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An enhanced almost blank sub-frame management for efficient eICIC in non-uniform HetNets

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Abstract: A new enhanced inter-cell interference coordination (eICIC) is adopted for managing almost blank sub-frame (ABS), which jointly exploits the time, frequency and power dimensions to improve the resource utilization. In particular, a non-uniform two tier heterogeneous network (HetNet) is considered, where the pico cells are located close to the macro cell and the number of users in each pico cell is different. To alleviate the interference caused by the co-channel deployment, the macro cells employ low power ABS (LP-ABS), and the resource blocks (RBs) are divided into two parts during an ABS. One is exclusively reserved for macro cell users and the other is reserved for pico cell users. The macro cells are allowed to use different percentages of RBs and different powers for their own transmission during the LP-ABS. The user association, resource allocation, ABS proportion, the frequency band partition parameter and the transmission power of macro cells are considered, aiming at maximizing the proportional fairness utility of the system. An iterative algorithm is also proposed and simulation results demonstrate that the proposed algorithm can improve both the system throughput and user fairness compared with the existing schemes.

Key words: low power almost blank sub-frame (LP-ABS); inter-cell interference coordination (eICIC); non-uniform heterogeneous network (HetNet)

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We have witnessed an exponential traffic growth in recent years. To address this issue, LTE heterogeneous networks (HetNets) have been proposed to increase the reuse of spectrum[1]. This architecture consists of the deployment of low power base stations (BS) complementary to the coverage layer of the macro cells. It is often assumed that the lower power BS and the macro cells share the same frequency band. The users that are associated with low power nodes may experience strong interference from the macro cells, and in order to alleviate the cross-tier interference problem, LTE standards have introduced the almost blank sub-frames (ABS) mechanism[2]. On a subset of sub-frames, the macro cells will be mute, thus reducing the interference on users associated with low power nodes. These are known as zero power ABS (ZP-ABS) during which there is no data transmission or low power ABS (LP-ABS) during which the transmission power of the macro cells is reduced.

Despite the improvements of the performance of the pico UEs brought by ZP-ABS, this has some drawbacks when it comes to the macro cells' user throughput. During the silent periods of the macro cells, the available resources may be under-utilized. Compared with ZP-ABS, LP-ABS can increase the throughput of macro UEs because the macro UEs can receive data on both ABS and non-ABS. On the other hand, LP-ABS increases the amount of interference caused for the pico UEs. Hence, an important design parameter is how much transmission power the macro cells should use on LP-ABS. In Ref. [3], the Monte Carlo simulation was used to verify that with the optimum transmission power of the macro cells on LP-ABS, substantially better performance than that of ZP-ABS can be achieved. In our previous work[4], we analyzed a non-uniform network topology where the number of pico cells under each macro cell is different. We showed that macro-cell specific transmission power on LP-ABS can improve the system throughput compared to ZP-ABS and LP-ABS where uniform transmission powers for the macro cells were employed.

When all small cells are located far away from the macro cell, the small cell users suffer less interference from the macro cells, and LP-ABS has been proven effective in increasing the system throughput[3-4]. However, when the small cells are located close to the macro cell, the small cell users are more susceptible to the interference from the macro cell. Therefore, the use of LP-ABS is similar to ZP-ABS, since even a low strictly positive power during the LP-ABS can cause too much interference for the pico UEs. In Refs. [5 – 6], a new eICIC scheme is presented, which exploits the frequency as well as the time dimension. They divided the resource blocks (RBs) during an ABS into those reserved for macro cell use exclusively and those reserved for pico cell use exclusively. The per-

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centage of RBs assigned to the pico cells is called the frequency band partition (FBP) parameter. The idea is that the scheme can ensure that pico users experience no interference from the RBs reserved for the pico cells in ABS, while at the same time, it also improves the throughput of the macro cell in ABS. However, Refs. [5 - 6] did not provide a precise formula for the FBP parameter. Furthermore, the scheme proposed assumes that each macro cell uses the same FBP parameter, and this works well for a uniform network topology, where each macro cell has the same number of pico cells, the pico cells have the same locations relative to its macro cell, and each pico has the same number of users.

In this paper, we adopt the scheme proposed in Refs. [5 -6] for managing ABS sub-frames that jointly exploits the time, frequency and power dimensions to improve the resource utilization. We allow for the macro cells to use different FBP parameters, as well as different powers during the LP-ABS. We formulate an optimization problem which aims to maximize the proportional fairness utility of the system by jointly optimizing the user association, i. e., which users should be offloaded to the pico cells, the resource allocation, i. e, how much resources should be assigned to each user, the ABS fraction that should be allocated, the FBP parameter, and the transmission power of the macro cells on LP-ABS. We decouple the joint problem into four subproblems and iteratively solve each one of them in an alternating manner. Simulation results show that for the non-uniform topology, pico cells are close to the center of the macro cells, and each pico has a different number of users, thus our proposed algorithm improves the system throughput compared to both ZP-ABS and LP-ABS. In addition, the algorithm guarantees user fairness and converges quickly.

1 System Model and Problem Formulation

We consider the downlink transmission in eICIC HetNet using the scheme proposed in Refs. [5 - 6] for managing ABS sub-frames that jointly exploits the time, frequency and power dimensions to improve the resource utilization. We formulate the resource allocation problem as a PF utility optimization problem, and solve the joint solution of user association, resource allocation, ABS proportion, the FBP parameter, and the transmission power of the macro cells on LP-ABS.

1.1 System model

Consider a HetNet consisting of N UEs, M macro cells configured with special LP-ABS and P pico cells. We denote $M = \{1, 2, \ldots, M\}$ as the set of macro cells, and U as the set of all users. We assume a repeating ABS pattern of frames configured at the macro cells, and synchronous ABS configuration is considered, i. e. all macro base stations configure LP-ABS in the same set of sub-frames. The proportion of the sub-frames used as LP-ABS for all the macros is β. In the sub-frames of the ABS, macro cell m divides the frequency resource into two parts, where proportion ε_m of the frequency resource is assigned to the pico cells, and the remaining proportion $(1 - \varepsilon_m)$ is assigned to the macro cells. Note that the parameter ε_m is a function of m, i. e., different macro cells can choose different frequency resource divisions. Furthermore, different macro cells can transmit using various low power in the ABS sub-frames on the frequency resource that has been assigned to the macro cell. We denote P_m as the low power transmitted by macro cell m in the ABS sub-frames.

To simplify the problem, we assume that each macro and pico UE are either scheduled to transmit on the nABS (normal sub-frames) or LP-ABS, but not on both[7]; i. e. macro edge UEs and pico center (CEN) UEs are scheduled to transmit only on the nABS sub-frames, while macro center UEs and pico edge (CRE) UEs are scheduled to transmit only in the ABS, albeit in different frequency bands, as shown in Fig. 1.

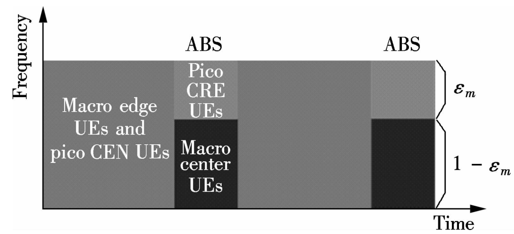

Fig. 1 Resource allocation principles in the proposed scheme

Based on this assumption, we can visualize each macro or pico cell as two sub-cells, with one sub-cell working on the nABS and the other sub-cell working on the ABS. Thus, we can assume that there are $2(M + P)$ sub-cells in the networks. Denote the set of macro sub-cells that is active only during ABS(nABS) as $M_{\text{ABS}}(M_{\text{nABS}})$, and the set of pico sub-cells that is active only during ABS (nABS) as $P_{\text{ABS}}(P_{\text{nABS}})$. Each macro has a frequency band partition scheme and affects all base stations within its coverage. We denote the set of base stations within the coverage of macro cell m as $B_m \triangleq \{0, 1, \ldots, |B_m|\}$, where 0 denotes the macro cell m and $b = 1, 2, \ldots, |B_m|$ denotes the $|B_m|$ pico cells.

1.2 Problem statement

First of all, we consider the SINR of the UEs. The four subsets of cells create four different downlink interference patterns. The SINR of UE u associated with sub-cell $b \in B_{\text{nABS}}$, where $B_{\text{nABS}} \triangleq M_{\text{nABS}} \cup P_{\text{nABS}}$ can be written as

$$\text{SINR}_{ub} = \begin{cases} \dfrac{P^M G_{ub}}{\sum\limits_{k \in M_{\text{nABS}}, k \neq b} P^M G_{uk} + \sum\limits_{k \in P_{\text{nABS}}} P^P G_{uk} + N_0} & b \in M_{\text{nABS}} \\ \dfrac{P^P G_{ub}}{\sum\limits_{k \in M_{\text{nABS}}} P^M G_{uk} + \sum\limits_{k \in P_{\text{nABS}}, k \neq b} P^P G_{uk} + N_0} & b \in P_{\text{nABS}} \end{cases} \tag{1}$$

where P^M is the transmission power of all macro cells on the nABS; P^P is the transmission power of all pico cells on all subframes; G_{ub} is the channel gain between sub-cell b and UE u, and the two subcells have the same channel gain if they are split from the same cell; and N_0 is the noise power. On the other hand, the SINR of UE u associated with sub-cell $b \in B_{\text{ABS}}$, $B_{\text{ABS}} = M_{\text{ABS}} \cup P_{\text{ABS}}$ is

$$\text{SINR}_{ub} = \frac{S_{ub}}{I_{ub} + N_0} \tag{2}$$

$$S_{ub} = \begin{cases} P_m G_{ub} & b \in M_{\text{ABS}} \\ P^P G_{ub} & b \in P_{\text{ABS}} \end{cases} \tag{3}$$

where S_{ub} denotes the signal power received from sub-cell b; P_m is the transmission power of macro m. Note that each macro cell can use a different transmission power in the LP-ABS. I_{ub} denotes the interference from the other cells to user u, which we divide into two parts. One is the interference from the cells within the same macro cell, and the other is from the other macro cells and the picos within their coverage. Sub-cell b is under the macro cell coverage, i. e., $b \in B_m$, and we can write

$$I_{ub} = I_{mub} + \sum_{\substack{m' \in M \\ m' \neq m}} I_{m'ub} \tag{4}$$

I_{mub} is the interference from the cells within the same macro, and we have

$$I_{mub} = \begin{cases} 0 & b \in M_{\text{ABS}} \\ \sum\limits_{\substack{k' \in B_m \\ k' \neq b}} P^P G_{uk'} & b \in P_{\text{ABS}} \end{cases} \tag{5}$$

where the macro cell's user experiences zero interference because the pico cells and the macro cells operate on different frequency bands during ABS.

As for $I_{m'ub}$, note that each macro cell can set different FBP in the ABS, so there is interference between the macro cell and the pico cells which belong to a different macro cell. The interference pattern consists of two possibilities as shown in Fig. 2. When $b \in M_{\text{ABS}}$, we have

$$I_{m'ub} = \begin{cases} \dfrac{1-\varepsilon_{m'}}{1-\varepsilon_m} P_{m'} G_{um'} + \dfrac{\varepsilon_{m'}-\varepsilon_m}{1-\varepsilon_m} \sum\limits_{k \in B_{m'}, k \neq 0} P^P G_{uk} & \varepsilon_m < \varepsilon_{m'} \\ P_{m'} G_{um'} & \varepsilon_m \geqslant \varepsilon_{m'} \end{cases} \tag{6}$$

To simplify the calculation, we consider the average interference for Case 1. When $b \in P_{\text{ABS}}$, we have

$$I_{m'ub} = \begin{cases} \sum\limits_{k \in B_{m'}, k \neq 0} P^P G_{uk} & \varepsilon_m < \varepsilon_{m'} \\ \dfrac{\varepsilon_m - \varepsilon_{m'}}{\varepsilon_m} P_{m'} G_{um'} + \dfrac{\varepsilon_{m'}}{\varepsilon_m} \sum\limits_{k \in B_{m'}, k \neq 0} P^P G_{uk} & \varepsilon_m \geqslant \varepsilon_{m'} \end{cases} \tag{7}$$

Then, based on the Shannon capacity formula, we can obtain R_{ub}, which denotes the expected data rate of UE u

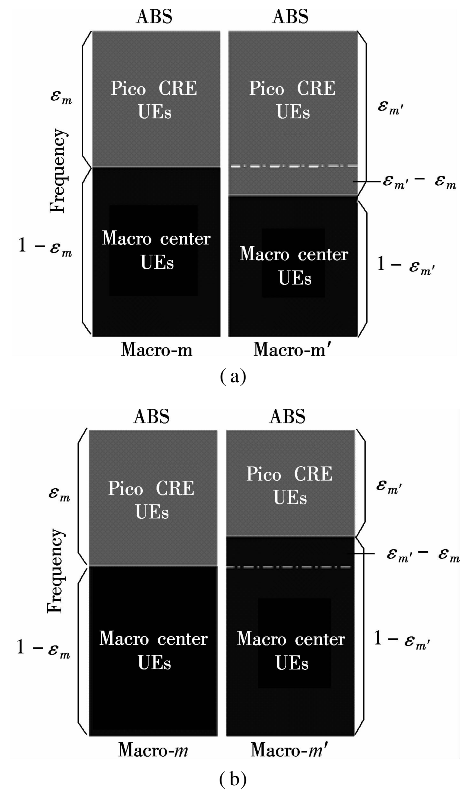

Fig. 2 Two cases of the FBP parameter in two adjacent macros. (a) Case 1 ($\varepsilon_m < \varepsilon_{m'}$); (b) Case 2 ($\varepsilon_m > \varepsilon_{m'}$)

associated with sub-cell b when it uses the entire frequency resource of the system, as

$$R_{ub} = B\log(1 + \text{SINR}_{ub}) \tag{8}$$

where B represents the total bandwidth of the system. We use indicators $\{x_{ub}\}$ to represent user-cell association, i. e., $x_{ub} = 1$ when user u is associated with cell b, and $x_{ub} = 0$ otherwise. We assume that a UE can only associate with one sub-cell, and the UE association constraint is

$$\sum_{b \in B} x_{ub} = 1 \qquad \forall u \in U \tag{9a}$$

$$x_{ub} = \{0, 1\} \qquad \forall u \in U, \ \forall b \in B \tag{9b}$$

where $B = M_{\text{ABS}} \cup M_{\text{nABS}} \cup P_{\text{ABS}} \cup P_{\text{nABS}}$ is the collection of all sub-cells. FBP parameter ε_m is the normalized parameter and it satisfies

$$0 \leqslant \varepsilon_m \leqslant 1 \qquad m \in M \tag{10}$$

Denote $\{y_{ub}\}$ as the proportion of resource allocated to UE u by cell b. Hence, we have the resource allocation constraints as follows:

$$\sum_{u \in U} y_{ub} = (1-\beta) \qquad b \in B_{\text{nABS}} \tag{11}$$

$$\sum_{u \in U} y_{ub} = \beta \varepsilon_m \qquad b \in P_{\text{ABS}}, b \in B_m \tag{12}$$

$$\sum_{u \in U} y_{ub} = \beta(1-\varepsilon_m) \qquad b \in M_{\text{ABS}}, b \in B_m \tag{13}$$

$$0 \leqslant y_{ub} \leqslant x_{ub} \qquad \forall u \in U, \forall b \in B \tag{14}$$

where (14) follows because a cell can only allocate its resources to the UEs associated with it. The transmission power of LP-ABS in macro cells cannot exceed the maximum transmit power P^M. Hence, we have

$$0 \leqslant P_m \leqslant P^M \qquad m \in M \tag{15}$$

The optimization objective we choose is the proportional fairness utility. It is well known that the proportional fairness objective strikes a good balance between system throughput and UE-throughput fairness[8]. Hence, the considered problem can be formulated as

$$\max_{\substack{\beta, x_{ub}, y_{ub} \\ P_m, \varepsilon_m}} \sum_{b \in B} \sum_{u \in U} x_{ub} \log(y_{ub} R_{ub}) \tag{16}$$
$$\text{s.t. (1) to (15)}$$

2 Problem Solution

According to Ref. [7], the above problem is NP-hard. We develop an iterative suboptimal solution to find the UE association, ABS allocation, FBP parameter and transmit power in LP-ABS. In each iteration, a single group of variables is optimized and the remaining variables are fixed. We decompose the optimization variables into four groups: $\{x_{ub}, y_{ub}\}$, β, $\{\varepsilon_m\}$ and $\{P_m\}$ which relate to the four sub-problems: the UE association and resource allocation, the ABS allocation, FBP parameter and the transmit power in LP-ABS, respectively.

2.1 Optimizing $\{x_{ub}, y_{ub}\}$ for given $\{\beta, \{\varepsilon_m\}$ and $\{P_m\}\}$

For determining the resource allocation variables $\{x_{ub}, y_{ub}\}$, we assume that the other optimizing variables, i. e., β, $\{\varepsilon_m\}$ and $\{P_m\}$, are given and fixed.

Define the load of cell K_b as the number of users associated with it, i. e., $K_b = \sum_{u \in U} x_{ub}$. The optimal resource allocation is equal allocation[7], i. e., $y_{ub} = 1/K_b$. As for the optimal UE association $\{x_{ub}\}$, we apply the algorithm in Ref. [9] to find the optimal $\{x_{ub}\}$. Ref. [9] proposed a novel user association scheme that achieve load balancing in HetNets through a network-wide utility maximization problem, based on the knowledge of the achievable rate of each user associated to each BSs. The achievable rate of UE u associated to BS b, denoted as $\bar{R}_{ub}$, is given as

$$\bar{R}_{ub} = \begin{cases} (1-\beta) R_{ub} & b \in B_{\text{nABS}} \\ \beta \varepsilon_m R_{ub} & b \in P_{\text{ABS}}, b \in B_m \\ \beta(1-\varepsilon_m) R_{ub} & b \in M_{\text{ABS}}, b \in B_m \end{cases} \tag{17}$$

For comprehensiveness, we list the algorithm applied to our problem in Algorithm 1. The algorithm has been proved to converge to a near-optimal solution[9] with a low complexity that is linear to the number of users and the number of cells.

Algorithm 1 UE association

Initialization: Lagrange multiplier $\mu = \{\mu_1, \ldots, \mu_{2M+2P}\} = 0$, the number of iterations $t = 0$, and tolerable error d.

repeat

Step 1 User u associate to cell b^* where $b^* = \operatorname{argmax}_b(\log(\bar{R}_{ub}) - \mu_b(t))$. Set

$$x_{ub}(t) = \begin{cases} 1 & b = b^* \\ 0 & b \neq b^* \end{cases} \tag{18}$$

Step 2 Each cell updates the value of K_b according to

$$K_b(t) = \mathrm{e}^{(\mu_b(t) - 1)} \tag{19}$$

Step 3 The new value of the Lagrange multiplier is updated by

$$\mu_b(t+1) = \mu_b(t) - \delta(t) \left(K_b(t) - \sum_{u \in U} x_{ub}(t) \right) \tag{20}$$

where $\delta(t)$ is a dynamically chosen step size, which is chosen according to Ref. [9].

Step 4 $t = t + 1$.

Step 5 Calculate

$$D(\mu(t)) = \sum_{b \in B} \sum_{u \in U} x_{ub}(t)(\log(\bar{R}_{ub}) - \mu_b(t)) + \sum_{b \in B} K_b(t)(\mu_b(t) - \log(K_b(t)))$$

until $|D(\mu(t)) - D(\mu(t-1))| < d$

return $\{x_{ub}^*\} = \{x_{ub}(t)\}$

2.2 Optimizing β for given $\{\{y_{ub}, x_{ub}\}, \{\varepsilon_m\}$ and $\{P_m\}\}$

In this subsection, we discuss the optimal ABS proportion. With the other optimizing variables fixed and plugging in optimal $\{y_{ub}\}$ found in the previous subsection, the joint problem can be rewritten as

$$\max_{\beta} \sum_{b \in B} \sum_{u \in U_b} \log\left(\frac{\bar{R}_{ub}}{K_b}\right) \tag{21}$$
$$\text{s.t. } 0 < \beta < 1$$

where U_b denotes the set of users associated with cell $b \in B$. The problem of (21) is convex, and with only one optimizing variable. The optimal ABS ratio can be found by setting the derivative of the objective function with respect to β to be equal to zero, i. e.,

$$\beta^* = \frac{\sum_{b \in B_{\text{ABS}}} K_b}{N} \tag{22}$$

where N is the total number of UEs. In other words, the optimal ABS ratio is equal to the ratio of the number of UEs scheduled to transmit in the LP-ABS and the total number of UEs.

2.3 Optimizing $\{\varepsilon_m\}$ for given $\{\{y_{ub}, x_{ub}\}, \beta$ and $\{P_m\}\}$

In this subsection, we discuss the FBP parameter.

With the other optimizing variables fixed, the joint problem can be rewritten as

$$\max_{\{\varepsilon_m\}} \left[\sum_{\substack{u \in U_b \\ b \in B_m, b = 0}} \log((1-\varepsilon_m)R_{ub}) + \sum_{\substack{b \in B_m \\ b \neq 0}} \sum_{u \in U_b} \log(\varepsilon_m R_{ub}) \right]$$
$$\text{s. t. } 0 \leqslant \varepsilon_m \leqslant 1,\ \forall m \in M \tag{23}$$

From Eqs. (6) and (7), it can be seen that R_{ub} is a discontinuous function of ε_m, and as a result, we cannot use the gradient descent method[10] to solve (23). To address this difficulty, we propose solving the problem in (23) with a fixed rate $\hat{R}_{ub}$ obtained from the previous iteration. Problem (23) is now reduced to

$$\max_{\{\varepsilon_m\}} \sum_{m \in M} \left[\sum_{\substack{u \in U_b \\ b \in B_m, b = 0}} \log((1-\varepsilon_m)\hat{R}_{ub}) + \sum_{\substack{b \in B_m \\ b \neq 0}} \sum_{u \in U_b} \log(\varepsilon_m \hat{R}_{ub}) \right]$$
$$\text{s. t. } 0 \leqslant \varepsilon_m \leqslant 1,\ \forall m \in M \tag{24}$$

The approximated problem of (24) is convex, and the optimal FBP parameter can be found by setting the derivation of the objective function with respect to ε_m to be equal to zero,

$$\varepsilon_m^* = \frac{\sum_{b \in B_m, b \neq 0} K_b}{\sum_{b \in B_m} K_b} \qquad \forall m \in M \tag{25}$$

In other words, the approximated optimal FBP parameter of macro cell m is equal to the ratio of the number of UEs scheduled in the LP-ABS in macro cell m and the number of UEs scheduled in the LP-ABS in pico cells within the coverage area of macro cell m. The idea of replacing an achievable rate with the value from the previous iteration was also used in Ref. [11].

2.4 Optimizing $\{P_m\}$ for given $\{\{y_{ub}, x_{ub}\}, \{\varepsilon_m\}$ and $\beta\}$

In this subsection, we discuss the power of macro cells in LP-ABS. As for the optimal power of macro cell in LP-ABS $\{P_m\}$, the gradient descent method can be used when the other optimizing variables are fixed. When the other optimizing variables are fixed, the joint problem can be rewritten as

$$\max_{\boldsymbol{P}} \sum_{b \in B} \sum_{u \in U_b} \log\left(\frac{\bar{R}_{ub}}{K_b}\right)$$
$$\text{s. t. } 0 < P_m < P^M,\ \forall m \in M \tag{26}$$

where $\boldsymbol{P} = \{P_m, m \in M\}$, denote the vector of the transmitting powers of macro cells in LP-ABS. There are only R_{ub} where $b \in B_{\text{ABS}}$ are related to $\boldsymbol{P}$, and we propose to solve this problem using the gradient descent method, then convert the maximization problem into a minimization problem, and (26) can be rewritten as

$$\min_{\boldsymbol{P}} f(\boldsymbol{P}) = -\sum_{b \in B_{\text{ABS}}} \sum_{u \in U_b} \log(R_{ub})$$
$$\text{s. t. } 0 < P_m < P^M,\ \forall m \in M \tag{27}$$

To solve this, first, the initial value $\boldsymbol{P}_0$ is chosen, where all the transmit powers of the macro cells in LP-ABS are zero. Secondly, we calculate the gradient $\frac{\partial f(\boldsymbol{P})}{\partial P_m}$, we have

$$\frac{\partial f(\boldsymbol{P})}{\partial P_m} = -\sum_{b \in B_{\text{ABS}}} \sum_{u \in U_b} \frac{\partial \log(R_{ub})}{\partial P_m} \tag{28}$$

When sub-cell b is under the coverage of macro cell m, i. e., $b \in B_m$. We have

$$\frac{\partial \log(R_{ub})}{\partial P_m} = \begin{cases} \dfrac{BG_{um}}{R_{ub}(1+\text{SINR}_{ub})(I_{ub}+N_0)} & b \in M_{\text{ABS}} \\ 0 & b \in P_{\text{ABS}} \end{cases} \tag{29}$$

and when $b \in B_{m'}$, where $m' \neq m$, we need to discuss two different cases. One case is $b \in M_{\text{ABS}}$, we have

$$\frac{\partial \log(R_{ub})}{\partial P_m} = \begin{cases} \dfrac{-B\text{SINR}_{ub}G_{um}}{R_{ub}(1+\text{SINR}_{ub})(I_{ub}+N_0)} \dfrac{1-\varepsilon_m}{1-\varepsilon_{m'}} & \varepsilon_{m'} < \varepsilon_m \\ \dfrac{-B\text{SINR}_{ub}G_{um}}{R_{ub}(1+\text{SINR}_{ub})(I_{ub}+N_0)} & \varepsilon_{m'} \geqslant \varepsilon_m \end{cases} \tag{30}$$

and the other case is $b \in P_{\text{ABS}}$, we have

$$\frac{\partial \log(R_{ub})}{\partial P_m} = \begin{cases} 0 & \varepsilon_{m'} < \varepsilon_m \\ \dfrac{-B\text{SINR}_{ub}G_{um}}{R_{ub}(1+\text{SINR}_{ub})(I_{ub}+N_0)} \dfrac{\varepsilon_{m'}-\varepsilon_m}{\varepsilon_{m'}} & \varepsilon_{m'} \geqslant \varepsilon_m \end{cases} \tag{31}$$

We substitute Eqs. (29), (30) and (31) into Eq. (28) to obtain $\frac{\partial f(\boldsymbol{P})}{\partial P_m}$. Let $\nabla f(\boldsymbol{P})$ be the vector of partial derivatives of $\frac{\partial f(\boldsymbol{P})}{\partial P_m}$, for all $b \in M$. We choose step size t via backtracking the line search[10]. First initialize $t = 1$, then see if t satisfies the expression

$$f(\boldsymbol{P} + t\Delta\boldsymbol{P}) < f(\boldsymbol{P}) + \alpha t \nabla f(\boldsymbol{P})^{\text{T}} \Delta\boldsymbol{P} \tag{32}$$

where the constant $\alpha \in (0, 0.5)$, and $\Delta\boldsymbol{P} = -\nabla f(\boldsymbol{P})$ represents the descent direction. If t does not satisfy (32), then update value $t = \gamma t$, where γ is a constant between 0 and 1, and see again if (32) is satisfied, we terminate until the updated t satisfies the condition in (32). Update the transmit power of P_m as $P_m + t\frac{\partial f(\boldsymbol{P})}{\partial P_m}$ if $P_m \leqslant P^M$, else, update P_m as P^M, $\forall m \in M$. The details of the procedure are shown in Algorithm 2.

Algorithm 2 Optimizing $\{P_m\}$ by using the gradient descent method

Input: $\alpha \in (0, 0.5)$, $\gamma \in (0, 1)$, d, where d means tolerable error.

Output: $\boldsymbol{P}$.
Initialization: $\boldsymbol{P} = \boldsymbol{P}_0$.
repeat
  $\Delta\boldsymbol{P} = -\nabla f(\boldsymbol{P})$
  $t = 1$
  while $f(\boldsymbol{P} + t\Delta\boldsymbol{P}) > f(\boldsymbol{P}) + \alpha t \nabla f(\boldsymbol{P})^{\mathrm{T}} \Delta\boldsymbol{P}$ do
  $t = \gamma t$
  end while
  $\boldsymbol{P} = \boldsymbol{P} + t\Delta\boldsymbol{P}$
  for all $m \in M$ such that $P_m > P^M$ do
  $P_m = P^M$
  end for
until $P \nabla f(\boldsymbol{P}) P_2 < d$

2.5 Joint optimization

The joint optimization is described in Algorithm 3. Each iteration includes user association $\{x_{ub}\}$, resource allocation $\{y_{ub}\}$, ABS proportion β, FBP parameter $\{\varepsilon_m\}$ and power $\{P_m\}$ adjustment. First, we initialize $\{P_m\}$, then optimize UE association and ABS configuration according to Algorithm 1 and Eq. (22). Since the UE association algorithm gives a near-optimal solution and the ABS configuration found is optimal, the value of the objective function with respect to the original value will increase. After that, $\{\varepsilon_m\}$ will be updated according to Eq. (25). Since the FBP parameter finds an approximated optimal value, in our extensive simulation scenarios, the value of the objective function with respect to the original value increases. Due to the close relationship between the user association, resource allocation, ABS proportion and the FBP parameter, for each power vector, we iterate until these converge. Then, $\{P_m\}$ will be updated based on the new resource allocation according to Algorithm 2. Due to (32), the value of the utility function will continue to increase. As we repeat Steps 1 to 4 in Algorithm 3 in our simulations, each iteration increases the value of the utility function, and Algorithm 3 convergences.

Algorithm 3 Joint optimizing $\{P_m\}$, $\{y_{ub}, x_{ub}\}$, $\{\varepsilon_m\}$ and β

repeat
  repeat
    Step 1 Find optimal $\{y_{ub}, x_{ub}\}$ according to Algorithm 1
    Step 2 Find optimal β according to (22)
    Step 3 Find optimal $\{\varepsilon_m\}$ according to (25)
  until convergence
  Step 4 Find optimal $\boldsymbol{P}$ according to Algorithm 2
until convergence

3 Performance Evaluation

In this section, the performance of the proposed scheme is analyzed by simulation. We consider a network which consists of a standard hexagonal grid of three-sector macro eNBs with a set of pico eNBs, see Fig. 3. There are a total of seven macro eNBs (21 macro cells) with wrap around. Each macro cell has two picos located close to the center of the eNB (90 m), and the number of UEs in each pico cell under different macro cells is different, e. g., the number of UEs in each pico under macros (1, 2, 3) is 5, 10 and 20, respectively. This results in a non-uniform network topology, and 10 users are randomly placed in the coverage area of each macro cell. In the case of LP-ABS, the macro power can be set between 0 and 46 dBm. We compare different schemes for the 5%-ile, 50%-ile user throughput and the whole network throughput performance. Other simulation parameters are in accordance to Ref. [12].

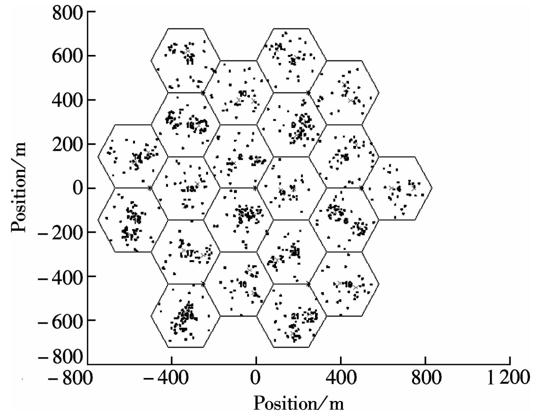

Fig. 3 HetNets scenario

For performance evaluation, the following schemes are compared by simulations.

- Proposed scheme: The FBP parameter is introduced in LP-ABS, and the power and FBP parameter of each macro cell are individually adjusted.
- LP-ABS: All macro cells apply LP-ABS and the power of each macro cell is individually adjusted[4].
- ZP-ABS: All macro cells apply ZP-ABS.
- no eICIC: Max-RSRP association policy without ABS.

Fig. 4 compares the total number of UEs in different types of BSs among different schemes. As expected, the no-eICIC scheme results in very unbalanced loads. The macros are over-loaded, while the picos serve fewer UEs. For the ZP-ABS and LP-ABS schemes, the number of

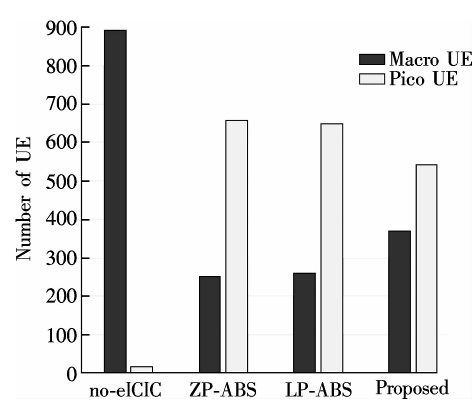

Fig. 4 Total number of UEs in BSs

UEs in the two tiers are more balanced, and there is not much difference between these two schemes. The UE distribution is the most balanced for the proposed scheme, where the UE numbers assigned to the macro cells and pico cells are close.

In Fig. 5, we plot the 5%-ile and 50%-ile user throughput of the whole network, the macro cells and the pico cells. We observe that the 5%-ile and 50%-ile user throughput of pico UE in no-eICIC schemes are high due to the fact that the number of UEs in the pico cells is few, and thus, the amount of resources assigned to each UE is large. Since both the 5%-ile and 50%-ile users have the same trend, here we discuss the 50%-ile user throughput. For macro, pico and the whole network, our proposed scheme offers a 26% gain against the ZP-ABS and LP-ABS scheme, which shows that the proposed scheme relative to other schemes can enhance the edge user and the average user throughput in this scenario. We observe that the ZP-ABS and LP-ABS schemes have almost the same performance when picos are close to eNB. In LP-ABS, since the macro cells and the pico cells work on the same frequency in the ABS sub-frames, in order to reduce the interference to pico cells, the macro cells will use very low power, and thus it is not much different from the ZP-ABS scheme.

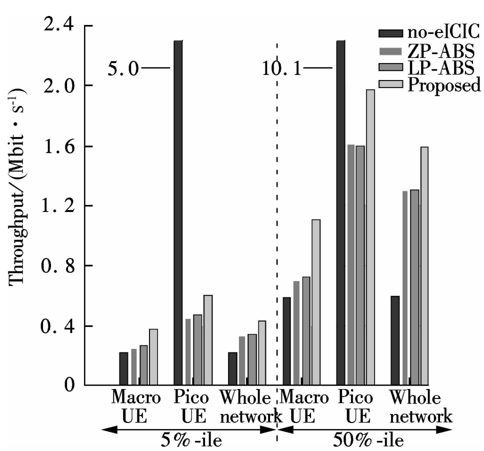

Fig. 5 Throughput performance with different schemes

Tab. 1 shows the fairness of throughput among UEs and the total throughput of the whole network for different schemes. We consider Jain's fairness index[8] as a measure of fairness among UEs. For fairness, compared with the ZP-ABS and LP-ABS schemes, our proposed scheme offers a 9% gain, and when compared to the no eICIC scheme, the gain is 170%. For the total throughput, our proposed scheme offers a 15% gain compared with the ZP-ABS and LP-ABS schemes. In conclusion, the proposed, ZP-ABS and LP-ABS schemes can guarantee fairness, while the fairness performance of the proposed scheme is a little better. At the same time, the proposed scheme can improve the total throughput of the system.

Tab. 1 Fairness and total throughput for different schemes

Scheme	Fairness index	Total throughput/(Mbit · s^{-1})
No eICIC	0.27	7 224.8
ZP-ABS only	0.67	1 434.3
LP-ABS only	0.67	1 434.1
Proposed	0.73	1 648.5

Tab. 2 shows the power and FBP parameter of macro cells in the proposed scheme, with the first row representing the index of the macro cell, the second row representing the transmission power of the corresponding macro cell in LP-ABS, and the last row representing the FBP parameter of the macro cell. We observe that some macro cells set their power to 0 and FBP to 1, which means that the power of the macro cell in LP-ABS is zero and the whole frequency band is reserved for its pico cells. In those macro cells, compared with the macro UEs, the pico UEs are more in need of the resources in ABS, so in ABS, the macro cell is mute across all frequencies. We can also observe that the power and FBP parameter of the macro cells are not uniform, which shows that our proposed scheme is effective when adapting to non-uniform topologies.

Tab. 2 Power and FBP of macro cells in LP-ABS

Index	Transmission power/dBm	FBP	Index	Transmission power/dBm	FBP
1	44.2	0.28	12	0	1
2	0	1	13	0	1
3	42.4	0.56	14	44	0.48
4	44.8	0.1	15	40.7	0.77
5	0	1	16	0	1
6	0	1	17	31.2	0.72
7	46	0.14	18	35.9	0.69
8	0	1	19	0	1
9	0	1	20	0	1
10	46	0.34	21	46	0.17
11	44	0.5			

Fig. 6 shows the utility function vs. the iterations of our proposed scheme. One can see that the utility function increases as the iterations progress and converge quickly.

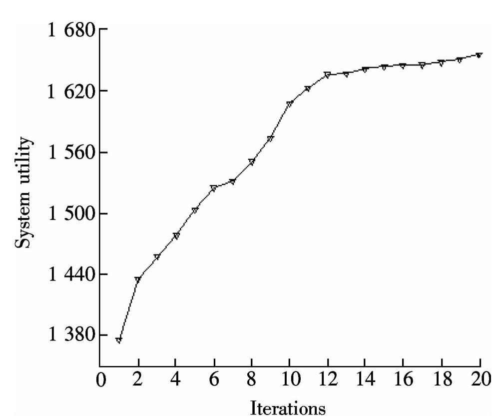

Fig. 6 The convergence of the proposed algorithm

4 Conclusion

We consider a non-uniform two-tier HetNets where the pico cells are located close to the macro cell and the number of users in each pico cell is different. Due to the non-uniform topology, we allowed different transmission powers and a frequency domain partition parameter of macro cells in LP-ABS. We jointly considered the user association, resource allocation, ABS configuration, FBP parameter and transmission power adjustment in LP-ABS to maximize the PF utility of the system. We also proposed a convergent iterative algorithm to solve this problem. Simulation results demonstrate that our proposed algorithm can improve the fairness and throughput of the pico cells as well as the macro cells.

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非均匀 HetNet 下基于增强几乎空白子帧的高效 eICIC

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摘要:采用了一种新的增强干扰协调(eICIC)来管理 ABS 子帧,该 eICIC 综合利用时域、频域以及功率调节来提高系统资源利用率. 特别地,考虑了一种 Pico 小区部署在 Macro 小区中心附近的 2 层非均匀异构网络,并且每个 Pico 小区的用户个数各不相同. 为了减轻同频信道部署所带来的干扰,Macro 小区使用 LP-ABS,并将 ABS 时隙的资源块划分为 2 部分,一部分只给 Macro 小区使用,另一部分只给 Pico 小区使用. 允许不同的 Macro 小区在 LP-ABS 时隙保留不同比率的频带资源以及不同的发送功率用于传输. 综合考虑了用户连接、资源分配、ABS 比率、频域划分参数以及 Macro 小区在 LP-ABS 时隙的发送功率,其目标为最大化系统比例公平效用,并且提出一种迭代算法求解. 仿真结果表明,该算法相比于现有方案在提高系统吞吐量的同时还保证了用户的公平性.

关键词:低功率 ABS;增强干扰协调;非均匀异构网络

中图分类号:TN929