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Non-Cooperative Game-Based Power Allocation for Energy-Efficient NOMA Heterogeneous Network

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ABSTRACT This paper focus on the two-tier downlink heterogeneous networks (HetNets) with non-orthogonal multiple access (NOMA). The aim is to jointly optimize user scheduling and power allocation to solve the problem of maximizing the energy efficiency (EE) of the NOMA HetNets. We formulate the basic principle of NOMA and develop the EE model of joint user scheduling, optimal power allocation factor among users on the same subchannel and power allocation across subchannels. Firstly, considering that the problem of formulation is a multi-objective optimization (MOO) problem, which is non-convex and NP-hard, we decouple the MOO problem into two single-objective optimization (SOO) problems: 1) joint the optimal power allocation factor of maximizing the EE among users on the same subchannel to solves the subchannel matching, and 2) the power allocation across subchannels. For subchannel matching, non-cooperative game and global optimal search (GOS) are respectively used to solve the power allocation factor among users on the same subchannel and user scheduling. For the power allocation factor among users on the same subchannel, the existence of Nash equilibrium (NE) is proved by introducing super-modular game. Besides, the Nash equilibrium point (NEP) of the game can be obtained by using the proposed algorithm. Then, for the correlation between users-subchannels, this paper proposes a non-cooperative game based user-subchannel global optimal search matching algorithm (NCG-US-GOSMA) with low-complexity. Finally, according to the obtained subchannel matching, the non-convex problem of power allocation across subchannels is converted into convex problem by successive convex approximation (SCA), and then solve it by iteration. Simulation results verify the effectiveness of the proposed scheme; in addition, the EE performance is better than the existing resource allocation algorithm and OFDMA scheme.

INDEX TERMS HetNets, NOMA, user scheduling, power allocation, non-cooperative game.

I. INTRODUCTION

The rapid development of 5G wireless communication technology will lead to many requirements [1], [2], such as massive connectivity, high throughput and high EE. Orthogonal frequency division multiple-access (OFDMA) has been utilized in 4G wireless communication technology. Because of the requirement of orthogonality between subcarriers, spectral efficiency has not been fully utilized. In the face of limited spectrum resources, it is very important to seek effective multiple access technology. NOMA can improve the spectral efficiency [3], [4] of the whole system by multiplexing multiple users with different power levels on the same frequency resource block. Therefore, NOMA has become one of the candidates for the 5G wireless communication technology.

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A. EXISTING RESEARCH ON NOMA

The important objectives of 5G wireless communication technology is improving EE [5]–[7]. When there are many wireless terminals with different channel states in HetNets, how to allocate resources to user groups superimposed on speciific time and frequency resources to maximize the total EE of the system is an urgent problem to be solved. As an important part of resource allocation, joint optimization user scheduling and power allocation can effectively control the interference of inter-cell and intra-cell, and then improve the total EE of the HetNets system [8]–[10].

A lot of research has been studied on the resource allocation of single cell. In [11], the multi-carrier non-orthogonal multiple access (MC-NOMA) is demonstrated to achieve better system performance than OFDMA network in terms of system throughput. In [12], the algorithm of user grouping based on channel gain is proposed by pairing users with different channel conditions (i.e., two users are allocated to an orthogonal resource block), which illustrates that NOMA technology has good performance improvement than orthogonal multiple-access (OMA) system. In [13] and [14], the NOMA system is proved to achieve higher performance improvement through effective resource allocation algorithm with perfect channel state information (CSI) and imperfect CSI, respectively. In [15], the problem of maximizing EE of NOMA system is solved by combining subchannel matching and power allocation with non-cooperative super-modular game model. In [16], the problem of spectrum resource and power allocation are converted into user pairing, subchannel matching and power allocation. In addition, proposed adaptive proportional fair algorithm (APFA) improves system throughput and user fairness compared with the traditional subchannel matching based on matching theory and power allocation with water-filling (WF) algorithm. In [17], an alternative optimization (AO) method is proposed to solve the problem of maximizing the data rate of the near NOMA user while satisfying the quality of service (QoS) requirement of the far NOMA user and the energy causality condition of the near NOMA user by joint the transmit beamforming, the power splitting (PS) ratio, the receiver filter, and optimal the power allocation factor in the simultaneous wireless information and power transfer (SWIPT) NOMA system, the sub-optimal solution of the optimal scheme is obtained by using the algorithm with low complexity. Besides, physical layer security is studied in NOMA system [18]–[20], the problem of resource allocation in the NOMA system is solved by combining the secrecy outage probability (SOP) and power allocation, and improve the performance of the network by a low complexity scheme. However, the research scenarios in the aforementioned works are limited to single cell, which has certain limitations for the future 5G large-scale HetNets.

In NOMA HetNets, the power allocation and user scheduling under perfect CSI and imperfect CSI conditions are studied in [21]. The tradeoff between system throughput and total EE is achieved, but the paper does not specifically address the issue of user fairness problem. In [22], based on the quality of experience (QoE), the resource allocation problem of MC-NOMA in multi-cell network is solved by combining power allocation and user scheduling, which achieves lower computational complexity in comparison to GOS algorithm and branch and bound algorithm. Besides, the performance of system is further improved compared with OMA system. However, the problem of EE has not been solved. In [23], the EE problem is modeled as a mixed integer non-convex optimization problem by considering the interference of inter-cell and intra-cell, and then power allocation algorithm is designed. The proposed algorithm can converge within ten iterations and achieve better EE than the original method in [24], but the complexity of the algorithm is still higher. In [25], an energy-cooperation NOMA HetNets is proposed, the authors solve the problem of optimal user association with fixed transmit power via a distributed algorithm. Furthermore, a joint power control and user association optimization algorithm is designed to solve the traffic load in the system, which has better EE performance than previous schemes [26]. However, the problem of user-subchannel matching is not considered in this paper. In [27], the energy-harvesting (EH) two-tier downlink NOMA HetNets is formulated to joint subchannel assignment and global EE power allocation (J-SA-GEE-PA) problem, which is converted into subchannel assignment by matching theory and GEE-maximizing power allocation, proposed scheme with lower computational-complexity and superior to OFDMA. For resource allocation problems, game theory is a useful scheme. In [28], the problem of rate and power allocation is expound to be a non-cooperative game and converged the NEP by use super-modular game. In [29], the problem of resource allocation in fog computing is solved via the Stackelberg game. Besides, in [30]–[37], the problem of resource allocation through game theory can also be found.

B. MOTIVATION AND CONTRIBUTIONS

As we discussed above, the existing resource allocation scheme focuses on the joint user-subchannel matching and power allocation under single cell and NOMA HetNets to solve the problem of throughput and EE maximization. However, joint user scheduling, power allocation on the same subchannel and across subchannels in NOMA HetNets to solve the problem of EE maximization, which is rather poor. In order to achieve further improvement of EE, new resource allocation schemes must be provided. The main contributions of this paper are summarized as follows:

- For the NOMA HetNets, user scheduling and power allocation are modeled as the problem of EE maximization. Then, this problem is transformed into a MOO function of joint user scheduling, the factor of power allocation among users on the same subchannel and power allocation across subchannels to maximize EE. In order to solve the non-convex and NP-hard of MOO problem, which is divided into two SOO problems: 1) joint the optimal power allocation factor of maximizing the EE among users on the same subchannel to solves the subchannel matching, and 2) the power allocation across subchannels.
- In order to solve the optimization problem 1), the author combines the non-cooperative game and the GOS to solve the problem of power allocation factor among users and user-subchannel matching respectively. To solve the power allocation factor among users, the NE is proved by introducing super-modular game.

Besides, the NEP of the game can be obtained by using the proposed algorithm. Then, the EE and power allocation factor of each user can be obtained. Finally, the user-subchannel matching scheme can be obtained through NCG-US-GOSMA.
- For the optimization problem 2), based on the user-subchannel matching scheme given in problem 1), this paper uses SCA method to solve the non-convex problem of power allocation across subchannels and solves it by iteration.

Our work is different from [15], [25] in several perspectives. In [15], single cell network is considered, while our network model is NOMA HetNets. Because the frequency spectrum is divided into a number of subchannels and each subchannel is shared by all the users, there are only intra-cell interference in [15], while there are two interference in our work: intra-cell interference and inter-cell interference. In addition, only two users are superimposed on each subchannel in [15], while our work considers that each subchannel can be shared to multiple users. In [25], the problem of user-base station (UE-BS) association has been solved, while our network model assumes fixed user association prior to the network operation. In addition, our network model assumes that a number of subchannels are shared by all the users rather than a single subchannel. In summary, the resource allocation scheme proposed in this paper is innovative.

C. PAPER ORGANIZATION

The organizational structure of paper is as follows. In Section II, the system model and the EE objective function will be described. In Section III, joint the optimal power allocation factor of maximizing the EE among users on the same subchannel to solves the subchannel matching and the power allocation across subchannels will be proposed. In Section IV, the simulation analysis and verification of the system is presented. Finally, Section V summarizes the whole article.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. NETWORK MODEL

This paper considers the downlink two-tier NOMA HetNets network as shown in Fig.1, assuming single antenna terminals and base-stations (BSs). Among them, a macro BS (MBS) is located in the center of a macro cell. The macro cell covers by several pico cells and there is a pico BS (PBS) in the center of each pico cell. Let $t \in \{1, \cdots, T\}$ represent the tth BS, in which $t = 1$ represents the MBS, otherwise represent PBSs. In the HetNets, there are M users distribute by Poisson point process, let $m \in \{1, \cdots, M\}$ be the mth user, and each user can access only one BS. Because of the NOMA system using OFDMA technology, all cells can utilize the same subchannel to improve the spectral efficiency of the system, the total bandwidth B of the system is divided into N subchannels, and each sub-channel's bandwidth is $B_s = {}^{B}\!/_{N}$, and let $n \in \{1, \cdots, N\}$ be the nth sub-channel. In addition, this paper assumes that perfect CSI is available.

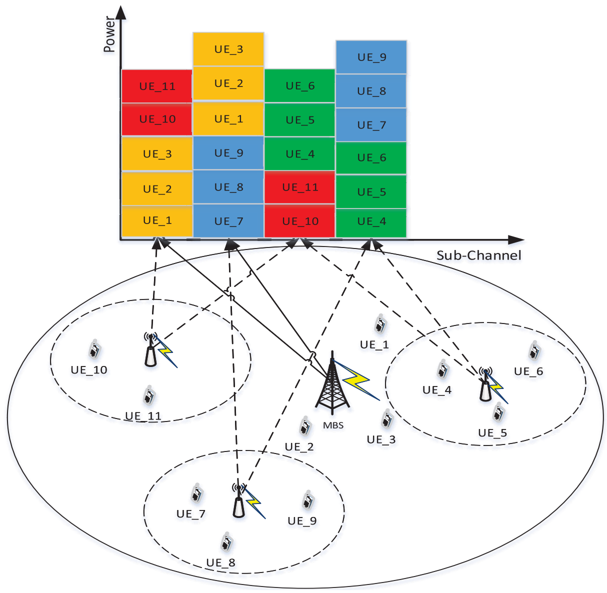

FIGURE 1. A two-tier NOMA HetNets.

It is assumed that the problem of UE-BS association is known, that is, the users within the coverage of the pico cell access to the PBS, and the other users access to the MBS. For each cell, let $x_{n,m} \in \{0, 1\}$ be the matching between mth user and nth subchannel, in which $x_{n,m} = 1$ represents that mth user matches nth subchannel and $x_{n,m} = 0$ means no match. According to NOMA protocol [3], [4], the superposition signal received by mth user on the nth subchannel in tth cell can be expressed as follows:

$$y_{n,m}^{t} = h_{n,m}^{t}\sqrt{p_{n,m}^{t}}s_m + h_{n,m}^{t}\sum_{m' \neq m}^{M} x_{n,m'}\sqrt{p_{n,m'}^{t}}s_{m'} + \sum_{t' \neq t} h_{n,m}^{t'}\left(\sum_{m' \neq m}^{M} x_{n,m'}\sqrt{p_{n,m'}^{t'}}s_{m'}\right) + z_{n,m}, \quad (1)$$

where let $h_{n,m}^{t} = g_{n,m}^{t} * PL^{-1}(d)$ be the channel coefficient from tth BS to mth user on the nth subchannel, $g_{n,m}^{t}$ is the fading channel gain from tth BS to mth user on the nth subchannel. We assume that the fading of each subchannel follows Rayleigh distribution and varies independently for different subchannels, let $PL^{-1}(d)$ be the path loss of distance. $p_{n,m}^{t}$ is the transmission power allocated by the mth user on the nth subchannel, s_m is the data stream of the mth user, $E\left[s_m^2\right] = 1$. Let $h_{n,m}^{t'}$ be the interference channel response from the t'th BS, $z_{n,m} \sim c\eta\left(0, \sigma_n^2\right)$ represent the additive white Gauss noise with mean value of 0 and variance of σ_n^2.

According to (1), the target signal of the mth user consists of interference signal of the intra-cell, interference signal of the inter-cell and noise. Assuming that there are M_n' users on the nth subchannel, the signal-to-interference-plus-noise ratio (SINR) of the mth user on the nth subchannel can be obtained by (1):

$$SINR_{n,m} = \frac{\left|h_{n,m}^t\right|^2 p_{n,m}^t}{\left|h_{n,m}^t\right|^2 \sum_{i \neq m}^{M_n'} p_{n,i}^t + \sum_{t' \neq t} \left|h_{n,m}^{t'}\right|^2 p_n^{t'} + \sigma_n^2}, \quad (2)$$

where $p_n^{t'} = \sum_{m' \neq m}^{M} x_{n,m'} p_{n,m'}^{t'}$ is the power of the t'th BS on the nth subchannel. In order to facilitate the calculation, let $H_{n,m}^t = \left|h_{n,m}^t\right|^2 / \sigma_n^2$ be the channel response to noise ratio (CRNR), (2) can be converted into (3):

$$SINR_{n,m} = \frac{H_{n,m}^t p_{n,m}^t}{H_{n,m}^t \sum_{i \neq m}^{M_n'} p_{n,i}^t + \sum_{t' \neq t} H_{n,m}^{t'} p_n^{t'} + 1}, \quad (3)$$

According to the successive interference cancellation (SIC) technology, the interference of users with low channel gain can be removed by users with high channel gain on the same subchannel, that is, the signal of user on the edge of the cell with strong interference to the target signal can be eliminated by SIC technology. Therefore, we assume that the priority of the CRNR of each user on the nth subchannel is:

$$\left|H_{n,1}^t\right| \geq \cdots \geq \left|H_{n,m}^t\right| \geq \cdots \geq \left|H_{n,M_n'}^t\right|, \quad (4)$$

At the receiving end, the SINR of the mth user after SIC on the nth subchannel is:

$$SINR_{n,m} = \frac{H_{n,m}^t p_{n,m}^t}{H_{n,m}^t \sum_{i=1}^{m-1} p_{n,i}^t + \sum_{t' \neq t} H_{n,m}^{t'} p_n^{t'} + 1}, \quad (5)$$

Then, the data rate received by the mth user on the nth subchannel is:

$$R_{n,m}^t = B_s \log_2 \left(1 + SINR_{n,m}\right). \quad (6)$$

B. ENERGY EFFICIENT MODEL

For EE optimization, this paper uses the ratio of data rate to total power of each user [15]. That is, the EE of the mth user on the nth subchannel is defined as:

$$E_{n,m}^t = \frac{x_{n,m} R_{n,m}^t}{p_c^t + p_{n,m}^t}, \quad (7)$$

where p_c^t is the circuit power consumption. From the EE of a user, the total EE of the nth subchannel can be obtained:

$$E_n^t = \sum_{m=1}^{M} E_{n,m}^t, \quad (8)$$

Since each cell in the HetNets shares the same subchannel, the total EE of the tth cell can be obtained as:

$$E^t = \sum_{n=1}^{N} E_n^t, \quad (9)$$

Therefore, the total EE of two-tier HetNets can be expressed as:

$$E_{total} = \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{m=1}^{M} \frac{x_{n,m} R_{n,m}^t}{p_c^t + p_{n,m}^t}. \quad (10)$$

C. PROBLEM FORMULATION

We aim to combine user scheduling, the factor of power allocation among users and the power allocation across subchannels to solve the problem of maximizing the EE of NOMA HetNets. For the problem of user scheduling, considering that the scarcity of spectrum resources and the number of superimposed users on the same subchannel will affect the complexity of SIC, we assume that each subchannel can superimpose at least l users and at most u users, $l \leq \sum_{m=1}^{M} x_{n,m} \leq u, \forall n \in \{1, \cdots, N\}$. For the factor of power allocation among users, let $\beta_{n,m}^t = p_{n,m}^t / p_n^t$ be the power allocation factor of the mth user on the nth subchannel. We can optimize the variables $\left\{x_{n,m}, \beta_{n,m}^t, p_n^t\right\}$ to maximize the total EE performance of NOMA HetNets. Therefore, the optimization objective function can be described as:

$$\max_{\left\{x_{n,m}, \beta_{n,m}^t, p_n^t\right\}} \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{m=1}^{M} \frac{x_{n,m} R_{n,m}^t}{p_c^t + p_{n,m}^t}, \quad (11)$$

$$s.t.: \; C1: x_{n,m} \in \{0, 1\}, \quad (12)$$

$$C2: l \leq \sum_{m=1}^{M} x_{n,m} \leq u, \quad (13)$$

$$C3: \sum_{m=1}^{M} x_{n,m} \beta_{n,m}^t \leq 1, \quad (14)$$

$$C4: p_{n,m}^t = \beta_{n,m}^t p_n^t, \quad (15)$$

$$C5: p_{n,m}^t \geq 0, \quad (16)$$

$$C6: \sum_{n=1}^{N} p_n^t \leq p^t. \quad (17)$$

Constraint (12) and (13) are to ensure the number of user scheduling on the each subchannel; Constraint (14) and (15) are to ensure that the total power of the superimposed users on each subchannel is less than the total power of the subchannel; Constraint (16) is to ensure that the power allocated by each user is non-negative value; Constraint (17) is to ensure that the total power of all subchannels in the cell does not exceed the total power of the cell. It can be seen from (11) that the optimization problem is constrained by binary variables $x_{n,m}$, optimal power allocation factor $\beta_{n,m}^t$ and power allocation across subchannels p_n^t, which is non-convex. Because joint subchannel matching and power allocation to solve the optimal solution is NP-hard. Therefore, the traditional centralized method to solve this problem may be too complex and can not effectively maintain the fairness between users. Therefore, the optimal solution can be replaced by suboptimal solution. In this paper, we propose a distributed resource allocation scheme and design the resource allocation algorithm.

First, we joint the optimal power allocation factor of maximizing the EE among users on the same subchannel to solve the subchannel matching. Then, according to the given subchannel matching, the power allocation problem across subchannels can be solved.

III. SUBCHANNEL MATCHING AND POWER ALLOCATION

This section mainly studies the resource allocation problem based on EE maximization. Firstly, this paper decouples (11) into two subproblems: 1) joint the optimal power allocation factor of maximizing the EE among users on the same subchannel to solves the subchannel matching; 2) the power allocation across subchannels. Then, for the problem 1), assume that the power of each BS is equally allocated to each subchannel, and then the power of each subchannel is allocated to the user. Since the superposed users on each subchannel pursue their own EE maximization from the selfish point of view, EE optimization on each subchannel can be modeled as non-cooperative games and algorithms can be designed to solve each user's power allocation factor, and then the subchannel matching can be realized with GOS. For the power allocation across subchannels, the non-convex problem is converted into convex problem by SCA, and then uses sequential quadratic programming (SQP) to solve it. Finally, the suboptimal solution is used to replace the optimal solution.

A. NON-COOPERATIVE GAME

In this subsection, the non-cooperative game model is used to solve the power allocation factor of users in each subchannel. Assuming that there are M_n' users on the nth subchannel, the power allocation factor of M_n' users can be expressed as $\beta_{n,i}^t = \left\{\beta_{n,1}^t, \cdots, \beta_{n,M_n'}^t\right\}$, where $t \in \{1, \cdots, T\}$, $n \in \{1, \cdots, N\}$. First of all, let $p_n^t = p^t/N$ be the power of the tth cell is allocated equally to each subchannel, where $t \in \{1, \cdots, T\}$. Then, let $p_{n,i}^t$ be the power of each user on the nth subchannel, which is calculated by using the designed algorithm. Finally, the power allocation factor of each user is calculated by $\beta_{n,i}^t = p_{n,i}^t/p_n^t$. For resource allocation problems, game theory is a useful method. In NOMA HetNets, because each subchannel can superpose multiple users, each user gets more power in a selfish way to maximize their EE. In this case, EE maximization can be modeled based on non-cooperative games. Let $U_n^t = \left\{1, \cdots, M_n'\right\}$ denote the user set composed of M_n' users on the nth subchannel. Let $P_n^t = \left\{P_{n,1}^t, \cdots, P_{n,M_n'}^t\right\}$ represent the power strategy set of M_n' users on the nth subchannel, where $P_{n,i}^t = \left\{p_{n,i}^t \middle| \sum_{m=1}^{M_n'} p_{n,m}^t \le p_n^t, 0 \le p_{n,i}^t\right\}$ represents the power strategy space of each user. Let $F_n^t = \left\{f_{n,1}^t, \cdots, f_{n,M_n'}^t\right\}$ represent the utility function set of M_n' users on the nth subchannel. Assuming that the CRNR of M_n' users satisfies (4), the utility function $f_{n,i}^t$ is expressed as:

$$f_{n,i}^t = \frac{B_s \log_2\left(1 + \frac{H_{n,i}^t p_{n,i}^t}{H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1}\right)}{p_c^t + p_{n,i}^t}, \quad (18)$$

In conclusion, N games are expressed as $G_n^t = \left\{U_n^t, P_n^t, F_n^t\right\}$, $\forall n \in \{1, \cdots, N\}$. Considering that each user wants to get higher EE, the penalty function needs to be added to prevent the user getting too much power in the power strategy set P_n^t. On the one hand, when users want to get more power to improve EE, the penalty function will play a restraining role. On the other hand, if one user's allocated power is too large, it will cause greater interference to other users. Different from the method proposed in [15], the penalty function introduced in this paper not only prices $p_{n,i}^t$, but also introduces $H_{n,i}^t$, which mainly considers the randomness of user distribution in the system and the fairness of users on the same subchannel. The randomness of user distribution will lead to the difference of channels in the cell. From the perspective of EE maximization, the system tends to allocate more power to users with poor channel conditions, so the penalty function grows linearly is reasonable. Update (18) to:

$$f_{n,i}^t = \frac{B_s \log_2\left(1 + \frac{H_{n,i}^t p_{n,i}^t}{H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1}\right)}{p_c^t + p_{n,i}^t} - e^{\alpha H_{n,i}^t p_{n,i}^t}, \quad (19)$$

where α is the penalty coefficient and controls the penalty function value, the value of α depends on the number of users on the same channel, the circuit power and the power of the BS.

NE is the key to solve the problem of non-cooperative game. In this paper, the method of super-modular game and iterative update are used to get NEP. For the problem of power allocation factor among users in each subchannel, any user in the subchannel can get higher EE by adjusting their own power without changing the power of other users, that is, $P_n^{t*} = \left\{p_{n,1}^{t*}, \cdots, p_{n,M_n'}^{t*}\right\}$ is NE, satisfying $f_{n,i}^t\left(p_{n,i}^{t*}, p_{n,-i}^{t*}\right) \ge f_{n,i}^t\left(p_{n,i}^t, p_{n,-i}^t\right)$, $\forall p_{n,i}^t \in P_{n,i}^t$. Here is a brief analysis.

Definition 1: If $p_{n,-i}^t$ is fixed, then the optimal power of the ith user is $p_{n,i}^t = \arg\max_{p_{n,i}^t \in P_{n,i}^t} \left(f_{n,i}^t\left(p_{n,i}^t, p_{n,-i}^t\right)\right)$, where $p_{n,-i}^t$ represents the power of all users except the ith user.

Conclusion 1: If power strategy $p_{n,-i}^t$ remains unchanged, then the utility function $f_{n,i}^t\left(p_{n,i}^t, p_{n,-i}^t\right)$ is concave.

The proof is given in Appendix A.

When the power strategy $p_{n,i}^t$ of all users reaches NE, their power strategy $p_{n,i}^t$ will not change, because the change of power strategy $p_{n,i}^t$ will not further improve their EE. Therefore, we introduce super-modular game to achieve the NE. In addition, the definition of super-modular game, the convergence and existence of NE have been proved in previous studies [38].

Definition 2: If the following conditions are satisfied, $G_n^t = \left\{U_n^t, P_n^t, F_n^t\right\}$ is defined super-modular game.

1). If $p_{n,-i}^t$ given, the power strategy space $P_{n,i}^t$ is nonempty.

2). There are M_n' power strategies $p_{n,i}^t$ in $P_{n,i}^t$. The utility function $f_{n,i}^t$ can be derived twice by $p_{n,i}^t$ and $p_{n,-i}^t$, $\frac{\partial^2 f_{n,i}^t}{\partial p_{n,i}^t \partial p_{n,-i}^t} \geq 0$.

Conclusion 2: If $G_n^t = \left\{U_n^t, P_n^t, F_n^t\right\}$ is a super-modular game, two properties exist:

1). NE always exists.

2). For the user set U_n^t, if each user's power strategy $p_{n,i}^t$ is updated from the minimum or maximum value in its power strategy space $P_{n,i}^t$, then the user's power strategy $p_{n,i}^t$ will monotonically converge to NE and the optimal power strategy $p_{n,i}^t$ is unique.

From the above conclusion 2, we can know that if the proposed $G_n^t = \left\{U_n^t, P_n^t, F_n^t\right\}$ is a super-modular game, we can initialize the power strategy $p_{n,i}^t$ and design an algorithm to achieve NE by the properties of super-modular game and the NE is convergent. Therefore, according to definition 2, we set the conditions of $G_n^t = \left\{U_n^t, P_n^t, F_n^t\right\}$ to satisfy the super-modular game.

Conclusion 3: $G_n^t = \left\{U_n^t, P_n^t, F_n^t\right\}$ is a super-modular game. When CRNR satisfies (4), except for the first user on the nth subchannel, the power strategies of other users are satisfied: $\sqrt{\frac{p_c^t\left(H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t' \neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{H_{n,i}^t}} \leq p_{n,i}^t, \forall i \in \left\{2, \cdots, M_n'\right\}$.

The proof is given in Appendix B.

Since the premise of this paper is that the channel condition of the first user is the best, in order to achieve NE, we can use conclusion 3 to update the power strategy space $P_{n,i}^t$ of all users except the first user, $P_{n,i}^t$ is expressed as:

$$P_{n,i}^t = \left\{ p_{n,i}^t | \sum_{m=1}^{M_n'} p_{n,m}^t \leq p_n^t, \theta_i \leq p_{n,i}^t \right\},$$
$$\theta_i = \sqrt{\frac{p_c^t\left(H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t' \neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{H_{n,i}^t}}. \quad (20)$$

According to 1) of definition 2, when all $p_{n,i}^t$ exceeds a certain value, the power strategy space $P_{n,1}^t$ may be an empty set. Therefore, we need to adjust the power strategy space $P_{n,1}^t$ to ensure that it is a nonempty set, update $P_{n,1}^t$ to:

$$P_{n,1}^t = \left\{ p_{n,1}^t | \sum_{m=1}^{M_n'} p_{n,m}^t \leq p_n^t, 0 \leq p_{n,1}^t \leq \theta_1 \right\},$$
$$\theta_1 = \frac{\left(p_{n,i}^t\right)^2}{p_c^t} - \frac{H_{n,i}^t \sum_{m=2}^{i-1} p_{n,m}^t + \sum_{t' \neq t} H_{n,i}^{t'} p_n^{t'} + 1}{H_{n,i}^t}. \quad (21)$$

When $M_n' = 2, 0 \leq p_{n,1}^t \leq \frac{\left(p_{n,2}^t\right)^2}{p_c^t} - \frac{\sum_{t' \neq t} H_{n,2}^{t'} p_n^{t'} + 1}{H_{n,2}^t}$.

The proof is given in Appendix C.

For the first user, the utility function $f_{n,1}^t$ does not contain power strategy $p_{n,i}^t$, but the power strategy space $P_{n,i}^t$ of the ith user will affect the power strategy space $P_{n,1}^t$ of the first user. Therefore, in order to ensure the fairness between users on the same subchannel, we use the upper limit of $p_{n,1}^t$ to limit the power strategy space $P_{n,1}^t$ of the first user and the lower limit of $p_{n,i}^t$ to limit the power strategy space $P_{n,i}^t$ of the ith user. Finally, the whole non-cooperative game process is converged to NEP by iterative updating. The specific process is summarized as algorithm 1.

B. SUBCHANNEL MATCHING

For subchannel matching, a low complexity NCG-US-GOSMA is proposed. The main idea of this algorithm is that if the user wants to match with a subchannel, then it puts forward access requests to the subchannel, and each subchannel has the right to accept or reject these requests. When all users put forward an access request, the one round of access requests is completed.

The NCG-US-GOSMA proposed in this paper consists of two phases: initialization and GOS. During initialization, all users $i \in M^t$ of the tth cell set the preference list $L_{SC}(i)$ according to the priority order of CRNR. In addition, let $USMT^t(n) = \Omega$ represent the initial matching of the nth subchannel. In the process of GOS, each user sends an access request to the optimal subchannel which has not been rejected by $L_{SC}(i)$, and the rejected user deletes the relevant subchannel in $L_{SC}(i)$. If the number of users on the nth subchannel is less than l, the subchannel retains these access requests and updates $USMT^t(n)$. If the number of users of on the nth subchannel exceeds l, then the subchannel uses algorithm 1 to calculate EE and select only access requests of less than $\mu + 1$ users and update $USMT^t(n)$. Finally, if no new user in the tth cell requests access, GOS is terminated. The specific process is summarized as algorithm 2.

For the convergence of NCG-US-GOSMA, since the ith user makes access request to the optimal subchannel in $L_{SC}(i)$ during each round of matching, the $L_{SC}(i)$ of each user will gradually decrease with the increase of iterations. Because there are N subchannels in the system, the number of requests made by each user to the subchannel does not exceed N. Therefore, NCG-US-GOSMA is convergent.

NCG-US-GOSMA has low complexity and the complexity mainly depends on two processes of the algorithm, namely CRNR sorting process in the initialization stage and GOS process. In the sorting process, each user gets the preference list of N subchannels and the complexity is $O\left(M^t N\right)$. In the process of GOS, each user will propose up to N times. Since there are T cells in the NOMA HetNets, the final complexity is $O\left(TM^t N^2\right)$. For exhaustive search, the BS searches all possible candidate user sets on each subchannel, then selects the most preferred user set and performs power allocation

Algorithm 1 super-Modular Game Solving NE Problem

Initialize $p^t_{n,1}[0]=0$, $p^t_{n,i}[0] = \sqrt{\frac{p^t_c\left(H^t_{n,i}\sum\limits_{m=1}^{i-1}p^t_{n,m}+\sum\limits_{t'\neq t}H^{t'}_{n,i}p^{t'}_n+1\right)}{H^t_{n,i}}}, \forall i \in \{2,\cdots,M'_n\}$, iteration times $k_1=0$ and the maximal iterations γ_1.
for $k_1 = 0:\gamma_1$ **do**
  Update $p^t_{n,1}$ by solving

$$p^t_{n,1}[k_1+1] = \underset{p^t_{n,1}\in P^t_{n,1}}{\arg\max}\left(f^t_{n,1}\left(p^t_{n,1},p^t_{n,-1}\right)\right).$$

  for $i=2:M'_n$ **do**
    Update the power strategy space $P^t_{n,i}$ of the ith user,

$$P^t_{n,i}=\left\{p^t_{n,i}|\sum_{m=1}^{i-1}p^t_{n,m}[k_1+1]+\sum_{m=i}^{M'_n}p^t_{n,i}\le p^t_n,\theta'_i\le p^t_{n,i}\right\}$$

    where

$$\theta'_i=\sqrt{\frac{p^t_c\left(H^t_{n,i}\sum\limits_{m=1}^{i-1}p^t_{n,m}[k_1+1]+\sum\limits_{t'\neq t}H^{t'}_{n,i}p^{t'}_n+1\right)}{H^t_{n,i}}}$$

    Update $p^t_{n,i}$ by solving

$$p^t_{n,i}[k_1+1] = \underset{p^t_{n,i}\in P^t_{n,i}}{\arg\max}\left(f^t_{n,i}\left(p^t_{n,i},p^t_{n,-i}\right)\right),$$

    Set $i+=1$,
  end for
  Update the power strategy space $P^t_{n,1}$, when $M'_n=2$:

$$P^t_{n,1}=\left\{p^t_{n,1}|p^t_{n,1}+\sum_{m=2}^{M'_n}p^t_{n,m}[k_1+1]\le p^t_n,0\le p^t_{n,1}\le\theta'_1\right\}$$

$$\theta'_1=\frac{\left(p^t_{n,2}[k_1+1]\right)^2}{p^t_c}-\frac{\sum\limits_{t'\neq t}H^{t'}_{n,2}p^{t'}_n+1}{H^t_{n,2}}$$

  when $M'_n\neq 2$:

$$P^t_{n,1}=\left\{p^t_{n,1}|p^t_{n,1}+\sum_{m=2}^{M'_n}p^t_{n,m}[k_1+1]\le p^t_n,0\le p^t_{n,1}\le\theta'_1\right\}$$

$$\theta'_1=\frac{\left(p^t_{n,i}[k_1+1]\right)^2}{p^t_c}-\frac{\phi}{H^t_{n,i}}$$

$$\phi=H^t_{n,i}\sum_{m=2}^{i-1}p^t_{n,m}[k_1+1]+\sum_{t'\neq t}H^{t'}_{n,i}p^{t'}_n+1$$

  Set $k_1+=1$,
  Until $\left|p^t_{n,1}[k_1+1]-p^t_{n,1}[k_1]\right|<\xi_1$ break.
end for
Using $\beta^t_{n,i}=\frac{p^t_{n,i}}{p^t_n}$ to calculate power allocation factor.

Algorithm 2 Non-Cooperative Game Based User-Subchannel Global Optimal Search Matching Algorithm (NCG-US-GOSMA)

Initialize the number of users $M=\sum_{t=1}^{T}M^t$ in NOMA HetNets, $\forall t\in\{1,\cdots,T\}$, the number of subchannels N, the upper limit μ and the lower limit l of the number of multiplexing users on the subchannel.
Initialize $L_{SC}(i)$ of all subchannels for the ith user and ranked by CRNR.
Initialize $USMT^t(n)=\Omega$, $\forall t\in\{1,\cdots,T\}$, $\forall n\in\{1,\cdots,N\}$.
for $t=1:T$ **do**
  for $i=1:M^t$ **do**
    Each user sends an access request to the nth best subchannel in $L_{SC}(i)$.
    if $\left|USMT^t(n)\right|<l$ **then**
      i). Add the ith user to the nth subchannel and remove the nth subchannel from $L_{SC}(i)$.
      ii). update $USMT^t(n)$.
    end if
    if $l\le\left|USMT^t(n)\right|=\eta<u$ **then**
      i). Calculate EE of user set U^t_n and $U^t_{n'}$ according to algorithm 1, where $U^t_n=\left\{USMT^t(n)\right\}$, $U^t_{n'}=\left\{USMT^t(n)\right\}\cup\{i\}$. When $E\left(U^t_n\right)<E\left(U^t_{n'}\right)$, the nth subchannel retains the access request of the ith user and removes the nth subchannel in $L_{SC}(i)$,
      ii). update $USMT^t(n)$.
    end if
    if $u\le\left|USMT^t(n)\right|$ **then**
      i). Select any u users from $USMT^t(n)$ as the new user set $\left|U^t_n\right|=C^u_{|USMT^t(n)|}$.
      ii). According to algorithm 1, $E\left(U^t_n\right)$ is calculated and the user set $U^t_{n'}=\arg\max E\left(U^t_n\right)$ with the largest EE is selected.
      iii). update $USMT^t(n)$;
      Output subchannel matching.
    end if
  end for
end for

on each subchannel. The complexity increases exponentially with the number of subchannels.

C. POWER ALLOCATION ACROSS SUBCHANNELS

In the previous subsection, the subchannel matching with equal subchannel power allocation has been solved. In this subsection, the power allocation across subchannels can be solved by combining the given subchannel matching and the factor of power allocation among users, that is, (11) is transformed into:

$$\max_{\{p_n^t\}} \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{M_n'} \frac{B_s \log_2\left(1+\frac{\beta_{n,i}^t H_{n,i}^t p_n^t}{H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1}\right)}{p_c^t + \beta_{n,i}^t p_n^t}, \tag{22}$$

$$C6: \sum_{n=1}^{N} p_n^t \le p^t. \tag{23}$$

Due to the non-convexity of the objective function, it is difficult to obtain the optimal solution of (22) and it has high computational complexity. Therefore, the non-convex problem is converted into convex problem by SCA method, and then SQP is used to solve convex problem. Finally, the suboptimal solution is used to replace the optimal solution. According to the definition of SCA [15], [39], we transform (22) into the form of the sum of two concave functions:

$$\begin{aligned}\max_{\{p_n^t\}} &\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{M_n'} \frac{B_s \log_2\left(H_{n,i}^t \sum_{m=1}^{i}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{p_c^t + \beta_{n,i}^t p_n^t} \\ &-\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{M_n'} \frac{B_s \log_2\left(H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{p_c^t + \beta_{n,i}^t p_n^t},\end{aligned} \tag{24}$$

The proof of concave function in (24) is the similar as Appendix A. In order to solve the non-convex problem (24), the lower bound approximation of $-\log_2\left(H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)$ is given by inequality $-\log(y) \ge -\log(x) - \frac{1}{x}(y-x), \forall x, y > 0$:

$$\begin{aligned}-\log_2&\left(H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right) \\ &\ge -\log_2(\delta[j]) - \frac{H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t}{\delta[j]}\left(p_n^t - p_n^t[j]\right),\end{aligned} \tag{25}$$

where $\delta[j] = H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t[j] + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1$. Therefore, $-\frac{B_s \log_2\left(H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{p_c^t + \beta_{n,i}^t p_n^t}$ can be expressed approximately as:

$$\begin{aligned}&-\frac{B_s \log_2\left(H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{p_c^t + \beta_{n,i}^t p_n^t} \ge \\ &-\frac{B_s \log_2(\delta[j])}{p_c^t + \beta_{n,i}^t p_n^t} - \frac{B_s H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t}{\delta[j]\left(p_c^t + \beta_{n,i}^t p_n^t\right)}\left(p_n^t - p_n^t[j]\right),\end{aligned} \tag{26}$$

According to the above deformation, the non-convex problem of power allocation across subchannels can be transformed into convex problem. Then, we can transform (24) into the minimum form and use SQP to solve it, namely:

$$\begin{aligned}\min_{\{p_n^t\}} &-\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{M_n'} \frac{B_s \log_2\left(H_{n,i}^t \sum_{m=1}^{i}\beta_{n,m}^t p_n^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{p_c^t + \beta_{n,i}^t p_n^t} \\ &+\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{M_n'} B_s\left(\frac{\log_2(\delta[j])}{p_c^t + \beta_{n,i}^t p_n^t} + \frac{\left(p_n^t - p_n^t[j]\right) H_{n,i}^t \sum_{m=1}^{i-1}\beta_{n,m}^t}{\delta[j]\left(p_c^t + \beta_{n,i}^t p_n^t\right)}\right),\end{aligned} \tag{27}$$

$$C6: \sum_{n=1}^{N} p_n^t \le p^t. \tag{28}$$

In summary, the power allocation across subchannels can be obtained by design an algorithm. Firstly, initialize the variables $p_n^t[0]$ and $p_n^{t'} = p^{t'}/N$. Then, the convex problem (27) is solved. The solution of the convex problem (27) is regarded as a new variable $p_n^t[j]$. Repeat the process until the objective function (22) converges to a constant. The specific algorithm flow is as follows:

Algorithm 3 SCA Solves Power Allocation Across Subchannels

1: Initialize $p_n^t[0] \ge 0$, $p_n^{t'} = p^{t'}/N$, $\forall t, t' \in \{1, \cdots, T\}$ and $t' \neq t$, $\forall n \in \{1, \cdots, N\}$,iteration times $k_2 = 0$ and the maximal iterations γ_2.
2: **for** $t = 1 : T$ **do**
3: **for** $n = 1 : N$ **do**
4: **for** $k_2 = 0 : \gamma_2$ **do**
5: Obtain $p_n^t[k_2+1]$ by solving problem (27) and calculate the solution of problem (22), let $F\left(p_n^t[k_2+1]\right)$.
6: $k_2 += 1$.
7: Until $\left|F\left(p_n^t[k_2+1]\right) - F\left(p_n^t[k_2]\right)\right| > \xi_2$,break.
8: **end for**
9: Update p_n^t.
10: **end for**
11: **end for**

IV. SIMULATION RESULTS

In this section, the performance of the proposed resource allocation scheme is evaluated by simulation analysis, which compared with the existing scheme and OFDMA scheme. On the one hand, the performance of NCG-US-GOSMA proposed in this paper is analyzed by simulation when the transmission power of subchannel is fixed. On the other hand, on the premise of the subchannel matching scheme based on NCG-US-GOSMA, the power allocation scheme proposed in this paper is compared with the existing power allocation scheme in NOMA HetNets and OFDMA scheme. In the existing power allocation scheme of NOMA HetNets, fractional transmit power allocation (FTPA) is selected for comparison. Users with higher CRNR in FTPA will allocate less power [15], [26], the power allocated by users sharing the same subchannel satisfies $p^t_{n,i} = p^t_n \frac{\left(H^t_{n,i}\right)^{-\lambda}}{\left(H^{t'}_{n,i}\right)^{-\lambda} + \sum_{m=1}^{M^t_n} \left(H^t_{n,m}\right)^{-\lambda}}$. In OFDMA scheme, each subchannel is allocated to only one user to satisfy the OFDM criterion. In addition, each user gets all the power of the subchannel. The specific simulation parameters are shown in Table 1.

TABLE 1. Simulation parameters.

Parameter	Value
MBS radius	500 m
PBS radius	150m
Max transmit power of MBS	46 dBm
Max transmit power of PBS	30 dBm
Path loss of MBS	128.1+37.6*log10(D)km
Path loss of MBS	140.7+36.7*log10(d)km
Noise power density	-174dBm/HZ
Minimum value of l	2
System bandwidth	10MHZ

A. SUBCHANNEL MATCHING UNDER FIXED TRANSMIT POWER

Fig. 2 shows the relationship between the number of scheduling users and the number of users within one time-slot of NOMA HetNets. In the simulation process, we set the NOMA HetNets includes one MBS and one PBS, $t \in \{1, 2\}$, and then the number of subchannels is set as $N = 10$ and the circuit power consumption is set as $p^t_c = 0.01w$. It can be seen from the Fig. 2 that when the number of subchannels is fixed, the number of scheduling users in macro cell and pico cell in NOMA HetNets increases with the number of users and gradually stabilizes at a certain value, which is less than $N\mu$.

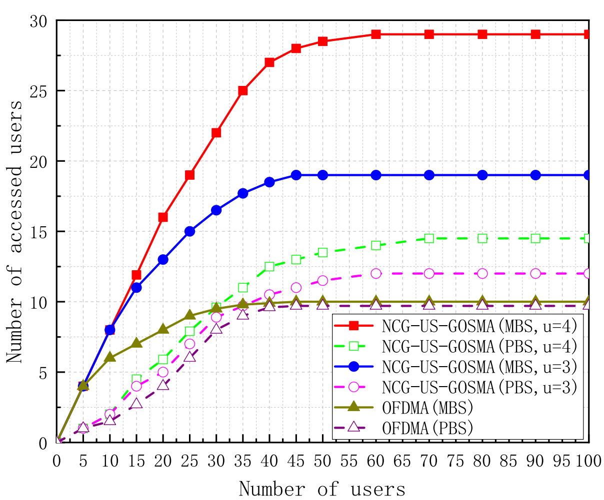

FIGURE 2. Number of scheduling users vs. Number of users.

Because each subchannel can be shared at most μ users in the system model proposed in this paper, N subchannel can be shared at most $N\mu$ users. In addition, the number of scheduling users in the macro cell is higher than that in the pico cell, and then the number of scheduling users increases with μ. Because the pico cell is contained in the macro cell and the random distribution of users will increase the probability of users accessing the subchannel of macro cell. Besides, the increase of μ will lead to the increase of the number of users superimposed on the same subchannel. For OFDMA HetNets, the number of scheduling users gradually approaches to the number of subchannels with the increase of the number of users. Because each subchannel can only access one user in OFDMA system.

Fig.3 shows the relationship between the power of users and the number of iterations on the same subchannel within one time-slot of NOMA HetNets. The simulated users come from the same subchannel in the user scheduling process. In the simulation process, we set the NOMA HetNets includes one MBS and one PBS, $t \in \{1, 2\}$, the number of users is set as $M = 20$, the number of subchannels is set as $N = 10$ and the circuit power consumption is set as $p^t_c = 0.01w$. Besides, each subchannel can be shared at most 3 users, $\mu = 3$. For users in macro cell and pico cell, their CRNR ranking relationships are $H^1_{n,1} \geq H^1_{n,2} \geq H^1_{n,3}$ and $H^2_{n,1} \geq H^2_{n,2}$, respectively. It can be seen from the Fig.3 that the power of users increases with the number of iterations. Users update power from the minimum value and stabilize at a value after 18 iterations and 14 iterations, respectively. The simulation results are consistent with conclusions 2 and conclusions 3, that is, each user's power is updated from the minimum value and monotonically converge to unique NE.

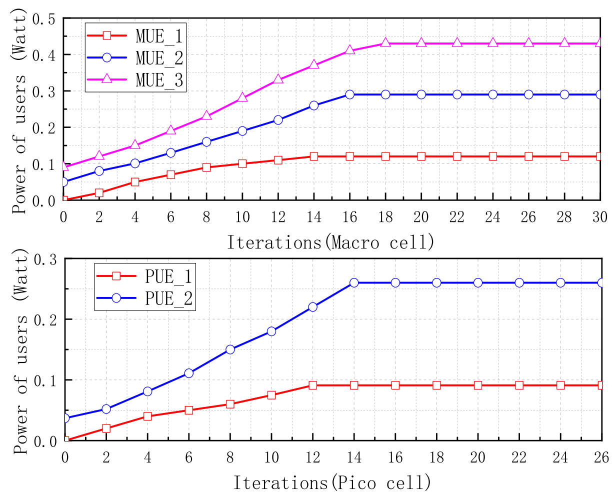

FIGURE 3. Power of users vs. Iterations.

Fig. 4 shows the relationship between the average EE of scheduling users and the number of users within one time-slot of HetNets. The simulation parameters of network are similar with Fig. 2. It can be seen from the Fig.4 that when the number of subchannel is fixed, the average EE of the scheduling user

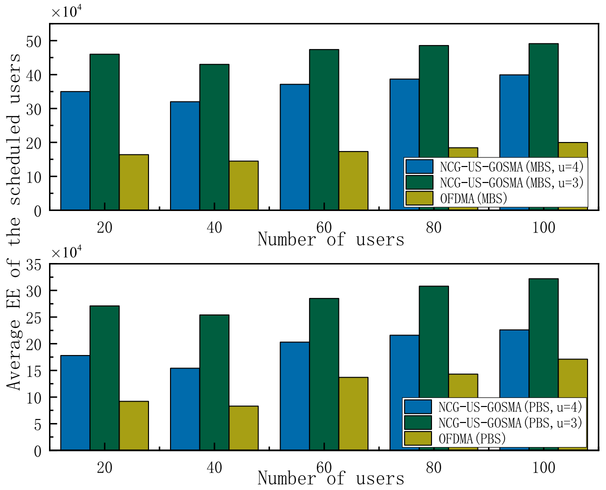

FIGURE 4. Average EE of scheduled users vs. Number of users.

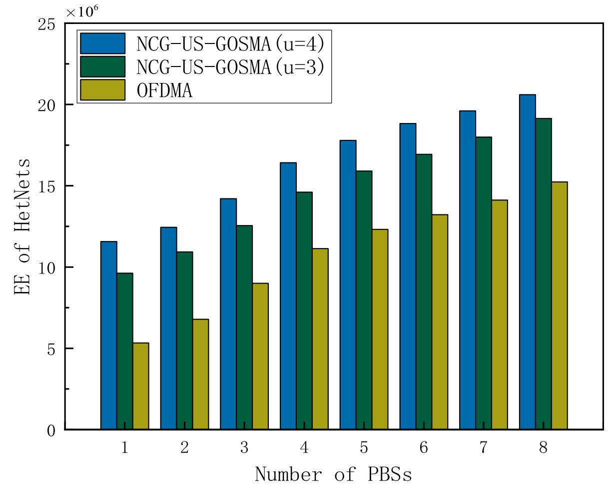

FIGURE 5. Number of PBSs vs EE of HetNets.

changes with the number of users, which decreases first and then increases, and the growth rate gradually slows down, but the performance is better than OFDMA HetNets. There are two reasons. On the one hand, when the number of users is relatively small, the average EE of the scheduled users decreases with the increase of the number of users because the transmission power of the BS and the number of subchannels are fixed. Besides, the power of the BS is allocated to each subchannel in the process of user scheduling. On the other hand, when the number of users is large, it can be seen from Fig. 2 that although the number of scheduled user will gradually stabilize with the increase of the number of users, the diversity gain of multiple users on the same subchannel will lead to the increase of the average EE of the scheduled users. In addition, the average EE of the scheduling user is inversely proportional to the number of superimposed users μ in the NOMA HetNets. The average EE of scheduling users decreases with the increase of μ, because the increase of the number of superimposed users on the same subchannel will lead to access more users with lower channel gain.

Fig. 5 shows the relationship between the EE of HetNets and the number of pico cells. In the simulation process, the number of MBS is set as 1, the number of users is set as $M = 20$, the number of subchannels is set as $N = 10$ and the circuit power consumption is set as $p_c^t = 0.01w$. It can be seen from Fig.5 that when the number of users is fixed, the EE of the NOMA HetNets increases with the number of superimposed users μ, because the increase of μ will lead to the subchannel access more users. Besides, the EE of NOMA HetNets increases with the number of PBS, and the trend is fast first and then slow, but the performance of NOMA HetNets based on NCG-US-GOSMA scheme is better than OFDMA HetNets. On the one hand, when the number of pico cells is small, more users will access to the pico cells with the increase of the number of pico cells, so the EE of system will increase rapidly. On the other hand, when the number of pico cells is large, although more users access to the pico cells, the increase of the number of pico cells will cause serious inter-cell interference, which will lead to the EE slow down gradually. In addition, users with high channel gain in NOMA HetNets can use SIC technology to eliminate users with low channel gain.

B. JOINT SUBCHANNEL MATCHING AND POWER ALLOCATION

Fig. 6 shows the relationship between the EE of HetNets and the number of users. In the simulation process, the number of MBS and PBS is set as 1, the number of subchannels is set as $N = 10$ and the circuit power consumption is set as $p_c^t = 0.01w$. It can be seen from the Fig. 6 that when the number of subchannels is fixed, the EE of NOMA HetNets increases with the number of users in the system and the number of users superposed on the same subchannel, the growth rate gradually slows down and tends to be stable. The reason is that, on the one hand, each user can make full use of all the subchannel resources when the number of users is small,

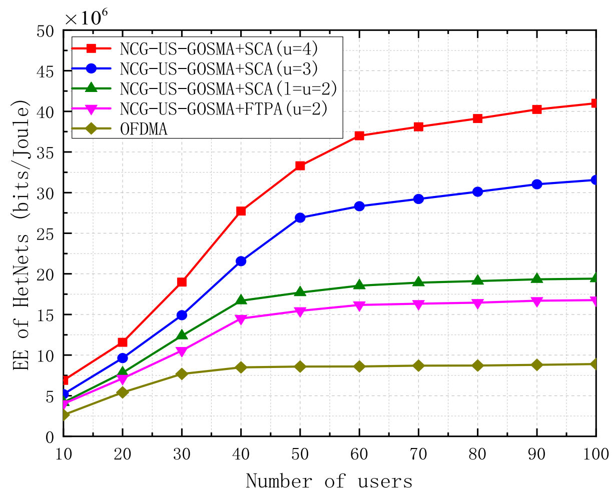

FIGURE 6. Numbers of users vs EE of HetNets.

so the EE of the system will improve significantly in the early stage. On the other hand, when the number of users is large, it can be seen from Fig. 2 that the number of users accessing the subchannel reaches a certain value due to the limited subchannel resources, so the performance of EE tends to be stable gradually. Besides, the increase of the number of users superimposed on the same subchannel will further improve the EE performance. The performance of the subchannel matching scheme and power allocation scheme proposed in this paper is better than FTPA and OFDMA schemes with the same subchannel matching scheme. Specifically, the performance of the proposed resource allocation scheme is better than FTPA method with the increase of the number of users when $\mu = 2$. For example, when the number of users is 20, the EE of the proposed scheme is 8.77% higher than FTPA method, and when the number of users is 50, the EE of the proposed scheme is 12.8% higher than FTPA method. The reason is that joint the power allocation on the subchannel and the power allocation across subchannels proposed in this paper can make full use of the power resources when the number of users is large.

Fig. 7 shows the relationship between the EE of HetNets and the number of subchannels. In the simulation process, the number of MBS and PBS is set as 1, the number of users is set as $M = 20$ and the circuit power consumption is set as $p_c^t = 0.01w$. It can be seen from the Fig. 7 that the EE of NOMA HetNets increases with the number of subchannels and the number of users superimposed on the same subchannel when the number of users is fixed. The reason is that the increase of the number of subchannels enables users to access more subchannels. Besides, each user will choose the subchannels with better channel conditions in the process of subchannel matching, so the EE of each user is further improved. In addition, compared with FTPA method and OFDMA scheme which have the same subchannel matching, the proposed subchannel matching scheme and power allocation scheme have better EE. In OFDMA scheme, each subchannel is allocated to only one user, so when the number of users is less than the number of subchannels, the EE of OFDMA HetNets remains unchanged.

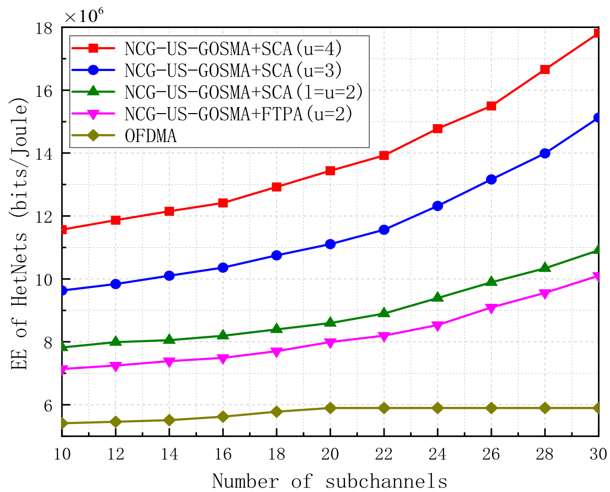

FIGURE 7. Numbers of subchannels vs EE of HetNets.

Fig. 8 shows the relationship between the EE of HetNets and circuit power consumption p_c^t. In the simulation process, the number of MBS and PBS is set as 1, the number of subchannel is set as $N = 10$ and the number of users is set as $M = 20$. It can be seen from the Fig. 8 that when the number of subchannels and the number of users are fixed, the EE of NOMA HetNets decreases with the increase of circuit power consumption. The larger the number of users superposed on the same subchannel, the faster the EE reduction. In addition, although the EE of the system decreases with the increase of circuit power consumption, compared with the FTPA method and OFDMA scheme with the same subchannel matching scheme, the proposed subchannel matching scheme and power allocation scheme still have high EE.

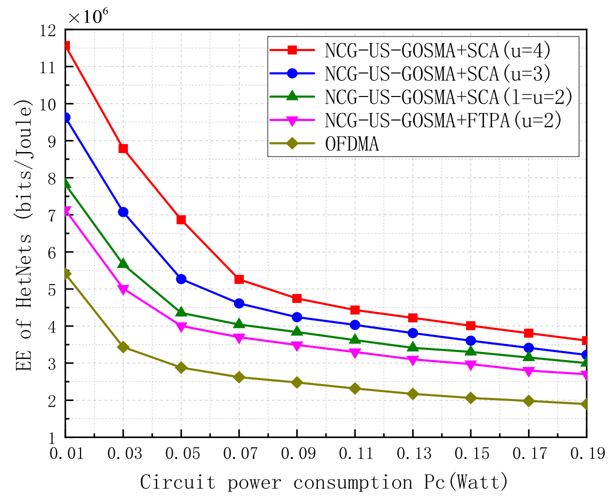

FIGURE 8. Circuit power consumption p_c^t vs EE of HetNets.

V. CONCLUSION

For downlink NOMA HetNets, this paper decouples the EE optimization problem into the optimal power allocation factor of maximizing the EE among users on the same subchannel to solves the subchannel matching and power allocation across subchannels. Firstly, for the subchannel matching, this paper models the power allocation among users on the same subchannel as a non-cooperative game and uses the super-modular game to ensure the existence of NE, and obtains its NEP through the super-modular algorithm. Then, a user-subchannel matching algorithm (NCG-US-GOSMA) based on non-cooperative game is proposed. Finally, in order to further improve the EE of the system, this paper solves the problem of power allocation across subchannels through the given subchannel matching scheme and the power allocation factor of users on the same subchannel. Because the objective function of power allocation across subchannels is non-convex, we use SCA method to transform the problem of power allocation across subchannels into a convex problem and solve it by iteration. The simulation results show that the NOMA HetNets based on the resource allocation scheme proposed in this paper is superior to the OFDMA HetNets with different the number of users, the number of subchannels and circuit power consumption in terms of EE. In addition, the performance of the proposed algorithm is better than that of FTPA with the same subchannel matching scheme.

APPENDIXES

APPENDIX A

Because there are M_n' users on the nth subchannel, we can get the utility function of each user according to (19). For the utility function first user $f_{n,1}^t = \frac{B_s\log_2\left(1+\frac{H_{n,1}^t p_{n,1}^t}{\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}+1}\right)}{p_c^t+p_{n,1}^t} - e^{\alpha H_{n,1}^t p_{n,1}^t}$, $f_{n,1}^t$ can be divided into the sum of three integers $\frac{B_s\log_2\left(H_{n,1}^t p_{n,1}^t+\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}+1\right)}{p_c^t+p_{n,1}^t}$, $-\frac{B_s\log_2\left(\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}+1\right)}{p_c^t+p_{n,1}^t}$ and $-e^{\alpha H_{n,1}^t p_{n,1}^t}$. Because $\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}$ is a fixed value, the second partial derivative of $-\frac{B_s\log_2\left(\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}+1\right)}{p_c^t+p_{n,1}^t}$ and $-e^{\alpha H_{n,1}^t p_{n,1}^t}$ for $p_{n,1}^t$ is less than 0, $-e^{\alpha H_{n,1}^t p_{n,1}^t}$ and $-\frac{B_s\log_2\left(\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}+1\right)}{p_c^t+p_{n,1}^t}$ are concave [40]. Since the concavity of $f' = \frac{B_s\log_2\left(H_{n,1}^t p_{n,1}^t+\sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'}+1\right)}{p_c^t+p_{n,1}^t}$ is equal to the convexity of its τ -sublevel set, the τ -sublevel set is defined as $S_\tau = \left\{p_{n,1}^t > 0 | f' \geq \tau\right\}$. When $\tau \leq 0$, because f' is nonnegative and $f' = \tau$ is an empty set, S_τ is convex. When $\tau > 0$,we rewrite the set as $S_\tau' = \left\{p_{n,1}^t > 0 | \Gamma \leq 0\right\}$,where $\Gamma = \tau\left(p_c^t + p_{n,1}^t\right) - B_s\log_2\left(H_{n,1}^t p_{n,1}^t + \sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'} + 1\right)$.

Because $-B_s\log_2\left(H_{n,1}^t p_{n,1}^t + \sum_{t'\neq t} H_{n,1}^{t'} p_n^{t'} + 1\right)$ is strictly convex, S_τ' is convex and f' is concave. In conclusion, $f_{n,1}^t$ is a concave function. For $f_{n,2}^t = \frac{B_s\log_2\left(1+\tilde{H}_{n,2}^t p_{n,2}^t\right)}{p_c^t+p_{n,2}^t} - e^{\alpha H_{n,2}^t p_{n,2}^t}$, where $\tilde{H}_{n,2}^t = \frac{H_{n,2}^t}{H_{n,2}^t p_{n,1}^t + \sum_{t'\neq t} H_{n,2}^{t'} p_n^{t'}+1}$, if $p_{n,1}^t$ is fixed, then $\tilde{H}_{n,2}^t$ is also fixed. Because $f_{n,2}^t$ and $f_{n,1}^t$ have the same form, $f_{n,2}^t$ is also a concave function. Similarly, $f_{n,i}^t$ is also a concave function, $\forall i \in \left[3, M_n'\right]$.

APPENDIX B

Obviously $\frac{\partial^2 f_{n,1}^t}{\partial p_{n,1}^t \partial p_{n,i}^t} = 0, \forall i \in \left\{2, \cdots, M_n'\right\}$.

$$\frac{\partial f_{n,i}^t}{\partial p_{n,i}^t} = \frac{\frac{B_s}{\ln 2}\frac{\frac{H_{n,i}^t\left(p_c^t+p_{n,i}^t\right)}{Q_1}}{1+\frac{H_{n,i}^t p_{n,i}^t}{Q_1}} - B_s\log_2\left(1+\frac{H_{n,i}^t p_{n,i}^t}{Q_1}\right)}{\left(p_c^t+p_{n,i}^t\right)^2},$$

$$\frac{\partial f_{n,i}^t}{\partial p_{n,i}^t} = \frac{B_s H_{n,i}^t}{\left(p_c^t+p_{n,i}^t\right) Q_2 \ln 2} - \frac{B_s\log_2\left(1+\frac{H_{n,i}^t p_{n,i}^t}{Q_1}\right)}{\left(p_c^t+p_{n,i}^t\right)^2},$$

$$\frac{\partial^2 f_{n,i}^t}{\partial p_{n,i}^t \partial p_{n,j}^t} = -\frac{B_s\left(H_{n,i}^t\right)^2}{\left(p_c^t+p_{n,i}^t\right)(Q_2)^2\ln 2} + \frac{B_s\left(H_{n,i}^t\right)^2 p_{n,i}^t}{\left(p_c^t+p_{n,i}^t\right)^2 Q_1 Q_2 \ln 2}.$$

where $Q_1 = H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1, Q_2 = H_{n,i}^t p_{n,i}^t + H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1, 1 < j < i \leq M_n'$. Because $\frac{\partial^2 f_{n,i}^t}{\partial p_{n,i}^t \partial p_{n,j}^t} \geq 0$,

$$\frac{B_s\left(H_{n,i}^t\right)^2 p_{n,i}^t}{\left(p_c^t+p_{n,i}^t\right)^2 Q_1 Q_2 \ln 2} \geq \frac{B_s\left(H_{n,i}^t\right)^2}{(Q_2)^2\left(p_c^t+p_{n,i}^t\right)\ln 2}$$

$$H_{n,i}^t (p_{n,i}^t)^2 \geq p_c^t Q_1$$

Therefore $p_{n,i}^t \geq \sqrt{\frac{p_c^t Q_1}{H_{n,i}^t}}$.

$$p_{n,i}^t \geq \sqrt{\frac{p_c^t\left(H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right)}{H_{n,i}^t}}.$$

APPENDIX C

Because $p_{n,i}^t \geq \sqrt{\frac{p_c^t\left(H_{n,i}^t \sum_{m=1}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'}+1\right)}{H_{n,i}^t}}$, When $M_n' \neq 2$,

$$H_{n,i}^t (p_{n,i}^t)^2 \geq p_c^t\left(H_{n,i}^t p_{n,1}^t + H_{n,i}^t \sum_{m=2}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1\right),$$

$$p_{n,1}^t \leq \frac{\left(p_{n,i}^t\right)^2}{p_c^t} - \frac{H_{n,i}^t \sum_{m=2}^{i-1} p_{n,m}^t + \sum_{t'\neq t} H_{n,i}^{t'} p_n^{t'} + 1}{H_{n,i}^t}.$$

Particularly, when $M_n' = 2$, $p_{n,1}^t \leq \frac{\left(p_{n,2}^t\right)^2}{p_c^t} - \frac{\sum_{t'\neq t} H_{n,2}^{t'} p_n^{t'}+1}{H_{n,2}^t}$.

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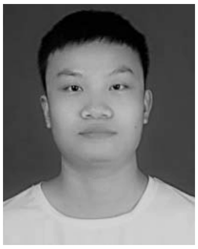

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