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Energy-Efficient Deployment and Adaptive Sleeping in Heterogeneous Cellular Networks

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ABSTRACT This paper focuses on energy efficiency that is a key performance metric in heterogeneous cellular networks to two key areas. First, based on the Poisson point process distributions of small-cell base stations (SBSs) and macrocell base stations (MBSs), the energy-efficiency model is formulated, and the effect of base stations' distribution on energy efficiency is analyzed. For maximizing energy efficiency, the joint optimal densities of SBSs and MBSs are deduced under the constraint of quality of service. Second, according to this, we propose a joint sleep strategy of MBSs and that of SBSs. We deduce the optimal threshold of traffic load according to the joint optimal densities. If the traffic load of SBSs (or MBSs) is less than the optimal threshold of traffic load, these SBSs (or MBSs) go to sleep; otherwise, it is activated. This makes the SBSs and MBSs adaptively and distributively sleep according to their own traffic loads. The simulation results verify that the deduced joint optimal densities of the SBS and the MBS are accurate, and energy efficiency is improved when SBSs and MBSs adaptively sleep.

INDEX TERMS Heterogeneous cellular network, energy efficiency, optimal distribution density, adaptive sleeping.

I. INTRODUCTION

Energy consumption of cellular networks is growing rapidly in order to meet the demand of the exponential increase in mobile traffic loads. The Fifth Generation (5G) cellular network faces the issues of increasing the capacity and decreasing the energy consumption [1], [2]. Small cells, such as femtocells, picocells and microcells, are used to improve the coverage and increase the capacity of cellular networks. This is a promising technique for the 5G cellular network, where the network architecture is a heterogeneous network (HetNet) with both small cells and macrocells [3], [4]. In a HetNet, macrocells are overlaid with small cells deployed randomly or deterministically. The distribution of macrocell base stations (MBSs) and that of small cells base stations (SBSs) significantly affects the capacity and energy consumption of HetNets. It is key to investigate the influence of the distribution of MBSs and that of SBSs on the performance of cellular networks.

Moreover, some related works have addressed the MBSs sleeping problem previously. For instance, in [5], when the MBS is selected to sleep, the selected MBS would switch its severing users to nearby MBSs with seamless handover before it goes to sleep. Reference [6] investigates the grid energy minimization problem by optimizing both the MBS active probability (MAP) and the SBS transmit power (STP). In 3G cellular networks without heterogeneous scenario, the MBS sleeping has been considered yet for energy saving. In contrast, in 4G or 5G with heterogeneous scenario, the related work mainly address the sleeping issue on SBS instead of MBS. Therefore, these inspire us to do this work that it is beneficial if the sleeping strategy decision could consider both the MBS and SBS. To this end, we extend the analysis model and jointly consider the density and sleeping strategy of MBSs and SBSs. The main contributions of this paper include:

1) Based on the PPP distributions of SBSs and that of MBSs, energy efficiency model is formulated. Under the constraint of quality of service, the joint optimization problem of distribution densities of SBSs and

TABLE 1. Basic notation.

λ_m ,λ_s	density of MBSs,SBSs	C_m ,C_s	successfully transmitted traffic of MBS, SBS
R_m ,R_s	maximum transmission radius of MBS,SBS	P_{tm}, P_{ts}	power consumption of MBSs,SBSs
μ_t	mean arrival numbers of active users	L_m , L_s	traffic load sent by MBS, SBS
ε_m, ε_s	average traffic transmitted to a macrocell,small cell user	Q_m , Q_s	successful transition probability atusers
r_m,r_s	distance between the user and its serving MBSsčňSBSs	N_s	number of SBSs within the average coverage of MBS
$p\left(r_m\right)$,$p\left(r_s\right)$	probability density function of the distance	β_m , β_s	SINR thresholds of user
$P_{a,m}$, $P_{a,s}$	users require minimum received power	a_m,a_s	losses of the power amplifier and feeder
P_m,P_m	transmission power of MBSs,SBSs	b_m,b_s	static power consumption of MBS,SBS
α	path fading factor	T_m,T_s	transmission rate of MBS,SBS
h_m ,h_s	fading factor between MBS,SBS and user	v	required outage probability
I_m,I_s	interference from other MBSs,SBSs to users	τ_m , τ_s	the OTTs of MBS and SBS

that of MBSs is formulated to maximize the energy efficiency.

2) Due to the dynamic changes of the traffic load, we further propose a joint sleep strategy of MBSs and that of SBSs. The optimal sleeping probabilities of MBSs and that of SBSs and the optimal sleeping threshold of traffic load (OTT) are proposed, which make MBSs and SBSs dynamic adaptive sleep to maximize the energy efficiency.
3) Finally, the accuracy of deduced optimal densities of MBSs and that of SBSs are validated and the energy efficiency of sleeping strategy is evaluated.

The remainder of this paper is organized as follows. Section II gives the system model of HetNets with MBSs and SBSs. Section III calculates the energy efficiency and formulates its optimization problem. Section IV deduces the optimal sleeping probabilities and optimal sleeping threshold OTT, and gives the sleeping strategy. The performance evaluation is performed in Section V and the work is concluded in Section VI.

II. RELATED WORK

A. POISSON POINT PROCESS (PPP) DISTRIBUTION

In recent years, there are a few works based on PPP distributions to analysis the influence of BSs density on energy efficiency. Xu *et al.* [7] analyze that the densities of BSs in different areas are different, the distribution of BSs is not uniform, and the existing analytical models based on uniform point process are inaccurate. Through taking photos (i.e., a technique of reading information quickly) of the different position of HetNets, ElSawy *et al.* [8] find that both the MBSs and SBSs are subject to Poisson Point Process (PPP) distribution. According to these existing works, since PPP distribution is widely used and regarded as an accurate distribution in most practical scenarios, we decide to use PPP distribution as the basic assumption in our work.

B. ENERGY EFFICIENCY

Several works have been done to analyze energy efficiency of HetNets through deploying SBSs. Arshad *et al.* [5] analyze the impact of SBSs deployed on hot spots on the energy efficiency. The result shows that, in one day, the energy efficiency can be improved by the introduction of SBSs is not obvious. However, in busy period time of one day, energy efficiency can be improved to a great extent through deploying SBS. In [10], the impact of deploying a number of pico BSs on the system performance of macrocellular network is investigated. The result shows that the introduction of SBSs can improve the throughput of cellular networks, and energy efficiency can be improved if the number of deployed SBSs is reasonable. In [11], the joint optimization of the positions and the serving range of SBSs for maximum uplink energy efficiency based on the uniform distribution of SBSs have been investigated.

BS density is an important technique to decrease energy consumption in HetNet. The influence of SBS density on the energy efficiency (EE) of cellular networks has also been studied in [12] using the stochastic geometry theory. The simulation validates the accuracy of the theoretical analysis, and demonstrates that the energy efficiency maximization can be achieved by the optimized BS deployment. Quek *et al.* [13] analyze the energy efficiency of downlink in HetNets. The analysis shows that there is an optimal femto-macro density ratio that maximizes the overall energy efficiency of heterogeneous networks. In [14], the optimal BS density for minimizing the energy cost is analyzed for homogeneous and heterogeneous cellular networks. The upper and lower bounds of the optimal BS density are derived for homogeneous cellular networks. For HetNets, both capacity extension and energy saving problems are formulated and solved by generalizing them into an optimal BS density combination problem. In [15], the optimal BS density is also investigated in both one and two-tier cellular networks. Energy efficiency optimization problem in two-tier scenario is formulated and solved by jointly optimizing the ratio and weighted sum of BS densities.

BS sleeping is also an important technique to decrease energy consumption in HetNets [16]. Soh *et al.* [17] investigate random sleeping strategy and dynamic sleeping strategy of BSs. They show that the dynamic sleeping according to the number of active users in the BSs is better than the random sleeping to improve the energy efficiency. Reference [18] proposes random and repulsive sleeping schemes in hypercellular network (HCN), and adjusts the number of sleeping small cells according to the traffic load to optimize energy efficiency.

C. RELATED WORKS

As the most related work in the paper, Rao and Fapojuwo [19] allow SBSs (which is mentioned as picocell BS in [19]) to sleep, and deduce an optimal load dependent pico tier BS activity factor to maximize the 2-tier EE (Energy Efficiency). In addition, the mathematical model in [19] considers the impact of pico tier user density and pico tier activity factor on energy efficiency. Compared with [19], we extend this work to focus on the adaptive sleeping problem under joint deployment of MBSs and SBSs, in which MBSs and SBSs could sleep dynamically considering their joint optimal densities. Moreover, as another related work, [20] studies the spectrum efficiency (SE) and energy efficiency (EE) in HetNets, in which the authors make SE and EE maximize by adapting the density of femtocells. Compared with [20], which only considers the femtocells sleep, our work mainly studies the joint sleeping for both MBSs and SBSs based on their densities.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We consider a two-tier HetNet, i.e. a network of MBSs and that of SBSs by randomly distributed. The location of MBSs follows PPP distribution by Θ_m with the density λ_m, and the maximum transmission radius of MBS is R_m. The location of SBSs also follows PPP distribution by Θ_s with the density λ_s, and the maximum transmission radius of SBS is R_s. The distributions of MBSs and that of SBSs are independent. The distribution of UE follows PPP with density μ_t, which indicates that the mean arrival numbers of active users per unit time per unit area in the HetNet. The UE is that associated with MBS (or SBS) is called as macro user (or small cell user), we assume that the average traffic transmitted to a macro user and that to a small cell user are ε_m and ε_s, respectively. The probability density function of the distance r_m between the macro user and its serving MBS is $p(r_m) = 2r_m/R_m^2$, $r_m \le R_m$, and the probability density function of distance r_s between the small cell user and its serving SBS is $p(r_s) = 2r_s/R_s^2$, $r_s \le R_s$.

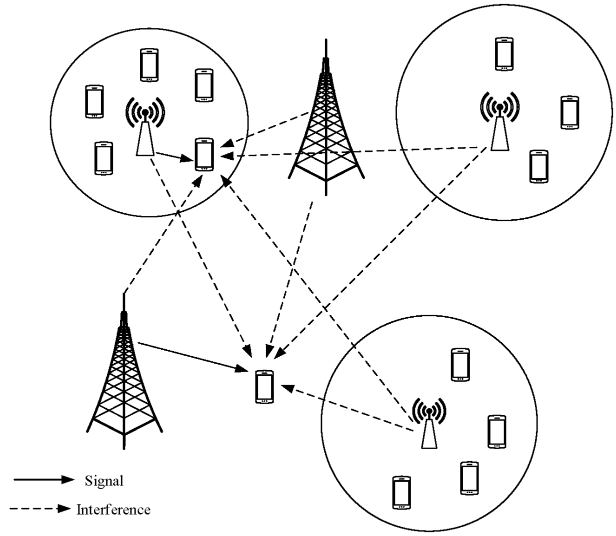

FIGURE 1. Two-Tire heterogeneous network.

In this paper, MBSs and SBSs share spectrum, the bandwidth is B, consisting of N sub-channels. In order to achieve the better effect of energy saving, we take Fractional Power Control (FPC) [21]. Let $P_{a,m}$ and $P_{a,s}$ be the required minimum received power of macro users and that of small cell users, respectively. The average transmission power of MBSs and that of SBSs are $P_m = P_{a,m}R_m^{\alpha(1-\kappa)}r_m^{\alpha\kappa}$ and $P_s = P_{a,s}R_s^{\alpha(1-\kappa)}r_s^{\alpha\kappa}$, respectively, where $\kappa \in [0, 1]$ is the power control factor, r_m and r_s are the distance between macro user and MBS and that between small cell user SBS, respectively, α is the path fading factor. In this paper, we adopt full path loss inversion (FPI) [21] policy, where $\kappa = 1$. Based on [19], the SINR for a macro user served by a MBS is:

$$SINR_m = \frac{P_{m,ik}h_{ik,m}r_{m,ik}^{-\alpha}}{I_m + I_s + N_o}, \tag{1}$$

where $P_{m,ik}$ is received power from MBS i to macro user k, $h_{ik,m}$ is the fading factor between MBS i and macro user k, and $r_{m,ik}^{-\alpha}$ is the path loss between MBS i and macro user k, $r_{m,ik}$ is the distance between MBS i and macro user k, respectively. The interference from other MBSs to macro user k is $I_m = \sum_{g\in\Theta_m\backslash i}P_{gk,m}h_{gk,m}r_{m,gk}^{-\alpha}$, where $r_{m,gk}^{-\alpha}$ is the path loss between the interfering MBS g and macro user k. The interference from SBS to macro user k is $I_s = \sum_{j\in\Theta_s}P_{s,jk}h_{jk,s}r_{s,jk}^{-\alpha}$. N_0 is the Gaussian noise.

Similarly, we also can get SINR of small cell user k as follows:

$$SINR_s = \frac{P_{s,ik}h_{ik,s}r_{s,ik}^{-\alpha}}{I_m + I_s + N_o}. \tag{2}$$

B. PROBLEM FORMULATION

1) THE ENERGY EFFICIENCY DEFINITION

We define the energy efficiency of HetNet as the amount of successfully transmitted traffic from BSs (MBSs and SBSs) to users (macro users and small cell users) per unit frequency and per unit power (bps/W/Hz), which is shown in Eq. (3).

$$EE = \frac{(\lambda_m C_m + \lambda_s C_s)/B}{\lambda_m P_{tm} + \lambda_s P_{ts}}, \tag{3}$$

where B is system bandwidth, C_m and C_s are the successfully transmitted traffic of MBS and that of SBS, respectively. P_{tm} and P_{ts} are average power consumption of MBS and that of SBS. The numerator of Eq. (3) is the traffic load of per unit bandwidth successfully transmitted of MBSs and that of SBSs per unit time and per unit area, and the denominator represents the total power consumption per unit area.

2) THE TRAFFIC RECEIVED BY USERS

As the traffic loads dynamically change over time in HetNet, we can adjust the densities of MBSs and SBSs based on the traffic loads. After deploying MBSs and SBSs, some of them will sleep according to adjusting densities of MBSs and SBSs. Let L_m and L_s be the traffic load sent by MBS and that by SBS, and the unit of L_m,L_s is bit/s. The successful transition probability at macro users and that at small cell users are Q_m and Q_s, respectively. Then

$$C_m = L_m \cdot Q_m, \tag{4}$$
$$C_s = L_s \cdot Q_s. \tag{5}$$

According to the mean user arrival rate μ_t and the traffic load transmitted to a macro user and a small cell user(ε_m and ε_s),

$$L_m = \mu_t \cdot \left(E[S] - N_s \pi R_s^2\right) \cdot \varepsilon_m, \tag{6}$$
$$L_s = \mu_t \cdot \pi R_s^2 \cdot \varepsilon_s, \tag{7}$$

where $E[S] = \int_0^\infty Sf(S)dS$ represents the average coverage area of MBS. Based on [22], the probability density function of macro cell area S is $f(S) = \frac{343}{15}\sqrt{\frac{7}{2\pi}}(S\lambda_m)^{\frac{5}{2}}\exp(-\frac{7}{2}S\lambda_m)\lambda_m$. $N_s = \lambda_s E[S]$ is the number of SBSs within the average coverage of MBS.

Let β_m and β_s be the SINR thresholds of macro user and small cell user, respectively. Under the condition of limited interference and FPI strategy, $N_0 = 0$, $\kappa = 1$, and the path loss exponent $\alpha = 4$, according to [19], we have

$$Q_m = \exp\left(-\frac{\pi^2}{4}\beta_m^{1/2}\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right), \tag{8}$$

where $\theta = P_{a,s}/P_{a,m}$.

Similarly, the successful transition probability of SBS is

$$Q_s = \exp\left(-\frac{\pi^2}{4}\beta_s^{1/2}\left(\lambda_s R_s^2 + \lambda_m R_m^2 \theta^{-1/2}\right)\right). \tag{9}$$

From (8) and (9), we can see that the successful transmission probability decreases with the increase of density of BSs, this is because that given the distance between a user and BS, increasing the density of BSs will strengthen the interference.

Inserting Eq. (6) and (8) into Eq. (4), and inserting Eq. (7) and (9) into Eq. (5), we can get the successfully transmitted traffic of MBS and that of SBS(C_m and C_s), respectively.

$$C_m = \mu_t \cdot \left(E[S] - N_s \pi R_s^2\right) \cdot \varepsilon_m \cdot \exp\left(-\frac{\pi^2}{4}\beta_m^{1/2}\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right), \tag{10}$$

$$C_s = \mu_t \cdot \pi R_s^2 \cdot \varepsilon_s \cdot \exp\left(-\frac{\pi^2}{4}\beta_s^{1/2}\left(\lambda_s R_s^2 + \lambda_m R_m^2 \theta^{-1/2}\right)\right). \tag{11}$$

3) POWER CONSUMPTION

Based on the power consumption model proposed in [18], the average power consumption of BS can be expressed as:

$$P_{tx} = a_x \cdot P_x \cdot \frac{L_x}{T_x} + b_x, \tag{12}$$

where a_x denotes the losses of the power amplifier and feeder, b_x is the static power consumption of BS, P_x is the average transmission power of BS, L_x and T_x are traffic load and transmission rate of BS, respectively.

a: POWER CONSUMPTION OF MBS

According to Eq. (12), when m is x, respectively, the average power consumption of MBS can be expressed as:

$$P_{tm} = a_m \cdot P_m \cdot \frac{L_m}{T_m} + b_m. \tag{13}$$

According to the Fractional Power Control (FPC) [21], the average transmission power of MBS can be expressed as:

$$\begin{aligned} P_m &= \mu_t \cdot \left(E[S] - N_s \pi R_s^2\right) \cdot \int_0^{R_m} P_{a,m} R_m^{\alpha(1-\kappa)} r_m^{\alpha\kappa} \cdot \frac{2r_m}{R_m^2} dr_m \\ &= \mu_t \cdot \left(E[S] - N_s \pi R_s^2\right) \cdot \frac{2P_{a,m}R_m^\alpha}{2+\kappa\alpha}. \end{aligned} \tag{14}$$

Under the conditions of limited interference and FPI strategy, where $N_0 = 0$, $\kappa = 1$, and the path loss exponent $\alpha = 4$, Eq. (14) can be simplified as follows:

$$P_m = \frac{1}{3}\mu_t \cdot \left(E[S] - N_s \pi R_s^2\right) \cdot P_{a,m} R_m^4. \tag{15}$$

The transmission rate T_m of MBS is MBS can achieve the maximum average transfer rate, defined as the transmission rate of Shannon limit:

$$T_m = E\left[B \ln\left(1 + SINR_m(r_m)\right)\right]. \tag{16}$$

Under the conditions of limited interference and FPI strategy, where $N_0 = 0$, $\kappa = 1$, and the path loss exponent $\alpha = 4$, Eq. (16) can be expressed based on [19] which is shown as follows:

$$\begin{aligned} T_m &= B\int_0^\infty \exp\left[-\frac{\pi^2}{4}(e^t - 1)^{1/2}\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right] dt \\ &= -2BE_i\left[-\left(\pi^2/4\right)\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right], \end{aligned} \tag{17}$$

where $E_i[\cdot]$ is exponential integral function. Inserting Eq. (6), (15) and (17) into Eq. (13), we can get the average power consumption of MBS:

$$P_{tm} = \frac{a_m P_{a,m} R_m^4 \cdot \mu_t \left(E[S] - N_s \pi R_s^2\right) \cdot \varepsilon_m}{-6BE_i\left[-\left(\pi^2/4\right)\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right]} + b_m. \quad (18)$$

b: POWER CONSUMPTION OF SBS

Similar to that of MBS, the average power consumption of SBS can be expressed as:

$$P_{ts} = a_s \cdot P_s \cdot \frac{L_s}{T_s} + b_s. \quad (19)$$

The average transmission power of SBS is

$$P_s = \pi R_s^2 \cdot \int_0^{R_s} P_{a,s} R_s^{\alpha(1-\kappa)} r_s^{\alpha\kappa} \cdot \frac{2r_s}{R_s^2} dr_s = \pi R_s^2 \cdot \frac{2P_{a,s}R_s^{\alpha}}{2+\kappa\alpha}. \quad (20)$$

And the transmission rate of SBS is

$$T_s = -2BE_i\left[-\left(\pi^2/4\right)\left(\lambda_s R_s^2 + \lambda_m R_m^2 \theta^{-1/2}\right)\right]. \quad (21)$$

Similarly, bringing Eq. (7), (20) and (21) into the Eq. (19), we can get the average power consumption of SBS:

$$P_{ts} = \frac{a_s P_{a,s} R_s^4 \cdot \mu_t \pi R_s^2 \cdot \varepsilon_s}{-6BE_i\left[-\left(\pi^2/4\right)\left(\lambda_s R_s^2 + \lambda_m R_m^2 \theta^{-1/2}\right)\right]} + b_s. \quad (22)$$

IV. OPTIMAL ENERGY EFFICIENCY AND DYNAMIC STRATEGY FOR SLEEPING

A. ENERGY EFFICIENCY OPTIMIZATION ANALYSIS

Inserting the formula of C_m, C_s, P_{tm}, P_{ts}(Eq. (10), Eq. (11), Eq. (18), and Eq. (22)), into Eq. (3), we can obtain the energy efficiency as follows.

Lemma 1: Given $\mu_t > 0$, $R_m > 0$, $R_s > 0$, $P_{tm} > 0$, $P_{ts} > 0$, the *EE* is strictly quasi-concave function of λ_m and λ_s, where $\lambda_m \in (0, \infty)$ and $\lambda_s \in (0, \infty)$.

Proof: According to Eq. (23), as shown at the top of the next page, the function of *EE* can be structured as follows,

$$f(x,y) = \frac{a_1 x e^{-(b_1 x + c_1 y)} + a_2 y e^{-(b_2 x + c_2 y)}}{\frac{a_3 x}{E_i[-d_3 x - e_3 y]} + \frac{a_4 y}{E_i[-d_4 x - e_4 y]} + b_m x + b_s y}. \quad (24)$$

For any determined value $x > 0$, denoted as x', $f(x,y) = f(x',y)$ can be seen as a function of y, and $f(x',y)$ can be written as:

$$f(x',y) = \frac{a_1' e^{-(b_1' + c_1 y)} + a_2 y e^{-(b_2' + c_2 y)}}{\frac{a_3'}{E_i[-d_3' - e_3 y]} + \frac{a_4 y}{E_i[-d_4' - e_4 y]} + b_m' + b_s y}. \quad (25)$$

where $a_1', a_2, a_3', a_4, b_1', b_2', c_1, c_2, d_3', d_4', e_3, e_4, x' \in R_+$, and $E_i[\cdot]$ is the exponential integral function given by $E_i[z] = \int_z^{\infty} \frac{e^{-x}}{x} dx$. For any real number β, there exists certain value x_m and x_n such that $f(x',y) > \beta$ for all x' in the interval $x_m < x' < x_n$. Thus, it follows that $x_m < qx_1' + (1-q)x_2' < x_n$ and $f(qx_1' + (1-q)x_2') > \beta$ for $x_1', x_2' \in X$ and $0 \le x_1' < x_2'$, where $q \in (0,1)$. Since $f(x',y)$ is quasi-concave.

Thus the projection of the corresponding function $\begin{cases} f(x,y) \\ y = kx + b \end{cases}$ to the *xoz* coordinate plane is a convex arc. Similarly, for any determined value $y > 0$, denoted as y', $f(x,y) = f(x,y')$ can be seen as a function of x, and this function is also convex. According to the literature [23], for the binary function $f(x',y)$, if the projection of the space curve $\begin{cases} z = f(x,y) \\ y = kx + b \end{cases}$ to the *xoz* coordinate plane is a convex arc and the projection of the space curve $\begin{cases} z = f(x,y) \\ x = c \end{cases}$ to the *yoz* coordinate plane is also a convex arc, the binary function $z = f(x,y)$ is quasi-concave. So, $f(x,y)$ is quasi-concave. ■

As the *EE* is strictly quasi-concave function of λ_m and λ_s, we can achieve the optimal densities λ_m^* and λ_s^* of MBSs and that of SBSs by the following partial derivatives, respectively.

$$\begin{cases} \partial EE / \partial \lambda_m^* = 0 \\ \partial EE / \partial \lambda_s^* = 0. \end{cases} \quad (26)$$

By Eq. (26), we can get Eq. (27), as shown at the top of the next page.

According to Eq. (8), (9), (10), (11), (17), (18), (21), (22) and (27), we can obtain $\lambda_m{}^*$ and $\lambda_s{}^*$. Here, a_1, $Z_1\left(\lambda_m^*, \lambda_s^*\right)$, $Z_2\left(\lambda_m^*, \lambda_s^*\right)$, C_m^c, C_s^c, C_m^{cc}, C_s^{cc}, P_{tm}^c, P_{ts}^c, P_{tm}^{cc}, P_{ts}^{cc} and the detailed calculations of Eq. (27) are given in the Appendix.

According to Eq. (27), the optimal densities of MBSs and that of SBSs are related to the traffic loads (L_m and L_s) in HetNet. As the traffic loads in a HetNet are different over time, we should adjust BSs densities according to L_m and L_s. After MBSs and SBSs are deployed, a feasible method to adjust the densities of MBSs and that of SBSs is to make some of them sleep according to the traffic loads. Therefore, we first deduce the optimal sleeping probabilities of MBSs and that of SBSs according to the joint optimal densities (JODs) of MBSs and that of SBSs ($\lambda_m{}^*$ and $\lambda_s{}^*$), and then further deduce the optimal threshold OTT according to JODS. This makes SBSs and MBSs adaptively and distributively sleep according to their own traffic loads.

B. THE OPTIMAL SLEEPING PROBABILITY

Let $1 - x(L_s)$ be the sleeping probability of SBS, which is related to its traffic load L_s, then the density of SBSs is $\lambda_s' = \lambda_s x(L_s)$. When SBS sleeps, its users should be served by a MBS, so the traffic load of MBSs (L_{mx}) will change to $L_{mx} = \mu_t \cdot \left(E[S] - N_s' \pi R_s^2\right) \cdot \varepsilon_m$. Here $N_s' = \lambda_s' E[S]$ is the number of active SBSs. The transmission rate of MBS (T_{mx}) is $T_{mx} = B\int_0^{\infty} \exp\left[-\frac{\pi^2}{4}\left(e^t - 1\right)^{1/2}\left(\lambda_m R_m^2 + \lambda_s' R_s^2 \theta^{1/2}\right)\right] dt$.

Let $1 - y(L_{mx})$ be the sleeping probability of MBS, then the density of active MBS will be $\lambda_m' = \lambda_m y(L_{mx})$.

Since this has been well addressed in the related work [30], [31], this manuscript does not study the specific handover mechanism between the MBS and the SBS. Moreover, when the MBS is going to turn off, the active macro users would be transferred to the neighboring active MBS, and the continuity of network coverage between MBSs and

$$E = \frac{\lambda_m \mu_t \varepsilon_m \left(E\left[S\right] - N_s \pi R_s^2\right) \cdot \exp\left(-\frac{\pi^2}{4}\beta_m^{1/2}\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right) + \lambda_s \mu_t \pi R_s^2 \varepsilon_s \cdot \exp\left(-\frac{\pi^2}{4}\beta_s^{1/2}\left(\lambda_s R_s^2 + \lambda_m R_m^2 \theta^{-1/2}\right)\right)}{\lambda_m \frac{a_m P_{a,m} R_m^4}{3} \cdot \frac{\mu_t \left(E[S] - N_s \pi R_s^2\right) \cdot \varepsilon_m}{-2BE_i\left[-(\pi^2/4)\left(\lambda_m R_m^2 + \lambda_s R_s^2 \theta^{1/2}\right)\right]} + b_m \lambda_m + \lambda_s \frac{\mu_t \pi R_s^2 \cdot \varepsilon_s}{-2BE_i\left[-(\pi^2/4)\left(\lambda_s R_s^2 + \lambda_m R_m^2 \theta^{-1/2}\right)\right]} + b_s \lambda_s}. \tag{23}$$

$$\begin{cases} \left[\left(a_1 + C_m^c \lambda_m^*\right) \exp\left(-\beta_m^{\frac{1}{2}} Z_1\left(\lambda_m^*, \lambda_s^*\right)\right) + \lambda_s C_s^c \exp\left(-\beta_s^{\frac{1}{2}} Z_2\left(\lambda_m^*, \lambda_s^*\right)\right)\right] \cdot \left(\lambda_m^* P_{tm} + \lambda_s^* P_{ts}\right) \\ \quad = \left[P_{tm} + \frac{P_{tm}^c \cdot \lambda_m^* \exp\left(-Z_1\left(\lambda_m^*, \lambda_s^*\right)\right)}{Z_1\left(\lambda_m^*, \lambda_s^*\right) E_i^2\left[-Z_1\left(\lambda_m^*, \lambda_s^*\right)\right]} + \frac{P_{ts}^c \cdot \lambda_s^* \exp\left(-Z_2\left(\lambda_m^*, \lambda_s^*\right)\right)}{Z_2\left(\lambda_m^*, \lambda_s^*\right) E_i^2\left[-Z_2\left(\lambda_m^*, \lambda_s^*\right)\right]}\right] \cdot \left(\lambda_m^* C_m + \lambda_s^* C_s\right) \\ \left[C_s + C_m^{cc} \lambda_m^* \exp\left(-\beta_m^{\frac{1}{2}} Z_1\left(\lambda_m^*, \lambda_s^*\right)\right) + \lambda_s^* C_s^{cc} \exp\left(-\beta_s^{\frac{1}{2}} Z_2\left(\lambda_m^*, \lambda_s^*\right)\right)\right] \cdot \left(\lambda_m^* P_{tm} + \lambda_s^* P_{ts}\right) \\ \quad = \left[P_{ts} + \frac{P_{tm}^{cc} \cdot \lambda_m^* \exp\left(-Z_1\left(\lambda_m^*, \lambda_s^*\right)\right)}{Z_1\left(\lambda_m^*, \lambda_s^*\right) E_i^2\left[-Z_1\left(\lambda_m^*, \lambda_s^*\right)\right]} + \frac{P_{ts}^{cc} \cdot \lambda_s^* \exp\left(-Z_2\left(\lambda_m^*, \lambda_s^*\right)\right)}{Z_2\left(\lambda_m^*, \lambda_s^*\right) E_i^2\left[-Z_2\left(\lambda_m^*, \lambda_s^*\right)\right]}\right] \cdot \left(\lambda_m^* C_m + \lambda_s^* C_s\right). \end{cases} \tag{27}$$

SBSs would be ensured. Therefore, UE can be successfully handed off between MBSs and SBSs itself.

When some SBSs and MBSs sleep, the densities of SBSs and that of MBSs have been changed, so we should update the successful transmission probabilities of MBSs and that of SBSs (Q'_m and Q'_s), the traffic successfully transmitted by MBS and that of SBS (C'_m and C'_s), the transmission rates of MBS and that of SBS (T'_m and T'_s) according to Eq. (8), (9), (10), (11), (17), (21) respectively. The average power consumption of MBS and that of SBS (P'_{tm} and P'_{ts}) should be recomputed according to updated densities of MBSs and that of SBSs ($\lambda_m{}'$ and $\lambda_s{}'$). And the energy efficiency (EE') is updated based on Eq. (28).

$$EE' = \frac{\lambda'_m C'_m / B + \lambda'_s C'_s / B}{\lambda'_m P'_{tm} + \lambda'_s P'_{ts}} \tag{28}$$

where

$$C'_m = \mu_t \left(E\left[S\right] - N'_s \pi R_s^2\right) \cdot \varepsilon_m \cdot \exp\left(-\frac{\pi^2}{4}\beta_m^{1/2}\left(\lambda'_m R_m^2 + \lambda'_s R_s^2 \theta^{1/2}\right)\right), \tag{29}$$

$$C'_s = \mu_t \pi R_s^2 \cdot \varepsilon_s \cdot \exp\left(-\frac{\pi^2}{4}\beta_s^{1/2}\left(\lambda'_s R_s^2 + \lambda'_m R_m^2 \theta^{-1/2}\right)\right), \tag{30}$$

$$P'_{tm} = \frac{a_m P_{a,m} R_m^4}{3} \cdot \frac{\mu_t \left(E\left[S\right] - N'_s \pi R_s^2\right) \cdot \varepsilon_m}{-2BE_i\left[-\left(\pi^2/4\right)\left(\lambda'_m R_m^2 + \lambda'_s R_s^2 \theta^{1/2}\right)\right]} + b_m. \tag{31}$$

$$P'_{ts} = \frac{a_s P_{a,s} R_s^4}{3} \cdot \frac{\mu_t \pi R_s^2 \cdot \varepsilon_s}{-2BE_i\left[-\left(\pi^2/4\right)\left(\lambda'_s R_s^2 + \lambda'_m R_m^2 \theta^{-1/2}\right)\right]} + b_s. \tag{32}$$

The EE' is also a strictly quasi-concave function of $x\left(L_s\right)$ and $y\left(L_{mx}\right)$ when $\mu_t > 0, R_m > 0, R_s > 0, P'_{tm} > 0, P'_{ts} > 0$ according to Lemma 1.

We define the optimal sleeping probabilities of MBSs and that of SBSs on unconstrained conditions as follows:

$$(x(L_s), y(L_{mx})) = argmax\{EE'\} \tag{33}$$

From Eq. (33), we can get the optimal value $x(L_s)$, $y(L_{mx})$ to let $\frac{\partial EE'}{\partial x(L_s)} = 0$ and $\frac{\partial EE'}{\partial y(L_{mx})} = 0$, and the optimal sleeping probability of MBS and that of SBS $(x(L_s), y(L_{mx}))$ can be obtained by Eq. (34), as shown at the top of the next page.

Furthermore, considering various requirements and resource limitation in practical wireless system, the outage probability-constrained and throughput-constrained optimization problem can be formulated as in Eq. (35).

$$\max_{x(L_s), y(L_{mx})} EE' \tag{35}$$

$$s.t. \int_{R_m}^{\infty} 2\pi \lambda'_m r_m \exp\left(-\pi \lambda'_m r_m^2\right) dr_m \le v, \tag{35.a}$$

$$T'_m \ge \delta_m, \tag{35.b}$$

$$T'_s \ge \delta_s, \tag{35.c}$$

Here, v is the required outage probability, which denotes the coverage constraint. δ_m and δ_s are the required throughput constraints.

Finally, the optimal sleeping probability $(1 - y^*\left(L_{mx}\right))$ of MBS under coverage and throughput constraint can be obtained as follows. The optimal sleeping probability of MBS $(1 - y_1\left(L_{mx}\right))$ without constraint can be obtained by Eq. (34). In order to guarantee the network coverage, the maximum sleeping probability of MBS is $1 - y_2\left(L_{mx}\right) = 1 + \ln(v) / \pi \lambda_m R_m^2$ according to Eq. (35). So the optimal sleeping probability of MBS under the coverage constraint is $1 - y_1^*\left(L_{mx}\right) = \min\left(1 - y_1\left(L_{mx}\right), 1 - y_2\left(L_{mx}\right)\right)$. Considering the throughput constraint, the optimal sleeping probability of a MBS is $1 - y_2^*\left(L_{mx}\right) = \max(1 - y_3\left(L_{mx}\right), 1 - y_4\left(L_{mx}\right))$, where $1 - y_3\left(L_{mx}\right)$ and $1 - y_4\left(L_{mx}\right)$ are obtained from Eq. (35), respectively. Under both the coverage and the throughput constraints, the optimal sleeping probability of MBS is

$$1 - y^*\left(L_{mx}\right) = \max(1 - y_1^*\left(L_{mx}\right), 1 - y_2^*\left(L_{mx}\right)). \tag{36}$$

Correspondingly, the optimal sleeping probabilities of SBS $(1 - x\left(L_s\right))$ can be obtained as Eq. (37), where $1 - x_1\left(L_s\right)$, $1 - x_2\left(L_s\right)$ and $1 - x_3\left(L_s\right)$ are the optimal sleeping probabilities of SBS without constraints, with coverage constraint and

$$\begin{cases} \left[\left(a_1 + C_m^c \lambda_m y\left(L_{mx}\right)\right) \exp\left(-\beta_m^{\frac{1}{2}} Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right) + \lambda_s x\left(L_s\right) C_s^c \exp\left(-\beta_s^{\frac{1}{2}} Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right)\right] \\ \cdot \left(\lambda_m y\left(L_{mx}\right) P'_{tm} + \lambda_s x\left(L_s\right) P'_{ts}\right) \\ = \left[P'_{tm} + \frac{P_{tm}^c \cdot \lambda_m y\left(L_{mx}\right) \exp\left(-Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right)}{Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right) E_i^2\left[-Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right]} \right. \\ \left. + \frac{P_{ts}^c \cdot \lambda_s x\left(L_s\right) \exp\left(-Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right)}{Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right) E_i^2\left[-Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right]}\right] \cdot \left(\lambda_m y\left(L_{mx}\right) C'_m + \lambda_s x\left(L_s\right) C'_s\right) \\ \left[C'_s + C_m^{cc} \lambda_m y\left(L_{mx}\right) \exp\left(-\beta_m^{\frac{1}{2}} Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right) + \lambda_s x\left(L_s\right) C_s^{cc} \exp\left(-\beta_s^{\frac{1}{2}} Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right)\right] \\ \cdot \left(\lambda_m y\left(L_{mx}\right) P'_{tm} + \lambda_s x\left(L_s\right) P'_{ts}\right) \\ = \left[P'_{ts} + \frac{P_{tm}^{cc} \cdot \lambda_m y\left(L_{mx}\right) \exp\left(-Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right)}{Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right) E_i^2\left[-Z_1\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right]} \right. \\ \left. + \frac{P_{ts}^{cc} \cdot \lambda_s x\left(L_s\right) \exp\left(-Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right)}{Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right) E_i^2\left[-Z_2\left(\lambda_m y\left(L_{mx}\right), \lambda_s x\left(L_s\right)\right)\right]}\right] \cdot \left(\lambda_m y\left(L_{mx}\right) C'_m + \lambda_s x\left(L_s\right) C'_s\right). \end{cases} \tag{34}$$

throughput constraint, respectively.

$$1 - x^*\left(L_s\right) = \max\left(1 - x_1\left(L_s\right), 1 - x_2\left(L_s\right), 1 - x_3\left(L_s\right)\right) \tag{37}$$

Therefore, the joint optimal sleeping probabilities of MBSs and that of SBSs are $\{1 - y^*\left(L_{mx}\right), 1 - x^*\left(L_s\right)\}$.

C. THE OPTIMAL THRESHOLD OTT FOR DYNAMICALLY SLEEPING

In section III, we obtain the optimal densities and optimal sleeping probabilities of MBSs and SBSs to maximize the energy efficiency in HetNets, which are related to the traffic load. In this section, according to the optimal sleeping probabilities, we deduce the OTT if MBS and SBS will go to sleep dynamically.

Let τ_m and τ_s be the OTTs of MBS and SBS, respectively. When the traffic load of MBS is less than $\tau_m (L_m < \tau_m)$, the MBS goes to sleep. Similarly, SBS goes to sleep if its traffic load is less than $\tau_s (L_s < \tau_s)$. In the following, we calculate τ_m and τ_s according to the optimal sleeping probabilities $(\{1 - y^*\left(L_{mx}\right), 1 - x^*\left(L_s\right)\})$.

The optimal sleeping probability of MBS $(1 - y^*\left(L_{mx}\right))$ is equal to the ratio of the number of optimal active MBSs to the total number of MBSs in a HetNet. The total number of MBSs is $N_m = A\lambda_m$ and the number of the optimal active MBSs is $n_m = A\lambda'_m$. Since users' distribution follows PPP with average arrival rate μ_t, and the number of users čĺdenoted as Xčľ in the coverage range of MBS follows PPP distribution with $\mu_m = \left(E\left[S\right] - N'_s \pi R_s^2\right) \cdot \mu_t$, the probability that the number of the users in MBS is smaller than ξ_{m} is

$$p_m = p_m\left(X \le \xi_m\right) = 1 - \sum_{k=\xi_m+1}^{\infty} \frac{e^{-\mu_m} \mu_m^k}{k!}. \tag{38}$$

Assuming that MBS goes to sleep when users in the coverage are less than or equal to ξ_{m}, then the probability p_m will be equal to the optimal sleeping probability $(1 - y^*\left(L_{mx}\right))$.

$$p_m = 1 - y^*\left(L_{mx}\right). \tag{39}$$

ξ_m can be calculated by Eq. (38) and Eq. (39), so as to get the OTT of MBS as follows:

$$\tau_m = \xi_m \cdot \varepsilon_m. \tag{40}$$

When the traffic load of MBS is smaller than τ_m, it goes to sleep and its traffic load is switched to adjacent MBSs.

Similarly, the number of users (denoted as Y) in the coverage range of SBS follows PPP distribution with $\mu_s = \pi R_s^2 \mu_t$. The probability p_s that Y is smaller than ξ_s is

$$p_s = p_s\left(Y \le \xi_s\right) = 1 - \sum_{k=\xi_s+1}^{\infty} \frac{e^{-\mu_s} \mu_s^k}{k!}. \tag{41}$$

Assuming that SBS goes to sleep when users in the coverage range of SBS are less than or equal to ξ_{s}, then the probability p_s is equal to the optimal sleeping probability of SBS, which is

$$p_s = 1 - x^*\left(L_s\right). \tag{42}$$

ξ_s can be calculated by Eq. (41) and Eq. (42), so the OTT of SBS is

$$\tau_s = \xi_s \cdot \varepsilon_s. \tag{43}$$

When the traffic load of SBS is smaller than τ_s, SBS goes to sleep, and its traffic load is switched to MBSs.

V. PERFORMANCE EVALUATION

A. SIMULATION SETTINGS AND PARAMETERS

In this section, we use simulation experiments based on parameters presented in Table 2 to validate the rightness and effectiveness of energy-efficient model and evaluate the performance of dynamic sleeping strategy. In Section V-B,

TABLE 2. Simulation parameters.

parameter	value
Frequency bandwidth B	10MHz
Transmission radiuses of MBS/SBS R_m /R_s	200m/20m
Average size of data download by macrocell/small cell user $\varepsilon_m/\varepsilon_s$	2Mbits/4Mbits
Required minimum received signal power of macrocell /small cell user $P_{a,m}$ / $P_{a,s}$	-35dBm/-30dBm
Loss of the power amplifier and feeder a_m/a_s	2.6/4
Static power consumption of MBS/SBS b_m/b_s	68.73W/5.5W
SINR thresholds of the macrocell/small cell users β_m/β_s	1
Outage probability v	0.05
Users arrival rate	0.0007 users/m^2/s

the performance evaluations are focus on energy efficiency, the optimal sleeping probability, the normalized OTT, successfully transmitted throughput, and transmission power per unit, respectively.

As the most related work in the paper, the author allow SBSs to sleep, and deduce an optimal load dependent pico tier BS activity factor to maximize the 2-tier *EE* in [19]. Compared with [19], we extend this work to focus on the adaptive sleeping problem under joint deployment of MBSs and SBSs, in which MBSs and SBSs could sleep dynamically with considering their joint optimal densities. Therefore, to show the effectiveness and improvement in our work, we will compare the proposed jointly sleeping with SBSs sleeping in [19] in terms of successfully transmitted throughput, transmission power per unit, and energy efficiency in Section V-B.

B. NUMERICAL RESULTS AND DISCUSSIONS

As shown in Fig.2, the energy efficiency is HetNet has a trend from rise to decline when the densities of MBSs and SBSs increase. The energy efficiency reaches to the maximum value when $\lambda_m = 1.696 \times 10^{-5}$ and $\lambda_s = 4.566 \times 10^{-4}$. As densities of BSs increase from small value, the throughput successfully transmitted of the BSs increases obviously, so the energy efficiency increases. However, the energy consumption and interference also increase with densities of BSs. After the optimal values of densities of BSs, the speed growth of energy consumption is bigger than that of the throughput, so the system energy efficiency decreases with the increase of the densities of the BSs.

The theoretical and simulated optimal sleeping probabilities of MBSs and that of SBSs for different user arrival rates are shown in Fig. 3. We can see that the theoretical results are very close to the simulation results. With the increase of user arrival rate, more BSs (including MBSs and SBSs) should be activated to serve users, so the optimal sleeping probabilities reduce. In Fig. 3, the optimal sleeping

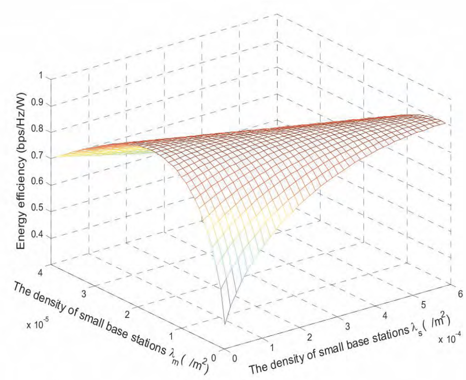

FIGURE 2. Energy efficiency changes with the density of MBSs and that of SBSs.

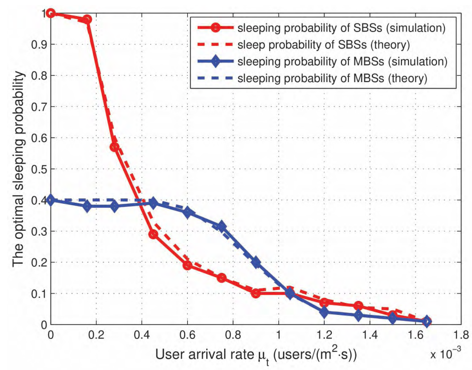

FIGURE 3. The optimal sleeping probability for different user arrival rates.

probability of MBSs is always about 0.4 when the user arrival rate is small (less than $0.4 \times 10^{-3} m^2/s$), since some MBSs should be activated to ensure the network coverage even the user arrival rate is small. With the increase of the user arrival rate, the change of the sleeping probabilities of BSs can be divided into three stages: Stage 1: the user arrival rate is less than $0.4 \times 10^{-3} m^2/s$. At this stage, with the increase of the user arrival rate, the optimal sleeping probability of MBSs does not change obviously, but the optimal sleeping probability of SBSs decreases rapidly to satisfy the increasing service requirement. Stage 2, the user arrival rate is more than $0.4 \times 10^{-3} m^2/s$ but less than $1.2 \times 10^{-3} m^2/s$. At this stage, when the user arrival rate increases, we should activate more MBSs and SBSs to satisfy the service requirement. Stage 3, the user arrival rate is more than $1.2 \times 10^{-3} m^2/s$. At this stage, almost all BSs (including MBSs and SBSs) should be awakened to serve the user.

Fig. 4 illustrates the relationship between the OTTs and sleeping probabilities. Here we use normalized OTT, which is defined as the ratio of OTT to the throughput of BS (an MBS or an SBS). When the optimal sleeping probabilities increase, more BSs go to sleep, so the normalized OTT increases.

To show the improvement of proposed jointly sleeping with considering constraints or not, SBSs sleeping with

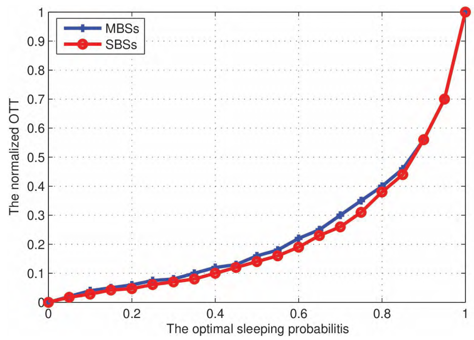

FIGURE 4. The normalized OTT for different user arrival rates.

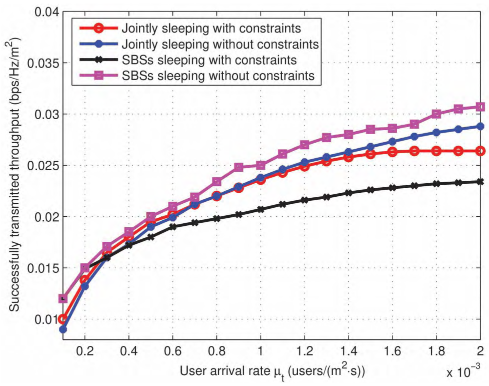

FIGURE 5. The throughput for different user arrival rates.

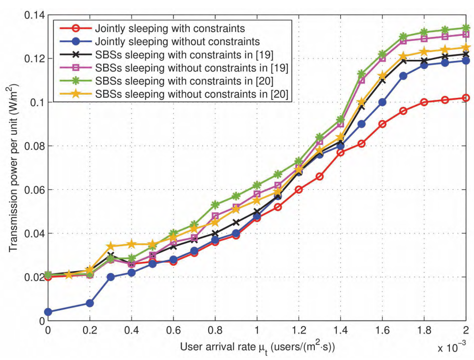

FIGURE 6. The transmission power for different user arrival rates.

considering constraints or not in [19] are evaluated as the benchmark in Figs. 5-7.

In Fig. 5, the throughput successfully transmitted increases as the user arrival rate increases. For our strategy, the throughput without constraints is higher than that with constraints when the user arrival rate is low (less than $0.4 \times 10^{-3}\, m^2/s$). Since more MBSs have to be active under the coverage and throughput constraints, which increases the system throughput. However, after the user arrival rate being higher than $0.4 \times 10^{-3}\, m^2/s$, more SBSs are activated to satisfy the increasing users' data rate, which increases the interference between different BSs, and in turn decreases the throughput per BS (including MBS and SBS). As the strategy with

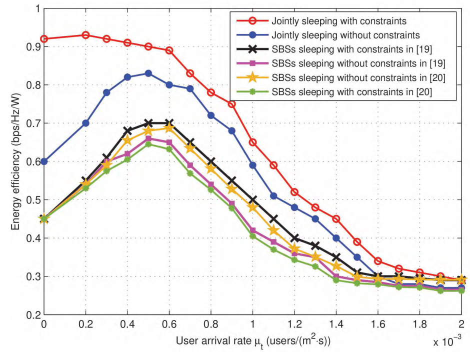

FIGURE 7. The energy efficiency for different user arrival rates.

constraints requires that the throughput per MBS and per SBS must be higher than δ_m and δ_s, which will limit the number of active MBSs and SBSs, the throughput of strategy with constraints should be less than that without constraints.

As an other related work, [20] only allows femtocells to sleep and make spectrum efficiency and energy efficiency maximize by adapting the density of femtocells. Therefore, we have compared transmission power per unit and energy efficiency with related references [19], [20] in Fig. 6 and Fig. 7.

In Fig. 6, the transmission power per unit area increases when the user arrival rate increases. For our strategy, when the user arrival rate is less than $0.6 \times 10^{-3}\, m^2/s$, the transmission power with constraints is bigger than that without constraints because more MBSs have to be activated to satisfy the coverage constraint. However, after the user arrival rate being higher than $0.6 \times 10^{-3}\, m^2/s$, increasing the number of active SBSs will increase the interference between different BSs, and in turn decrease the throughput per BS (including MBS and SBS). In order to satisfy the throughput constraint per BS, we have to limit the number of SBSs. Therefore, the transmission power per unit with constraints is less than that without constraints. The similar results can be observed for the scheme in [19] and [20].

In Fig. 7, except the results of our strategy without constrains, the energy efficiency firstly increases and then decreases when the user arrival rate increases. For the scheme in [19] and [20] and our strategy with constraints, there are always some active MBSs to ensure the coverage even there is no user arrives, which makes the energy efficiency low for low user arrival rate. When the number of users gradually increases from a small value, the energy efficiency increases. With the increase of user arrival rate, more BSs are awakened, the total throughput increases, but in turn the energy consumption and interference also increase. After some point, the grow speed of energy consumption is bigger than that of the throughput, and in turn the system energy efficiency decreases with the increase of the user arrival rate. For our strategy without constraints, as there are no needs to make MBSs be active to ensure coverage, so the energy efficiency is big even the number of users is small.

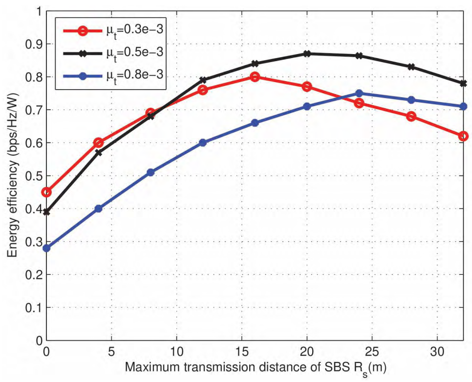

FIGURE 8. The energy efficiency for different coverage range of SBSs.

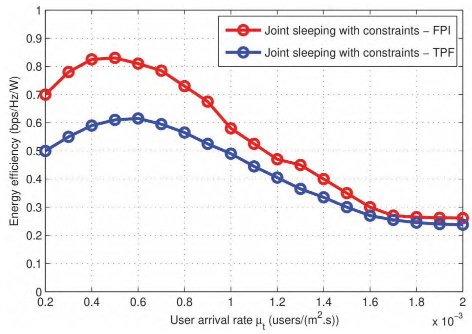

FIGURE 9. The energy efficiency for different user arrival rates.

In addition, in Fig. 7, it is easy to see that when the user arrival rate is less than $1.6\times10^{-3}\,m^2/s$, the energy efficiency of joint MBSs and SBSs sleeping strategy is always better than the SBSs sleeping strategy in [19] and [20]. Therefore, it is possible to increase the energy efficiency considering the sleeping of the MBSs.

Given the user arrival rate to 0.8 users$/(m^2\cdot s)$, we also evaluate influence of the coverage range of the SBSs on the energy efficiency, which is shown in Fig. 8. The energy efficiency increases firstly and then decreases with the increase of the coverage range of the SBSs. Because the throughput successfully transmitted by the BSs increases obviously as the increase of the coverage range of the SBSs, the energy efficiency increases. As the coverage range of the SBSs increases gradually to some degree, the power consumption of the SBSs increases significantly, so the energy efficiency declines.

In Fig. 9, we evaluate the impact of full path loss inversion approach (FPI) and fixed transmit power approach (FTP) on the energy efficiency. Obviously, we can see that FPI outperforms than FTP, the reason is that for FPI approach, when the user arrival rate is small, the average transmission power of MBS and that of SBS will decline to save energy which result in the energy efficiency higher. In contrast, using FTP approach, the average transmission power is always fixed even it is not necessary in this case. Meanwhile, with the increase of user arrival rate, more BSs become active, the interference becomes greater, and the overall energy consumption increases faster than the total throughput. As a result, the energy efficiency declines in this case. Finally, the energy efficiency goes flat.

VI. CONCLUSION

This work investigates the energy efficiency of HetNets with macrocells and small cells. Using PPP distributions of MBSs and that of SBSs, the energy efficiency model in Bit/s/Hz/m^2 is proposed. We formulate the *EE* maximization problem with considering constraints or not. The JODs of MBSs and that of SBSs are deduced, which can be used to guide the deployment of MBSs and that of SBSs in the planning stage of HetNets. As the optimal densities of MBSs and that of SBSs are related to the traffic load in HetNets, a feasible approach to keep densities of MBSs and that of SBSs in optimal values is to dynamically make MBSs and SBSs go to sleep according to the traffic load. Therefore, we can furthermore deduce the optimal sleeping probabilities of MBSs and that of SBSs, and the optimal threshold OTT at which MBSs and SBSs can dynamically sleep to maximize the energy efficiency of HetNet. The simulations validate our model and evaluate the performance of our dynamic sleeping strategy.

APPENDIX
DETAILED CALCULATIONS OF EQ. (27)

According to Eq. (23), we know that:

$$EE=\frac{(\lambda_m C_m+\lambda_s C_s)/B}{\lambda_m P_{tm}+\lambda_s P_{ts}}, \tag{44}$$

where

$$C_m=\mu_t\left(E\left[S\right]-N_s\pi R_s^2\right)\cdot\varepsilon_m \cdot\exp\left(-\frac{\pi^2}{4}\beta_m^{1/2}\left(\lambda_m R_m^2+\lambda_s R_s^2\theta^{1/2}\right)\right), \tag{45}$$

$$C_s=\mu_t\pi R_s^2\cdot\varepsilon_s\cdot\exp\left(-\frac{\pi^2}{4}\beta_s^{1/2}\left(\lambda_s R_s^2+\lambda_m R_m^2\theta^{-1/2}\right)\right), \tag{46}$$

$$P_{tm}=\frac{a_m P_{a,m}R_m^4}{3}\cdot\frac{\mu_t\left(E\left[S\right]-N_s\pi R_s^2\right)\cdot\varepsilon_m}{-2BE_i\left[-\left(\pi^2/4\right)\left(\lambda_m R_m^2+\lambda_s R_s^2\theta^{1/2}\right)\right]} +b_m, \tag{47}$$

$$P_{ts}=\frac{a_s P_{a,s}R_s^4}{3}\cdot\frac{\mu_t\pi R_s^2\cdot\varepsilon_s}{-2BE_i\left[-\left(\pi^2/4\right)\left(\lambda_s R_s^2+\lambda_m R_m^2\theta^{-1/2}\right)\right]} +b_s, \tag{48}$$

C_m, C_s, P_{tm} and P_{ts} are the functions of λ_m and λ_s. In order to obtain the optimal values of λ_m and λ_s, denoted as λ_m^* and λ_s^*, respectively, we take the partial derivatives of *EE* to λ_m and λ_s.

For simplification, we introduce the following functions.

$$a_1=\mu_t\left(E[S]-N_s\pi R_s^2\right)\cdot\varepsilon_m, \tag{49}$$

$$Z_1\left(\lambda_m,\lambda_s\right)=\frac{\pi^2}{4}\left(\lambda_m R_m^2+\lambda_s R_s^2\theta^{\frac{1}{2}}\right), \tag{50}$$

$$Z_2\left(\lambda_m,\lambda_s\right)=\frac{\pi^2}{4}\left(\lambda_s R_s^2+\lambda_m R_m^2\theta^{-\frac{1}{2}}\right). \tag{51}$$

A. TAKE THE PARTIAL DERIVATIVE OF EE TO λ_m

According to Eq. (44), we calculate the partial derivatives C_m, C_s, P_{tm} and P_{ts} to λ_m, that is

$$\frac{\partial C_m}{\partial \lambda_m} = -\frac{\pi^2}{4} a_1 \beta_m^{\frac{1}{2}} R_m^2 \exp\left[-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right] = C_m^c \exp\left[-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right], \quad (52)$$

where

$$C_m^c = -\frac{\pi^2}{4} a_1 \beta_m^{\frac{1}{2}} R_m^2. \quad (53)$$

$$\frac{\partial C_s}{\partial \lambda_m} = -\frac{\pi^2}{4} \beta_s^{\frac{1}{2}} R_m^2 \theta^{-\frac{1}{2}} \mu_t \pi R_s^2 \varepsilon_s \exp\left[-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right] = C_s^c \exp\left[-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right], \quad (54)$$

where

$$C_s^c = -\frac{\pi^2}{4} \beta_s^{\frac{1}{2}} R_m^2 \theta^{-\frac{1}{2}} \mu_t \pi R_s^2 \varepsilon_s. \quad (55)$$

$$\frac{\partial P_{tm}}{\partial \lambda_m} = \frac{\frac{\pi^2}{4} a_m P_{a,m} R_m^6 a_1 \cdot \exp(-Z_1(\lambda_m, \lambda_s))}{6BZ_1(\lambda_m, \lambda_s) \cdot E_i^2[-Z_1(\lambda_m, \lambda_s)]} = \frac{P_{tm}^c \cdot \exp(-Z_1(\lambda_m, \lambda_s))}{Z_1(\lambda_m, \lambda_s) \cdot E_i^2[-Z_1(\lambda_m, \lambda_s)]}, \quad (56)$$

where

$$P_{tm}^c = \frac{\frac{\pi^2}{4} a_m P_{a,m} R_m^6 a_1}{6B}. \quad (57)$$

$$\frac{\partial P_{ts}}{\partial \lambda_m} = \frac{\frac{\pi^2}{4} a_s P_{a,s} R_s^6 \mu_t \pi \varepsilon_s R_m^2 \theta^{\frac{-1}{2}} \cdot \exp(-Z_2(\lambda_m, \lambda_s))}{6BZ_2(\lambda_m, \lambda_s) \cdot E_i^2[-Z_2(\lambda_m, \lambda_s)]} = \frac{P_{ts}^c \cdot \exp(-Z_2(\lambda_m, \lambda_s))}{Z_2(\lambda_m, \lambda_s) \cdot E_i^2[-Z_2(\lambda_m, \lambda_s)]}, \quad (58)$$

where

$$P_{ts}^c = \frac{\frac{\pi^2}{4} a_s P_{a,s} R_s^6 \mu_t \pi \varepsilon_s R_m^2 \theta^{\frac{-1}{2}}}{6B}. \quad (59)$$

According to the partial derivatives of C_m, C_s, P_{tm} and P_{ts} to λ_m, we can have the partial derivative EE to λ_m.

Inserting the formula of Eq. (52), Eq. (54), Eq. (56), and Eq. (58) into Eq. (60), as shown at the bottom of this page, and assuming that $\frac{\partial EE}{\partial \lambda_m} = 0$, we can have Eq. (61), as shown at the bottom of this page, as follows.

B. TAKE THE PARTIAL DERIVATIVE OF EE TO λ_s

Similar to the process in A, we firstly calculate the partial derivatives C_m, C_s, P_{tm} and P_{ts} to λ_s:

$$\frac{\partial C_m}{\partial \lambda_s} = -\frac{\pi^2}{4} a_1 \beta_m^{\frac{1}{2}} R_s^2 \theta^{\frac{1}{2}} \exp\left[-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right] = C_m^{cc} \exp\left[-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right], \quad (62)$$

$$\frac{\partial EE}{\partial \lambda_m} = \frac{\frac{\partial(\lambda_m C_m + \lambda_s C_s)}{\partial \lambda_m}(\lambda_m P_{tm} + \lambda_s P_{ts}) - \frac{\partial(\lambda_m P_{tm} + \lambda_s P_{ts})}{\partial \lambda_m}(\lambda_m C_m + \lambda_s C_s)}{(\lambda_m P_{tm} + \lambda_s P_{ts})^2}. \quad (60)$$

$$\left[\left(a_1 + C_m^c \lambda_m\right)\exp\left(-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right) + \lambda_s C_s^c \exp\left(-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right)\right] \cdot (\lambda_m P_{tm} + \lambda_s P_{ts}) = \left[P_{tm} + \frac{P_{tm}^c \cdot \lambda_m \exp(-Z_1(\lambda_m, \lambda_s))}{Z_1(\lambda_m, \lambda_s) E_i^2[-Z_1(\lambda_m, \lambda_s)]} + \frac{P_{ts}^c \cdot \lambda_s \exp(-Z_2(\lambda_m, \lambda_s))}{Z_2(\lambda_m, \lambda_s) E_i^2[-Z_2(\lambda_m, \lambda_s)]}\right] \cdot (\lambda_m C_m + \lambda_s C_s). \quad (61)$$

$$\frac{\partial EE}{\partial \lambda_s} = \frac{\frac{\partial(\lambda_m C_m + \lambda_s C_s)}{\partial \lambda_s}(\lambda_m P_{tm} + \lambda_s P_{ts}) - \frac{\partial(\lambda_m P_{tm} + \lambda_s P_{ts})}{\partial \lambda_s}(\lambda_m C_m + \lambda_s C_s)}{(\lambda_m P_{tm} + \lambda_s P_{ts})^2}. \quad (70)$$

$$\left[C_s + C_m^{cc} \lambda_m \exp\left(-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right) + \lambda_s C_s^{cc} \exp\left(-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right)\right] \cdot (\lambda_m P_{tm} + \lambda_s P_{ts}) = \left[P_{ts} + \frac{P_{tm}^{cc} \cdot \lambda_m \exp(-Z_1(\lambda_m, \lambda_s))}{Z_1(\lambda_m, \lambda_s) E_i^2[-Z_1(\lambda_m, \lambda_s)]} + \frac{P_{ts}^{cc} \cdot \lambda_s \exp(-Z_2(\lambda_m, \lambda_s))}{Z_2(\lambda_m, \lambda_s) E_i^2[-Z_2(\lambda_m, \lambda_s)]}\right] \cdot (\lambda_m C_m + \lambda_s C_s). \quad (71)$$

$$\begin{cases} \left[\left(a_1 + C_m^c \lambda_m\right)\exp\left(-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right) + \lambda_s C_s^c \exp\left(-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right)\right] \cdot (\lambda_m P_{tm} + \lambda_s P_{ts}) \\ \quad = \left[P_{tm} + \frac{P_{tm}^c \cdot \lambda_m \exp(-Z_1(\lambda_m, \lambda_s))}{Z_1(\lambda_m, \lambda_s) E_i^2[-Z_1(\lambda_m, \lambda_s)]} + \frac{P_{ts}^c \cdot \lambda_s \exp(-Z_2(\lambda_m, \lambda_s))}{Z_2(\lambda_m, \lambda_s) E_i^2[-Z_2(\lambda_m, \lambda_s)]}\right] \cdot (\lambda_m C_m + \lambda_s C_s) \\ \left[C_s + C_m^{cc} \lambda_m \exp\left(-\beta_m^{\frac{1}{2}} Z_1(\lambda_m, \lambda_s)\right) + \lambda_s C_s^{cc} \exp\left(-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right)\right] \cdot (\lambda_m P_{tm} + \lambda_s P_{ts}) \\ \quad = \left[P_{ts} + \frac{P_{tm}^{cc} \cdot \lambda_m \exp(-Z_1(\lambda_m, \lambda_s))}{Z_1(\lambda_m, \lambda_s) E_i^2[-Z_1(\lambda_m, \lambda_s)]} + \frac{P_{ts}^{cc} \cdot \lambda_s \exp(-Z_2(\lambda_m, \lambda_s))}{Z_2(\lambda_m, \lambda_s) E_i^2[-Z_2(\lambda_m, \lambda_s)]}\right] \cdot (\lambda_m C_m + \lambda_s C_s). \end{cases} \quad (72)$$

where

$$C_m^{cc} = -\frac{\pi^2}{4} a_1 \beta_m^{\frac{1}{2}} R_s^2 \theta^{\frac{1}{2}}. \tag{63}$$

$$\frac{\partial C_s}{\partial \lambda_s} = -\frac{\pi^2}{4} \beta_s^{\frac{1}{2}} R_s^2 \mu_t \pi R_s^2 \varepsilon_s \exp\left[-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right]$$
$$= C_s^{cc} \exp\left[-\beta_s^{\frac{1}{2}} Z_2(\lambda_m, \lambda_s)\right], \tag{64}$$

where

$$C_s^{cc} = -\frac{\pi^2}{4} \beta_s^{\frac{1}{2}} R_s^2 \mu_t \pi R_s^2 \varepsilon_s. \tag{65}$$

$$\frac{\partial P_{tm}}{\partial \lambda_m} = \frac{\frac{\pi^2}{4} a_m P_{a,m} R_m^4 R_s^2 a_1 \theta^{\frac{1}{2}} \cdot \exp(-Z_1(\lambda_m, \lambda_s))}{6BZ_1(\lambda_m, \lambda_s) \cdot E_i^2[-Z_1(\lambda_m, \lambda_s)]}$$
$$= \frac{P_{tm}^{cc} \cdot \exp(-Z_1(\lambda_m, \lambda_s))}{Z_1(\lambda_m, \lambda_s) \cdot E_i^2[-Z_1(\lambda_m, \lambda_s)]}, \tag{66}$$

where

$$P_{tm}^{cc} = \frac{\frac{\pi^2}{4} a_m P_{a,m} R_m^4 R_s^2 a_1 \theta^{\frac{1}{2}}}{6B}. \tag{67}$$

$$\frac{\partial P_{ts}}{\partial \lambda_m} = \frac{\frac{\pi^2}{4} a_s P_{a,s} R_s^6 \mu_t \pi \varepsilon_s R_s^2 \cdot \exp(-Z_2(\lambda_m, \lambda_s))}{6BZ_2(\lambda_m, \lambda_s) \cdot E_i^2[-Z_2(\lambda_m, \lambda_s)]}$$
$$= \frac{P_{ts}^{cc} \cdot \exp(-Z_2(\lambda_m, \lambda_s))}{Z_2(\lambda_m, \lambda_s) \cdot E_i^2[-Z_2(\lambda_m, \lambda_s)]}, \tag{68}$$

where

$$P_{ts}^{cc} = \frac{\frac{\pi^2}{4} a_s P_{a,s} R_s^6 \mu_t \pi \varepsilon_s R_s^2}{6B}. \tag{69}$$

According to the partial derivatives of C_m, C_s, P_{tm} and P_{ts} to λ_s, we have the partial derivative EE to λ_s.

Inserting the formula of Eq. (62), Eq. (64), Eq. (66), and Eq. (68) into Eq. (70), as shown at the bottom of the previous page, and assuming that $\frac{\partial EE}{\partial \lambda_m} = 0$, we can have Eq. (71), as shown at the bottom of the previous page.

So we can get the Eq. (72), as shown at the bottom of the previous page, by Eq. (61) and (71) as follows, which is the same as Eq. (27).

REFERENCES

[1] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[2] Y. Li, C. Liao, Y. Wang, and C. Wang, "Energy-efficient optimal relay selection in cooperative cellular networks based on double auction," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4093–4104, Aug. 2015.

[3] T. Yang, F. Heliot, and C. H. Foh, "A survey of green scheduling schemes for homogeneous and heterogeneous cellular networks," *IEEE Commun. Mag.*, vol. 53, no. 11, pp. 175–181, Nov. 2015.

[4] Y. Li, H. Celebi, M. Daneshmand, C. Wang, and W. Zhao, "Energy-efficient femtocell networks: Challenges and opportunities," *IEEE Wireless Commun.*, vol. 20, no. 6, pp. 99–105, Dec. 2013.

[5] P. Lahdekorpi, M. Hronec, P. Jolma, and J. Moilanen, "Energy efficiency of 5G mobile networks with base station sleep modes," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Helsinki, Finland, 2017, pp. 163–168.

[6] Y. Song, H. Wei, M. Zhao, W. Zhou, P. Dong, and L. Zhao, "Optimal base station sleeping control in energy harvesting heterogeneous cellular networks," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Montreal, QC, Canada, Sep. 2016, pp. 1–5.

[7] J. Xu, J. Zhang, and J. G. Andrews, "On the accuracy of the Wyner model in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3098–3109, Sep. 2011.

[8] H. Elsawy, E. Hossain, and M. Haenggi, "Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 996–1019, 3rd Quart., 2013.

[9] M. W. Arshad, A. Vastberg, and T. Edler, "Energy efficiency gains through traffic offloading and traffic expansion in joint macro pico deployment," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Shanghai, China, Apr. 2012, pp. 2203–2208.

[10] N. Obaid and A. Czylwik, "The impact of deploying pico base stations on capacity and energy efficiency of heterogeneous cellular networks," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 1904–1908.

[11] Y. Li, X. Zhu, C. Liao, C. Wang, and B. Cao, "Energy efficiency maximization by jointly optimizing the positions and serving range of relay stations in cellular networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 6, pp. 2551–2560, Jun. 2015.

[12] T. Zhang, J. Zhao, L. An, and D. Liu, "Energy efficiency of base station deployment in ultra dense HetNets: A stochastic geometry analysis," *IEEE Wireless Commun. Lett.*, vol. 5, no. 2, pp. 184–187, Apr. 2016.

[13] T. Q. S. Quek, W. C. Cheung, and M. Kountouris, "Energy efficiency analysis of two-tier heterogeneous networks," in *Proc. Eur. Wireless-Sustain. Wireless Technol.*, Vienna, Austria, Apr. 2011, pp. 1–5.

[14] D. Cao, S. Zhou, and Z. Niu, "Optimal combination of base station densities for energy-efficient two-tier heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4350–4362, Sep. 2013.

[15] L. Li, M. Peng, C. Yang, and Y. Wu, "Optimization of base-station density for high energy-efficient cellular networks with sleeping strategies," *IEEE Trans. Wireless Commun.*, vol. 65, no. 9, pp. 7501–7514, Sep. 2016.

[16] J. Wu, Y. Zhang, M. Zukerman, and E. K.-N. Yung, "Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 803–826, 2nd Quart., 2015.

[17] Y. S. Soh, T. Q. S. Quek, M. Kountouris, and H. Shin, "Energy efficient heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, pp. 840–850, May 2013.

[18] S. Zhang, J. Gong, S. Zhou, and Z. Niu, "How many small cells can be turned off via vertical offloading under a separation architecture?" *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5440–5453, Oct. 2015.

[19] J. Rao and A. O. Fapojuwo, "Analysis of load dependent energy efficiency of two-tier heterogeneous cellular networks," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, London, U.K., Sep. 2013, pp. 3095–3099.

[20] J. B. Rao and A. O. Fapojuwo, "An analytical framework for evaluating spectrum/energy efficiency of heterogeneous cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3568–3584, May 2016.

[21] N. Jindal, S. Weber, and J. G. Andrews, "Fractional power control for decentralized wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5482–5492, Dec. 2008.

[22] J. S. Ferenc and Z. Néda, "On the size distribution of Poisson Voronoi cells," *Phys. A, Stat. Mech. Appl.*, pp. 518–526, 2007.

[23] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310–1322, Jul. 2006.

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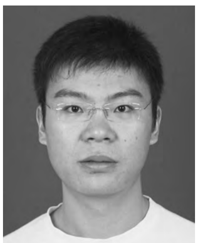

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