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Power Savings with CoMP Technology in Cellular Networks

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***Abstract*—With the rapid growth of network infrastructure, the power-efficiency of cellular networks has become an important problem. In this paper, we propose a power-savings scheme that turns off lightly-loaded base stations (BSs) and switches the clients/users of the powered-off BSs to their neighbor BSs by utilizing the Coordinate Multi-Point (CoMP) transmission technology. In order to guarantee the users' QoS, the CoMP cluster should cover the switched-off BSs, and each coordinated BS in the CoMP cluster should have enough radio resources. Our in-depth simulation results show that the proposed scheme achieves near-optimal power savings and improves the power-efficiency up to 35%.**

I. INTRODUCTION

In recent years, the emergence of intelligent and mobile terminal equipments has led to the explosion of data [1], which has resulted in the expansion of network infrastructure. Such expanded infrastructure provides much needed network bandwidths, but at the expense of high energy consumption [2]. Since energy shortage and environmental pollution caused by energy generation and consumption have been a prime concern [3], effective energy savings is very important for both wireless operators and the public.

Wireless access networks are a major contributor to energy consumption; according to [4], [5], they constitue more than 70% of the operators' electricity usage. The main energy consumers of wireless access networks are the base stations (BSs), especially in view of their quantity and capability. Therefore, an energy-efficient cellular network BS operation is needed to reduce both the operational cost and the carbon footprint of telecommunication/network industry.

Once a network has been set up, the locations of its BSs are fixed and its topology usually does not change. Due to the mobility and usage dynamics of the users in an actual network, BSs will handle different amounts of load at different times, which is called a *tidal phenomenon*. The tidal phenomenon indicates that the actual service capacity of a network should be higher than the traffic load in the network. According to [6], [7], the BS would still consume a large proportion of energy even when the BS is idle or lightly loaded, hence wasting energy. This calls for a novel scheme that turns off some idle/lightly-loaded BSs to reduce the network's energy consumption. However, how to guarantee the communication QoS of users in the turned-off BSs remains as an unsolved problem.

To address this problem, we propose a power-savings algorithm that turns off some BSs and uses CoMP to guarantee the users's QoS in the switched-off BSs. Specifically, we

- establish a system model to minimize power consumption of all the BSs by considering the necessary conditions that (i) the users in the switched-off BSs can be covered by other cooperative clusters and (ii) the cooperative BSs (CBSs) have enough spectrum resources;
- prove that power saving of a BS is related with the used spectrum resource of the switched-off BS and the number of CBSs in a cooperative cluster (since minimizing power consumption by BSs is an NP-hard problem, we transform the problem to the one of choosing BSs to be turned off while maximizing power savings);
- propose our algorithm that turns off the BS with the minimum use of spectrum resource, and chooses the cooperative cluster with the smallest number of CBSs.

Our simulation results show that the proposed algorithm achieves near-optimal power savings and improves power-efficiency up to 35%, compared to existing ones.

The rest of this paper is organized as follows. Section II discusses related work to put our approach in a comparative perspective. Section III presents the assumptions and the system model we use throughout the paper. Section IV presents a heuristic algorithm and the relevant proof. Section V specifies the simulation parameters and then presents the simulation results, and the paper concludes with Section VI.

II. RELATED WORK

There have been numerous proposals of power savings of wireless networks.

Some existing energy-saving methods focused on transmission power control. The authors of [8], [9] allocated the users different power levels according to the different channel state information. These methods can reduce the transmission power with the same throughput, but only the power control alone cannot achieve the optimal energy efficiency. The authors of [10]–[13], [15]–[17] proposed the solutions which could turn off some BSs to reduce the network's total energy consumption. These methods took different approaches to guarantee the users' quality of service. According to the standards of 3GPP, the cell under a powered-off BS is called an *energy saving cell*, and the cell that helps the users in the energy

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saving cell is called an *energy compensation cell*. In [10], the BS without users associated was switched off, saving lots of energy. However, the mobility of users will change their associations. Users in the switched-off cell cannot be served. The authors of [11]–[13] increased the transmission power of the energy compensation BS to cover the energy saving cell. Due to the path loss, the signal intensity from an energy compensation BS to the users of an energy saving cell may be so weak that the users' QoS need may not always be met, or may cause interference to other BSs because of the increased power.

Coordinate Multi-Point transmission (CoMP) is the key technology in the LTE-A system. By using the MIMO technology, it is introduced to increase data rate of the users at the edge of a macrocell without changing the network topology [14]. The CoMP technology can extend the coverage area of cooperative clusters [15]. Therefore, with the same transmission power of a BS, CoMP technology can be used to reduce the number of BSs per unit area, thus saving energy. However, this method will change the network topology, making it impractical. The authors of [16], [17] proposed four schemes and analyzed their performance by using outage and blocking probabilities. However, two of these references assumed that all BSs in the network have the same traffic load, which is unrealistic.

III. THE SYSTEM MODEL

A. Assumptions and power consumption model

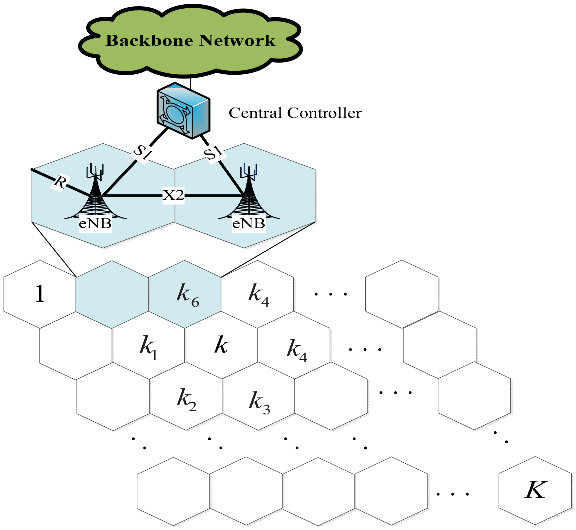


Fig. 1. System model

We consider a cellular network covered with K hexagonal cells, each of which is managed by a BS located at the center of the cell. Suppose BS k has A_k neighbors, represented as $\mathbf{A}_k = \{k_1, \dots, k_a, \dots, k_{A_k}\}$. Let set $\mathrm{U}_k = \{u_k\}$ denote the users of BS k. We assume that there are R RBs (Resource Blocks) available for each BS, and let R_k^u represent the RBs which have been used.

Assume each BS will consume power P^{on} which can be represented as [18]

$$\begin{aligned} P_k^{on} &= P_s + P_o + P_d \\ &= P_s + P_o + \rho \times R_k^u \end{aligned} \tag{1}$$

where, P_s is the power consumption of the signal processing, P_o is the fixed power consumption, P_d is the power consumption on the user imposed load of the BS, which equals the power consumption on the unit RB ρ times the number of the RBs used.

When the k-th BS is determined to be turned off, we should choose a final cooperative cluster from the candidate cooperative cluster set $\Phi_k = \{\phi_{k,1}, \dots, \phi_{k,j}, \dots, \phi_{k,J_k}\}$ to serve users in BS k, let $\phi_{k,j}$ denote the j-th cluster which consists of the remaining active neighbor BSs with CoMP, and J_k represent the number of candidate cooperative clusters in set Φ_k. According to [19], [20], the BS participating in CoMP would consume additional power due to the extra MIMO signal processing, which can be equivalent to the power consumption of a switched-off BS as

$$\begin{aligned} P_k^{off} &= (P_s^{add} + \rho \times R_k^u) \times B_k \\ &= (P_s \times (e + f \times B_k + g \times B_k^2 - 1) + \rho \times R_k^u) \times B_k \end{aligned} \tag{2}$$

where, P_s^{add} is the additional signal processing power due to the CoMP transmission, B_k represents the number of cooperative BSs which provide service for users in switched-off BS, e and f denote the gain coefficient relevant with the MIMO signal processing and g denotes the pilot signal overhead.

B. system model

We use x_k to represent the state of BS k. If the k-th BS can be turned off, $x_k = 0$. Therefore, the power consumption of the BS k can be described as

$$\begin{aligned} &P_k = x_k P_k^{on} + (1 - x_k) P_k^{off} \\ &x_k = \begin{cases} 0, & \text{off} \\ 1, & \text{on} \end{cases} \end{aligned} , \tag{3}$$

The total power consumption of the system can be calculated by

$$P = \sum_{k=1}^{K} P_k. \tag{4}$$

The problem, which aims to save power of the system, can be formulated as

$$\begin{aligned} \min_X P &= \min_X \sum_{k=1}^{K} P_k \\ &= \min_X \sum_{k=1}^{K} \left(x_k P_k^{on} + (1 - x_k) P_k^{off} \right) \end{aligned} , \tag{5}$$

subject to the constraints

$$\begin{cases} \Phi_k \neq \emptyset \\ \sum_{j=1}^{J_k} y_{\phi_{k,j}}^k = 1 \qquad , \text{ if } x_k = 0 \\ SNR_{u_k} \geq SNR_{th}, u_k \in U_k \end{cases} . \tag{6}$$

$$\sum_{a=1}^{A_k} y_k^{k_a} R_{k_a}^u + R_k^u \leq R, \text{ if } x_k = 1$$

Constraint 1 represents the fact that BS k can be turned off only when the selected cooperative cluster can guarantee the signal-to-noise (SNR) of user $u_k \in U_k$ larger than the threshold SNR_{th}. We use $y_{\phi_{k,j}}^k = 1$ to represent cooperative cluster $\phi_{k,j}$ will help BS k serve the users, and vice versa. SNR_{u_k}can be represented as

$$SNR_{u_k} = \frac{\sum_{n \in \phi_{k,j}} ||H_{u_k}^n||^2 P_{BS}}{N_{noise}}, \tag{7}$$

where P_{BS} denotes the transmission power of BS and N_{noise} denotes the gaussian white noise, and the inter-cell interference has been eliminated by the interference alignment methods. Assume each BS is equipped with M_B antennas and the user has M_u antennas, let $[H_{u_k}^n]_{M_B \times M_u}$ denote the channel matrix from BS n to user u_k.

Constraint 2 represents that BS k can be a CBS if its RBs are enough to serve for its neighbor BSs. We use $y_k^{k_a} = 1$ or 0 to represent that BS k will serve the users in its neighbor BS k_a or not.

We want to get the minimum power consumption with different on/off state of BSs and the power compensation BSs. This problem is modeled as an integer programming problem and which turns out to be an NP-hard problem [21]. This is because the on/off state of a BS is related with that of its neighbour BSs. If the state of a BS changes, all change. When the network becomes big, it is difficult to achieve the closed form optimal solution.

IV. SELECTION OF CBSS AND A COOPERATIVE CLUSTER

Before the k-th BS turns off to save power, its users must be served by its active neighbor BSs. So we discuss how to select CBSs from the neighbor BSs, and how to form a cooperative cluster.

A. Cooperative BS

Let us consider the BS k with A_k neighbor BSs and let Γ_k denote the CBS set of BS k.

Definition 1. *: If the RBs in the neighbor BS k_a are enough to serve the users in BS k, it can be a CBS of BS k. That is, if*

$$R_{k_a}^u + R_k^u \leq R \tag{8}$$

then put the neighbor BS k_a into the CBS set Γ_k of BS k.

This definition guarantees that the users in the switched-off BS k can be served by the neighbor BSs which have enough frequency resource. After checking each neighbor BS's residual RBs, we can get the k-th BS's CBS set Γ_k.

B. Candidates of the Cooperative Cluster

In order to serve for the users in BS k, each cooperative cluster should cover the area of the BS k.

Definition 2. *: A combination of any CBSs in the CBS set Γ_k can be a cluster. If the SNR of received signals from the cluster is higher than a prespecified threshold, this can be a candidate cooperative cluster.*

There could be a variety of cooperative clusters to choose for a switched-off BS. According to the results in [16], if the cluster's topology matches one of these in Fig. 2, the users in the power saving cell can be covered. So we add those eligible cooperative clusters to the candidate cooperative clusters set Φ_k. At the same time each cooperative cluster must have at least 3 CBSs, that is, $B_k \geq 3$.

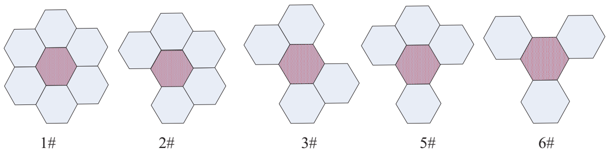

1# 2# 3# 5# 6#

Fig. 2. CoMP clusters

V. THE PROPOSED POWER-SAVING ALGORITHM

During low-traffic hours, some BSs are switched off and the corresponding traffic load is served by the remaining active BSs, achieving a more power-efficient network operation.

The problem that we formulated has been turned out to be NP-hard. It is difficult to find out the optimal solution of the power-saving BSs and the power compensation BSs. In this section, we will give the suboptimal solution.

Lemma 1. *The minimization of power consumption can be equivalent to the maximization of saving power of all the switched-off BSs.*

Proof: The Eq. (5) can be transformed into as follow,

$$\begin{aligned} \min \sum_{k=1}^{K} P_k &= \min \sum_{k=1}^{K} (x_k P_k^{on} + (1 - x_k) P_k^{off}) \\ &= \min \sum_{k=1}^{K} (P_k^{on} - (1 - x_k)(P_k^{on} - P_k^{off})) \\ &= \sum_{k=1}^{K} P_k^{on} - \max \left(\sum_{k=1}^{K} (1 - x_k)(P_k^{on} - P_k^{off}) \right), \\ &= \sum_{k=1}^{K} P_k^{on} - \max \left(\sum_{k=1}^{K} (1 - x_k) P_k^{save} \right) \end{aligned} \tag{9}$$

where, P_k^{save} denotes the power of BS k saved by turning it off. ■

From the equation, we can see that the optimal problem is equivalent to the maximization of saving power of all the switched-off BSs. The problem is still NP-hard, so we find a feasible near-optimum solution using the greedy idea in [22], which selects switched-off BSs one-by-one, each time choosing one BS in the most power-efficient way. So the problem is transformed to the one of guaranteeing the maximum P_k^{save} of switched-off BS k in the network.

The expression for P_k^{save} is formulated as

$$\begin{aligned} P_k^{save} &= P_k^{on} - P_k^{off} \\ &= P_o + \left(1 + (1-e)B_k - f(B_k)^2 - g(B_k)^3\right) P_s \\ &\quad - (B_k - 1)\rho \times R_k^u \end{aligned} \tag{10}$$

where P_o, P_s, ρ, e, f, g are constants. P_k^{save} is the saving power of BS k that is the function of R_k^u and B_k. That is, the number of CBSs in cooperative cluster and the used resource have influence on the power-saving effect of the k-th BS. So we will explore this relationship next.

A. Selection of the BS to be switched off

Theorem 1. *Turn off the BS with the minimum RB demand*

Proof: Taking the first partial derivative of P_k^{save} with respect to the R_k^u, we get

$$\frac{\partial P_k^{save}}{\partial R_k^u} = -(B_k - 1) \times \rho. \tag{11}$$

Due to $B_k \geq 3$, $\frac{\partial P_k^{save}}{\partial R_k^u} < 0$. In other words, the less R_k^u is, the more P_k^{save} is. To save more power, each time we would choose the BS with minimum RB demand to switch off. ■

B. Selection of cooperative cluster

Theorem 2. *Choose a cooperative cluster with the smallest number of CBSs.*

Proof: Taking the first partial derivative of P_k^{save} with respect to B_k, we get:

$$\frac{\partial P_k^{save}}{\partial B_k} = -3gP_s \times (B_k)^2 - 2fP_s \times B_k - \rho \times R_k^u + (1-e)P_s. \tag{12}$$

According to Definition 2, $B_k \geq 3$. Because the first partial derivative is a quadratic function of B_k, we take the second partial derivative of P_k^{save} with respect to B_k, and get

$$\frac{\partial^2 P_k^{save}}{\partial B_k^2} = -6gP_s \times B_k - 2fP_s. \tag{13}$$

[19], [20] provide the values of the variables as shown in Table I. All the parameters are positive. The second partial derivative of P_k^{save} with respect to B_k is negative in any case. That is, the first partial derivative is a decreasing function of B_k. When $B_k = 3$, we can work out the maximum value of first partial derivative as:

TABLE I
VALUE OF THE VARIABLES

Parameters	Value
minB_k	3
ρ	1.46
P_S	58 W
P_o	493 W
e	0.87
f	0.1
g	0.03

$$\begin{aligned} \frac{\partial P_k^{save}}{\partial B_k} &= (1 - e - 27g - 6f) \times P_s - \rho \times R_k^u \\ &= -74.24 - \rho \times R_k^u < 0 \end{aligned}. \tag{14}$$

Then, we can get that P_k^{save} is a decreasing function of B_k. That is, the smaller the number of CBSs in the selected cooperative cluster is, the more power will save by switched-off BS. ■

C. The proposed power saving algorithm

With the above proof, we get some criteria which can be used to achieve sub-optimal power consumption. First, turn off the BS with the minimum RB demand. Second, choose a cooperative cluster with the smallest number of CBSs. Then we give the proposed power saving algorithm based on the criteria as shown in Alg. 1.

Algorithm 1 The proposed power-saving algorithm

```
Initialization: Suppose all of BSs constitute an undetermined BS set $\Lambda = \{1, 2, \ldots, K\}$, and set $T$ keeps the ID of switched-off BSs, let $T = \emptyset$;
1: Collect all the information of the BSs, select the BS that uses the minimum RB demand as the determined BS $k^*$ at the basis of theorem 1, $k^* = \arg\min R_k^u$;
2: Construct the CBSs set $\Gamma_{k^*}$ according to definition 1;
3: Construct the candidate cooperative clusters set $\Phi_{k^*}$ according to Definition 2 and CBSs set $\Gamma_{k^*}$;
4: if $\Phi_{k^*} = \emptyset$ then
5:     BS $k^*$ must be open and $x_{k^*} = 1$;
6: else
7:     BS $k^*$ can be turned off and $x_{k^*} = 0$;
8:     Sort the candidate cooperative clusters by the number of CBSs in ascending order, choose the final cluster $\phi_{k^*}$ with smallest number of CBSs and add $k^*$ into set $T$;
9: end if
10: Update the $R^u$ of the CBSs in cooperative clusters $\phi_{k^*}$, remove BS $k^*$ and the CBSs of $\phi_{k^*}$ from the set $\Lambda$;
11: if $\Lambda \neq \emptyset$ then
12:     back to step 1;
13: end if
```

In step 8, we get final ϕ_{k^*} with the smallest number of CBSs from these candidate cooperative clusters according to Theorem 2. But if there are more than one cluster with the same smallest number of CBSs, we adopt the sum of used resource R^u of the CBSs in the cluster as the second criterion, which has three selection method as follows. The “Proposed-min” method is to select the minimum sum of all CBSs’ R^u in the candidate cooperative clusters. The “Proposed-max” method is to select the maximum sum of all CBSs’ R^u in the candidate cooperative clusters. The “Proposed-random” method is to randomly select one candidate cooperative cluster. We will evaluate which of them is the best for power efficiency.

VI. EVALUATION

This section evaluates the performance of the proposed algorithm and compares it with other power-saving schemes.

A. Simulation parameters

The cellular network in Fig. 1 consists of K hexagonal cells, each BS located at the center of the cell. The parameters used in our simulation are listed in Table II.

TABLE II
SIMULATION PARAMETER

No. of BSs K	25, 49
macrocell radius	500 m
No. of available RBs	50
the bandwidth of each RB	180KHz
traffic load of each BS	[0,40 Erl]
tolerable blocking prob. p_b^{th}	2%

According to Theorem 2, we choose the final cooperative clusters as pattern 6 in Fig. 2.

To compare our algorithm with others in the references, we use E_k to represent traffic load in the BS k. According to the equation Erlang-B, the relationship between traffic load E_k, the number of the used RBs R_k^u, and the blocking probability p_b can be described as:

$$p_b = \frac{\frac{(E_k)^{R_k^u}}{(R_k^u)!}}{\sum_{i=0}^{R_k^u} \frac{(E_k)^i}{i!}} \leq p_b^{th}. \tag{15}$$

To guarantee the users' QoS, p_b should be less than the tolerable call blocking probability p_b^{th}. We can get the maximum traffic load $E_{threshold}$ that BS can carry for the given available resource R and p_b^{th}. When the traffic load E_k is greater than $E_{threshold}$, traffic will be blocked.

In what follows, we will evaluate the power consumption along with the traffic load of BS.

In [16], the authors explored the traffic load each BS can serve when the four power-saving patterns operate, the results are listed in Table III. According to [16], with the constraints that the call blocking probability is less than 0.2, we can find that when the traffic load is large than 20.13 Erl, there would be no patterns can work to save power. To compare the power saving efficiency with the proposed method with different loads in different BSs, the references would adopt max traffic load and mean traffic load of BSs to choose a power-saving pattern, labeled as "Reference-max load" and "Reference-mean load", respectively.

TABLE III
THE RANGE OF THETRAFFIC LOAD SERVED BY FOUR PATTERNS

Patterns	1	2	3	4
Load range	(0,20.13Erl)	(0,10.06Erl)	(0,8.05Erl)	(0,5.75Erl)

B. The simulation results

In our simulation, the performance of the algorithm is first evaluated by the system's power consumption. Although an exhaustive search method that explores all combinations of the states of BSs could achieve the optimal power-saving effect, it is too complex to use in reality. So, we use the exhaustive search method only for comparison.

From Fig. 3, given the traffic load of each BS is uniformly distributed in (0,E), we can see that the power consumptions of three proposed algorithms have little difference and the difference will be reduced as the traffic load increases. The proposed algorithm in Fig. 3(a) with 25 BSs can save about 18% of power consumption and in Fig. 3(b) with 49 BSs can save about 25% of power consumption. While under the same condition, the exhaustive search can achieve about 22% and 32%, indicating that the proposed algorithm performs well, and as the traffic load increases, its difference from the exhaustive method gradually decreases. And the reference algorithms have certain abilities to save power when the traffic load is less than 20.13 Erl, but as the traffic load increases, they cannot save power. "Reference-mean load" can save more power than "Reference-max load". Both algorithms have better performance than the proposed algorithm when the traffic load is low.

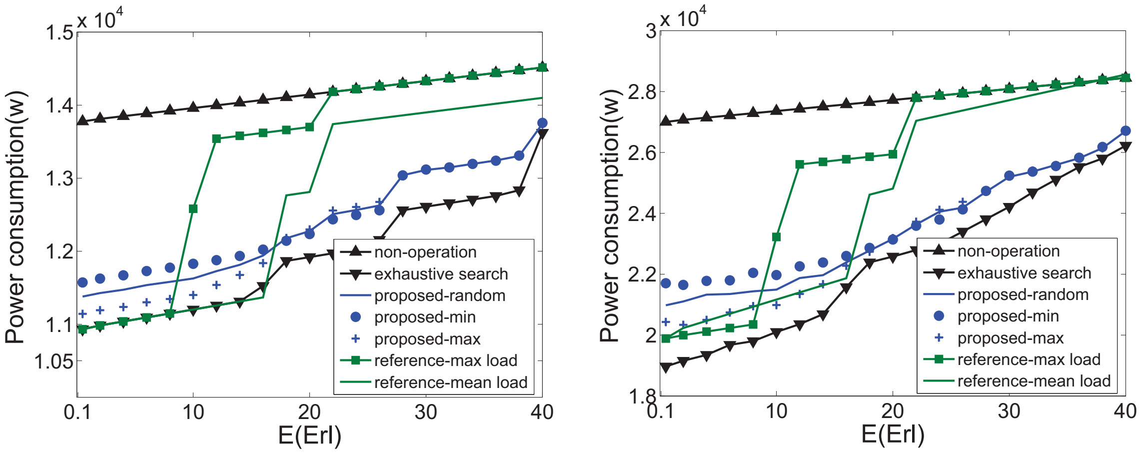
Let us see the users' QoS which is evaluated by the percentage of number of BSs with different call blocking probabilities when traffic load distribution is set to (0,30 Erl). As shown in Table IV, there are more BSs which can provide service to the users with a lower call blocking probability by our proposed algorithm than the existing algorithms. Specifically, the reference-mean load method can only make 78.19% BSs to meet the call blocking probability $p_b \leq 0.2$, but our proposed method can guarantee the QoS of all the BSs. That is, our proposed method outperforms the reference methods for different BSs with different traffic loads.

TABLE IV
THE PERCENTAGE OF NUMBER OF BSS WITH DIFFERENT CALL BLOCKING PROBABILITIES

	No-operation	Proposed-random	Reference
$p_b \leq 1.0\%$	100%	92.59%	72.63%
$p_b \leq 1.2\%$	100%	92.60%	73.93%
$p_b \leq 1.5\%$	100%	93.52%	75.66%
$p_b \leq 2.0\%$	100%	100%	78.19%
$p_b > 2.0\%$	0%	0%	21.81%

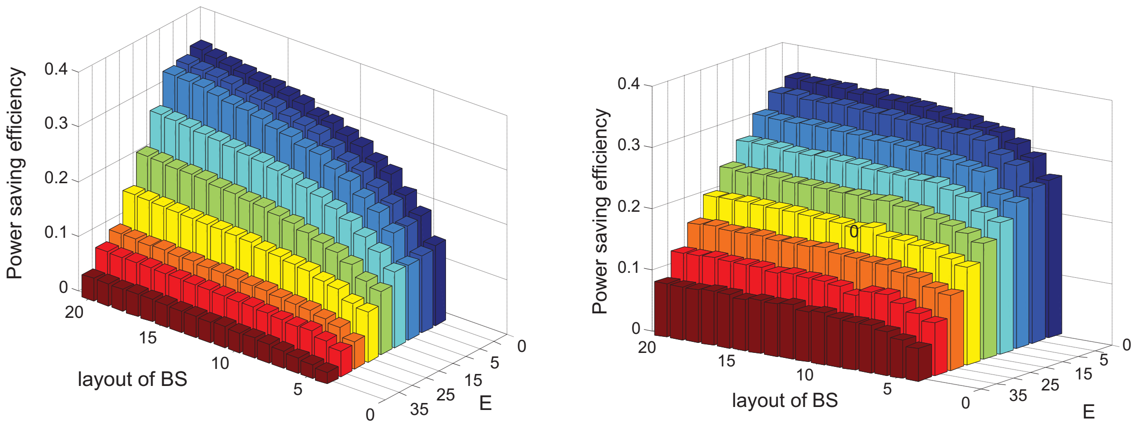
Fig. 3 shows that the algorithms with 49 BSs can save more power than 25 BSs, because BSs located at the edge of the network cannot be switched off and they take up a larger proportion in the 25 BSs network than in the 49 BSs network. To calculate the effect of BSs at the edge, we define the power saving efficiency as the ratio of the saving power and the power consumption of non-operation. When the network size changes from 3×3 to 20×20 and the traffic load is uniformly distributed in (0,E), the power saving efficiency of the proposed-random algorithm is plotted in Fig. 4.

In Fig. 4(a), we calculate the power of all the BSs in



(a) (b)

Fig. 3. Power consumption when the traffic load is uniformly distributed in (0,E). (a) K = 25; (b) K = 49



(a) (b)

Fig. 4. Power saving efficiency of the network. (a) including BSs at the edge; (b) excluding BSs at the edge

the networks. With the same traffic load, the power saving efficiency changes with the number of BSs, and the more BSs are, the better the power saving efficiency is. In Fig. 4(b), we calculate the power of BSs except for the BS at the edge of network, with the same traffic load, the power efficiency is almost the same and not influenced by network size. It indicates that the number of BSs at the edge of the network has a certain effect on the power efficiency. The simulation results show that the power saving efficiency can be up to 35%.

VII. CONCLUSION

In this paper, we proposed a power-efficient BS switching strategy in which some BSs are turned off and BS cooperation is used to effectively extend coverage with guaranteed QoS. Based on the standard hexagonal cell network model, we presented three algorithms to select the power-saving cells and their power compensation cells in the network. The simulation results indicate that the proposed algorithms can save power significantly and can work in realistic settings.

VIII. ACKNOWLEDGMENT

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