

Energy-Efficient Base Station Sleep Scheduling in Relay-Assisted Cellular Networks

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Abstract

We Relay-assisted cellular network architecture has been developed to cover cell-edge users and to improve capacity. However, the deployment of relay stations (RSs) in cellular networks may increase the total energy consumption. Though energy efficiency has become a major concern in cellular networks, little work has studied the energy efficiency of relay-assisted cellular networks by sleep scheduling. In this paper, a distributed base stations (BSs) sleep scheduling scheme in relay-assisted cellular networks is proposed. The goal is to maximize the energy efficiency under the spectral efficiency constraint. Firstly, whether the BSs should be sleeping or active is determined by the traffic profile. Then, the transmission powers of the active BSs are optimized within the game-theoretic framework, by using an interior-point method, so as to maximize the energy efficiency. Simulation results demonstrate that the effectiveness of the proposed scheme is superior to that turning on all the BSs without sleep scheduling.

Keywords: Relay-assisted cellular network, spectral efficiency, energy efficiency, sleep scheduling.

1. Introduction

1.1 Motivation

In recent years, there has been an explosive growth in mobile data traffic with the rapid development of information and communication technologies, which is mainly driven by smart phones that offer ubiquitous internet access and diverse multimedia applications. And the traditional cellular networks cannot satisfy the demand of the exponentially increasing traffic load. Therefore, new approaches such as deploying RSs or increasing the density of BSs have been developed to extend the coverage/improve the capacity of cellular networks and meet the demands for more business [1-4]. However, the deployment of BSs and RSs can lead to much more energy consumption as well as more CO₂ emissions. It is reported that the amount of CO₂ emission from information and communication systems has reached 2%. Thus, it is imperative to save energy and enhance energy efficiency during the energy shortage and environment crisis period. In addition, from the economic point of view, it can reduce the expenditure of the operators and governments. The BSs consume a significant portion of energy in cellular networks, which has reported to amount to about 60%-80% of the total network energy consumption [5]. Therefore, it is necessary to improve energy efficiency to satisfy such traffic demands and keep energy consumption comparatively low at the same time [6].

Most cellular networks are designed to support peak traffic load and BSs also retain the active state continuously. However, the traffic load changes dynamically and there will exist idle BSs when the traffic load is low, which will cause energy waste. The traffic load in cellular networks exhibits significant fluctuations in both temporal and spatial domains [7, 8]. The traffic load in the daytime is heavy in office areas and light in residential areas relatively. Based on this observation, some BSs can be switched off when the traffic load is low. Moreover, intelligent sleep scheduling schemes should be designed in order not to violate the Quality of Service (QoS). In this paper, under the spectral efficiency constraint, sleep scheduling scheme of the BSs in relay-assisted cellular networks is studied, so as to maximize the energy efficiency. Taking the deployment of BSs into consideration, [9] revealed the best type of BSs to be deployed for capacity extension. In [10], the authors showed the fluctuations of traffic load in time and space can influence the energy efficiency in cellular networks. Accordingly, a distributed BS sleep scheduling scheme is proposed in this paper.

1.2. Related work

Many BS sleep scheduling schemes have been put forward in earlier studies, which can greatly reduce energy consumption of cellular networks. For example, [5] and [11] proposed static BS sleeping schemes by dynamically switching BSs depending on the traffic load. However, they did not consider the traffic variations in both time and space domains. To save energy, the authors in [12] proposed the concept of cell zooming, which was indeed a distributed BS sleep scheduling algorithm through minimizing the number of active BSs. However, it did not consider the difficulty of implementation in practice. At the same time, in [13, 14], BSs were dynamically switched off one by one through taking the network impact of the extra load of neighboring BSs into account. As a potential solution to improve energy efficiency, dynamic BS sleep scheduling schemes have been studied by a lot of researchers [15-17]. When some BSs are turned into sleep, the QoS may be deteriorated. To reduce energy

consumption while ensuring the QoS, [15-17] investigated sleep operations by considering transmission delay, spectral efficiency, and traffic load, respectively. However, they ignored the coverage performance and did not maintain the QoS. To promote energy efficiency, an exhaustive search algorithm was proposed in relay-assisted cellular networks through BS switching [18], which was a complex algorithm. In [19], a decentralized sleep mechanism in heterogeneous cellular networks was developed, in order to minimize the total energy consumption while maintaining the QoS of users. Since BS sleeping can reduce energy consumption, every BS in a cellular network wants to get into sleep. Once a BS gets into sleep, any users in the corresponding cell should associate with the BSs of the adjacent cells, which cause the increase of the BSs' transmission power. It has been noticed that the relationship between BSs is competitive and cooperative. Therefore, after finding out the active BSs with a distributed sleep scheduling algorithm, we determine the optimal transmission powers of the active BSs by an interior-point method within the game-theoretic framework. This work differs from the above-mentioned works in two aspects. Firstly, we try to balance the spectral efficiency and the energy efficiency of relay-assisted cellular networks by BS sleep scheduling. Secondly, the optimal transmission powers of the active BSs are obtained via game theory.

The rest of this paper is organized as follows. In Section 2, the relay-assisted cellular network model is formally described. In Section 3, we propose a distributed BS sleep scheduling algorithm and an interior-point method for seeking the transmission powers of the active BSs based on game theory. In Section 4, the performance of the proposed scheme is illustrated by some simulation results. Finally, concluding remarks are made in Section 5.

2. SYSTEM MODEL

2.1. Relay-Assisted Cellular Network

We consider a downlink, multi-cell, and two-hop relay-assisted wireless cellular network as depicted in Fig. 1. In this system, there is no central controller. We focus on hexagonal cells where the BSs are located at the center of the cells. Moreover, coordinated multi-point transmission is not considered. The series of cells are represented by H in the relay-assisted cellular network. There is one BS, a set of K_h relay stations (RSs) and a set of N_h mobile users (MUs) staying within the h -th cell, for $h = 1, 2, \dots, H$. The set of BSs is denoted by $B = \{B_1, \dots, B_H\}$. Without loss of generality, we assume that the number of MUs is greater than or equal to the number of RSs, i.e., $N_h \geq K_h$. All the stations are assumed to be half-duplex and are equipped with a single antenna. Each MU is associated with the BS or a RS that has the strongest signal strength.

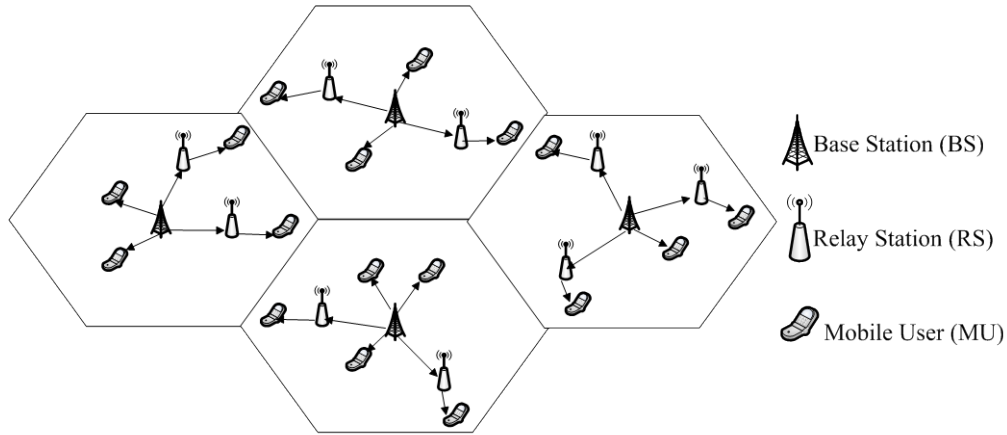


Fig. 1. A relay-assisted cellular network model

Each RS is allowed to connect one MU only but the BS is allowed to connect many MUs. The decode-and-forward relaying protocol is adopted. Each transmission frame is divided into two stages. For ease of analysis, the direct links between the BS and MUs that are associated with the RSs is ignored due to, for instance, the shadowing effects. In the first stage, the BS transmits signals to each associated MU or RS. The signals received at the RSs and the MUs in the h -th cell can be written as

$$y_{k,h}^{(1)} = \sqrt{P_{b,h}} g_{k,h}^{(1)} x_h + u_{k,h}^{(1)} + I_{k,h}^{(1)}, k = 1, \dots, K_h \quad (1)$$

$$y_{n,h}^{(1)} = \sqrt{P_{b,h}} g_{n,h}^{(1)} x_h + u_{n,h}^{(1)} + I_{n,h}^{(1)}, n = K_h + 1, \dots, N_h \quad (2)$$

where $P_{b,h}$ is the transmission power of the BS, x_h is the unit-variance transmitted signal from the BS, $g_{k,h}^{(1)}$ and $g_{n,h}^{(1)}$ are channel coefficients from the BS to the k -th RS and the n -th MU respectively, $I_{k,h}^{(1)}$ and $I_{n,h}^{(1)}$ are the inter-cell interference from neighboring cells to the k -th RS and the n -th MU respectively, $u_{k,h}^{(1)}$ and $u_{n,h}^{(1)}$ are additive white Gaussian noises with zero mean and variance σ^2 .

In the second stage, the RSs forward their decoded signals to the associated MUs. It is assumed that the decoding is always successful. The received signals at the corresponding MUs in the h -th cell can be written as

$$y_{k,h}^{(2)} = \sqrt{P_{k,h}} g_{k,h}^{(2)} x_h + u_{k,h}^{(2)} + I_{k,h}^{(2)} \quad (3)$$

where $P_{k,h}$ is the transmission power of the k -th RS, $g_{k,h}^{(2)}$ is the channel coefficient from the k -th RS to the associated MU, $u_{k,h}^{(2)}$ is additive white Gaussian noises with variance σ^2 , $I_{k,h}^{(2)}$ is the interference among the RSs.

The signal-to-interference-plus-noise ratios (SINRs) of the MUs associated with the BSs and the k -th RSs in the h -th cell can be respectively calculated as

$$\begin{aligned}
 BS - MU : SINR_{n,h} &= \frac{P_{b,h} |g_{n,h}^{(1)}|^2}{\sum_{t=1, t \neq h}^H P_{b,t} |g_{b,t}|^2 + \sigma^2}, n = K_h + 1, \dots, N_h \\
 RS - MU : SINR_{k,h} &= \frac{P_{k,h} |g_{k,h}^{(2)}|^2}{\sum_{j=1, j \neq k}^{K_h} P_{j,h} |g_{j,h}|^2 + \sigma^2}, k = 1, \dots, K_h
 \end{aligned} \tag{4}$$

where $\sum_{t=1, t \neq h}^H P_{b,t} |g_{b,t}|^2$ is the inter-cell interference, $\sum_{j=1, j \neq k}^{K_h} P_{j,h} |g_{j,h}|^2$ is the interference among RSs. The h -th cell throughput can be expressed as

$$R_h = \frac{1}{2} \sum_{k=1}^{K_h} W_h \log_2(1 + SINR_{k,h}) + \frac{1}{2} \sum_{n=K_h+1}^{N_h} W_h \log_2(1 + SINR_{n,h}) \tag{5}$$

where W_h is the bandwidth in each cell and the total bandwidth in the system is $B = \sum_{h=1}^H W_h$.

Therefore, the total throughput of the system can be written as

$$R = \sum_{h=1}^H R_h \tag{6}$$

2.2. Power Consumption

The power consumption of the stations can be expressed as a liner form similar to [20, 21]:

$$P_{i-tot} = a_i P_i^t + b_i, \quad i = B, R \tag{7}$$

where the coefficients a_B, a_R respectively account for power consumption that scales with the average radiated power, the terms b_B, b_R model the static power consumed by signal processing, battery backup, and cooling. We set the power parameters of BS and RS as $a_B = 22.6, a_R = 5.5, b_B = 412.4W, b_R = 32W$ according to [20]. Therefore, the total power consumption is written as

$$P = \sum_{h=1}^H (a_B P_{b,h} + b_B) + \sum_{h=1}^H \sum_{k=1}^{K_h} (a_R P_{k,h} + b_R) \tag{8}$$

The spectral efficiency and energy efficiency can be respectively expressed as

$$\eta_{SE} = \frac{R}{B}, \quad \eta_{EE} = \frac{R}{P} \tag{9}$$

3. SLEEP SCHEDULING SCHEME

In this section, a distributed sleep scheduling scheme depending on the traffic variation in both time and space domains is proposed. The target is to maximize the energy efficiency under the spectral efficiency constraint, which can be formulated as

$$\begin{aligned} \max \quad & \eta_{EE} \\ \text{s.t.} \quad & \eta_{SE} \geq \tau \end{aligned} \quad (10)$$

where τ is the expected value of spectral efficiency.

3.1. Sleep Scheduling Algorithm

Without loss of generality, the number of neighboring BSs of the h -th BS B_h is denoted by N_b . It is assumed that the information of the neighboring BSs can be shared among the BSs. When a BS turns into sleep, the traffic load of that BS is transferred to its neighboring BSs. $\rho_{h \rightarrow n}$ is the external traffic load from the BS h to its neighboring BS n , for $n = 1, \dots, N_b$. The total traffic load of the neighboring BS is $\rho_{n,tot} = \rho_n + \rho_{h \rightarrow n}$, where ρ_n represents the own traffic load of the BS n . Due to the hexagonal cellular network structure, we approximate the transferred traffic load as $\rho_{h \rightarrow n} = \frac{\rho_h}{N_b}$. A utility function for each B_h is defined in the cell based on the traffic load, as

$$U(B_h) = \rho_h \quad (11)$$

Similar to [22], which conveyed the real normalized traffic profile, the key idea of the distributed sleep scheduling algorithm is that after finding the BS with the least utility function, if there exists at least one neighboring BS whose traffic load $\rho_{n,tot}$ is lower than the maximum ρ_{max} , then the BS which has the least utility function will be turned into sleep. Otherwise, the BS keeps active. The detail of the BS sleep scheduling algorithm is listed as follows.

Algorithm 1 Distributed BS sleep scheduling

Initialize B_{on} , all the BSs are active.

For $\forall h \in [1, H]$,

Find $h^* = \arg \min U(B_h)$

For $\forall n$, calculate the total traffic load $\rho_{n,tot} = \rho_n + \rho_{h \rightarrow n}$.

if $\rho_{n,tot} \leq \rho_{max}$, then associate the users to B_n .

else $N_b = N_b - 1$

end if

If $N_b = 0$, the BS h^* keeps active.

else the BS h^* turns to sleep. $B_{on} = B_{on} - 1$.

end if

end

This algorithm can determine the status of the BSs and the set of active BSs is denoted by $B_{on} = \{B_1, B_2, \dots, B_s\}$, $0 < s < H$. Next, we propose an algorithm to update the transmission powers of the active BSs based on game theory.

3.2. Transmission Powers Update

According to the above system model, we consider a non-cooperation game in which each active BS optimally determines its transmission power to maximize its own payoff function.

1) Game-Theoretic Formulation

The iterative transmission power update game can be mathematically stated in the following structure

$$G = \left\{ \Omega, \{p_{b,s}\}_{s \in \Omega}, \{u_s\}_{s \in \Omega} \right\} \quad (12)$$

where $\Omega = \{1, 2, \dots, S\}$ is the set of active BSs, $p_{b,s}$ is the set of admissible power update strategies of active BSs, and u_s is the payoff function of active BSs. Since each active BS is selfish and wants to maximize its own benefit, the payoff function should compass income and expense to avoid the selfishness of the active BSs. Moreover, the goal of our algorithm is to maximize the energy efficiency of the relay-assisted cellular network. Accordingly, the payoff function can be designed based on the energy efficiency as

$$u_s = \frac{\frac{1}{2} \sum_{k=1}^{K_s} W_h \log_2(1 + SINR_{k,s}) + \frac{1}{2} \sum_{n=K_s+1}^{N_s} W_h \log_2(1 + SINR_{n,s})}{a_B P_{b,s} + b_B + \sum_{k=1}^{K_s} (a_R P_{k,s} + b_R)} - \lambda P_{b,s} \left| g_{\hat{s},s}^{\wedge} \right|^2 \quad (13)$$

where K_s, N_s are the number of RSs and MUs in the s -th active cell, respectively, $P_{b,s}$ is the transmission power of the set of active BSs B_{on} , $SINR_{n,s}$ and $SINR_{k,s}$ are the signal-to-interference-plus-noise ratios at the MUs, which directly associate with the active BSs and with the RSs, respectively, as similar to (4), λ is a positive constant, $P_{b,s} \left| g_{\hat{s},s}^{\wedge} \right|^2$ is the interference power to other BSs \hat{s} , for $\hat{s} \in \{1, \dots, S | s\}$. Therefore, we establish an optimization problem as

$$\begin{aligned} & \max \sum_{s=1}^S u_s \\ & s.t. \quad \eta_{SE} \geq \tau, \\ & \quad \quad 0 \leq P_{b,s} \leq P_{\max}, \forall s \in B_{on} \end{aligned} \quad (14)$$

where P_{\max} is the maximum transmission power of the active BSs. Consequently, the objective of the non-cooperative game is to reach Nash Equilibrium (NE) of the transmission powers of the active BSs.

2) Existence of NE

To analyze the outcome of the game, the existence of a NE is a well-known optimality criterion. At an NE point, every player is unilaterally optimal and no player can increase its utility alone through its own strategy. According to the fundamental game theory [23], the strategic non-cooperative game admits at least one NE point if for all $s \in \Omega$,

- i) The feasible set $P_{b,s}$ is a nonempty compact convex subset of the Euclidean space.
- ii) The utility function u_s is continuous and quasi-concave on $P_{b,s}$.

We can prove that the utility function of BSs satisfy all the required conditions for the existence of at least one NE. The detailed proof is omitted for brevity.

Due to the optimization problem with constraints, we adopt an interior-point method and combine it with a Newton method to update transmission powers of the active BSs until convergence. Since the interior-point method is to solve a minimum value problem, we establish a penalty function by converting the maximum value problem to a minimum value problem. Firstly, we select the initial point $P_{b,s}^{(0)}$ within the scope of the feasible region and initialize the penalty factor $r^{(0)}$, reduction factor c , convergence accuracy ε , and iteration k . Then, we construct the penalty function and solve the extreme value without constraints by using the Newton method. Finally, we judge whether the extreme value meets the convergence conditions or not. If it is satisfied, the iteration is terminated. Otherwise, we reduce the iteration factor, increase the number of iterations, and make the extreme point as the initial point until convergence. The detail of the algorithm is listed as follows.

Algorithm 2 Transmission powers update

1. **Initialize** $P_{b,s}^{(0)}, r^{(0)}, c, \varepsilon, k = 0$.
 2. Establish the penalty function by using an interior-point method

$$\phi(P_{b,s}, r^{(k)}) = -u_s(P_{b,s}) - r^{(k)} \left\{ \frac{1}{P_{b,s} - P_{\max}} + \frac{1}{\tau - \eta_{SE}} \right\}.$$
 3. Find out the extreme value $P_{b,s}^*$ by using a Newton method.
 4. **If** $|P_{b,s}^{*(k+1)} - P_{b,s}^{*(k)}| \leq \varepsilon$ **break**;
 else $P_{b,s}^{(0)} = P_{b,s}^*, r^{(k+1)} = cr^{(k)}, k = k + 1$, repeat Step 3.
end if
-

4. SIMULATION RESULTS

In the simulation, it is assumed that all the channel coefficients are zero-mean and unit-variance complex Gaussian random variables. The total bandwidth of each cell is set as 5 MHz, $P_{\max} = 40$ W, the Gaussian noise variance σ^2 as 10^{-10} W, the inter-cell interference power as 10^{-10} W, the interference power among the RSs as 10^{-5} W, transmission power of the RSs as $P_{k,h} = 2$ W, and $\rho_{\max} = 1$.

Fig. 2 shows the result of energy efficiency versus transmission power of the BS in a cell under different number of RSs K . The number of MUs is set as 20. As observed in **Fig. 2**, with the increase of the transmission power of the BS P_{bs} , the energy efficiency first increases and then decreases. The reason is that when the value of P_{bs} is small, the increase of the energy consumption is slower than the increase of the throughput, which causes the increase of energy efficiency. However, the energy consumption of the BS increases quickly with the increase of P_{bs} and leads to energy efficiency reduction. Therefore, there exists a maximum energy efficiency in the range $0 < P_{b,s} \leq P_{\max}$. It can be seen that the energy efficiency increases with the number of RSs for $K = 5, 10, 15$ but decreases when $K = 18$. The reason is that when the

number of RSs is small, the energy consumption increases slowly and the energy efficiency increases while the energy consumption increases quickly with the increase of the number of RSs and leads to energy efficiency reduction.

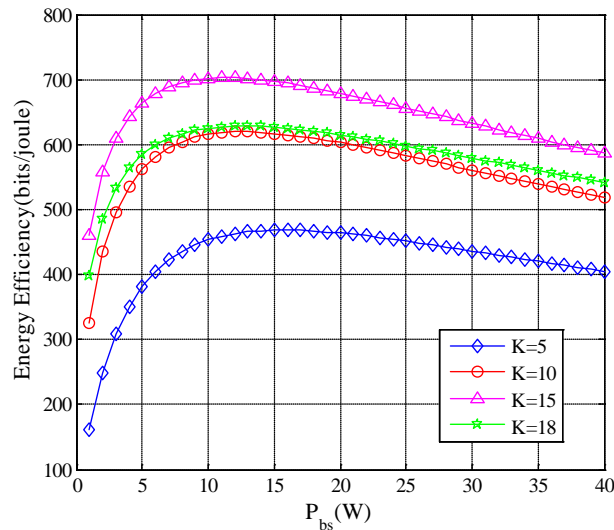


Fig. 2. Energy efficiency versus transmission power of the BS under different number of RSs

Next, we will simulate the average number of active BSs versus the variation of traffic load. The number of RSs is set as 5 in every cell. We use the ideal normalized traffic profile, which approximates the sinusoidal traffic profile in an entire day. The mean and variance of a day's traffic load variation is 1 [22]. **Fig. 3** shows the average numbers of active BSs varying with 24 hours in an entire day when the total number of BS is 3, 4, and 7, respectively. It is seen that the more the number of total BSs, the more the average number of active BSs. When the traffic load is low from 0:00 to 8:00, the average number of active BSs is less. With the increase of the traffic load, the average number of active BSs also increases. However, the average numbers of active BSs reduces in the evening when the traffic load decreases. The computer program is repeated for 10 000 times.

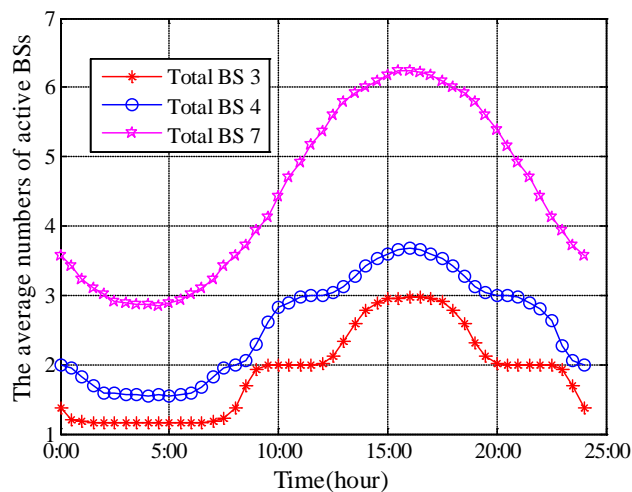


Fig. 3. Average numbers of active BSs over a day

The average numbers of active BSs is determined. Then, we maximize the energy efficiency under the spectral efficiency constraint by updating the transmission powers of the active BSs based on game theory. **Fig. 4** plots the utility function of one cell versus iteration and shows the convergence behavior of Algorithm 2. The total iteration is set to 10 and we set $\lambda = 0.5$, $\tau = 0.5$, $r^{(0)} = 1.0$, $c = 0.1$, convergence accuracy as $\varepsilon = 10^{-5}$. To clearly show the converging trend, the bandwidth has been normalized to 1 Hz.

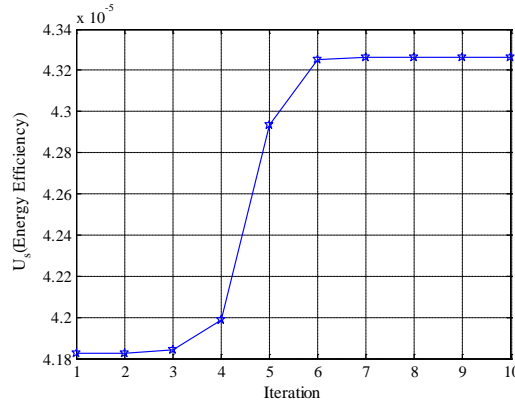


Fig. 4. Convergence behavior of the utility function

It is observed that the utility function converges in 7 iterations. By updating the transmission powers with an interior-point method, the utility function will converge. The optimal transmission powers of the active BSs are nearly 15W. **Fig. 5** compares the energy efficiency with/without sleep of the BSs over an entire day. The more the number of total BSs, the higher the energy efficiency. Moreover, when the total number of BSs is 3 or 4, the energy efficiency with BS sleeping is higher than the energy efficiency without BS sleeping. This is because some energy can be saved with BS sleeping. When the traffic load is low, the energy consumption is less and the energy efficiency is higher. When the traffic load increases, the energy efficiency reduces gradually since the average number of active BSs and energy consumption increase. However, the energy efficiency increases in the evening when the traffic load decreases. The results coincide with those in **Fig. 3**. There also have some fluctuations of the pink line and blue line under low traffic load. The reason is that the traffic load changes dynamically.

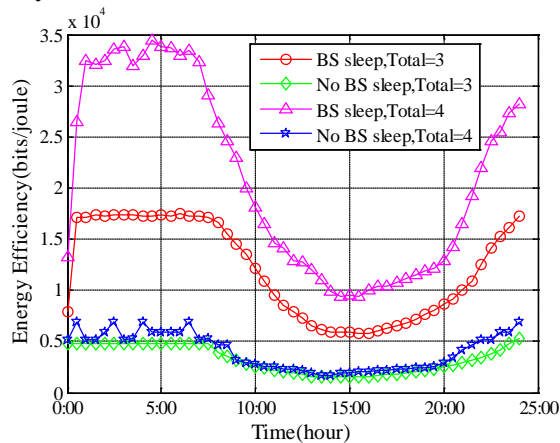


Fig. 5. Energy efficiency comparison over a day

5. CONCLUSION

In this paper, aiming at maximizing the energy efficiency of relay-assisted cellular networks, a distributed sleep scheduling scheme has been proposed considering that the traffic load varies in time and space. It is shown that the average number of active BSs matches well with the variation of traffic load in time and space. As a result, by updating the transmission powers of the active BSs based on game theory, convergence of the proposed sleep scheduling scheme is proved and the optimal transmission powers are obtained by using an interior-point method. In this way, the maximum energy efficiency is achieved under the spectral efficiency constraint. Note that sleep scheduling of RSs may also have effect on the energy efficiency and spectral efficiency. As a future work, joint sleep scheduling of BSs and RSs will be studied to further improve the energy efficiency while satisfying the spectral efficiency requirement.

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