p_{i,k} - \sum_{u=1}^{k-1} p_{i,u}\right) g_{i,k-1} = P_{diff}. \tag{27}$$

After some algebraic operations, the minimum power allocation for UE-(i, k), $p'_{i,k}$, is expressed as:

$$p'_{i,k} = \frac{P_{diff}}{g_{i,k-1}} + \sum_{u=1}^{k-1} p_{i,u}^{\min}. \tag{28}$$

Similarly, as the inequality (8) is an equation, the minimum power allocation $p''_{i,k}$ is given by:

$$p''_{i,k} = I_{i,k}^{th}\left(\sum_{u=1}^{k-1} p_{i,u}^{\min} + \frac{1}{g_{i,k}}\right). \tag{29}$$

Since the constraints (C9.3) and (8) should be satisfied simultaneously, the minimum power allocation for user k, $k \in \{2, 3, \cdots, U_i\}$ is $p_{i,k}^{min} = \max\{p'_{i,k}, p''_{i,k}\}$. Therefore, the minimum power allocation for each user can be successively calculated along with the ascending order of normalized channel condition for user set $\mathcal{U}_i$.

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DADONG NI received the B.S. degree in electronic and information engineering from PLA Information Engineering University, Zhengzhou, China, in 2010, and the M.S. degree in Information and Communication Systems from Southwest Jiaotong University, Chengdu, China, in 2013. He is currently pursuing the Ph.D. degree in information and communication systems with the Key Laboratory of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, China. His research interests include non-orthogonal multiple access, heterogeneous networks, and radio resource management.

LI HAO received the B.S. degree from Tianjin University in 1993, the M.S. degree from the University of Electronic Science and Technology of China in 1996, and the Ph.D. degree from Southwest Jiaotong University, China, in 2003. Since 2005, she has been with Southwest Jiaotong University, Chengdu, China, where she is currently a Professor with the School of Information Science and Technology and serves as the Director of the Dean's Office. Her research interests include 5G technologies, communication and information systems, wireless transmission, and high-mobility communication. She served as the Chair of the IEEE Chengdu Section.

QUANG THANH TRAN received the B.S. and M.S. degrees in telecommunication engineering from the University of Transport and Communications, Hanoi, Vietnam, in 2005 and 2009, respectively, and the M.S. degree in information and communication systems from Southwest Jiaotong University, Chengdu, China, in 2012. He is currently pursuing the Ph.D. degree in information and communication systems with the Key Laboratory of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, China. Since 2005, he has been a Lecturer with the Faculty of Electrical and Electronic Engineering, University of Transport and Communications, Hanoi, Vietnam. His research interests include wireless traffic prediction, high mobility, and wireless communication design.

XIAOMIN QIAN received the B.S. degree in electronic and information engineering from PLA Information Engineering University, Zhengzhou, China, in 2009. She is currently pursuing the Ph.D. degree in communication and information system with the Key Laboratory of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, China. Her research interests include wireless communication theory, with particular focus on cognitive radio, spectrum sensing, and access and vehicular networks.