Energy-Efficient Design in Heterogeneous Cellular Networks Based on Large-Scale User Behavior Constraints

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***Abstract*—Large-scale user behavior can be used as the guidance for deployment, configuration, and service control in heterogeneous cellular networks (HCNs). However, in wireless networks, large-scale user behavior (in terms of traffic fluctuation in spatial domain) follows inhomogeneous distribution, which brings enormous challenges to energy-efficient design of HCNs. In this paper, the heterogeneity of large-scale user behavior is quantitatively characterized and exploited to study the energy efficiency (EE) in HCNs. An optimization problem is formulated for energy-efficient two-tier deployment and configuration, where the base station (BS) density, BS transmit power, BS static power, and quality of service are taken into account. We present closed-form formulas that establish the quantitative relationship between large-scale user behavior and energy-efficient HCN configuration. These results can be used to determine BS density and BS transmit power with the objective of achieving optimal EE. Furthermore, we present three energy-efficient control strategies of micro BSs, including micro BS sleep control, coverage expansion control, and coverage shrinking control. Simulation results validate our theoretical analysis and demonstrate that the proposed control strategies can potentially lead to significant power savings.**

***Index Terms*—Heterogeneous cellular networks, energy efficiency, resource management, large-scale user behavior, traffic.**

I. Introduction

IT has been reported that the information communication technology (ICT) infrastructure leads to 2% of CO_2 emissions and 3% of worldwide energy, which is expected to double by 2020. Every year, 0.2% of global energy is consumed by mobile communication networks [1]. Therefore, green wireless communication is considered as the most promising method for reducing energy consumption to meet the increasing traffic demands.

Manuscript received April 19, 2013; revised October 5, 2013, February 28, 2014, and May 23, 2014; accepted May 27, 2014. Date of publication June 12, 2014; date of current version September 8, 2014. This work was supported in part by the National 973 Program of China under Grant 2012CB316005, by the National Science Foundation of China under Grants 61372114 and U1035001, and by the Beijing Higher Education Young Elite Teacher Project under Grant YETP0434. The associate editor coordinating the review of this paper and approving it for publication was M. Rossi.

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Digital Object Identifier 10.1109/TWC.2014.2330334

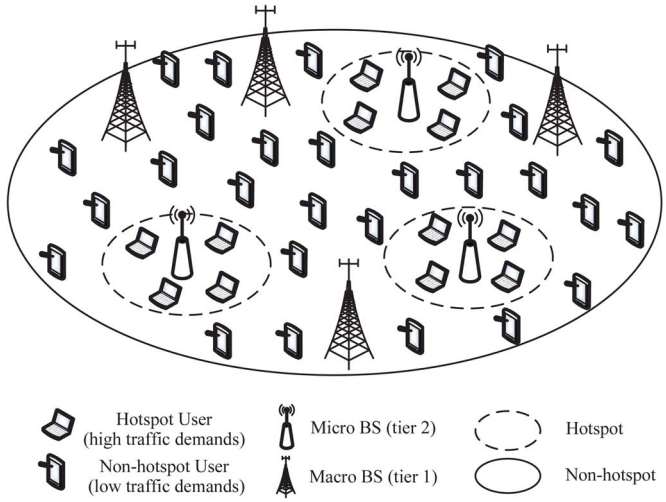


Fig. 1. System model and traffic demands spatial distribution.

In wireless networks, the traffic demands vary in both temporal and spatial domains. As shown in Fig. 1, a large amount of traffic demands may be generated in small hotspot regions, while only a small amount of traffic demands may be generated in vast non-hotspot regions. In the time dimension, a large number of users may request intensive traffic over the network in peak hours. Such user behavior is referred to as the large-scale user behavior [2]. Unsurprisingly, the large-scale user behavior creates enormous difficulties in energy consumption analysis. Some energy-efficient designs of heterogeneous cellular networks (HCNs) and several dynamic transmit mode adjustment schemes based on large-scale user behavior were proposed in our pervious works [3]–[5].

A. Related Work

HCNs including conventional macro BSs and distributed low power BSs are shown to have higher spectrum efficiency (SE) and energy efficiency (EE). Soh *et al.* [6] confirmed that the deployment of low power BSs generally leads to higher EE, but this gain saturates as the density of low power BSs increases. As a result, both the performance analysis and the energy-efficient design of HCNs [7]–[10] have become very popular recently.

The locations of BSs may have a significant impact on the outage and throughput performance of a network. However, the locations are usually unknown in the analysis and the design of

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the HCNs. The spatial stochastic process model is widely used to model the locations of BSs, such as the Poisson Point Process (PPP) and Poisson Cluster Process (PCP) [11]. A tractable, flexible and accurate model for a downlink HCN consisting of multi-tier BSs was recently presented in [12]. Analytical results of important metrics like the Signal-to-Interference-plus-Noise-Ratio (SINR), coverage probability and average rate were obtained.

Several important energy-efficient techniques were proposed including network planning, on-off BS operation, cell zooming and resource allocation. Cao *et al.* [13] investigated the optimal combination of the density of macro BSs and micro BSs with a tradeoff between capacity extension and energy saving. For the case of low traffic demands, it was shown that turning off some underutilized BSs can improve EE significantly. Marsan *et al.* [14] investigated the sleeping strategy according to the temporal traffic variation and similarly the authors in [15] proposed a cell activation mechanism that enables BSs to be activated repulsively according to traffic demands and thus the effective BS density can be scalable for traffic fluctuation.

For energy-efficient operation of low power BSs, Niu *et al.* [16], [17] proposed a cell zooming mechanism where it was shown that the power consumption can be reduced by means of turning off some BSs and extending the coverage of the other BSs during periods of low traffic demands. Resource allocation focusing on reducing the cross-tier interference can also save the energy of HCNs. Quek *et al.* [18] used the subchannel allocation mechanism to optimize HCN EE with a fairness constraint, and the authors in [19] extended the work to joint and disjoint subchannel allocation for open access femtocells and closed access femtocells respectively. Rao *et al.* [20] surveyed the recent findings in the area of energy-efficient resource allocation for HCNs.

B. Our Contributions

In this paper, we consider a general case: 1) Users in hotspot regions and non-hotspot regions are different in terms of traffic volume and the size of two regions. 2) BS coverage can be larger or smaller than the hotspot regions or non-hotspot regions. The existing approaches cannot be applied in this case, which motivates us to design a completely new approach for modeling and analyzing HCNs based on large-scale user behavior. Specifically, our main contributions are summarized as follows:

- A tractable expression to quantitatively characterize large-scale user behavior is presented for a scenario where heterogeneous traffic demands in hotspot regions and non-hotspot regions are taken into account.
- The quantitative relationship between large-scale user behavior and energy-efficient HCN configuration is presented in closed-form formulas. These results can be used to determine the density and the transmit power of BSs with the objective of achieving optimal EE.
- Three energy-efficient control strategies for large-scale user behavior are proposed, including micro BS sleep control, coverage expansion control and coverage shrinking control.

The rest of this paper is organized as follows. Section II describes the system model for HCNs. In Section III, the user behavior model for large-scale user behavior is proposed. In Section IV, energy-efficient optimization problem for two-tier HCN deployment and configuration is formulated and solved. In Section V, three energy-efficient control strategies are presented. We then present numerical results in Section VI and conclude the paper in Section VII.

II. System Model

A. Heterogeneous Cellular Network Model

We consider two kinds of regions (i.e., the hotspot regions and non-hotspot regions shown in Fig. 1), which are covered by a 2-tier HCN consisting the conventional macro BSs that guarantee non-hotspot region coverage, and micro BSs that guarantee hotspot region traffic demands. The hotspot regions and the non-hotspot regions are differentiated by two characteristics of traffic demands (i.e., volume/density and size). Specifically, the volume/density of traffic demands in hotspot regions is generally higher than that in non-hotspot regions. The size of hotspot regions is generally smaller than that of non-hotspot regions. In this paper, the distribution of user location and the distribution of traffic demands are considered to be different concepts. The locations of the users in two kinds of regions are assumed to follow uniform distribution with the same density but the traffic demands and size of hotspot regions and non-hotspot regions can be different.

The notations used in this paper are summarized in Table I. The BSs in either macro or micro BS tiers (denoted as $k \in \{M, m\}$) are assumed to have same spatial density λ_k, transmit power P_k, SINR threshold β_k, which can be different in different tiers. Their locations are modeled by independent PPPs denoted as Φ_k. Without loss of generality, we assume that a typical user is located at the origin. $\|x\|$ is denoted as the distance between a BS located at point x and the typical user and h_x is the channel fading (power), which is assumed to follow exponential distribution (Rayleigh fading). The path loss of desired or interference signals between them is given by $\|x\|^{-\alpha}$. Thus the received power of the typical user can be expressed as $P_k h_x \|x\|^{-\alpha}$, where α is path loss exponent. The total interference power consists of the interference power from the BSs in the same tier and that from BSs in other tiers. Consequently, the SINR of the typical user associated with the BS located at point x in the kth tier is:

$$SINR_x^k = \frac{P_k h_x \|x\|^{-\alpha}}{\sigma_n^2 + \sum_{i\in\{m,M\}} \sum_{x\in\Phi_i/\{x\}} P_i h_x \|x\|^{-\alpha}}, \quad (1)$$

where the σ_n^2 is the additive noise power. Note that the channel fading here can be extended to the general case that includes both small-scale fading and long-term shadowing. The long-term shadowing effects can be interpreted as a random displacement of the BSs [21]. As a result, transmit power of BSs should be scaled by $\mathbb{E}[\mathcal{X}^{2/\alpha}]$, where $\mathcal{X}$ is the shadowing following any general distribution as long as $\mathbb{E}[\mathcal{X}^{2/\alpha}] < \infty$.

TABLE I
SUMMARY OF NOTATION

Symbol	Description
k	Index of macro/micro BS tier, $k \in \{M, m\}$
Φ_k	PPP for the locations of the BSs belonging to k^{th} tier
λ_k	Density of the BSs belonging to k^{th} tier
P_k	Transmit power of the BSs belonging to k^{th} tier
β_k	Received SINR threshold of the BSs belonging to k^{th} tier
x	Location of a BS
$\|x\|$	Distance between a BS and a typical user
$\mathbb{P}(SINR < \beta_k)$	Outage probability of the typical user
r_k	Average rate of the typical user
ASR_k	Average spatial rate of BSs in the k^{th} tier
ASR	Average spatial rate of the HCN
t_i	Traffic demands of the i^{th} user
γ_m	Ratio between the area of hotspot regions and that of non-hotspot regions (referred to as area ratio for simplicity)
ν_m	Ratio between the traffic rate per unit area in hotspot regions and that in non-hotspot regions (referred to as traffic rate ratio for simplicity)
$\widetilde{\gamma}_m$	Ratio between the coverage area of micro BSs and that of macro BSs (referred to as coverage ratio for simplicity)
$\widetilde{\nu}_m$	Ratio between the ASR of micro BSs and that of macro BSs (referred to as ASR ratio for simplicity)

B. HCN Average Rate

We assume that the typical user is associated with the BS that offers the maximum SINR, who is in the coverage if the maximum SINR is no less than the received SINR threshold β_k. The macro BSs and micro BSs guarantee coverage and traffic demands in non-hotspot regions and hotspot regions separately. Therefore, users in non-hotspot regions and hotspot regions are assumed to be connected to macro BSs and micro BSs respectively and such access model can be treated as the closed access model. Following the contribution of **corollary 3** in [12], we can obtain outage probability $\mathbb{P}(SINR < \beta_k)$ as follow:

$$\mathbb{P}(SINR < \beta_k) = 1 - \frac{\pi}{C(\alpha)} \frac{\lambda_k \left(P_k/\beta_k\right)^{\frac{2}{\alpha}}}{\lambda_M {P_M}^{\frac{2}{\alpha}} + \lambda_m {P_m}^{\frac{2}{\alpha}}}, \quad (2)$$

where

$$C(\alpha) = \frac{2\pi^2}{\alpha} \csc\left(\frac{2\pi}{\alpha}\right).$$

Because the typical user can be connected to a BS when its instantaneous SINR is no less than a SINR threshold, the average rate of the typical user associated to the kth tier can be expressed as follow:

$$r_k = \mathbb{E}[R|SINR < \beta_k]\mathbb{P}(SINR < \beta_k) + \mathbb{E}[R|SINR \geqslant \beta_k]\mathbb{P}(SINR \geqslant \beta_k), \quad (3)$$

where

$$R = \log\left(1 + \max_{x \in \cup \Phi_k} (SINR(x))\right). \quad (4)$$

It is important to note that the expectation in the first term equals to zero because the received SINR is lower than the SINR threshold and the expectation in the second term is in fact the average rate under coverage, which can be calculated based on the **corollary 4** in [12]. Since the expression of average rate under coverage are intractable in general, we assume that the special case where the received SINR thresholds in different tiers are the same (i.e., $\beta_k = \beta_{th}$) to obtain some insight. Substituting (2) into (3), the average rate of the typical user can be obtained as follow:

$$r_k = D(\alpha, \beta_{th}) \frac{\lambda_k {P_k}^{\frac{2}{\alpha}}}{\lambda_M {P_M}^{\frac{2}{\alpha}} + \lambda_m {P_m}^{\frac{2}{\alpha}}}, \quad (5)$$

where

$$D(\alpha, \beta_{th}) = \frac{\pi \log(1+\beta_{th})}{C(\alpha) {\beta_{th}}^{2/\alpha}} + \frac{{}_2F_1\left(1, 2/\alpha, 1+2/\alpha, -1/\beta_{th}\right)\alpha\pi}{2C(\alpha){\beta_{th}}^{2/\alpha}}, \quad (6)$$

and ${}_2F_1$ is the hypergeometric function. The average spatial rate (ASR) associated to the kth tier is defined as $ASR_k = n_k r_k / S = \lambda_k r_k$, where n_k is the number of BSs belonging to kth tier in area S. Therefore, the ASR associated to the kth tier is:

$$ASR_k = D(\alpha, \beta_{th}) \frac{\lambda_k^2 {P_k}^{\frac{2}{\alpha}}}{\lambda_M {P_M}^{\frac{2}{\alpha}} + \lambda_m {P_m}^{\frac{2}{\alpha}}}, \quad (7)$$

and the ASR of HCNs is:

$$ASR = \sum_k ASR_k = D(\alpha, \beta_{th}) \frac{\lambda_M^2 {P_M}^{\frac{2}{\alpha}} + \lambda_M^2 {P_M}^{\frac{2}{\alpha}}}{\lambda_M {P_M}^{\frac{2}{\alpha}} + \lambda_m {P_m}^{\frac{2}{\alpha}}}. \quad (8)$$

According the expression of ASR of HCNs, the ASR ratio $\widetilde{\nu}_m$ can be given as:

$$\widetilde{\nu}_m = \frac{\lambda_m^2 {P_m}^{\frac{2}{\alpha}}}{\lambda_M^2 {P_M}^{\frac{2}{\alpha}}}. \quad (9)$$

According to the **proposition 3** in [12], the ratio between coverage area of the BSs belonging to kth tier and the whole area is $\lambda_k {P_k}^{2/\alpha} / (\lambda_M {P_M}^{2/\alpha} + \lambda_m {P_m}^{2/\alpha})$ and thus the coverage ratio $\widetilde{\gamma}_m$ can be given as:

$$\widetilde{\gamma}_m = \frac{\lambda_m {P_m}^{\frac{2}{\alpha}}}{\lambda_M {P_M}^{\frac{2}{\alpha}}}. \quad (10)$$

According to (9) and (10), the ratio between the density of micro BSs and that of macro BSs is:

$$\frac{\lambda_m}{\lambda_M} = \frac{\widetilde{\nu}_m}{\widetilde{\gamma}_m} \quad (11)$$

and the ratio between the transmit power of micro BSs and that of macro BSs is:

$$\frac{P_m}{P_M} = \left(\frac{\widetilde{\gamma}_m^2}{\widetilde{\nu}_m}\right)^{\frac{\alpha}{2}}. \tag{12}$$

According to (11) and (12), the ASR of HCNs can be further expressed as:

$$\begin{aligned} ASR &= \lambda_M D(\alpha, \beta_{th}) \frac{(1+\widetilde{\nu}_m)}{(1+\widetilde{\gamma}_m)} \\ &= \lambda_m D(\alpha, \beta_{th}) \frac{\widetilde{\gamma}_m (1+\widetilde{\nu}_m)}{\widetilde{\nu}_m (1+\widetilde{\gamma}_m)}. \end{aligned} \tag{13}$$

It can be observed that if the macro BS density λ_M is fixed, the HCN ASR increases monotonically with the ASR ratio $\widetilde{\nu}_m$ and decreases with the coverage ratio $\widetilde{\gamma}_m$. Conversely, if the micro BS density λ_m is fixed, the HCN ASR increases monotonically with the coverage ratio $\widetilde{\gamma}_m$ and decreases with the ASR ratio $\widetilde{\nu}_m$.

C. Power Consumption Model and Energy Efficiency Metric

The power consumption of the BS belonging to kth tier is given by $P = P_k + P_k^c$, where P_k^c is the static power consumption and the transmit power depends on the traffic demands. Further, the average spatial power consumption of the BS belonging to kth tier is $\lambda_k(P_k + P_k^c)$. We also denote the power consumption of micro BSs in sleep mode as P_m^s. Thus the EE of HCNs can be defined as follows:

$$\begin{aligned} EE &= \frac{\text{Average Spatial Rate}}{\text{Average Spatial Power Consumption}} \\ &= \frac{ASR}{\lambda_m (P_m + P_m^c) + \lambda_M (P_M + P_M^c)}. \end{aligned}$$

In real HCNs, the ranges of transmit power for micro BSs and macro BSs are 10 mW $\sim$ 2 W and 5 W $\sim$ 80 W. The typical values of static power can be found in [22].

III. Large-Scale User Behavior Modeling for Two-Tier HCNs

In this section, we present a user behavior model for large-scale user behavior in two-tier HCNs, where the concept of Gini coefficient [23] in economics is used to characterize the heterogeneous degree of large-scale user behavior.

A. User Behavior Curve and User Behavior Coefficient

The user behavior is defined mathematically based on the Lorenz curve and is shown in [2]. The model is re-drawn in Fig. 2. In this paper, it is noted that the locations of user are assumed to follow uniform distribution.

As in [2], the user behavior coefficient h, which is the ratio between the area (marked as "A" in Fig. 2) over the total area ("A" and "B" in Fig. 2). It is defined as follows:

$$h = \frac{A}{A+B}. \tag{14}$$

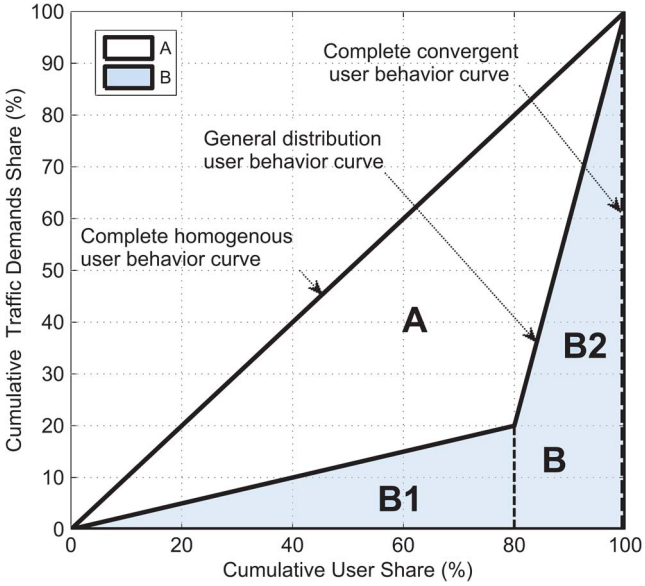


Fig. 2. User behavior curve for two-tier HCNs.

The value of user behavior coefficient is in the interval [0,1]. In practice, both extreme values are not usually reached. On one hand, a low user behavior coefficient indicates the large-scale user behavior follows a more even distribution, with 0 corresponding to complete equality. On the other hand, a high user behavior coefficient indicates large-scale user behavior follows uneven distribution, with 1 corresponding to complete convergence (i.e., all of the traffic demands are requested by one user).

B. User Behavior Coefficient Calculation

We first consider a general case that the traffic rate in hotspot regions is higher than that in non-hotspot regions, i.e., $\nu_m > 1$. Note that the traffic rate is same in hotspot regions or non-hotspot regions and thereby the user behavior curve $\rho(x)$ consists of two fold lines. Because the γ_m is the ratio between the area of hotspot regions and that of non-hotspot regions and thus the ratio between the area of non-hotspot regions and that of all regions is $1/(\gamma_m + 1)$. Note that the ratio between the total traffic volume of hotspot regions and that of non-hotspot regions is $\gamma_m \nu_M$ and thus the ratio between the total traffic volume in non-hotspot regions and that in all regions is $1/(\gamma_m \nu_M + 1)$. As a result, the coordinate of the fold point of the user behavior curve $\rho(x)$ is $(1/(\gamma_m + 1), 1/(\gamma_m \nu_M + 1))$.

The area of the region B can be divided into a triangle "B1" and a trapezium "B2". The area of the triangle and the trapezium can be easily obtained, which are $(1/2)(1/(\gamma_m + 1))(1/(\gamma_m \nu_M + 1))$ and $(1/2)(\gamma_m/(\gamma_m + 1))(1 + (1/(\gamma_m \nu_M + 1)))$ respectively. The area of A in Fig. 2 can be simply calculated by subtracting area of the region B from the area of the triangle (i.e., 0.5), which is shown as follows:

$$\begin{aligned} A &= \frac{1}{2} - \frac{1}{2}\frac{1}{\gamma_m + 1}\frac{1}{\gamma_m \nu_M + 1} \\ &\quad - \frac{1}{2}\frac{\gamma_m}{\gamma_m + 1}\left(1 + \frac{1}{\gamma_m \nu_M + 1}\right) \\ &= \frac{1}{2}\left[\frac{\gamma_m \nu_m}{\gamma_m \nu_m + 1} - \frac{\gamma_m}{\gamma_m + 1}\right]. \end{aligned} \tag{15}$$

In the other case where $\nu_m < 1$, the area of A can be calculated similarly. According to the definition of user behavior coefficient, we have:

$$h = \frac{\gamma_m \nu_m}{\gamma_m \nu_m + 1} - \frac{\gamma_m}{\gamma_m + 1}, \quad if \quad \nu_m < 1; \tag{16}$$

$$= \frac{\gamma_m}{\gamma_m + 1} - \frac{\gamma_m \nu_m}{\gamma_m \nu_m + 1}, \quad if \quad \nu_m < 1. \tag{17}$$

where $\gamma_m \nu_M / (\gamma_m \nu_M + 1)$ is in fact the ratio between the total traffic volume in hotspot regions and that in all regions, and $\gamma_m / (\gamma_m + 1)$ is in fact the ratio between the area of hotspot regions and that of all regions. An important observation from user behavior coefficient expression is that the user behavior coefficient can be simply given as the absolute difference between these two ratios.

In the case that traffic rate in hotspot regions is much higher than that in non-hotspot regions (e.g. in the rush hours), we can have $\nu_M \to \infty$ and $h \to (1/(\gamma_m + 1))$, which means the user behavior coefficient only depends on the area ratio. Furthermore, if the area of hotspot regions is much smaller than that of non-hotspot regions, we can have $\gamma_m \to 0$ and $h \to 1$, which means the all traffic demands are only generated in tiny hotspot regions and thereby the large-scale user behavior is completely convergent.

In the other case that traffic rate in hotspot regions is much lower than that in non-hotspot regions (e.g. early in the morning), we have $\nu_M \to 0$ and $h \to (\gamma_m / (\gamma_m + 1))$, which means the user behavior coefficient also only depends on the coverage area proportion. Furthermore, if the hotspot regions is much smaller than non-hotspot regions, we have $\gamma_m \to 0$ and $h \to 0$, which means the traffic demands are almost the same over the whole area and thus the large-scale user behavior is completely equality.

IV. Power and Density Optimization for HCNs Based on Large-Scale User Behavior

In this section, we introduce two optimization problems with fixed micro BS density or fixed macro BS density. The optimal BS transmit power and the optimal BS density based on user behavior are derived. Then we analyze the impact of the large-scale user behavior on HCN EE. Note that traffic demands in hotspot regions are completely guaranteed by micro BSs and traffic demands in non-hotspot regions are completely guaranteed by macro BSs. Therefore, the ASR ratio $\widetilde{\nu}_m$ and the coverage ratio $\widetilde{\gamma}_m$ should equal to the traffic rate ratio ν_m and the area ratio γ_m respectively (i.e., $\widetilde{\nu}_m = \nu_m$ and $\widetilde{\gamma}_m = \gamma_m$).

A. Scenario 1: Fixed Micro BS Density

First, we consider the case where each hotspot region should be covered by one micro BS and thus the micro BS density is pre-determined by hotspot regions density (denoted as λ_h). Only the macro BS density and the transmit power of macro BSs and micro BSs can be adjusted. As a result, the optimization problem becomes:

$$\begin{aligned} \max_{\lambda_M, P_M, P_m} \quad & EE = \frac{ASR}{\lambda_m (P_m + P_m^c) + \lambda_M (P_M + P_M^c)}; \\ s.t. \quad & \widetilde{\gamma}_m = \gamma_m; \\ & \widetilde{\nu}_m = \nu_m; \\ & SINR_{edge} \geq \beta_{th}; \\ & \lambda_m = \lambda_h. \end{aligned}$$

According to (11) and (12), the HCN EE can be given as follow:

$$\begin{aligned} EE &= \frac{D(\alpha, \beta_{th})(1+\nu_m)(1+\gamma_m)^{-1}}{(P_m + P_m^c)\,\nu_m \gamma_m{}^{-1} + (P_M + P_M^c)} \\ &= \frac{D(\alpha, \beta_{th})(1+\nu_m)(1+\gamma_m)^{-1}}{\left(\gamma_m{}^{\alpha-1} \nu_m{}^{1-\frac{\alpha}{2}} + 1\right) P_M + \nu_m \gamma_m{}^{-1} P_m^c + P_M^c}. \end{aligned}$$

We then proof that the optimal EE can be achieved when the received SINR at the macro cell edge equals to β_{th}. We define P_{edge} is the probability that a user at the macro cell edge and the distance between such user and the serving BS is d_{edge}. Note that P_{edge} can be given by $\exp(-\pi \lambda_M d_{edge}^2)$ in PPP model. Hence, we have

$$d_{edge} = \sqrt{\frac{-\ln(P_{edge})}{\pi \lambda_M}}. \tag{18}$$

Note that received SINR at the macro cell edge $SINR_{edge}$ should large than the SINR threshold (i.e., $SINR_{edge} = (P_M {d_{edge}}^{-\alpha} / \sigma_n^2) \geqslant \beta_{th}$). It can be observed that the HCN EE decreases monotonically with P_M and thereby decreases monotonically with $SINR_{edge}$. As a result, we can achieve the maximum HCN EE with the smallest P_M. So we have $P_M {d_{edge}}^{-\alpha} / \sigma_n^2 = \beta_{th}$. Using (18), we obtain:

$$P_M \lambda_M^{\frac{\alpha}{2}} = \sigma_n^2 \beta_{th} \left(\frac{-\ln P_{edge}}{\pi} \right)^{\frac{\alpha}{2}} \tag{19}$$

Based on (11), the optimal density of macro BSs can be given as:

$$\lambda_M^{opt} = \lambda_h \frac{\gamma_m}{\nu_m}. \tag{20}$$

It can be observed that the optimal density of macro BSs λ_M^{opt} increases monotonically with both area ratio γ_m and the hotspot density λ_h while decreases with traffic rate ratio ν_m. Following (19) and (20), we can have the optimal transmit power of macro BSs:

$$P_M^{opt} = \sigma_n^2 \beta_{th} \left(\frac{\nu_m}{\gamma_m} \right)^{\frac{\alpha}{2}} \left(\frac{-\ln P_{edge}}{\pi \lambda_h} \right)^{\frac{\alpha}{2}}. \tag{21}$$

We can observe that the optimal transmit power of macro BSs P_M^{opt} decreases monotonically with both area ratio γ_m and the hotspot density λ_h, while increases with the traffic rate ratio ν_m.

Based on (11) and (12), we can obtain the optimal transmit of micro BSs power:

$$P_m^{opt} = \sigma_n^2 \beta_{th} {\gamma_m}^{\frac{\alpha}{2}} \left(\frac{-\ln P_{edge}}{\pi \lambda_h} \right)^{\frac{\alpha}{2}}. \tag{22}$$

We can observe that the optimal transmit power of micro BSs P_m^{opt} increases monotonically with the area ratio γ_m while decreases with the hotspot density λ_h and does not change with traffic rate ratio ν_m.

Based on the relationship among the HCN parameters $(\lambda_m, \lambda_M, P_m, P_M)$ and the large-scale user behavior parameters $(\lambda_h, \gamma_m, \nu_m)$, we can summarize the HCN configuration strategies as follows:

Case 1: When the hotspot users request higher traffic rate but stay in the hotspot regions without moving to other non-hotspot regions, the transmit power of macro BSs should increase and the density of macro BSs should decrease. Meanwhile the transmit power of micro BSs and the density of micro BSs remain unchanged. According to (20), (21) and (22), it can be found that such changes of λ_m, λ_M, P_m, P_M do not change the coverage area of micro BSs. However, the ASR provided by micro BSs in hotspot regions increases.

Case 2: When the size of hotspot regions expand but traffic rate remains the same, the transmit power of macro BSs should decrease and both the density of macro BSs and the transmit power of micro BSs should increase. Meanwhile, the density of micro BSs remains unchanged. According to (20), (21) and (22), it can observed that the changes of λ_m, λ_M, P_m, P_M do not change the ASR provided by micro BSs in hotspot regions. However, the coverage area of micro BSs increases.

Case 3: When the density of hotspots increases but the traffic rate and the size of hotspot regions remains constant, the density of micro BSs and macro BSs should increase. However, the transmit power of micro BSs and macro BSs should be reduced. According to (20), (21) and (22), it can be found that the changes of λ_m, λ_M, P_m, P_M do not change the ASR provided by micro BSs in hotspot regions and the coverage area of micro BSs. However, the number of hotspots increases.

Based on (20), (21) and (22), we can have the optimal EE:

$$EE^{opt} = D(\alpha, \beta_{th})(1+\nu_m)(1+\gamma_m)^{-1} E_1^{-1}, \tag{23}$$

where

$$E_1 = \nu_m {\gamma_m}^{-1} P_m^c + P_M^c + \sigma_n^2 \beta_{th} \pi^{-\frac{\alpha}{2}} \lambda_h^{-\frac{\alpha}{2}} {\gamma_m}^{\frac{\alpha}{2}-1} \nu_m$$

$$\times (-\ln P_{edge})^{\frac{\alpha}{2}} + \sigma_n^2 \beta_{th} \pi^{-\frac{\alpha}{2}} \lambda_h^{-\frac{\alpha}{2}} {\gamma_m}^{-\frac{\alpha}{2}} {\nu_m}^{\frac{\alpha}{2}} (-\ln P_{edge})^{\frac{\alpha}{2}}.$$

B. Scenario 2: Fixed Macro BS Density

In this subsection, we consider the case that the macro BS density is fixed and only the density of micro BSs and the transmit power of macro BSs and micro BSs can be adjusted. We define the corresponding optimization problem in the following:

$$\begin{aligned} \max_{P_M, \lambda_m, P_m} \quad & EE = \frac{ASR}{\lambda_m (P_m + P_m^c) + \lambda_M (P_M + P_M^c)} \\ s.t. \quad & \widetilde{\gamma}_m = \gamma_m; \\ & \widetilde{\nu}_m = \nu_m; \\ & SINR_{edge} \geq \beta_{th} \end{aligned}$$

Using (11), we can further obtain the optimal density of micro BSs:

$$\lambda_m^{opt} = \lambda_M \frac{\nu_m}{\gamma_m} \tag{24}$$

The optimal density of micro BSs λ_m^{opt} increases monotonically with traffic rate ratio ν_m while decreases with the area ratio γ_m. According to (19), we can have the optimal transmit power of macro BSs:

$$P_M^{opt} = \sigma_n^2 \beta_{th} \left(\frac{-\ln P_{edge}}{\pi \lambda_M} \right)^{\frac{\alpha}{2}}. \tag{25}$$

The optimal transmit power of macro BSs P_M^{opt} remains constant when area ratio γ_m or the traffic rate ratio ν_m changes, which is different from (21) in the case of fixed density of micro BSs. According to (25) and (12), the optimal transmit power of micro BSs is:

$$P_m^{opt} = \sigma_n^2 \beta_{th} \left(\frac{{\gamma_m}^2}{\nu_m} \right)^{\frac{\alpha}{2}} \left(\frac{-\ln P_{edge}}{\pi \lambda_M} \right)^{\frac{\alpha}{2}}. \tag{26}$$

It can be observed that the optimal transmit power of micro BSs P_m increases monotonically with the area ratio γ_m while decreases with the traffic rate ratio ν_m. Based on the relationship among the HCN parameters (λ_m, P_m, P_M) and the large-scale user behavior parameters (γ_m, ν_m), we can have the following configuration strategies:

Case 1: When the hotspot users request higher traffic rate but stay in the hotspot regions without moving to other non-hotspot regions, the density of micro BS should increase and the transmit power of micro BSs should be reduced. Meanwhile the transmit power of macro BSs and the density of macro BSs remain unchanged. According to (24), (25) and (26), it can be observed that these changes on λ_m, P_m, P_M do not change the coverage area of micro BSs. However, the ASR provided by micro BSs in hotspot regions increases.

Case 2: When the hotspot users move to a broader region and request the same traffic rate, the density of micro BSs should be reduced and the transmit power of micro BSs should increase. Meanwhile the transmit power of macro BSs remains unchanged. According to (20), (21) and (22), it can be found that the changes of λ_m, P_m, P_M will not change the ASR

provided by micro BSs in hotspot regions. However, the coverage area of micro BSs will increase.

Based on (20), (21) and (22), the optimal EE is:

$$EE_{opt} = D(\alpha, \beta_{th})(1+\nu_m)(1+\gamma_m)^{-1}{E_2}^{-1}, \quad (27)$$

where

$$E_2 = \nu_m{\gamma_m}^{-1}P_m^c + P_M^c + \sigma_n^2\beta_{th}\pi^{-\frac{\alpha}{2}}\lambda_M^{-\frac{\alpha}{2}}(-\ln P_{edge})^{\frac{\alpha}{2}} + \sigma_n^2\beta_{th}\pi^{-\frac{\alpha}{2}}\lambda_M^{-\frac{\alpha}{2}}{\gamma_m}^{\alpha-1}{\nu_m}^{1-\frac{\alpha}{2}}(-\ln P_{edge})^{\frac{\alpha}{2}}.$$

According to (23) and (27), two items containing σ_n^2 in the denominator is much smaller than the other two items and thus the optimal EE in (23) and (27) can be approximated as:

$$EE_{opt} \approx \frac{D(\alpha, \beta_{th})\gamma_m(1+\nu_m)}{(1+\gamma_m)\left(P_m^c\nu_m + P_M^c\gamma_m\right)}. \quad (28)$$

C. Traffic Rate Ratio ν_m and EE_{opt}

It is difficult to obtain the optimal close-form expression of EE using the user behavior coefficient h. However, from (23), we can see that the EE_{opt} depends on two parameters: the area ratio γ_m and the traffic rate ratio ν_m. According to (16), the user behavior coefficient h also depends on these two parameters. As a result, we try to establish the connection between the optimal energy efficiency EE_{opt} and the large-scale user behavior by changing γ_m and ν_m respectively. Specifically, we first take derivative of EE_{opt} in terms of ν_m:

$$EE'_{\nu_m} = \frac{D(\alpha, \beta_{th})\gamma_m(1+\gamma_m)}{(1+\gamma_m)^2\left(\nu_m P_m^c + \gamma_m P_M^c\right)^2}\left(\gamma_m P_M^c - P_m^c\right). \quad (29)$$

Therefore, when $\gamma_m P_M^c > P_m^c$, the EE_{opt} increases monotonically with traffic rate ratio ν_m and when $\gamma_m P_M^c < P_m^c$, the EE_{opt} decreases monotonically with traffic rate ratio ν_m. Because γ_m is the ratio of the area of hotspot regions (denoted as S_{hp}) to that of non-hotspot regions (denoted as S_{nhp}), i.e., $\gamma_m = S_{hp}/S_{nhp}$. Therefore, the condition $({P_m}^{2/\alpha}/P_m^c) > ({P_M}^{2/\alpha}/P_M^c)$ is equivalent to $(P_m^c/S_{hp}) < (P_M^c/S_{nhp})$, which means the static power consumption per unit coverage area of micro BSs is smaller than that of macro BSs and thus we have:

$$\begin{cases} EE_{opt} \text{ increases with } \nu_m & \frac{P_m^c}{S_{hp}} < \frac{P_M^c}{S_{nhp}} \\ EE_{opt} \text{ decreases with } \nu_m & \frac{P_m^c}{S_{hp}} > \frac{P_M^c}{S_{nhp}}. \end{cases} \quad (30)$$

An important observation from (30) is that when the traffic rate increases in hotspot regions, the optimal EE does not always increase but depends on the static power consumption per unit coverage area of macro BSs and micro BSs.

D. Area Ratio γ_m and EE_{opt}

We then take derivative of (28) in terms of γ_m and obtain

$$EE'_{\gamma_m} = \frac{D(\alpha, \beta_{th})(1+\nu_m)}{(1+\gamma_m)^2\left(\nu_m P_m^c + \gamma_m P_M^c\right)^2}\left(\nu_m P_m^c - P_M^c\gamma_m^2\right). \quad (31)$$

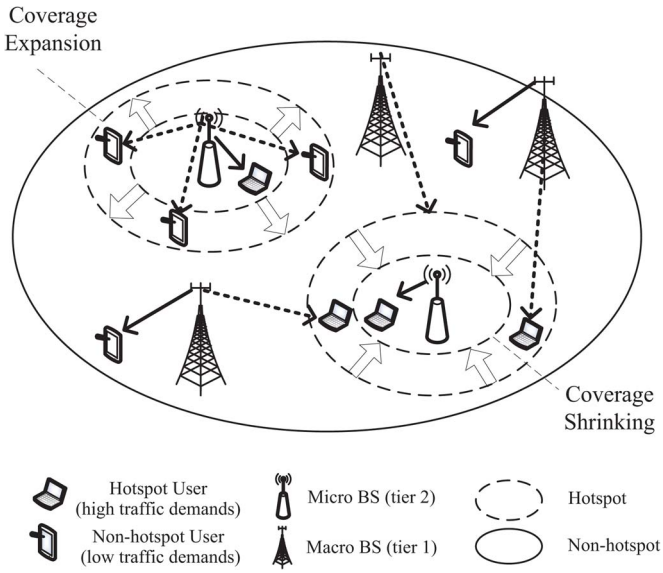


Fig. 3. Coverage expansion control strategy and coverage shrinking control strategy.

Therefore, when $\nu_M P_m^c > P_M^c\gamma_m^2$, the optimal EE EE_{opt} increases monotonically with the area ratio γ_m and when $\nu_M P_m^c < P_M^c\gamma_m^2$, the optimal energy efficiency EE_{opt} decreases monotonically with the area ratio γ_m. Based on the relationship $\gamma_m = S_{hp}/S_{nhp}$, we can see that the condition $\nu_M P_m^c > P_M^c\gamma_m^2$ is equivalent to $(P_m^c/S_{hp}) > (\gamma_m/\nu_M) \times (P_M^c/S_{nhp})$, which is slight different from the monotone conditions of $EE(\gamma_m)$, i.e., the static power consumption per unit coverage area of macro BSs multiplied by γ_m/ν_M. Therefore we have:

$$\begin{cases} EE_{opt} \text{ increases with } \gamma_m & \frac{P_m^c}{S_{hp}} > \frac{\gamma_m}{\nu_m} \times \frac{P_M^c}{S_{nhp}} \\ EE_{opt} \text{ decreases with } \gamma_m & \frac{P_m^c}{S_{hp}} < \frac{\gamma_m}{\nu_m} \times \frac{P_M^c}{S_{nhp}}. \end{cases} \quad (32)$$

An important observation from (32) is that when the hotspot region area increases in hotspot regions, the optimal energy efficiency does not always increase but depends on the static power consumption per unit coverage area of macro BSs and micro BSs and γ_m/ν_M.

V. Energy-Efficient BS Control Strategies for Two-Tier HCNs

In the previous sections, we assumed that traffic demands in hotspot regions is completely guaranteed by micro BSs and traffic demands in non-hotspot regions is completely guaranteed by macro BSs. In this section, we relax this assumption to obtain more flexible micro control strategies. For example, no matter what size the area of hotspot regions is, we should turn the micro BSs into sleep mode if the optimal micro BS coverage is zero. On the other hand, if the optimal micro BS coverage is larger/smaller than hotspot regions, as shown in Fig. 3, we should enhance/reduce the transmit power of micro BSs to expand/shrink the coverage area. Therefore, the ASR ratio $\widetilde{\nu}_m$ and the coverage ratio $\widetilde{\gamma}_m$ can be larger or smaller than the traffic rate ratio ν_m and the area ratio γ_m respectively. Next, we present three micro BS control strategies.

A. Sleep Control Strategy

We first study the relationship between the HCN EE_{opt} and both area ratio γ_m and the traffic rate ratio ν_m, and then present the micro BS sleep control strategy. The relationship between ν_m and EE_{opt} implies that when power consumption per unit coverage area of micro BSs is larger than that of macro BSs $((P_m^c/S_{hp}) > (P_M^c/S_{nhp}))$, using a micro BS to cover a hotspot will make the optimal EE decrease with traffic rate in hotspot regions. Therefore, we can turn off the micro BSs and use the macro BSs to cover all of the hotspot regions. Note that such scenario actually the homogeneous network scenario and according to the expression of EE of HCNs, we can obtain ASR provided by macro BSs is

$$ASR_{sleep} = \lambda_M D(\alpha, \beta_{th}). \tag{33}$$

We compute the EE under two constraints as follows:

A) The ASR provided by macro BSs should equal to the average traffic rate in the whole area.
B) The SINR of the users in cell edge should equal to the SINR threshold.

Therefore, the EE in such scenario can be expressed as follow:

$$\begin{aligned} EE_M &= \frac{\lambda_M D(\alpha, \beta_{th})}{\lambda_m P_m^s + \lambda_M \sigma_n^2 \beta_{th} \left(\frac{-\ln P_{edge}}{\pi \lambda_M}\right)^{\frac{\alpha}{2}} + \lambda_M P_M^c} \\ &\approx \frac{D(\alpha, \beta_{th})\gamma_m}{\nu_m P_m^s + \gamma_m P_M^c}. \end{aligned} \tag{34}$$

Therefore, let $EE_M > EE_{opt}$ and we can obtain the condition of micro BS sleep control:

$$\frac{\lambda_m P_m^c + \lambda_M P_M^c}{\lambda_m P_m^s + \lambda_M P_M^c} > \frac{1+\nu_m}{1+\gamma_m}. \tag{35}$$

Note that the term $\lambda_m P_m^c + \lambda_M P_M^c$ is the power consumption per unit area when both macro BSs and micro BSs are active. The term $\lambda_m P_m^s + \lambda_M P_M^c$ are the power consumption per unit area if only macro BSs are active. In the special case where $P_m^s = P_m^c$, the condition of micro BS sleep control becomes $\gamma_m > \nu_m$.

B. Coverage Expansion Control Strategy

The relationship between area ratio γ_m and EE_{opt} implies that if regions area ratio is so small that the condition $(P_m^c/S_h) > (\gamma_m/\nu_M) \times (P_M^c/S_w)$ is satisfied, a higher coverage ratio $\widetilde{\gamma}_m > \gamma_m$ will lead to higher HCN EE until the condition $(P_m^c/S_h) < (\gamma_m/\nu_M) \times (P_M^c/S_w)$ is met. Therefore, expending the coverage of micro BSs properly can improve EE.

Specifically, if $\nu_m > 1$, the traffic rate in hotspot regions is higher than that in non-hotspot regions and thus the average traffic rate in the coverage area of micro BSs will decrease when the micro BS coverage expands. Therefore, the ASR provided by micro BSs can also be reduced. As a result, expanding the micro BS coverage region leads to $\widetilde{\gamma}_m > \gamma_m$ and $\widetilde{\nu}_m < \nu_M$. Note that the EE_{opt} increases monotonically with the area ratio γ_m and but decreases with the traffic rate ratio ν_m, when conditions $\nu_M P_m^c - P_M^c \gamma_m^2 > 0$ and $\gamma_m P_M^c - P_m^c < 0$ are both satisfied. Consequently, these two requirements become the execution condition of micro BS coverage expansion when $\nu_m > 1$.

On the other hand, if $\nu_m < 1$, the traffic rate in hotspot regions is lower than that in non-hotspot regions and thus the average traffic rate in the coverage area of micro BSs will increase when the micro BS coverage expands. Therefore, the ASR provided by micro BSs will also increase. As a result, expanding the micro BS coverage region leads to $\widetilde{\gamma}_m > \gamma_m$ and $\widetilde{\nu}_m > \nu_M$. Note that the EE_{opt} increases monotonically with the area ratio γ_m and the rate ratio ν_m, when conditions $\nu_M P_m^c - P_M^c \gamma_m^2 > 0$ and $\gamma_m P_M^c - P_m^c > 0$ are both satisfied. Consequently, these two requirements become the execution condition of micro BS coverage expansion when $\nu_m < 1$.

Hence, we obtain the execution conditions of micro BS coverage expansion:

$$\begin{cases} \frac{P_m^c}{P_M^c} > \max\left(\frac{\gamma_m^2}{\nu_m}, \gamma_m\right), & \nu_m > 1 \\ \nu_m > \gamma_m, \frac{P_m^c}{P_M^c} > \frac{\gamma_m^2}{\nu_m}, & \nu_m < 1. \end{cases} \tag{36}$$

We further study the optimal coverage ratio $\widetilde{\gamma}_m^{opt}$ for micro BS coverage expansion control strategy. Note that the HCN EE can be improved through expanding the coverage of micro BSs when the conditions (36) are met and thus the largest (optimal) coverage ratio of micro BSs can be achieved by choosing a smallest coverage ratio which makes the conditions (36) are no longer satisfied. Therefore, we can obtain the optimal coverage ratio:

$$\begin{cases} \widetilde{\gamma}_m^{opt} = \max\left(\sqrt{\nu_m \frac{P_m^c}{P_M^c}}, \frac{P_m^c}{P_M^c}\right), & \nu_m > 1 \\ \widetilde{\gamma}_m^{opt} = \sqrt{\nu_m \frac{P_m^c}{P_M^c}}, & \nu_m < 1 \end{cases}. \tag{37}$$

Because the total volume of traffic demands remains the same whether or not the coverage expanding control strategy is adopted. Thus we have:

$$\begin{aligned} &\frac{\gamma_m}{1+\gamma_m}\frac{\nu_m}{1+\nu_m} + \frac{1}{1+\gamma_m}\frac{1}{1+\nu_m} \\ &\qquad = \frac{\tilde{\gamma}_m^{opt}}{1+\tilde{\gamma}_m^{opt}}\frac{\tilde{\nu}_m}{1+\tilde{\nu}_m} + \frac{1}{1+\tilde{\gamma}_m^{opt}}\frac{1}{1+\tilde{\nu}_m}. \end{aligned} \tag{38}$$

Then, the ASR ratio can be obtained as follow:

$$\tilde{\nu}_m = \frac{\kappa - 1}{\tilde{\gamma}_m^{opt} - \kappa}, \tag{39}$$

where $\kappa = (1+\nu_M\gamma_m)(1+\tilde{\gamma}_m^{opt})/(1+\gamma_m)(1+\nu_M)$. In order to guarantee at least one micro BS in each hotspot, the density of micro BSs should equal to the density of hotspot and remain unchanged in the coverage expanding control strategy. According to expressions (20)–(22) given in Section IV, the transmit powers and densities of macro/micro BSs can be obtained using the values of coverage ratio $\tilde{\gamma}_m^{opt}$ and ASR ratio $\tilde{\nu}_m$.

C. Coverage Shrinking Control Strategy

The relationship between area ratio γ_m and EE_{opt} also implies that if regions area ratio is so large that the condition $(P_m^c/S_h) < (\gamma_m/\nu_M) \times (P_M^c/S_w)$ is satisfied, a lower coverage ratio $\widetilde{\gamma}_m < \gamma_m$ will lead to higher EE until the condition $(P_m^c/S_h) > (\gamma_m/\nu_M) \times (P_M^c/S_w)$ is satisfied. Therefore, shrinking the micro BS coverage properly can improve EE.

If $\nu_m > 1$, the traffic rate in hotspot regions is higher than that in non-hotspot regions and thus the average traffic rate in the coverage area of micro BSs will decrease when the micro BS coverage shrinks. Therefore, the ASR provided by macro BSs should increase. As a result, reducing the micro BS coverage region leads to $\widetilde{\gamma}_m < \gamma_m$ and $\widetilde{\nu}_m < \nu_M$. Note that the optimal EE_{opt} increases monotonically with the area ratio γ_m and decreases with the traffic rate ratio ν_m, when conditions $\nu_M P_m^c - P_M^c \gamma_m^2 < 0$ and $\gamma_m P_M^c - P_m^c < 0$ are satisfied. Consequently, these two requirements become the execution condition of micro BS coverage shrinking when $\nu_m > 1$.

On the other hand, if $\nu_m < 1$, the traffic rate in hotspot regions is lower than that in non-hotspot regions and thus the average traffic rate in the coverage area of micro BSs will increase when the micro BS coverage shrinks. Therefore, the ASR provided by macro BSs should decrease. As a result, expanding the micro BS coverage region leads to $\widetilde{\gamma}_m < \gamma_m$ and $\widetilde{\nu}_m > \nu_M$. Note that the EE_{opt} increases monotonically with the area ratio γ_m and the traffic rate ratio ν_m, when conditions $\nu_M P_m^c - P_M^c \gamma_m^2 < 0$ and $\gamma_m P_M^c - P_m^c > 0$ are satisfied. Consequently, these two requirements becomes the execution condition of micro BS coverage shrinking when $\nu_m < 1$.

Therefore, we obtain the micro BS coverage shrinking execution conditions:

$$\begin{cases} \nu_m < \gamma_m, \frac{P_m^c}{P_M^c} < \frac{\gamma_m^2}{\nu_m}, & \nu_m > 1 \\ \frac{P_m^c}{P_M^c} < \min\left(\frac{\gamma_m^2}{\nu_m}, \gamma_m\right), & \nu_m < 1 \end{cases}. \tag{40}$$

We further study the optimal coverage ratio $\widetilde{\gamma}_m^{opt}$ for micro BS coverage shrinking control strategy. Note that the HCN EE can be improved by means of shrinking the micro BS coverage when the conditions (40) are met and thus the smallest (optimal) micro BS coverage ratio can be achieved by choosing a largest coverage ratio which makes the conditions (40) are no longer satisfied. As a result, we can obtain the optimal coverage ratio:

$$\widetilde{\gamma}_m^{opt} = \min\left(\sqrt{\nu_m \frac{P_m^c}{P_M^c}}, \frac{P_m^c}{P_M^c}\right). \tag{41}$$

The transmit powers and densities of macro/micro BSs can be obtained similar to the coverage expansion control strategy.

VI. Numerical Results

In this section, simulation results are presented to validate theoretical analysis and justify the effectiveness of the proposed methods. We demonstrate the impact of the area ratio γ_m on EE under different values of traffic rate ratio ν_m. The performance of the proposed configuration approach and three micro BS control strategies including sleep control, coverage expansion control and coverage shrinking control are also evaluated via simulation using MATLAB. In our simulation, we set the key parameters as follows: $\alpha = 4$, $P_{edge} = 0.05$, $P_m^c = 10$ W and $P_M^c = 30$ W.

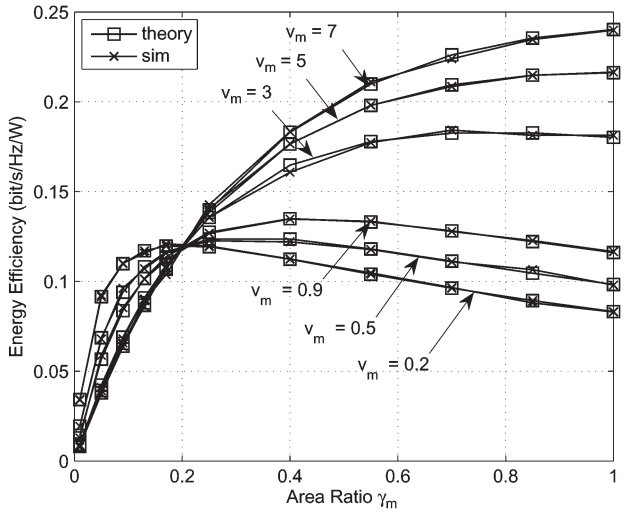


Fig. 4. EE achieved by HCN optimal configuration vs. γ_m and ν_m.

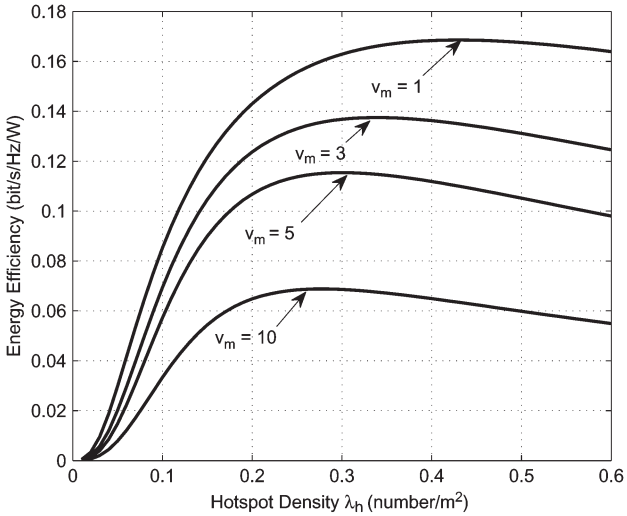


Fig. 5. HCN EE vs. hotspot density under different values of traffic rate ratio. ($\nu_m = 1$, 3, 5, 10 and hotspot area $= 5$ m^2).

The EE performance achieved by the HCN optimal configuration and under different values of γ_m and ν_m is shown in Fig. 4, where both the theory curves and the Monte-Carlo simulation results are presented. As can be observed from the figure, the EE decreases with the traffic rate ν_m under small area ratio $\gamma_m < 0.2$ and increases with the traffic rate ν_m under large area ratio $\gamma_m > 0.2$, which is consistent to (30). In addition, the HCN EE first increases with γ_m under small γ_m. Then HCN EE decreases under large γ_m. These results imply that the micro BSs should be turned on when HCN EE increases with γ_m and be put into sleep mode when HCN EE decreases with γ_m.

The simulation results of HCN EE achieved by the optimal configuration under different values of traffic rate ratio are shown in Fig. 5. As can be observed from the figure, the HCN EE does not always increase with hotspot density λ_h. When λ_h is relatively small, the HCN EE increases because the micro

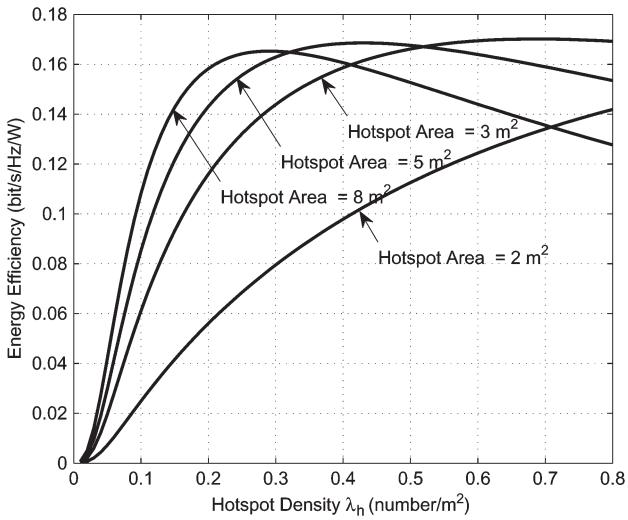


Fig. 6. HCN EE vs. hotspot density under different values of hotspot area. (hotspot area $= 1$ m^2, 3 m^2, 5 m^2, 8 m^2 and $\nu_m = 10$).

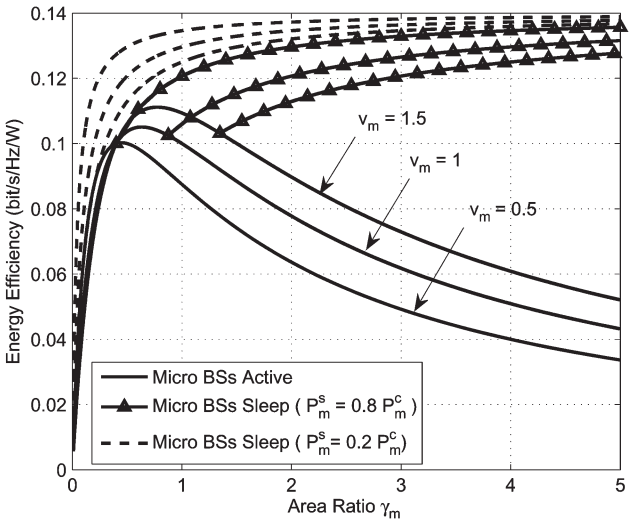


Fig. 7. HCN optimal configuration vs. micro BS sleep control with small traffic rate ratio. ($\nu_m = 0.5$, 1, 1.5, $P_m^s = 0.2P_m^c$ and $P_m^s = 0.8P_m^c$).

BS is more energy-efficient than the macro BS in terms of guaranteeing the coverage of hotspot regions. However, the interference of the micro BS diminishes HCN EE severely with increasing number of the micro BS and thus the HCN EE decreases when λ_h becomes large. In addition, the maximum value of HCN EE decreases with traffic rate ratio ν_m, which is due to larger traffic rate in hotspot regions requires larger transmit power of micro BS and thus leads to more severe interference. The HCN EE achieved by the optimal configuration under different values of hotspot area is shown in Fig. 6. Similar to Fig. 5, the HCN EE does not always increase with hotspot density λ_h and the maximum value of HCN EE decreases with traffic rate ratio ν_m, since larger area of hotspot regions also requires larger transmit power of micro BS and leads to more severe interference.

In Fig. 7, the solid lines show the EE achieved by the optimal configuration under low traffic rate ratio. The dashed lines and the triangle-mark lines show the micro BS sleep control strategy

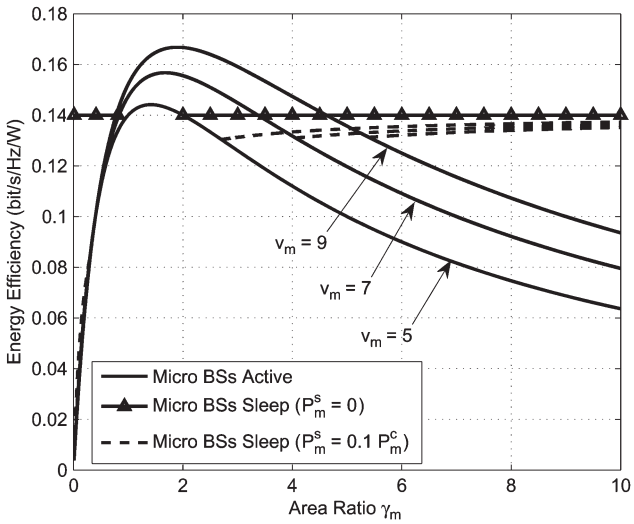


Fig. 8. HCN optimal configuration vs. micro BS sleep control with large traffic rate ratio. ($\nu_m = 5$, 7, 9, $P_m^s = 0$ and $P_m^s = 0.1P_m^c$).

with $P_m^s = 0.2P_m^c$ and $P_m^s = 0.8P_m^c$ respectively. As can be observed from the figure, the EE can always be improved by the micro BS sleep control when $P_m^s = 0.2P_m^c$, which is consistent with (35). However, the micro BS sleep control is energy-efficient only under large area ratio γ_m when $P_m^s = 0.8P_m^c$. These results show that the EE in the micro BSs sleep mode also has an important effect on the micro BSs sleep control strategy under small traffic rate ratio and the micro BSs can always be put into sleep mode when the traffic rate ratio and the sleep power consumption of micro BSs are both low.

Fig. 8 shows the HCN EE achieved by the optimal configuration and the micro BS sleep control under high traffic rate ratio. The solid lines show the HCN EE achieved by the optimal configuration while the triangle-mark lines and the dashed lines show the micro BSs sleep control strategy with $P_m^s = 0$ and $P_m^s = 0.1P_m^c$ respectively. We use the extreme case $(P_m^s = 0)$ to show the highest HCN EE achieved by the micro BS sleep control. As can be observed from the figure, the HCN EE can only be improved by the micro BS sleep control under the small and large area ratios γ_m even if the micro BS power consumption is 0. These results show that the EE in the micro BSs sleep mode has no impact on the micro BSs sleep control strategy under high traffic rate ratio and the micro BSs can always be put into sleep mode when the traffic rate ratio is high.

In Figs. 9 and 10, the solid lines show the HCN EE achieved by the optimal configuration. The dashed lines and the triangle-mark lines show the micro BS coverage expansion and shrinking control strategies respectively. From the figure, we can see that the EE can be improved by using the micro BS coverage expansion control when the area ratio γ_m is relatively small. On the other hand, the EE can be improved by using the micro BS coverage shrinking control when the area ratio γ_m is relatively large. These results show that when the area ratio γ_m is relatively small, the micro BSs should cover part of the non-hotspot regions. However, when the area ratio γ_m is relatively large, the macro BSs should cover part of hotspot regions, which is consistent to the theoretical analysis in Section V.

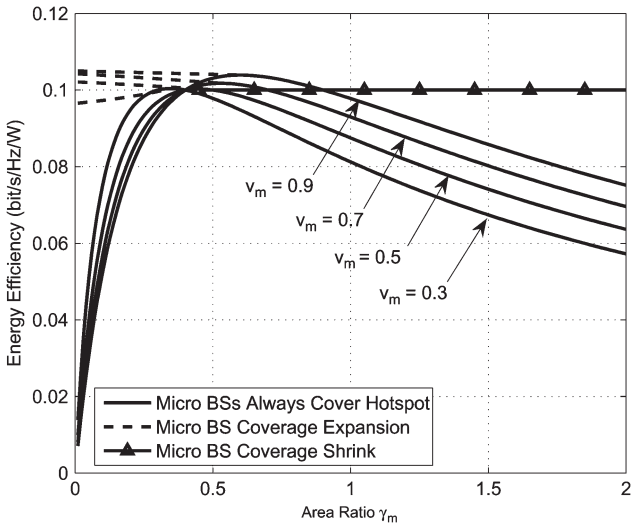


Fig. 9. HCN optimal configuration vs. micro BS coverage expansion and shrinking with small traffic rate ratio. ($\nu_m = 0.3, 0.5, 0.7, 0.9$).

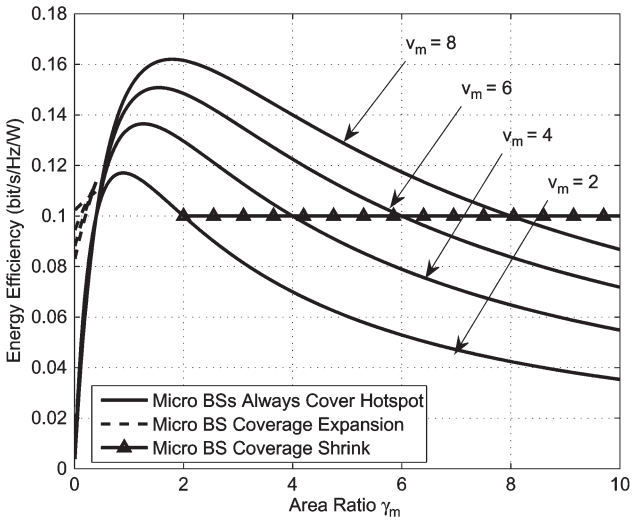


Fig. 10. HCN optimal configuration vs. micro BS coverage expansion and shrinking under large traffic rate ratio. ($\nu_m = 2, 4, 6, 8$).

VII. Conclusion

We have characterized the heterogeneous degree of large-scale user behavior and presented closed-form formulas that establish the quantitative relationship between large-scale user behavior and energy-efficient HCN configuration. In addition, we have proposed three energy-efficient control strategies of micro BSs for the special case that the traffic demands and/or the size of hotspot regions are much lower than those of the non-hotspot regions. Simulation results validate the theoretical analysis and demonstrate that the proposed control strategies can potentially lead to significant improvement of HCN EE. These theoretical results can be used to determine the density, the transmit power and the control strategies of BSs for HCNs to achieve optimal EE. The possible extensions of this work could include multiple antennas, bandwidth allocation and interference cancellation.

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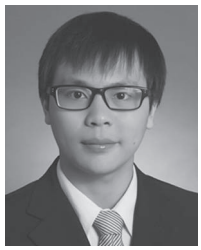
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