Energy-Efficient Femtocells Active/Idle Control and Load Balancing in Heterogeneous Networks

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Abstract. In this paper, we present a network energy-efficient resource-allocation scheme for dense small cell heterogeneous networks by jointly controlling femtocell base stations active/idle strategies and load balancing with SINR constraints among users. The optimization problem is NP-hard, thus obtaining the optimal solution is extremely computationally complex. Therefore, we formulate the optimization problem to two sub-optimization problems: the load balancing design and the femtocell base stations active/idle switch strategies control. In load balancing design scheme, we optimize the load balancing of the small cell heterogeneous networks under the fixed femtocell base stations active/idle strategies. In femtocell base stations active/idle switch strategies scheme, we optimize the network energy efficiency while achieving the minimum service requirement among users. Combined with the optimal load balancing design, we solve the femtocell base stations active/idle switch strategies scheme by observation that the network energy efficiency is an increasing function of both user number and femtocell number. Simulation results show that the proposed algorithm could achieve a considerable performance improvement in terms of network energy efficiency compared with the traditional algorithms.

Keywords: Energy efficient · Femtocell · Load balancing · Stations active/idle switch

1 Introduction

Recently, the amount of mobile data traffic widespread has been increasing explosively. On the one hand, to meet surging traffic need, one of the promising solutions is to increase heterogeneity for cellular networks, particularly through development of small cell base stations (SBSs). e.g., picocell base stations (PBSs)

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and femtocell base stations (FBSs), which differ primarily in terms of maximum transmit power, easy-of-deployment, physical size, and cost [1]. Because the difference between the power and the number of access node, the traditional cell association scheme is no longer applicable, so the cell association issue should be reconsidered. Existing works have dealt with various issues related to small cells (SCs) problems, such as coverage improvement, traffic offload, load balancing (LB) and others. In [2], the authors proposed the offloading based on LB, which studied the offloading process performance from the macrocell layer to the small cell layer and exploited LB in the small cell layer with Voronoi diagrams. In order to maximize the network utility, the authors in [3] deployed the edge SBSs to serve users far from marco base stations (MBSs). A general quality of service (QoS) cell association scheme is provided in [4], which maximize the user's transmission rate as the target function and model the cell association to NP-hard problem.

On the other hand, seeking for high network energy efficiency (NEE) is a trend for the next generation wireless communication [5]. Recently, there are many existing research works such as [6–8] focus on NEE. In [6], the authors proposed an optimization scheme based on heuristic algorithm to minimize network energy consumption. The work issues in [7] aim to maximize the NEE under the rate fairness constraints among users. In [8], authors developed the optimization problem of long-term BS turning off scheme, which jointly optimizes the developed BS-user association and subcarrier allocation to maximize the NEE or minimize total power consumption by taking the constraints of rate proportion and average sum rate into consideration. Nevertheless, none of these existing works consider the impact of the BSs active/idle operation with the corresponding LB design on the network performance.

In this paper, we study the problem of NEE in dense small cell heterogeneous networks (HetNets), the work aims to maximize the NEE under the constraints of network outage probability and user's QoS requirements by jointly considering optimal FBSs strategies and LB design. Apparently, due to the interference coupling between FBSs and LB constraints involving various variables, the optimization problem is non-convex, thus the optimal solution is extremely computationally complicated. By exploiting the properties of the optimization problem, we transform original problem into two sub-optimization problems and solve them iteratively, which optimize the LB and FBSs active/idle strategies separately.

The rest of the paper is organized as follows. Section 2 describes the system model and problem formulation. Section 3.1 introduces the proposed LB algorithm. Based on the above LB algorithm, the FBSs active/idle switch strategies algorithm is proposed in Sect. 3.2. Simulation results with various parameters are presented in Sect. 4. Finally, Sect. 5 concludes the paper.

2 System Model

In this section, we present the system model. As shown in Fig. 1, we consider downlink communication scenarios in a spectrum sharing small cell HetNets with 3-tiers of BSs, each tier models a particular type of BS: tier 1 consist of

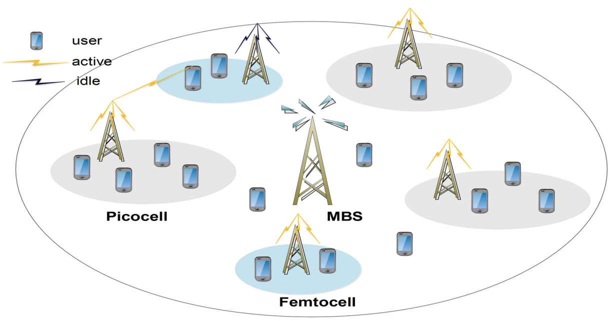

Fig. 1. Small cell heterogeneous networks

traditional MBSs, tier 2 and tier 3 are comprised of PBSs and FBSs respectively. In the scenario, users are randomly distributed in the coverage of the MBS.

We denote the sets of BSs and users by $\mathcal{B}$ and $\mathcal{U}$ with size $|N_\beta|$ and $|N_u|$, respectively. The transmission power of BS $n \in \mathcal{B}$ is P_n, Denote λ_n, $n \in \mathcal{B}$, as the indicators corresponding to the BS state, i.e., when BS n is active, $\lambda_n = 1$, and otherwise $\lambda_n = 0$, and let $\lambda = [\lambda_1, \ldots, \lambda_{|N_\beta|}]$. Thus the received SINR at user k association with BS n is given by:

$$SINR_{kn}(\lambda) = \frac{P_n \cdot L(d_{k,n}) \cdot \lambda_n}{\sum_{i \in I_k} P_i \cdot L(d_{k,i}) \cdot \lambda_i + N_0} \tag{1}$$

where N_0 is the noise power, and I_k denotes the BSs set containing all BSs interfering user k, L$(\cdot)$ is the pathloss function, $d_{k,i}$ and $d_{k,n}$ is the distance from user k to BS i and BS n, respectively. In the network, we use the path loss models from [3]. The pathloss is calculated by:

MBS to user	$L_I(d) = 34 + 40\log_{10}(d)dB$
PBS to user	$L_I(d) = 34 + 40\log_{10}(d)dB$
FBS to user	$L_{II}(d) = 37 + 30\log_{10}(d)dB$

The achievable data rate of user k when associated with BS n is $r_{kn}(\lambda) = \log(1 + SINR_{kn}(\lambda))$. Let X_{kn} denote the network selection parameter of user k at BS n, i.e., $X_{kn} = 1$ means that user k is associated with BS n, otherwise, $X_{kn} = 0$. In this paper, we assume that users can be associated with only one BS at a time. The rate of user k is given by $R_k(\lambda, X) = \sum_{n \in \mathcal{B}} X_{kn} r_{kn}(\lambda)$. Because the FBSs will switch between active/idle state, two categories of power consumption need to be taken into account, i.e., basic power and transmit power consumption. The power consumption model described in [8] is used in our scenario.

$$E_n(\lambda) = \sigma P_n \lambda_n + (1 - \delta) P_n^0 \lambda_n + \delta P_n^0 \tag{2}$$

where $E_n(\lambda)$ is the power consumption of BS n, P_n^0 denotes the baseline power consumption when there is no user in the cell, (i.e., $\sum_{k \in \mathcal{U}} X_{kn} = 0$). However, in order to improve the NEE, the FBSs could choose their state to decrease the baseline power consumption to $P_s = \delta P_n^0$, where $0 < \delta < 1$. Here, σ represent the portion of the power consumption due to feeder losses and power amplifier. We address an optimization problem in dense small HetNets, and jointly optimize the FBSs operation strategies and LB designs. The optimization problem can be expressed as P1:

$$\begin{aligned} \max_{\lambda, X} \quad & \frac{\sum_{k\in\mathcal{U}} R_k(\lambda, X)\cdot\theta_k^n}{\sum_{n\in\mathcal{B}} E_n(\lambda)} \\ \text{s.t.} \quad & C_1\colon \sum\nolimits_{k\in\mathcal{U}} X_{k,n} \le L_{n\_max}, \forall n \in \mathcal{B} \\ & C_2\colon \sum\nolimits_{n\in\mathcal{B}} X_{k,n} \le 1, \forall k \in \mathcal{U} \\ & C_3\colon \sum\nolimits_{n\in\mathcal{B}} X_{k,n} SINR_k^n \ge SINR_k^{target}, \forall k \in \mathcal{U} \\ & C_4\colon P_{net} < \varrho \\ & C_5\colon X_{k,n} \in (0,1), \forall n, k \\ & C_6\colon \lambda_n \in (0,1), \forall n \end{aligned} \tag{P1}$$

The constraint C_1 ensure that the number of users associated with BS n is no more than its maximum load, where L_{n_max} denotes the maximum load of BS n. The constraint C_2 mean that users could be associated with only one BS at a time. In addition, the constraint C_3 ensure the received SINR of user k associated with BS n to meet the minimum requirement of user k, where $SINR_k^{target}$ is the SINR threshold of user k. The constraint C_4 guarantee the network outage probability (i.e., ϱ). P_{net} is defined as the number of outage users divided by the total users. θ_k^n denotes access factor to control the probability of users association with BS n.

3 LB and FBSs Active/Idle Switch Strategies Algorithm

Notice that the optimization is difficult to obtain the optimal solution, due to the following reasons. Firstly, the problem is a discrete optimization problem involving the FBSs state control and users assignment. Secondly, the issue is influenced by not only the LB but also the FBSs operation strategies, which is complicated by the potential interference coupling among FBSs due to optimizing variables λ. In order to reduce the computation complexity, we decompose the optimization into two sub-optimization problems. i.e., namely LB design under the fixed FBSs active/idle strategies, and then select the optimal FBSs active/idle strategies that lead to the maximum NEE among all possible choices of λ.

3.1 Load Balancing Design Under Fixed FBSs Active/Idle Strategies

For a given FBSs operation strategy, we focus on maximizing the NEE, while take into account the requirement of the user's target-SINR and LB. We propose optimal cell association LB (CALB) algorithm consisting of cell selection step and cell association step. In CALB, firstly, we choose a candidate cell list which could meet the SINR requirement. Then, we choose the optimal cell from their candidate cell list of each user to maximize the utility function. Considered both LB and the SINR requirements of users, we first define an utility function, which composes of access factor and the user's energy efficiency. The access factor is related to the available resources and the scheduling method of the BS, and it represents the probability of user successfully access to a certain cell. The utility function is defined as:

$$\omega_k^n(\lambda) = \theta_k^n(\lambda) \cdot EE_k^n(\lambda) \tag{3}$$

where ω_k^n is the integrated utility value, θ_k^n is the access factor, EE_k^n is the energy efficiency of user k associated with BS n. We define the effective load of BS n as the number of users associated with it, L_n is the current load of BS n, and L_{n_max} is maximum acceptable load (the maximum number of users could be serviced by BS n). Generally, L_{n_max} is related with the maximum resources of the BS n could be provided as well as the scheduling scheme. Let L_{n_sim} denote the maximum number of users of BS n could be served in each Transmission Time Interval (TTI). If $L_n > L_{n\_sim}$, the BS n is not considered as an over-loaded BS, since in the following TTI, some users may be served by other BSs due to the dynamic LB schedule. In this paper, we adapt the Rounding Robin Scheduling (i.e., $L_{n\_max} = 2L_{n\_sim}$), and update θ_k^n by the following process:

$$\theta_k^n = \begin{cases} \frac{L_{n\_max} - L_n}{L_{n\_max}} & \text{if } L_n < L_{n\_sim} \\ \frac{L_{n\_max} - L_n}{L_{n\_max}} \cdot \frac{L_{n\_sim}}{L_n} & \text{if } L_n \geq L_{n\_sim} \end{cases} \tag{4}$$

During the updating process, the BSs with smaller load will get lager access factor, thus the cells with smaller load are more likely to be selected. When a BS is full-loaded, the access factor reduce to zero, therefore, the user can not access the over-loaded cells. EE_k^n in (3) represents the energy efficiency of user k, which is given by

$$EE_k^n(\lambda) = \frac{\alpha \log_2(1 + SINR_k^n(\lambda))}{P_n} \tag{5}$$

Thus, the energy efficiency of $BS\ n$ can be calculated by

$$EE_n(\lambda) = \frac{\sum r_{k,n}(\lambda)}{P_n},\ k \in \{k|X_{k,n} = 1\} \tag{6}$$

where $\alpha = 0.6$ represents the Shannon fading loss. Let $\Psi(k)$ denote the degree of freedom of user k, which is the number of BSs could be selected by user k under the SINR target constraint. For user k, we conclude the LB design algorithm to the following steps:

- Step 1: User k obtain its respective candidate cell list C_k, in which all cells could meet its SINR target requirement, and calculate the degree of freedom $\Psi(k)$ of user k.

- Step 2: Repeat step 1 until every user in the network obtain its candidate set, then the users exchange their candidate list to the nearby BSs.
- Step 3: Let the users with smaller degree of freedom to select the cell preferentially. During the cell selection, the BS circularly send the feedback information to the users, and the feedback information contains the current load, maximum load and downlink transmission power of the BS.
- Step 4: When the user k obtained all the feedback information from its candidate cells, the $\omega_k^n(\lambda)(\forall n \in C_k)$ can be calculated.
- Step 5: The BS n^* with the largest $\omega_k^n(\lambda)$ will be selected for user k. Once a user makes the choice, it sends an access request signal to the BS n^* before access it.

  The proposed optimal cell association LB algorithm is summarized in Algorithm 1.

Algorithm 1. Optimal Cell Association LB Algorithm (CALB)

Initialization :
$L = \mathbf{0}_{|\mathbf{N}_\beta| \times \mathbf{1}}$; $X = \mathbf{0}_{|\mathbf{N}_\mu| \times |\mathbf{N}_\beta|}$; $\Psi = \mathbf{0}_{|\mathbf{U_k}| \times \mathbf{1}}$;
Cell Selection Step
for all $k \in \mathbf{U}$ **do**
    $\mathbf{C_k} = \{n \in B | SINR_k^n \geq SINR_k^{target}\}$
    for all $k \in \mathbf{C_k}$ **do**
        $TRAN(n, C_k)$: transfer C_k to BS
    end for
end for
Cell Association Step
for all $n \in B$ **do**
    $U_n = \{k \in U | n \in C_k\}$;
    for all $k \in U_n$ **do**
        Calculate $\Psi(k) = |C_k|$;
    end for
    $SU_n = SORT(D, U_n)$; % $SORT$ array users in ascending order according to their degree of freedom.
    for all $k \in SU_n$ **do**
        Calculate $\omega_k^n, \forall n \in C_k$;
        $n^* = arg_n\{max(\omega_k^n)\}$;
        $X_k^{n^*} = 1$;
        $L_n^* = L_n^* + 1$;
        if $L_n^* = L_{n^*\_max}$;
        BS n^* notifies the users $\in U_n$ to delete the $BS\ n^*$ in its cell list.
        Update degree of freedom of users$\in U_n$.
        $SU_n = SORT(D, U_n)$;
        end if
    end for
end for

Notably, the CALB algorithm is a low-complexity distributed algorithm and not need to search the entire network for each user.

3.2 FBSs Active/Idle Switch Strategies Control

Based on the LB design from the previous steps. We determine the optimal FBSs active/idle strategies to maximize the NEE. Since a large of portion power consumption is assumed by the circuits of active BSs. Our main concern is how to save energy by switching off unnecessary FBSs. Problem (P1) is a discrete optimization problem, and the optimal FBSs active/idle operation strategies can be found by exhaustive search over $2^{|B_s|}$ possible cases, where the B_s denotes the number of FBSs. However, it is difficult to get a closed-form solution on optimal operation strategies, which results in high complexity and time-consumed by exhaustive search. To deal with problem mentioned above, we optimize the FBSs active/idle operation strategies that maximize the NEE under the network outage constraint. The optimal FBSs active/idle switch strategies control algorithm (FAIS) combined with the optimal solution from CALB algorithm to maximize the NEE is composed of two steps.

Algorithm 2. Optimal FBSs Active/Idle Switch Strategies Control Algorithm (FAIS)

Initialization :
All BSs are active, i.e., $N_p = 0$ and $\lambda_0 = I_{1\times|B|}$
repeat
Calculate the NEE $\zeta^{'}(N_p)$ by CALB Algorithm with a given SCS operation strategy λ_{N_p}
Calculate EE_n for all active BSs based on equation (6)
Find femtocell n^* such that $n^* = argminEE_{n_{(\lambda n=1)}}$
Update λ_{N_p} with $\lambda_{n^*} = 0$, and $N_p = N_p + 1$
until $\zeta^{'}(N_p - 2) > \zeta^{'}(N_p - 1)$
return $\lambda^{'} = \lambda_{(Np-1)}$

- Step 1: Based on a given FBSs active/idle operation strategy, we can obtain the optimal cell selection by CALB algorithm and a NEE value.
- Step 2: Denote the number of idle FBSs is N_p, there are $C_{B_s}^{N_p}$ numbers of NEE corresponding to the associated FBSs active/idle operation strategies. Among these NEE, we can obtain the optimal FBSs operation strategies with the maximum NEE. which is denoted as $\zeta(N_p)$.

To avoid the exhaustive search for getting the optimal N_p, we can switch FBSs in turns, when increasing the idle FBSs number N_p can not improve the NEE the algorithm stop. The proposed optimal FBSs active/idle switch strategies control algorithm (FAIS) is summarized in Algorithm 2. Notice that the proposed algorithm combined with the optimal LB design provides a sub-optimal solution for problem (P1). Moreover, the idle FBSs could be periodically active and broadcast beacon messages. Therefore, we can periodically process FAIS algorithm to adapt the variation of the system traffic.

4 Simulation Results

In this section, we provide simulation results to evaluate the performance of the proposed scheme described in the previous section. The analytical results show a better communication service and a larger performance gain by the proposed CALB algorithm and the maximum NEE could be achieved by FAIS algorithm. In the simulation, we only switch off the FBSs. The main simulation parameters used in the simulation are summarized in Table 1. Parameter σ refers to literature [9], and $\delta = 0.1$ when FBS is idle. We consider the following conventional algorithms for comparison with the proposed algorithm:

- Baseline algorithm (Max-SINR): user association based on max-SINR scheme, and FBSs are not switch off.
- No association off algorithm (NAO) [8]: user association based on max-SINR scheme, and the FBSs initially without associated users will be switched off.
- Lowest association off algorithm (LAO) [10]: user association based on max-SINR scheme, and half of the FBSs with the smallest number of associated users will be switched off.

Table 1. Simulation parameter

Parameter name	Value
Macro cell radius	200 m
MBS transmission power	46 dBm
PBS transmission power	35 dBm
FAP transmission power	20 dBm
MBS load ($L_{sim}^{macro}, L_{max}^{macro}$)	40,80
PBS load ($L_{sim}^{pico}, L_{max}^{pico}$)	8,16
FAP load ($L_{sim}^{femto}, L_{max}^{femto}$)	4,8
Bias-SINR offset	3 dB
Shadow fading	Log-normal
N_0 noise power	−174 dB/Hz

In Fig. 2, we show the normalized load (defined as the current load divided by the maximum load of BS) per BS with different algorithms for $|N_\beta| = 10$ and $|N_\mu| = 150$. It is observed that the Max-SINR and the Bias-SINR algorithm could be overloaded. BS No. 7, 8, 9 are over-load by Max-SINR algorithm, whereas BS No. 6, 7, 8, 9 are over-load by Bias-SINR algorithm. Compared with the tradition LB algorithm, the proposed CALB/FAIS algorithm could achieve the load balancing (the normalized load of each BS is less or equal 1).

In Fig. 3, the outage probability of network (defined as the number of outage users divided by the total users)is illustrated with respect to the number of users. With the increasing number of users, compared with the proposed CALB/FAIS algorithm, the Max-SINR and the Bias-SINR algorithm have higher outage probability, which could reached 14% and 17% when the number of users increased

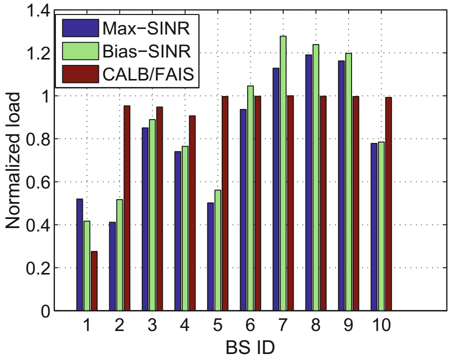

Fig. 2. Normalized load of different algorithms

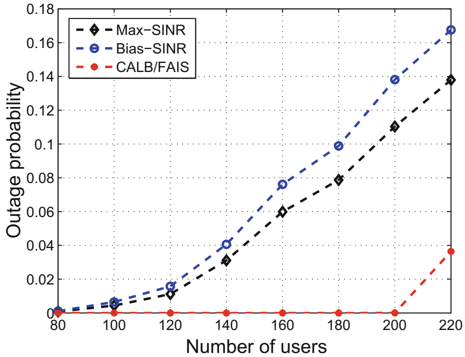

Fig. 3. Outage probability of different algorithms v.s. the number of users

to 220. For the proposed algorithm, when the number of users is less than 200, the outage probability is zero. Moreover, even the number of users increase to 220, the outage probability is less than 4% due to the limited resources.

In Fig. 4, the performance gains of various algorithms compared to the baseline algorithm is depicted respectively. It is observed that the proposed algorithm could achieved the largest NEE and EC improvement. Apparently, it can obtain the highest energy saving gain at the cost of the network throughput.

Figure 5 shows NEE gain of various algorithms compared to the baseline algorithm v.s. the number of FBSs $|\beta_S|$. It is shown that the NEE gains of all algorithms are increasing in $|\beta_S|$. Because with the number of FBSs increasing, the network load becomes lower. Therefore, larger percentage of FBSs can be switched off to save energy, so as to improve NEE.

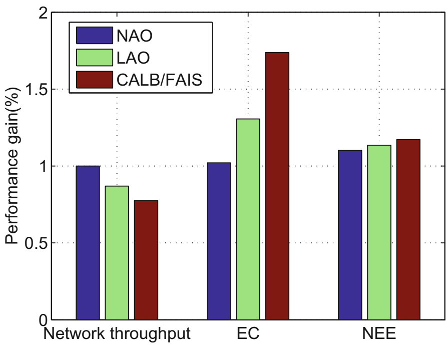

Fig. 4. Performance gain of different algorithms

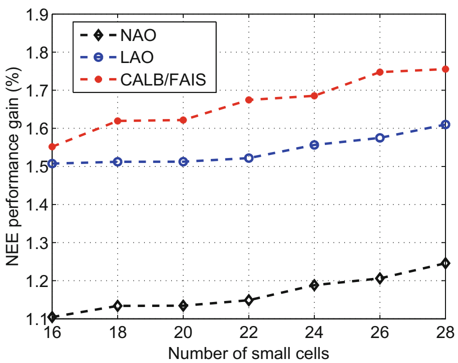

Fig. 5. NEE gain of different algorithms v.s. $|\beta_s|$

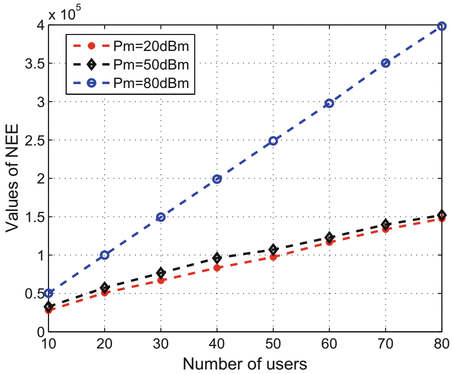

Fig. 6. NEE with different P_m v.s. number of users

To investigate the impact of transmission power of MBS in HetNet, we compare the NEE of the proposed CALB/FAIS algorithm with different P_m in Fig. 6. Particularly, when the network become dense, there will be more users association from FBSs to MBSs. This is because the MBSs can provide greater NEE with higher P_m. In this case, the larger number of FBSs can be switched off to improve NEE.

5 Conclusion

We investigate the joint LB design and FBSs active/idle strategies for maximizing the NEE in dense HetNets. The optimization problem is NP-hard. In order to reduce the complexity of algorithm, we decomposed the optimization problem into two sub-optimization problems. i.e., LB design and FBSs active/idle switch strategies control. For LB design, we optimize the load balancing under the fixed FBSs active/idle strategies. Combined with the result from LB, an optimal FBSs active/idle switch strategies is proposed. By exploring the relationship between the NEE and the number of idle FBSs, we could obtained the optimal solution.

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