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An Interference Coordination-Based Distributed Resource Allocation Scheme in Heterogeneous Cellular Networks

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ABSTRACT As a result of the significant increase of overlapped coverage areas among base stations (BSs), interference coordination in heterogeneous cellular networks (HetCNets) becomes necessary, since interference would degrade network performance and even cause dropped calls. In addition, various types of BSs coexist in HetCNets, and BSs with low power (such as Pico BSs and Femto BSs) are deployed more arbitrarily than those in macrocell BSs (MBSs) so that the traditional anti-interference technologies are not enough in HetCNets. To reduce the interference between MBSs and low-power BSs within the coverage, a novel distributed resource allocation algorithm is proposed. First, an interference graph is established, by which the corresponding orthogonal resources can be assigned to different BSs, and the users can be classified into center and edge users, respectively. After that, users select appropriate resource blocks according to an improved proportional fair algorithm, and BSs distribute transmission power to different resource blocks to enhance network throughput further. Simulation results demonstrate the effectiveness of our proposed scheme in resource allocation and utilization.

INDEX TERMS Heterogeneous cellular networks, resource optimization, power control, interference coordination, network optimization.

I. INTRODUCTION

As the ever increasing applications of Internet of Things and intelligent terminals, mobile Internet businesses develop rapidly and information interactions among users become the mainstream of data services. In order to keep pace with traffic growing, the 3rd Generation Partnership Project (3GPP) starts the Long Term Evolution (LTE), which introduces advanced wireless access technologies, supports flexible bandwidth and flat network architecture, and improves the utilization of wireless spectrum resource. LTE-Advanced (LTE-A), considering smooth evolution and compatibility, can access the LTE system and satisfy the requirements of network capacity, transmission rate, spectrum effectiveness and low cost [1].

In order to handle the ever growing data traffic and satisfy the transmission requirements of different users, 3GPP presents the concept of Heterogeneous Cellular Networks (HetCNets) during the standardized process of LTE-A [2]. HetCNets deploy low-power nodes in the coverage area, including Picocell Base Station (PBS), Femtocell Base Station (FBS) and relay nodes. By the deployment of Base Station (BS) with low power, the distance between BS and mobile users can be shorten and the Received Signal Strength (RSS) is enhanced [3]. Furthermore, the coverage problem of blind and busy spots can also be alleviated by deploying PBSs and FBSs, so that transmission rate and network capacity can be increased [4], [5].

As the development of HetCNets, many challenges emerge. For example, the overlapped region increases sharply, the network performance under strong interference degrades largely, and more calls are dropped. In order to reuse the band frequency resource of MBS, BSs are deployed within the coverage of MBS. However, the edge users within the coverage of BS suffer strong interference, which lowers down the communication quality of cell users.

Generally speaking, the signal received by the terminal located at the cell center has high Signal to Interference Noise Ratio (SINR) value, while the counterpart obtained by the terminals located at the cell edge is weak. In order to alleviate this phenomenon in HetCNets, interference coordination technology has been advocated, which includes time and frequency domains based and power control based interference coordination schemes [6], [7].

Meanwhile, various kinds of BSs coexist in HetCNets, which leads to large interferences among edge users in the cell, and the interference coordination on the cell edge becomes more complex. Since BSs with low transmission power make the frequency allocation rather complex, in order to decrease network interference, some researchers have presented different orthogonal frequency division schemes. One typical solution is scheduling the control channel and physical signal in frequency domain according to channel conditions [8], [9]. For example, the PBS utilizes the measurement report from pico-cellular subscribers to calculate the interference from other BSs, and transfers the received information back to MBS, or the MBS detects the PBSs with interference and allocates orthogonal frequency resources to different BSs. Although users do not interfere with each other by utilizing the abovementioned method, the frequency utilization is low.

In addition, various types of BSs coexist in HetCNets, and BSs with low power (such as Pico BSs and Femto BSs) are deployed more arbitrarily than those in Macrocell BSs (MBSs), the traditional anti-interference technologies are not suitable in HetCNets. In [10], a sequential frequency reuse scheme was presented by allocating high transmission power to the subcarriers on the cell edge. However, the corresponding computational complexity is high.

An intelligent resource block allocation scheme, by mitigating the downlink intra as well as the inter interferences in OFDM-based HetNets, was studied in [11]. However, rather simple interference has been considered in the small cell networks. He *et al.* in [12] designed an energy-efficient coordinated beamforming scheme for heterogeneous multi-cell multi-user downlink systems. Due to the high computational complexity of the formulated problem, an energy-efficient transmission method for small-cell network has been developed. Since the nodes with different transmission powers are located in the same network, advanced interference coordination and radio resource allocation schemes are required. In [13], a joint frequency reuse and power control method to coordinate the interference among nodes was studied, and Lagrange dual function was derived for the proposed problem. However, the fractional frequency reuse has not been considered. A flow-based framework for the joint optimization of resource allocation, interference coordination, and user association in HetNets was studied in [14]. However, the number of traffic flows on each node is assumed to be the same, which is unrealistic.

Since complex interference exists in HetNets, it would cause the call performance declines sharply in the cell with strong interference. Therefore, how to manage the interference in HetNets is the fundamental problem to guarantee the implementation of HetNets. In order to reduce the interference between macrocell BSs and low-power BSs within network coverage, we propose a novel resource allocation algorithm for HetCNets. The main contributions of this paper are shown as follows:

- The interference graph has been established at first, which is based on the interference relationships between BSs and the corresponding orthogonal resources.
- We classify the users into the center and edge users according to the constructed interference graph, and then assign network resources to the users correspondingly. The center users are able to use all the frequency resources in the networks, while the edge users can only utilize orthogonal frequency resources to eliminate interferences between BSs.
- An improved proportional fair scheme is presented for resource blocks selection, based on which BSs are able to assign transmission power to different resource blocks for throughput improvement. Our proposed scheme can not only reduce mutual interference between BSs and users, but also enhances the performance of users.

The rest of this paper is organized as follows: A novel resource allocation algorithm in HetCNets is presented in Section II. Section III proposes a power control based optimization scheme for resource allocation to decrease network interference between BSs and users. Section IV illustrates the simulation results and Section V concludes our work.

II. A NOVEL RESOURCE ALLOCATION ALGORITHM IN HetCNets

In order to increase the utilization of wireless spectrum, the PBSs are commonly deployed inside the MBSs. However, the interference in HetCNets becomes complex, where the BSs under strong interference degrade network performance, even cause communication failure. It has been demonstrated in [15] that spectral efficiency can be improved by decreasing interference among BSs. Generally speaking, three kinds of spectrum allocation methods can be classified: 1) BSs share all the spectrum resource; 2) the orthogonal spectrum resource is allocated to the BSs with interference; 3) BSs not only occupy the orthogonal spectrum resource, but also share the common spectrum resource with neighboring BSs. Since strong interference coexists among BSs, the resource utilization in the first kind of methods is the lowest, especially in the complex network situation [16]. For the second kind of schemes, network throughput can be increased to some extent since network intereference is small, however, the spectrum utilization is low. For the third kind of solutions, network throughput can be enhanced by distributing spectrum resource to decrease interference among BSs under the condition that the interference is below a predefined threshold [17]. In this section, based on the third kind of schemes, we propose a proportional share resource allocation algorithm, by which the performance of edge users can be improved so that network throughput can be increased. For simplicity and without loss of generality, we merely consider the interference between two BSs, and this situation can be generalized to multiple BSs.

A. RESOURCE ALLOCATION AMONG BSs

We first construct the interference graph according to the interference among BSs, by which the orthogonal resource can be allocated to the center and edge users in BSs. The former can utilize all the frequency resource while the latter can only use the orthogonal resource to decrease the interference among BSs. In HetCNets, the BSs within the coverage of MBSs can use all the frequency, however, the PBSs within the region of MBSs share the same frequency resource which causes network interference. To increase the utilization of spectrum resource, an orthogonal resource allocation algorithm is presented to select the users that can share network resource with other users with interference.

Assume the channel condition can be obtained beforehand, the main point focuses on the selection of interference judgment criterion. We utilize the Reference Signal Received Power (RSRP) to denote the judgment criterion, which can be illustrated as:

$$SINR_u^i = \frac{RSRP_i}{\sum_{j\neq i} RSRP_j + N_0} < SINR_{th} \tag{1}$$

where $SINR_u^i$ is the received SINR value of edge user u within the coverage of BS i, $SINR_{th}$ is the threshold to illustrate the required SINR value for communication, $RSRP_i$ is the obtained signal power of BS i that can cover the edge of the cell, $RSRP_j$ is the received signal power with interference from other BSs, and N_0 is noise power. The main steps to determine the BSs with interference can be shown as follows:

Step 1: Ensure the coverage of different BSs according to the transmission power and channel condition;

Step 2: Calculate the signal powers of the edge users in BS i;

Step 3: Find out the potential interference BSs according to Equation (1). Then, rank the received $RSRP_j$ values in a descending order according to Step 2, and remove these values one by one until the $SINR_u^i$ value calculated by (1) is larger than the threshold $SINR_{th}$. Thus, the moved out BSs are considered as the primary interference in BSs;

Step 4: Repeat Step 3 and find out the interference collection. For the BSs with interference, connect these BSs and construct the interference graph.

Then the resource allocation problem is transferred to the node coloring problem in the interference graph, where the vertices represent BSs and edges illustrate the interference relationships. The chromaticity refers to the number of the nodes connected with BSs. It has been demonstrated in [14] that by utilizing the maximum chromaticity coloring algorithm, the minimum number of colors can be used to fulfill the coloring process. This is because the utilized resources by neighboring BSs are different, so that the resource allocation among BSs is orthogonal. However, the frequency utilization by merely applying coloring algorithm is low. Therefore, we consider how to share the resource in BSs with interference and increase the frequency utilization further. The main solution is allocating the orthogonal resource to the cell edge far from the BSs. For the users near to the BSs, they share the frequency resource of the neighboring BSs with interference.

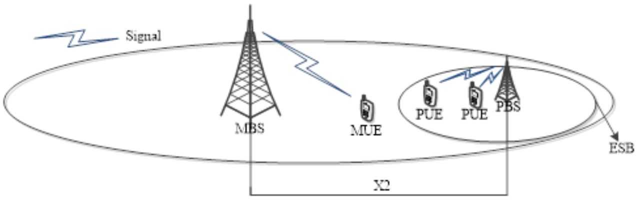


FIGURE 1. Illustration of MBS and PBS.

As shown in Fig. 1, MUE and PUE stand for the Macrocell and Picocell users, respectively. X2 is the interface between MBS and PBS, and ESB is the edge of signal border. $RSS_{m,u}$ and $RSS_{p,u}$ represent the received signal strength from the macro and pico cells respectively. If $RSS_{m,u} > RSS_{p,u}$, the user will access into MBS, otherwise, the user will access into PBS. The coverage of the PBS can be calculated by setting $RSS_{m,u} = RSS_{p,u}$, that is:

$$RSS_{m,u} = P_m \cdot \frac{G_m}{\xi_{m,u} \cdot \sigma_{m,u}} = P_p \cdot \frac{G_p}{\xi_{p,u} \cdot \sigma_{p,u}} = RSS_{p,u} \tag{2}$$

where P_m and P_p are the transmission powers of MBS and PBS, respectively. G_m and G_p are the antenna gains of MBS and PBS, respectively. $\xi_{m,u}(\xi_{p,u})$ is the wall penetration loss between MBS (PBS) and users. $\sigma_{m,u}(\sigma_{p,u})$ represents the transmission loss between MBS (PBS) and users. Define α_m and α_p as the path losses of the macro cell and micro cell respectively. Since $\sigma_{m,u} = \varphi_m \cdot (d_{m,u})^{\alpha_m}$ and $\sigma_{p,u} = \varphi_p \cdot (d_{p,u})^{\alpha_p}$, Equation (2) can be derived as:

$$\frac{P_m \cdot G_m}{\varphi_m \cdot \xi_{m,u} \cdot (d_{m,u})^{\alpha_m}} = \frac{P_p \cdot G_p}{\varphi_p \cdot \xi_{p,u} \cdot (d_{p,u})^{\alpha_p}}. \tag{3}$$

For illustration, we set $p_m = \frac{P_m \cdot G_m}{\varphi_m \cdot \xi_{m,u}}$ and $p_p = \frac{P_p \cdot G_p}{\varphi_p \cdot \xi_{p,u}}$, and Equation (3) can be illustrated as:

$$\frac{p_m}{(d_{m,u})^{\alpha_m}} = \frac{p_p}{(d_{p,u})^{\alpha_p}}. \tag{4}$$

By the $\frac{2}{\alpha_p}$th extraction of Equation (4), it can be converted into (5), which is shown as:

$$\frac{p_m^{2/\alpha_p}}{(d_{m,u})^{2\varphi}} = \frac{p_p^{2/\alpha_p}}{(d_{p,u})^{2}} \tag{5}$$

herein, $\varphi = \frac{\alpha_m}{\alpha_p}$.

Define x_m, y_m as the location coordinates of the macro cell, and x_p, y_p as the location coordinates of the micro cell, respectively. Since $d_{m,u} = \sqrt{(x - x_m)^2 + (y - y_m)^2}$ and

$d_{p,u} = \sqrt{(x-x_p)^2+(y-y_p)^2}$, Equation (5) can be converted into:

$$p_p^{\frac{2}{\alpha_p}}(x^2+x_m^2-2x_mx+y^2+y_m^2-2y_my)^{\varphi} - p_m^{\frac{2}{\alpha_p}}(x^2+x_p^2-2x_px+y^2+y_p^2-2y_py)^{\varphi} = 0. \quad (6)$$

Generally speaking, $\alpha_m < \alpha_p$ is satisfied in HetCNets, thus $0 < \varphi < 1$. According to the expansion of Taylor Series, the expansion of equation $(x^2+x_m^2-2x_mx+y^2+y_m^2-2y_my)^{\varphi}$ in (6) on node (x, y) can be shown as:

$$\begin{aligned} T(i,j) \simeq{}& f(i,j)+(x-i)f_x(i,j)+(y-j)f_y(i,j) \\ &+\frac{1}{2}(x-i)^2f_{xx}(i,j)+\frac{1}{2}(y-j)^2f_{yy}(i,j) \\ &+(x-i)(y-j)f_{xy}(i,j) \end{aligned} \quad (7)$$

herein, $f(i,j) = (i^2+j^2-2ix_m-2jy_m+x_m^2+y_m^2)^{\varphi}$, $f_x(i,j) = 2\varphi[f(i,j)]^{\frac{\varphi-1}{\varphi}}(i-x_m)$, $f_y(i,j) = 2\varphi[f(i,j)]^{\frac{\varphi-1}{\varphi}}(j-y_m)$, $f_{xx}(i,j) = 4\varphi(\varphi-1)[f(i,j)]^{\frac{\varphi-2}{\varphi}}(i-x_m)^2+2\varphi[f(i,j)]^{\frac{\varphi-1}{\varphi}}$, $f_{yy}(i,j) = 4\varphi(\varphi-1)[f(i,j)]^{\frac{\varphi-2}{\varphi}}(j-y_m)^2+2\varphi[f(i,j)]^{\frac{\varphi-1}{\varphi}}$, and $f_{xy}(i,j) = 4\varphi(\varphi-1)[f(i,j)]^{\frac{\varphi-2}{\varphi}}(j-y_m)(i-x_m)$. By substituting (7) into (6), we can obtain,

$$ax^2+2bxy+cy^2+2dx+2fy+g = 0 \quad (8)$$

where $a = \frac{1}{2}p_p^{2/\alpha_p}f_{xx}(i,j) - p_m^{2/\alpha_p}$, $b = \frac{1}{2}p_p^{2/\alpha_p}f_{xy}(i,j)$, $c = \frac{1}{2}p_p^{2/\alpha_p}f_{yy}(i,j) - p_m^{2/\alpha_p}$.

$d = \frac{p_p^{2/\alpha_p}[f_x(i,j)-if_{xx}(i,j)-jf_{xy}(i,j)]+2p_m^{2/\alpha_p}x_p}{2}$, $f = \frac{p_p^{2/\alpha_p}[f_y(i,j)-if_{yy}(i,j)-jf_{xy}(i,j)]+2p_m^{2/\alpha_p}y_p}{2}$ and $g = p_p^{2/\alpha_p}[f(i,j)-if_x(i,j)-jf_y(i,j)+\frac{i^2}{2}f_{xx}(i,j)+\frac{j^2}{2}f_{yy}(i,j)] - p_m^{2/\alpha_p}(x_p^2+y_p^2)$.

From (8), we can see that if $a \neq c$ and $b^2 < 4ac$, the coverage of MBS is an ellipse, and the corresponding parameters are: $x_e = \frac{cd-bf}{b^2-ac}$, $y_e = \frac{af-bd}{b^2-ac}$, $s_1 = \sqrt{\frac{2(af^2+cd^2+gb^2-2bdf-acg)}{(b^2-ac)[\sqrt{(a-c)^2+4b^2}-(a+c)]}}$ and $s_2 = \sqrt{\frac{2(af^2+cd^2+gb^2-2bdf-acg)}{(b^2-ac)[-\sqrt{(a-c)^2+4b^2}-(a+c)]}}$. Herein, (x_e, y_e) is the center coordinate of the ellipse. s_1 and s_2 are the lengths of the major and minor semi-axes, respectively. The intersection angle θ between the major semi-axis and the line connected with MBS and PBS can be obtained by [18]:

$$\theta = arctan(\frac{y_p-y_e}{x_p-x_e}) = \begin{cases} 0, & b=0 \cap a<c \\ \frac{\Pi}{2}, & b=0 \cap a>c \\ \frac{1}{2}arccot(\frac{a-c}{ab}), & b\neq 0 \cap a<c \\ \frac{1}{2}acccot(\frac{a-c}{ab})+\frac{\Pi}{2}, & b\neq 0 \cap a>c. \end{cases} \quad (9)$$

Therefore, the coverage of the PBS is an elliptic area, and the main corresponding parameters can be calculated by the equations stated above to determine the coverage of PBS.

Then we analyze the interference among BSs when the distances between different users vary. The deployment of BS j will bring interference to BS i, whose received SINR value is:

$$SINR_u^i = \frac{P_i \cdot \Gamma_u^i}{P_j \cdot \Gamma_u^j + N_0} \quad (10)$$

where $\Gamma_u^i = (G_iG_u)/(\xi_{i,u}\delta_{i,u})$ and $\Gamma_u^j = (G_jG_u)/(\xi_{j,u}\delta_{j,u})$. G_i and G_u are the antenna gains of BSs and users, respectively. Since $\delta_{i,u} = \varphi_i \cdot (d_{i,u})^{\alpha_i}$ and $\delta_{j,u} = \varphi_j \cdot (d_{j,u})^{\alpha_j}$, we can obtain:

$$SINR_u^i = \frac{P_i \cdot (G_iG_u) \cdot \xi_{j,u} \cdot \varphi_j \cdot (d_{j,u})^{\alpha_j}}{[P_j \cdot (G_jG_u) + o^2 \cdot \xi_{j,u} \cdot \varphi_j \cdot (d_{j,u})^{\alpha_j}] \cdot \xi_{i,u} \cdot \varphi_i \cdot (d_{i,u})^{\alpha_i}} \quad (11)$$

where φ_i and φ_j are the fixed loss of BSs i and j, respectively. $d_{i,u}$ ($d_{j,u}$) is the distance between BSs i(j) and user, respectively. Under the condition that the values of other parameters keep unchanged, when the user moves from the left endpoint to the right endpoint of the ellipse, the diagrammatic sketch of the SINR value is shown as in Fig. 2.

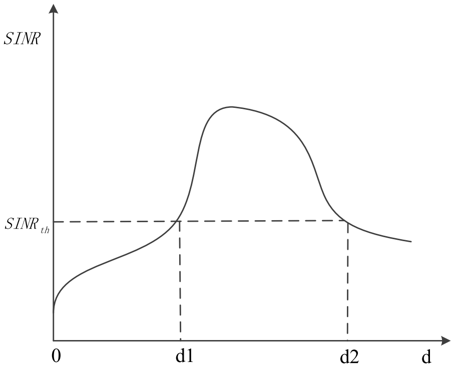


FIGURE 2. Diagrammatic sketch of the SINR value variance with different distance.

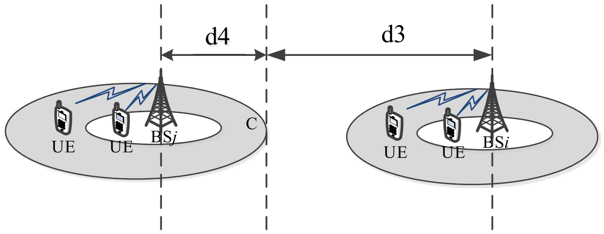


FIGURE 3. Illustration of interference between center users and edge users.

As the user moves from the left endpoint to the right endpoint of the ellipse, the obtained SINR value increases at first and then decreases. When the user arrives point d_1, the minimum communication requirement is satisfied, and network resource can be shared by different users. When the user reaches d_2, the received SINR value decreases constantly, and the communication requirement cannot be satisfied. Therefore, the resource can be shared when the user locates close to BS, otherwise, the user should utilize other orthogonal resource to alleviate the interference with BS. As shown in Fig. 3, the white region is the area that user can share the frequency resource, which is determined by d_1 and d_2. The gray region is the edge area, which suffers strong interference and cannot share the resource with BS. When the user in BS i reuses the resource in BS j, it will bring interference to the edge users in BS j, and the SINR value calculated by the edge of BS j is:

$$SINR_u^i = \frac{P' \cdot (G_i G_u) \cdot \xi_u^j \cdot \varphi_j \cdot (d_u^j)^{\alpha_j}}{[P_j \cdot (G_j G_u) + o^2 \cdot \xi_u^j \cdot \varphi_j \cdot (d_u^j)^{\alpha_j}] \cdot \xi_u^i \cdot \varphi_i \cdot (d_u^i)^{\alpha_i}} \tag{12}$$

The distance between BS and the user can be calculated by:

$$d_u^i = \alpha_i \sqrt{\frac{P' \cdot (G_i G_u) \cdot \xi_u^j \cdot \varphi_j \cdot (d_u^j)^{\alpha_j}}{[P_j \cdot (G_j G_u) + o^2 \cdot \xi_u^j \cdot \varphi_j \cdot (d_u^j)^{\alpha_j}] \cdot \xi_u^i \cdot \varphi_i \cdot SINR_{th}}}. \tag{13}$$

where $d_u^j = d_3 + d_4 - d_u^i$.

The user in the center region can reuse the resource in the neighboring BSs with interference, its transmission power is P', and the transmission power of the orthogonal resource allocated to edge user equals to P_i.

B. RESOURCE ALLOCATION INSIDE BS

Since the partial sharing algorithm categories the clients into center and edge users, the complexity of spectrum resource scheduling increases [19]. In order to keep node fairness during link scheduling, an improved proportional scheduling algorithm is presented. According to the user type and spectrum resource, the priority of link scheduling can be determined. In our work, if the user locates at the cell center, the priority value is low for the consideration of fairness. Otherwise, the priority value is set to a high number, which can be shown as:

$$Pr_u^k = \alpha_u \times \frac{r_u^k(t)}{R_u(t)} \tag{14}$$

$$R_u(t) = \frac{1}{T} \times r_u^k(t) + \frac{T-1}{T} R_u(t-1) \tag{15}$$

herein, α_u stands for the weighting factor of user. $r_u^k(t)$ is the transmission rate on resource block k during time t. $R_u(t)$ is the average transmission rate from 0 to time t of user u. T is the time window to calculate average transmission rate. Therefore, the user priority is judged according to the weighting factor decided by the transmission rate and fairness.

III. POWER CONTROL-BASED OPTIMIZATION SCHEME FOR RESOURCE ALLOCATION

A resource allocation scheme has been studied in Section II to solve the frequency division problem. However, the users covered by PBSs reuse the spectrum resource with interference, which would degrade network performance. Therefore, based on the proposed scheme, we present a power control based optimization scheme to increase frequency utilization.

A. PROBLEM FORMULATION

Since the frequency reuse of the edge users brings interference to other clients, it is necessary to control transmission power so that the interference among users can be decreased [20]. Since the orthogonal spectrum resource is used by the edge user in BS, the transmission of each user will not interfere with each other. Therefore, the transmission power of the edge user is set to the maximum value, and the main focus of power control is to confirm the transmission power of the center user. The proposed power control scheme in HetCNets includes the following parts:

1) The SINR value of BS in the center region should satisfy the threshold of communication requirement, by which the minimum required transmission power can be calculated.

2) The summation of the distributed transmission power in the center region of BS should not exceed the total power allocated to the center region of BS.

3) BS transmits the information of the utilized resource to the neighboring BSs, and calculates the throughput loss by using the resource block, which is caused by the interference from neighboring BSs.

An optimization function is constructed according to these three steps, and the optimal transmission power is calculated by the formulated function. In our work, the state of subcarrier in each wireless channel is assumed to be the same, and the corresponding SINR calculation is:

$$SINR_{n,k}^{c,1} = \frac{P_{n,k}^{c,1} \cdot g_{n,k}^1}{P_{n,k}^{e,2} \cdot g_{n,k}^2 + N_0} \tag{16}$$

where $SINR_{n,k}^{c,1}$ represents the SINR value of user n on resource block k of BS 1, $P_{n,k}^{c,1}$ is the transmission power of user n on resource block k of BS 1, and $P_{n,k}^{e,2}$, $g_{n,k}^2$ can be defined similarly. The SINR value of edge user n on resource block k of BS 2 can be calculated by:

$$SINR_{n,k}^{e,2} = \frac{P_{n,k}^{e,2} \cdot g_{n,k}^2}{P_{n,k}^{c,1} \cdot g_{n,k}^1 + N_0} \tag{17}$$

and the variances are defined similarly with those in (17).

B. CONSTRAINTS OF TRANSMISSION POWER

In order to satisfy the communication requirement, the users may not use only one resource block. Assume the shared number of resource blocks between BS 1 and BS 2 is $K1$, and the shared number of resource blocks between the center range of BS 2 and the edge range of BS 1 is $K2$. The total user numbers of BS 1 and BS 2 are $N1_{total}$ and $N2_{total}$, respectively. The numbers of center users in BS 1 and BS 2 are $N1$ and $N2$, respectively. Thus, the transmission rate of center user n in BS 1 is:

$$R_n^{c,1} = \sum_{k=1}^{K1} \rho_{k,n} r_{n,k}^{c,1} = \sum_{k=1}^{K1} \rho_{k,n} B \log_2 \left(1 + \frac{P_{n,k}^{c,1} \cdot g_{n,k}^1}{P_{n,k}^{e,2} \cdot g_{n,k}^2 + N_0}\right) \tag{18}$$

where $\rho_{k,n}$ represents whether the resource has been assigned to the user, and $\rho_{k,n} \in \{0, 1\}$. $R_n^{c,1}$ is the transmission rate that center user n in BS 1 can achieve. The transmission rate of edge user n in BS 1 can be calculated by:

$$R_n^{e,1} = \sum_{k=1}^{K1} \rho_{k,n} r_{n,k}^{e,1} = \sum_{k=1}^{K1} \rho_{k,n} B \log_2 \left(1 + \frac{P_{n,k}^{e,1} \cdot g_{n,k}^1}{P_{n,k}^{c,2} \cdot g_{n,k}^2 + N_0}\right) \tag{19}$$

where $R_n^{c,2}$ and $R_n^{e,2}$ can be obtained similarly.

The threshold of the transmission rate is set to R_n^{min}. If the transmission rate of the center user is lower than R_n^{min}, the transmission power on the resource block should be adjusted by:

$$R_n^{c,1} = \sum_{k=1}^{K1} \rho_{k,n} B \log_2 \left(1 + \frac{P_{n,k}^{c,1} \cdot g_{n,k}^1}{P_{n,k}^{e,2} \cdot g_{n,k}^2 + \sigma^2}\right) \geq R_n^{min}. \tag{20}$$

As the transmission power on resource block k increases, the interference of edge user on block also enhances, which may affect the normal packet transmission. Therefore, the path loss brought to block k should be controlled to some extent, which can be illustrated by:

$$\sum_{n=1}^{N1} B \rho_{n,k} \left[\log_2 \left(1 + \frac{P_{n,k}^{e,2} \cdot g_{n,k}^2}{o^2}\right) - \log_2 \left(1 + \frac{P_{n,k}^{e,2} \cdot g_{n,k}^2}{P_{n,k}^{c,1} \cdot g_{n,k}^1 + \sigma^2}\right)\right] \leq R_k^{max} \tag{21}$$

Its main objective is to control the transmission power of center user so that the strong interference from the neighboring BSs can be alleviated. This problem can be formulated as:

$$Objective: \quad max f_1(p_{n,k}^{c,1}) = max \sum_{n=1}^{N1} \sum_{k=1}^{K1} (\rho_{n,k} r_{n,k}^{c,1}) \tag{22}$$

Constraints:

$$R_n^{c,1} \geq R_n^{min}, n = 1 \ldots N1 \tag{23}$$

$$\sum_{n=1}^{N1} \sum_{k=1}^{K1} \rho_{n,k} p_{n,k}^{c,1} \leq P_{total}^{c,1} \tag{24}$$

$$\sum_{n=1}^{N1} B \rho_{n,k} [\log_2 (1 + \frac{P_{n,k}^{e,2} g_{n,k}^2}{N_0}) - \log_2 (1 + \frac{P_{n,k}^{e,2} g_{n,k}^2}{P_{n,k}^{c,1} g_{n,k}^1 + N_0})] \leq R_k^{max} \quad \forall k \tag{25}$$

$$\sum_{n=1}^{N1} \rho_{n,k} = 1 \quad \rho_{n,k} \in \{0, 1\}, \ \forall n, k \tag{26}$$

The objective function is to maximize network throughput of the center user. Equation (23) represents the minimum transmission rate that each user requires. The power constraint for user is illustrated by (24), that is the used power should be less than the total power distributed to the user from BS. Equation (25) means if the center user has shared the resource block, the loss of the transmission rate in the neighboring BS should be less than R_k^{max}. $\rho_{n,k}$ is a binary variance, which illustrates whether the resource block has been utilized by the user. The formulated problem involves the decisions of resource allocation and power control, which are represented by $\rho_{n,k}$ and $r_{n,k}^{c,1}$, respectively.

C. LAGRANGIAN MULTIPLIER-BASED OPTIMIZATION METHOD

Since the optimization function is nonlinear, Lagrangian multiplier method is applied to solve this problem. By the method presented in Section II, the resource allocation problem can be solved, thus, the optimization problem can be simplified as:

$$Objective: \quad max f_1(p_{n,k}^{c,1}) = max \sum_{n=1}^{N1} \sum_{k=1}^{K1} r_{n,k}^{c,1} \tag{27}$$

Constraints:

$$R_n^{c,1} \geq R_n^{min}, n = 1 \ldots N1 \tag{28}$$

$$\sum_{n=1}^{N1} \sum_{k=1}^{K1} p_{n,k}^{c,1} \leq P_{total}^{c,1} \tag{29}$$

$$\sum_{n=1}^{N1} B [\log_2 (1 + \frac{P_{n,k}^{e,2} g_{n,k}^2}{o^2}) - \log_2 (1 + \frac{P_{n,k}^{e,2} g_{n,k}^2}{P_{n,k}^{c,1} g_{n,k}^1 + \sigma^2})] \leq R_k^{max}. \tag{30}$$

In order to maximize the objective function, the constraints of the transmission power on different resource blocks should be guaranteed, therefore, it is necessary to transform these constraints into the equations represented by the transmission power. According to (30), the transmission power of user n on resource block k should satisfy:

$$Q_k = \frac{N_0 (P_{n,k}^{e,2} \cdot g_{n,k}^2 + N_0)(2^{\frac{R_n^{max}}{B}} - 1)}{g_{n,k}^1 (P_{n,k}^{e,2} \cdot g_{n,k}^2 + \sigma^2 (1 - 2^{\frac{R_n^{max}}{B}}))} \geq p_{n,k}^{c,1}. \tag{31}$$

Since the edge users utilize the orthogonal spectrum resource, in order to maximize their network performances, the corresponding maximum transmission powers are set, i.e. $P_{n,k}^{e,1} = P_{total}^1 / N1_{total}$ and $P_{n,k}^{e,2} = P_{total}^2 / N2_{total}$. To describe the parameters effectively, we set $x = P_{n,k}^{c,1}$, $a = g_{n,k}^1$, $b = P_{n,k}^{e,2} = P_{total}^2 / N2_{total}$ and $c = g_{n,k}^2$. In order to change the formulated problem into convex optimization problem, the objective function should be converted into convex function. For variance x, the sub-function is a concave function, and the objective function becomes:

$$
\begin{aligned}
minf_1'(x) &= min(-\sum_{n=1}^{N1}\sum_{k=1}^{K1}(r_{n,k}^{c,1})) \\
&= min - \sum_{n=1}^{N1}\sum_{k=1}^{K1}\left(B\log_2\left(1+\frac{x\cdot a}{b\cdot c+\sigma^2}\right)\right) \qquad (32)
\end{aligned}
$$

The constraints are:

$$\sum_{k=1}^{K1} B\log_2\left(1+\frac{x\cdot a}{b\cdot c+\sigma^2}\right) \geq R_n^{min}, \quad n=1\ldots N1 \qquad (33)$$

$$\sum_{n=1}^{N1}\sum_{k=1}^{K1} x \leq P_{total}^{c,1} \qquad (34)$$

$$0 \leq x \leq Q_k \quad \forall k. \qquad (35)$$

By Lagrangian relaxation, the objective function and constraints become:

$$
\begin{aligned}
L = &-\sum_{n=1}^{N1}\sum_{k=1}^{K1}\left(B\log_2(1+\frac{x\cdot a}{b\cdot c+\sigma^2}) \right. \\
&\left. + B\log_2\left(1+\frac{b\cdot c}{x\cdot a+\sigma^2}\right)\right) \\
&-\lambda\left(P_{total}^{c,1}-\sum_{n=1}^{N1}\sum_{k=1}^{K1} x\right)+\beta_k(x-Q_k) \\
&-\mu_n\left(\sum_{k=1}^{K1} B\log_2\left(1+\frac{x\cdot a}{b\cdot c+\sigma^2}\right)-R_n^{min}\right) \qquad (36)
\end{aligned}
$$

In order to obtain the optimal solution, the first order of partial derivative is calculated by:

$$\frac{\partial L}{\partial x} = \frac{B}{\ln 2}\left(\frac{(1+\mu_n)a}{ax+\sigma^2+bc}\right)-\lambda-\beta_k. \qquad (37)$$

If Constraint (35) is ignored, the other constraints satisfy Karush-Kuhn-Tucker condition. According to Lagrangian relaxation, we can obtain:

$$
\begin{cases}
\dfrac{\partial L(x,\lambda,\beta_k,\mu_n)}{\partial x^*}\begin{cases} =0 & p_{n,k}^{c,1*}>0 \\ <0 & p_{n,k}^{c,1*}=0 \end{cases} & \forall n,k \\
\lambda\left(P_{total}^{c,1}-\sum_{n=1}^{N1}\sum_{k=1}^{K1}x^*\right)=0 & \\
\beta_k(x^*-Q_k)=0 & \forall k \\
\mu_n\left(\sum_{k=1}^{K1} B\log_2(1+\dfrac{x^*\cdot a}{b\cdot c+\sigma^2})-R_n^{min}\right)=0 & \\
\lambda,\beta_n,\mu_k \geq 0, & \forall n,k.
\end{cases}
\qquad (38)
$$

By solving these inequations, we can get:

$$x^* = max\left(0, \frac{B(1+\mu_n)}{\ln 2(\lambda+\beta_k)}-\frac{bc+\sigma^2}{a}\right) \qquad (39)$$

It can be observed that (39) satisfies the model of water-filling algorithm. Since the optimal factor x^* has relationship with λ, μ_n, and β_k. We then discuss how to obtain the optimal parameter x^* by utilizing these values, and define:

Algorithm 1 The Steps of the Proposed Power Control Method

```
Input: $\lambda, \mu_n, \beta_k$
Output: $L_{k,n}^*$                    ▷ the optimal transmission power
initialize: $L_0 = \frac{B}{\lambda \ln 2}$
$Q_k = \frac{N_0(P_{n,k}^{e,2}\cdot g_{n,k}^2+N_0)(2^{\frac{R_n^{max}}{B}}-1)}{g_{n,k}^1(P_{n,k}^{e,2}\cdot g_{n,k}^2+\sigma^2(1-2^{\frac{R_n^{max}}{B}}))}$
loop
    $R_n', N_n = |\Omega_n|$
    loop
        $L_{n,k}' = \frac{(2^{\frac{R_n^{min}-R_n'}{B}})^{1/N_k}(bc+\sigma^2)}{a}$
        $k^* = \mathrm{argmin}_{k\in\Omega_n}(L_k^{mask})$
        if $L_{k^*,n}' > L_{k^*}^{mask}$ then
            $L_{k^*,n}^{min} = L_{k^*}^{mask}$
            $\Omega_n = \Omega_n \setminus (k^*)$
            $N_n = N_n - 1$
            $R_n' = R_n' + B\log 2(L_{k^*,n}^{min}\cdot\frac{a}{bc+\sigma^2})$
        else
            $L_{k,n}^{min} = L_{k,n}'$
            Break;
        end if
    end loop
end loop
$\Delta P = P_{total} - \sum_{n=1}^{N1}\sum_{k\in\Delta n}(L_{k,n}^{min}-\frac{bc+\sigma^2}{a})$
$L_{min} = min(L_{k,n}^{min})$
$L_{max} = L_{min} + \Delta P$
loop
    $L_0 = (L_{min}+L_{max})/2, L_{k,n}^* = max(L_0, L_{k,n}^{min})$
    $P_T = \sum_{n=1}^{N1}\sum_{k\in\Delta n}(L_{k,n}-\frac{bc+\sigma^2}{a})$
    if $P_T > P_{total}$ then
        $L_{max} = L_0$
    else
        $L_{min} = L_0$
    end if
    if $P_T > P_{total}$ then
        Break;
    end if
end loop
$p_{k,n}^* = L^*(k,n) - \frac{bc+\sigma^2}{a}$
```

$$L_{n,k}^* = \frac{B}{\ln 2}\left(\frac{\mu_n+1}{\lambda+\beta_k}\right) \qquad (40)$$

then the discussion of x^* can be classified as:

Case 1: If $\lambda = 0$, since λ and β_k cannot be 0 simultaneously, according to network constraints, $x^* = Q_k$, no matter what the values of β_k and μ_n are, $L_{n,k}^{c,1} = Q_k + \frac{bc+\sigma^2}{a}$.

Case 2: If $\lambda \neq 0$ and $\mu \neq 0$, define $L_0 = \frac{B}{\lambda \ln 2}$, three situations are included:

a) If $\beta_k \neq 0$, according to the constraints, $x^* = Q_k$ and $P_{total}^{c,1} = \sum_{n=1}^{N1}\sum_{k=1}^{K1}x^*$, thus, $L_{n,k}^* = Q_k + \frac{bc+\sigma^2}{a}$.

b) If $\beta_k = 0$, then $L^*_{n,k} = \frac{B}{\ln 2}(\frac{\mu_k+1}{\lambda}) > L_0$. Since $\mu_n \neq 0$, $\sum_{k=1}^{K1} B \log 2(1 + \frac{x^* \cdot a}{b \cdot c+\sigma^2}) = R_n^{min}$, and $L^*_{n,k} = \frac{2^{\frac{R_n^{min}}{B}}(bc+\sigma^2)}{a}$, $x^* = \frac{(2^{\frac{R_n^{min}}{B}}-1)(bc+\sigma^2)}{a}$.

c) If $\beta_k \neq 0, \forall k \in \Omega_{n0}$ and $\beta_k = 0, \forall k \in \Omega_{n1}$, where $\Omega_{n0} \bigcup \Omega_{n1} = \Omega_n$, $R'_n = \sum_{\Omega_{n0}} B \log 2(1 + Q_k H_{k,n})$, $x^* = Q_k$, and $L^*_{n,k} = Q_k + \frac{bc+\sigma^2}{a}$. When $\forall k \vdash \Omega_{n1}$, the optimal threshold is:

$$L^*_{n,k} = \frac{(2^{\frac{R_n^{min}-R'_n}{B}})^{1/N_k}(bc+\sigma^2)}{a} \tag{41}$$

herein, $N_n = |\Omega_n|$ represents the number of resource blocks assigned to the *n*th user, and the optimal transmission power on this block is $x^* = (bc+\sigma^2)[(2^{\frac{R_n^{min}-R'_n}{B}})^{1/N_k} - 1]/a$.

Case 3: When $\lambda \neq 0$ and $\mu = 0$, if $\beta_k \neq 0$, $L^*_{n,k} = Q_k + \frac{bc+\sigma^2}{a}$; if $\beta_k = 0$, $L^*_{n,k} = L_0$ and $x^* = \frac{B}{\lambda \ln 2} - \frac{bc+\sigma^2}{a}$.

Algorithm 1 states the main steps of the proposed power control method. From the steps analyzed in Algorithm 1, the optimal transmission power of center user on BS 1 can be calculated. Since the center user on BS 2 is independent with the user on BS 1, the corresponding optimal transmission power can be obtained similarly.

TABLE 1. Simulation parameter values.

Parameter	Value
Carrier frequency	2.0 GHz
Speed of dynamic user	3 km/h
Number of subcarrier	600
Loss of wall through	20 dB
Number of MBS	50 DL/50 UL
Number of PBS	50 DL/50 UL
Power of MBS	46 dBm
Power of PBS	30 dBm
Path loss of MBS	128.1+37.6$\log_{10}$(R)dB
Path loss of PBS	140.7+36.7$\log_{10}$(R)dB
Coverage radius of MBS	1000 m
Coverage radius of PBS	5 dBi
Antenna gain of MBS	14 dBi
Antenna gain of PBS	0 dBi

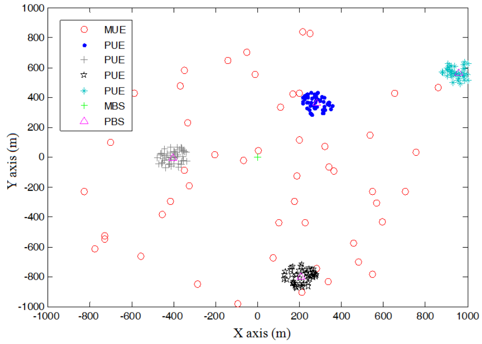
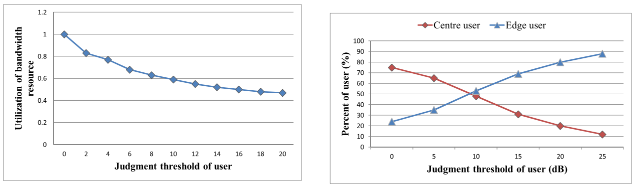


FIGURE 4. Simulation topology of HetCNets.



(a)

(b)

FIGURE 5. Selection of SINR threshold. (a) Utilization of bandwidth. (b) Percent of users.

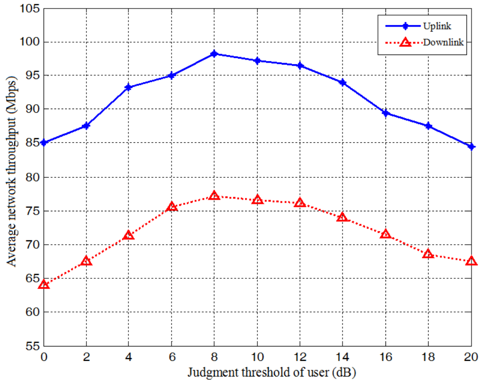


FIGURE 6. Average network throughput versus different threshold values.

IV. SIMULATION RESULTS

The considered simulation scenario includes 1 MBS and 4 PBSs, and these 4 PBSs are randomly distributed in the coverage of the MBS, as illustrated in Fig. 4. The coverage of the MBS is 1000m, the minimum distance between MBS and PBS is 75m, and the minimum distance between different PBSs is 40m. The path loss model and other parameters are set according to the 3GPP standard, as shown in Table 1. The dynamic user has higher priority than the static user.

The selection of SINR threshold can be seen on Fig. 5. It can be seen in Fig. 5(a) that the value of SINR threshold ($SINR_{th}$) has a large impact on network resource utilization. Since we merely consider the spectrum reuse of central users, network resource utilization decreases constantly. As illustrated in Fig. 5(b), as the increase of judgement threshold, the proportion of central and edge users decreases and enhances, respectively. This is because the closer user to the BS, the better network performance user can obtain. As the judgement threshold becomes larger, more users satisfying threshold are close to the BS so that network coverage becomes smaller. Therefore, the number of central users and edge users decreases and increases, respectively.

Fig. 6 is the average network throughput on uplink and downlink, respectively. It can be observed that if the $SINR_{th}$ value is too large, the number of the center users within the coverage of BS is small, which results in the average network throughput is low; Otherwise, the number of the users for resource reuse is large, which brings high interference and decreases network throughput as a result.

From Fig. 7, we can see that as the transmission power of center user enhances, network throughput increases and then decreases. This is because the center user shares

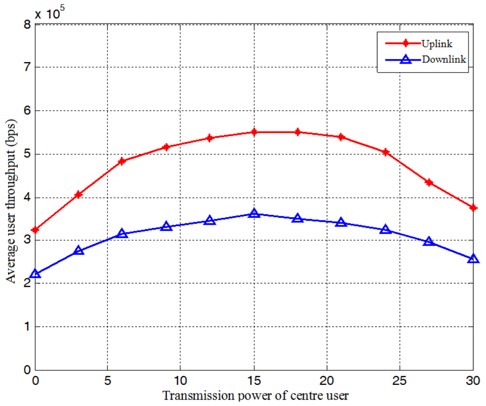


FIGURE 7. Average user throughput versus different power.

TABLE 2. Network performance of different schemes.

	Utilization percent of frequency resource	Average throughput	Total throughput
Method 1	62%	2.1×10^5 bps	9.8×10^7 bps
Method 2	38%	7×10^5 bps	5.8×10^7 bps
Method 3	100%	5.2×10^5 bps	6.1×10^7 bps

network resource with edge users. Although network throughput enhances with the improvement of transmission power, high transmission power introduces more interference to neighboring BSs. As the transmission power increases to some extent, the enhanced network throughput keeps balance with the interference brought to other BSs, then the network performance deteriorates. Therefore, the objective of our scheme is to select the optimal transmission power based on the partial shared resource scheme, so that network throughput can be optimized.

Network performances obtained by different methods without power control are illustrated on Table 2. Methods 1 to 3 are partial shared resource, orthogonal shared resource, and all shared resource allocation. It can be observed that for orthogonal allocation scheme, the utilization of spectrum resource and the number of users accessed into the BS are the lowest. Our proposed scheme can guarantee more users to obtain high throughput and the total network can also be increased. For orthogonal allocation scheme, user average throughput is the largest since the users are interference free, while for all-shared resource scheme, the average throughput is the smallest. Our method makes a tradeoff between the utilization of frequency band and the achieved network throughput.

Figures 8 and 9 illustrate the variances of Cumulative Distribution Function (CDF) curves with SINR value in MBS and PBS, respectively. For partial resource allocation scheme, since the shared resource of the center user interferes with each other, the required SINR value is smaller than the all-shared resource allocation scheme. However, the edge users are interference free so that the obtained SINR values are large. For the schemes under power control, comparing with no power control scheme, the SINR values achieved by the

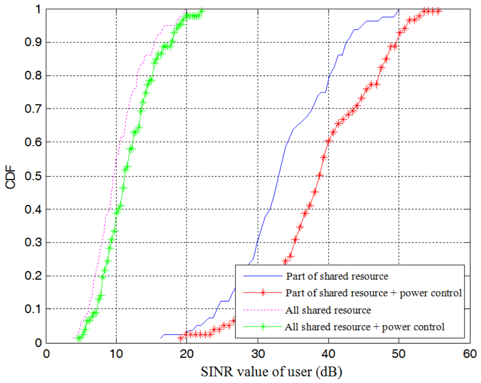


FIGURE 8. SINR in MBS versus different optimized allocation of resources.

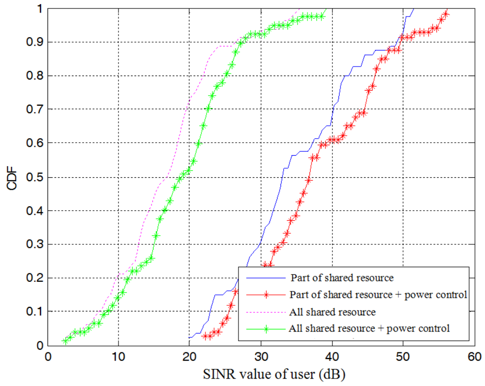


FIGURE 9. SINR in PBS versus different optimized allocation of resources.

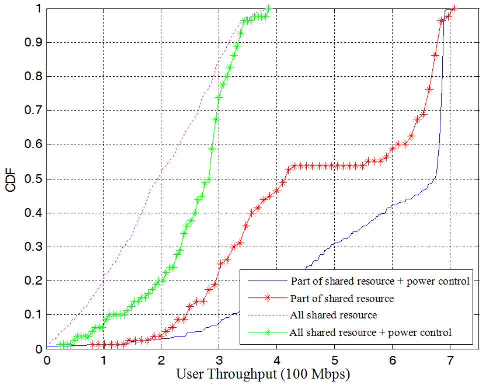
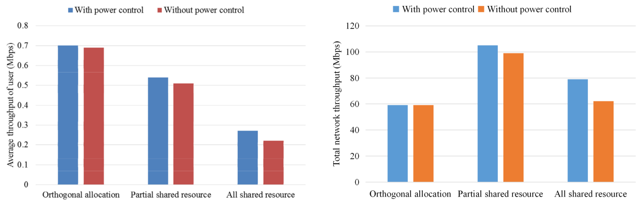


FIGURE 10. CDF curves of user throughput versus different optimized allocation of resources.

users in MBS and PBS distribute into the area with larger CDF value, which means higher network throughput can be gained. Similar conclusions can be drawn in Fig. 10.

Throughput of individual user and the whole network has been illustrated in Fig. 11. It demonstrates the superiority of the power control-based method. It can be observed that although the user average throughput gained by orthogonal allocation scheme is high, the achieved total network throughput is low since the frequency resource for utilization is



(a) (b)

FIGURE 11. **Throughput comparison among different schemes. (a) Throughput of individual user. (b) Throughput of the whole network.**

not rich enough. For all shared frequency resource scheme, although the spectrum utilization is the largest, the interference among users decreases network throughput.

V. CONCLUSIONS

The main objective of our work is to solve the resource allocation problem among different types of BSs in HetCNets, so that strong interference among users can be alleviated. A novel resource allocation scheme has been presented at first, and the interference graph is constructed according to the network interference, by which the orthogonal resources can be allocated to different BSs. Then, the clients are divided into center and edge users, where the former utilizes all the frequency resource, while the latter only leverages the orthogonal resource to alleviate interference. In order to decrease network interference further while satisfying the communication requirements of BSs, an optimization algorithm based on power control has been presented, according to which the network resources can be assigned effectively. Simulation results demonstrate that compared with the existing methods, our scheme can not only increase resource utilization and decrease interference among BSs, but also enhances the performance of edge users and improves the overall network throughput.

We have mainly considered the HetCNets including two kinds of BSs, i.e. macro cells and micro cells, more general situation will be considered further, which consists of family cell and the relay cell with low power.

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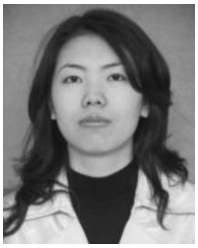

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