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Energy Efficiency for 5G Multi-Tier Cellular Networks

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Abstract

The heterogeneous cellular network (HCN) is most significant as a key technology for future fifth-generation (5G) wireless networks. The heterogeneous network consists of randomly macrocell base stations (MBSs) overlaid with femtocell base stations (FBSs). Stochastic geometry has been shown to be a very powerful tool to model, analyze, and design networks with random topologies such as wireless ad hoc, sensor networks, and multi-tier cellular networks. HCNs can be energy-efficiently designed by deploying various BSs belonging to different networks, which has drawn significant attention to one of the technologies for future 5G wireless networks. In this chapter, we propose switching off/on systems enabling the BSs in the cellular networks to efficiently consume the power by introducing active/sleep modes, which is able to reduce the interference and power consumption in the MBSs and FBSs on an individual basis as well as improve the energy efficiency of the cellular networks. We formulate the minimization of the power consumption for the MBSs and FBSs as well as an optimization problem to maximize the energy efficiency subject to throughput outage constraints, which can be solved by the Karush-Kuhn-Tucker (KKT) conditions according to the femto tier BS density. We also formulate and compare the coverage probability and the energy efficiency in HCN scenarios with and without coordinated multi-point (CoMP) to avoid coverage holes.

Keywords: heterogeneous cellular networks, stochastic geometry, poisson point process (PPP), different sleeping policy, CoMP, energy efficiency, power consumption

1. Introduction

Looking ahead to the year 2020 and beyond, there will be explosive growth in mobile data traffic. The existing cellular networks are experiencing some basic challenges such as higher data rates, excellent end-to-end performance, user coverage in hot-spots and crowded areas with lower latency energy consumption and amount of expenditure per information transfer.

The fifth-generation (5G) cellular networks are envisioned to overcome these challenges. It is expected that 5G systems will have the ability to adopt a multi-tier architecture consisting of macrocells, different types of licensed small cells, relays, and device-to-device (D2D) networks to serve users with different quality-to-service (QoS) requirements in an energy efficient manner [1]. It is expected that 5G wireless communication technologies will attain 1000 times higher mobile data volume per unit area, 10–100 times number of connecting devices and longevity of battery 10 times, user data rate, and 5 times reduced latency [2]. A key attribute of 5G networks is that the expected cell data rate will be of the order of 10 Gb/s, whereas average data rate for single 4G networks is 1 Gb/s. Therefore, such a heterogeneous cellular network (HCN) architecture has drawn significant research attention and been recognized as a key technology for future 5G wireless networks. An HCN consisting of K tiers [3] is considered, in which each tier models base stations (BSs) of a particular class such as femtocells, picocells, microcells, or macrocells as shown in **Figure 1a**. The energy efficiency (EE) of small cell networks is of great concern as the BS density will be significantly increased. We study that
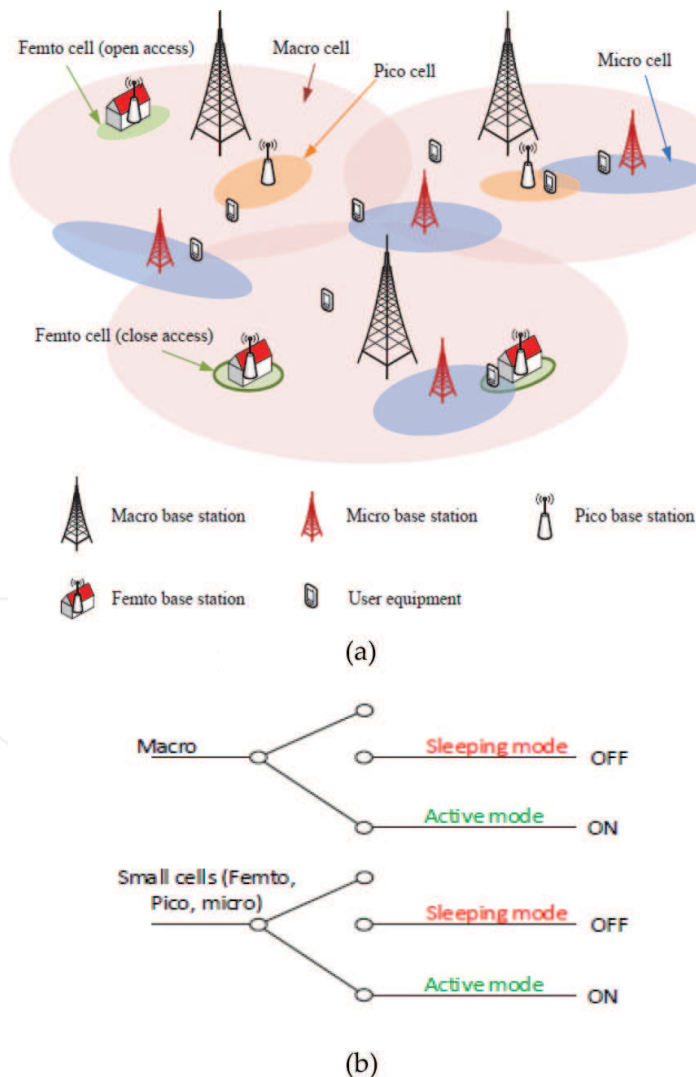

(a)

(b)

Figure 1. (a) Heterogeneous cellular networks [11] and (b) switching system for BSs power consumption.

the optimal energy efficiency of a two-tier heterogeneous network consists of a macrocell and many small cells under coverage performance constraints for different deployments. The other more important challenge is the greater energy consumption in HCNs because of the dense and randomly deployment of femto BSs (FBSs). In order to realize the aspect of green wireless networks, energy efficiency is an important tool. Because of the increasing share of wireless systems, the total energy expended in communications and networking systems are deemed important. Report shows that total amount of global carbon dioxide emission is originated from information and communication technologies (ICT), more than 9% of emits from wireless and mobile communication [4]. However, within the sleep mode, some key issues must be considered. When BSs are switched off, radio coverage and QoS must be still guaranteed. As BSs are densely deployed, users in sleeping BS coverage can be served by neighboring active BSs by slightly increasing BS transmit power [5]. For sleep mode operation, small cells can always be managed by operators. Nowadays, efforts have been made related to power saving in cellular networks with the introduction of sleep modes [6–8] for BSs. Power consumption is reduced by using sleep mode in low traffic [9] as a case study for saving the energy of macro BSs (MBSs). In a wireless network where multiple links share the same radio spectrum, the signal-to-interference-plus-noise ratio (SINR) at any receiver is a function of the locations of the transmitting nodes and the transmit powers of the transmitters using the same channel. Therefore, the network topology has a fundamental impact on the performance of wireless networks. By assuming that the network operators have some information of the traffic usage patterns, they can employ a coordinated sleeping mode [9], where certain MBSs will be shut off, while others increase their coverage areas to avoid coverage hole [10].

Thus, we provide a stochastic geometry-based model for studying the BSs cooperation in downlink HCNs, which consists of two tiers of located BSs where each tier is characterized by different density and power and develops the performance of coverage probability. We investigate the energy saving problem through switching off/on for MBS and FBS in HCNs. We also derive two-tier HCNs under different sleeping policies and formulate the power consumption minimization for MBS and FBS. An optimization problem is formulated to maximize the energy efficiency subject to throughput outage constraints and solved by the Karush-Kuhn-Tucker (KKT) conditions in terms of femto tier BS density. BSs in sleeping mode might cause coverage holes, which have a negative impact on the connectivity of the network, combined coordinated multi-point (CoMP) and BS sleeping scheme in HCNs for energy efficiency. We introduce the energy efficiency performance based on two-state Markovian wireless channel model.

2. System model

We consider a HCN composed by K independent network tiers of BSs with different deployment densities and transmit powers in **Figure 1a**. We assume that the BSs in the ith tier are spatially distributed as a Poisson point process (PPP) φ of density λ, transmit at a power P_i, and have a SINR target of threshold T. The locations of the BSs in the two tiers are distributed as two spatial PPPs in the $\mathbb{R}^2$ Euclidian space denoted by ϕ_M and ϕ_F, with densities λ_M and λ_F, respectively. The probability density function (pdf) is given by $f(r) = 2\pi\lambda r \exp\left(-\lambda\pi r^2\right)$.
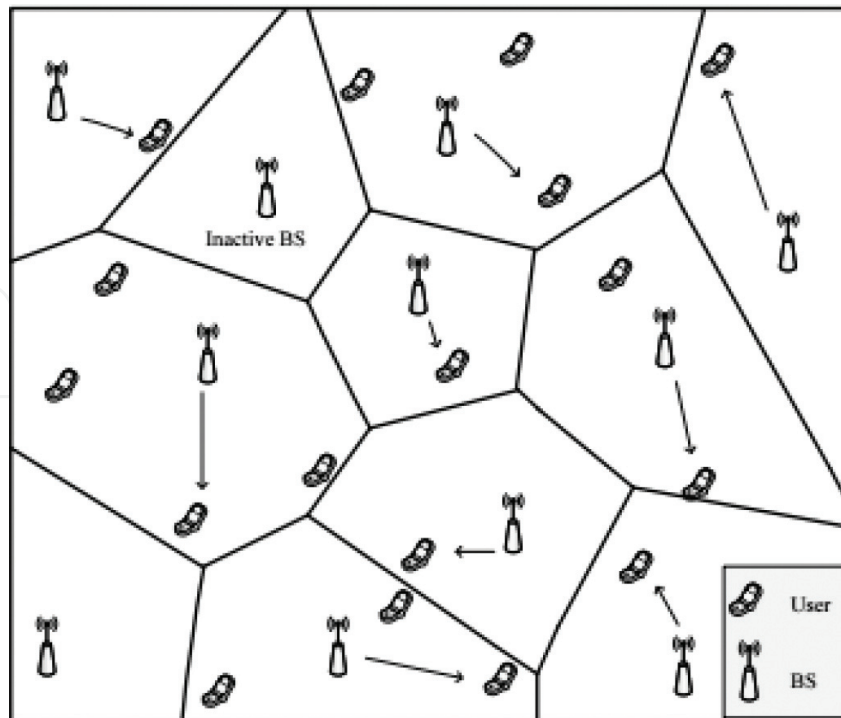
Figure 2. Poisson distributed BSs and mobiles, with each mobile associated with the nearest BS. The cell boundaries are shown and form a Voronoi tessellation [12].
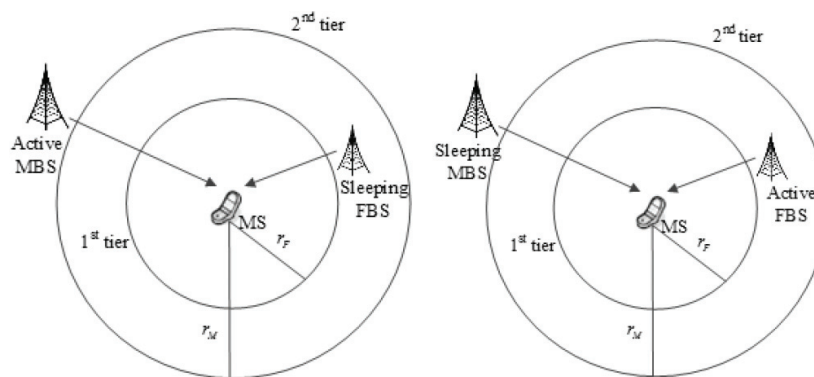

Figure 3. The activity level of BSs and location of users.

We focus on a typical user located and assume that a subset of the total ensemble of BSs cooperates by jointly transmitting a message to this tagged receiver, if we consider a nearest BS connectivity model, where a mobile tried to connect with its closest BS. This results in a Voronoi tessellation of the plane corresponding to the BS locations. In this case, the service area of a BS is the Voronoi cell associated with it (in **Figure 2**). When femtocells operate in closed access mode, only registered femtocells user can be allowed to contact to FBSs. On other hand, in open access mode, both macrocell user and unregistered femtocells user can be allowed to contact to FBSs, and then, the coverage region of FBS includes femtocells user and macrocell user connecting to femtocell as shown in **Figure 3**. We can see that r_M and r_F are the distances of MBS and FBS from user. From our proposed scheme, when the FBS is in sleeping mode, the

user communicates with the active MBS. On the contrary, the user communicates with the active FBS as shown in **Figure 3**.

2.1. Signal-to-interference-plus-noise ratio

We denote a BS by its location, while the user is at the origin 0. For downlink transmission of a MBS to the typical user 0, the SINR experienced by a macrocell user is given by:

$$SINR = \frac{P_i h_i r^{-\alpha}}{\sum\limits_{i=1,\ i \neq j} P_j h_j |r_i|^{-\alpha} + \sigma^2}, \tag{1}$$

where h is channel, the background noise is assumed to be additive white Gaussian with variance σ^2 and α being the path loss exponent.

2.2. Power consumption

Without employing any sleeping mode at each base station in the ith tier, the average power consumption of the ith tier heterogeneous networks is given by

$$P_{\text{Het},i} = \lambda_i (P_{io} + \Delta_i \beta P_i). \tag{2}$$

In a two-tier cellular network, the total power consumption comes from macrocell tier and femtocell tier, which are expressed as:

$$P_{\text{total}} = \underbrace{\lambda_M (P_{M0} + \Delta M \beta P_{MBS})}_{macro-tier} + \pi r_M^2 \underbrace{\lambda_F (P_{F0} + \Delta F \beta P_{FBS})}_{femto-tier}, \tag{3}$$

where P_{M0} and P_{F0} are the static power expenditure of the MBS and FBS, and ΔM, and ΔF are the slope of the load-dependent power consumption in MBS and FBS, respectively. β is the power control coefficient of MBS and FBS. P_{MBS} and P_{FBS} are the transmit powers of MBSs and femto BSs, respectively.

2.3. Network energy efficiency

The throughput outage probability defined as the probability that a user in the macro (femto) tier is unable to achieve a certain minimum target throughput as follows:

$$\begin{aligned} \varepsilon_M(\lambda_F) &= 1 - \mathbb{P}\Big(B_M \ln(1 + SINR_M) > T_M\Big) \\ \varepsilon_F(\lambda_F) &= 1 - \mathbb{P}\Big(B_F \ln(1 + SINR_F) > T_F\Big). \end{aligned} \tag{4}$$

Network energy efficiency can be defined as the ratio of the total amount of throughput and total power consumption in the network. The energy efficiency (EE) function can be written as:

$$EE = \frac{\lambda_M C_M + \lambda_F \pi r_M^2 C_F}{P_M + \pi r_M^2 P_F}$$

$$= \frac{\lambda_M (1-\varepsilon_M)\log_2(1 + SINR_M) + \lambda_F \pi r_M^2 (1-\varepsilon_F)\log_2(1 + SINR_F)}{\lambda_M (P_{M0} + \Delta M P_M) + \lambda_F \pi r_M^2 (P_{F0} + \Delta F P_F)},$$

(5)

where C is the throughput and ε is coverage probability of macro and femto users, respectively.

3. Coverage probability

In this section, we use stochastic geometry theory to analyze the coverage performance of MBS and FBS system under different allocation strategies. Under orthogonal deployment, the spectrum allocation for MBS and FBS is orthogonal, which avoids the cross-tier interference [4]. The received SINR of macro-mobile station (MS) located at the cell boundary is given by:

$$SINR_M = \frac{P_{M,tr} h_M r_M^{-\alpha}}{\sigma^2}.$$

(6)

To guarantee the coverage performance of macrocell, the received SINR of the MS at the macrocell edge should satisfy the following equation:

$$\mathbb{P}[SINR_M {\geq} T_M] = \mathbb{P}\left[\frac{P_{M,tr} h_M r_M^{-\alpha}}{\sigma^2} {\geq} T_M\right].$$

(7)

There is no interference coordination in femtocell. So, inter-tier interference will provide in femtocell. The received SINR of MS at femtocell edge is written as:

$$SINR_F = \frac{P_{F,tr} h_F r_F^{-\alpha}}{I_F + \sigma^2}.$$

(8)

Similar way, the received SINR of the MS at the femtocell edge should satisfy the following equation:

$$\mathbb{P}[SINR_F {\geq} T_F] = \mathbb{P}\left[\frac{P_{F,tr} h_F r_F^{-\alpha}}{I_F + \sigma^2} {\geq} T_F\right] = \mathbb{P}\left[h_F {\geq} \frac{T_F r_F^{\alpha}}{P_{F,tr}}(I_F + \sigma^2)\right].$$

(9)

Conditioning on the nearest BS being at a distance r from the typical user, the probability of coverage averaged over the plane is written as:

$$p_c(T, \lambda, \alpha) = \mathbb{E}_r[\mathbb{P}[SINR > T|r]] = \int\limits_{r>0} \mathbb{P}[SINR > T|r]f_r(r)dr$$

$$= \int\limits_{r>0} \mathbb{P}\left[\frac{h_F r^{-\alpha}}{\sigma^2 + I_F + I_M} > T\Big|r\right]e^{-\lambda\pi r^2}2\pi\lambda r dr$$

$$= \int\limits_{r>0} e^{-\lambda\pi r^2}\mathbb{P}[hr^{-\alpha} > T_F(\sigma^2 + I_F + I_M)|r]2\pi\lambda r dr. \tag{10}$$

$$= \int\limits_{r>0} e^{-\lambda\pi r^2}\mathbb{P}[h > Tr^{\alpha}(\sigma^2 + I_F + I_M)|r]2\pi\lambda r dr$$

Using the fact that $h \approx \exp(\mu)$, the coverage probability can be expressed as:

$$\mathbb{P}[h > Tr^{\alpha}(\sigma^2 + I_F + I_M)|r] = \mathbb{E}_{I_\psi}[\mathbb{P}[h > Tr^{\alpha}(\sigma^2 + I_F + I_M)|r, I_r]]$$

$$= \mathbb{E}_{I_r}[\exp\left(-\mu Tr^{\alpha}(\sigma^2 + I_F + I_M)\right)|r] = e^{-\mu Tr^{\alpha}\sigma^2}\mathcal{L}_{I_F}(\mu Tr^{\alpha})\mathcal{L}_{I_M}(\mu Tr^{\alpha}), \tag{11}$$

where $\mathcal{L}_{I_F}(s)$ and $\mathcal{L}_{I_M}(s)$ are the Laplace transform of random variable I_φ evaluated at the distance to the closest BS from the origin. This gives a coverage expression:

$$p_c(T, \lambda, \alpha) = \int\limits_{r>0} e^{-\lambda\pi r^2}e^{-\mu Tr^{\alpha}\sigma^2}\mathcal{L}_{I_F}(\mu Tr^{\alpha})\mathcal{L}_{I_M}(\mu Tr^{\alpha})2\pi\lambda r dr. \tag{12}$$

The definition of Laplace transform yields [13]

$$\mathcal{L}_{I_r}(s) = \mathbb{E}_{I_\varphi}[e^{-sI_\varphi}] = \mathbb{E}_{I_\varphi}[\exp(-s\sum_i g_i R_i^{-\alpha})]$$

$$= \mathbb{E}_{I_\varphi}[\prod_i \exp(-sg_i R_i^{-\alpha})] = \mathbb{E}_{I_r}[\prod_i \mathbb{E}_g[\exp(-sg_i R_i^{-\alpha})]] \tag{13}$$

$$= \exp\left(-2\pi\lambda\int\limits_r^\infty \left(1-\mathbb{E}_g[\exp(-sg_i R_i^{-\alpha})]\right)vdv\right).$$

Now, we have

$$\mathcal{L}_{I_\varphi}(s) = \mathbb{E}_{\phi,\{g_i\}}[\prod_{i\in\phi} E_{g_i}[\exp(-sg_i R_i^{-\alpha})]] = \mathbb{E}_\Phi\left[\prod_{i\in\phi}\frac{\mu}{\mu + sR_i^{-\alpha}}\right] = \exp\left(-2\pi\lambda\int\limits_r^\infty \left(1-\frac{\mu}{\mu + sv^{-\alpha}}\right)vdv\right). \tag{14}$$

Let $g_i \approx \exp(\mu)$ and $s = \mu Tr^{\alpha}$.

$$\mathcal{L}_{I_\varphi}(\mu Tr^{\alpha}) = \exp\left(-2\pi\lambda\int\limits_r^\infty \frac{T}{T + (r/v)^{\alpha}}vdv\right), \tag{15}$$

Again, $u = (v/rT^{1/\alpha})^2$, then we get

$$\mathcal{L}_{I_\varphi}(\mu Tr^{\alpha}) = \exp\left(-2\pi\lambda T^{2/\alpha}\int\limits_{T^{-2/\alpha}}^\infty \frac{1}{1 + u^{\alpha/2}}du\right) = \exp\left(-2\pi\lambda\rho(T, \alpha)\right), \tag{16}$$

where $\rho(T, \alpha) = T^{2/\alpha}\int\limits_{T^{-2/\alpha}}^\infty \frac{1}{1 + u^{\alpha/2}}du.$

Putting (16) into (12) with gives the desired result.

4. Propose base stations sleep mode strategies

We know that the coverage probability is independent of the sleeping mode. However, we need to maintain the coverage of the cellular networks when we implement sleeping mode in MBSs through power control small cells as shown in **Figures 1b** and **3**. In Ref. [9], authors introduced active/sleep (on/off) modes in MBSs and improved the energy efficiency in cellular networks. In this chapter, we consider the HCNs comprised of macrocell and femtocell tiers. We propose switching off/on systems for the efficient power consumption at the BSs in the cellular networks, which introduce active/sleep modes in the MBSs and FBSs. The active/sleep modes reduce the interference and power consumption as well as improve the energy efficiency of the cellular networks. We derive the two-tier HCNs under different sleeping policies as well as formulate power consumption minimization for the MBSs and FBSs. An optimization problem is formulated to maximize the energy efficiency subject to throughput outage constraints as well as solved by the KKT conditions in terms of the femto tier BS density. Thus, the total power consumed by each BS in the macro and femto tiers is modeled as follows:

$$
\begin{aligned}
P_M &= \begin{cases} P_{M0} + \Delta M \beta P_{MBS}, & \text{for } \textit{active mode} \\ 0_M, & \text{for } \textit{sleeping mode} \end{cases} \\
P_F &= \begin{cases} P_{F0} + \Delta F \beta P_{FBS}, & \text{for } \textit{active mode} \\ 0_F, & \text{for } \textit{sleeping mode} \end{cases}
\end{aligned}
\tag{17}
$$

From Eq. (17), we can see that the MBS and FBS are active modes, and the maximum power is consumed by BSs. Otherwise, power consumption is zero when it is in sleeping mode.

4.1. Random sleeping

In random sleeping strategy, we take it as a Bernoulli trial, that is, each BS actives with probability q and sleeps with probability $1 - q$ independently for macro and femto BSs [9, 14]. Then, the sleep modes of other BSs are determined according to the distances between a BS and user. Power consumption of random sleeping problem is formulated as follows:

$$
P_{RS}(MBS) = \lambda_M q_M (P_{MO} + \Delta M \beta P_{MBS}) + \lambda_M (1 - q_M) P_{sleep},
\tag{18}
$$

and

$$
P_{RS}(FBS) = \lambda_F q_F (P_{FO} + \Delta F \beta P_{FBS}) + \lambda_F (1 - q_F) P_{sleep}.
\tag{19}
$$

The power is consumed in the macro tier and femto tier BS when operating in the active and sleep mode, and then the total average power is given by:

$$P_{total} = \underbrace{\lambda_M q_M (P_{M0} + \Delta M \beta P_M) + \lambda_M (1 - q_M) P_{sleep}}_{macro-tier} + \pi r_M^2 .$$

$$\underbrace{\lambda_F (P_{F0} + \Delta F \beta P_F) + \lambda_F (1 - q_F) P_{sleep}}_{femto-tier}$$

(20)

Thus, the energy efficiency of the network for random sleeping is given by:

$$EE = \frac{\lambda_M (1 - \varepsilon_M) \log_2 (1 + SINR_M) + \pi r_M^2 \lambda_F (1 - \varepsilon_F) \log_2 (1 + SINR_F)}{\lambda_M q_M (P_{M0} + \Delta M \beta P_M) + \lambda_M (1 - q_M) P_{sleep} + \pi r_M^2 \lambda_F (P_{F0} + \Delta F \beta P_F) + \lambda_F (1 - q_F) P_{sleep}}.$$

(21)

The network energy efficiency is expressed in the units of nats/Joule. The numerator in Eq. (21) is the total average throughput achieved by all the users in the two-tier network, and the denominator is the total power consumption use of Eqs. (18), (19) and (20).

4.2. Strategic sleeping

The sleep mode strategy can be considered as a load-aware policy and can incorporate traffic profile in the optimization problem. By applying strategic sleeping, the average power consumption can be expressed as:

$$P_{SS}(MBS) = \lambda_M \Big(E\{s\}(P_{MO} + \Delta M \beta_M P_{MBS}) + \lambda_M (1 - E\{s\}) P_{sleep} \Big),$$

(22)

and

$$P_{SS}(FBS) = \lambda_F \Big(E\{s\}(P_{FO} + \Delta F P_{MBS}) + \lambda_F (1 - E\{s\}) P_{sleep} \Big).$$

(23)

In case of random sleeping mode, a network is developed that is adaptive to the fluctuating activity levels during the day. The strategic sleeping mode can go one step further. It can model a network that is adaptive to fluctuating activity levels within the location [9]. In addition, the strategic sleeping model can measure the impact of cooperation among MBSs. The energy efficiency of the network for strategic sleeping is given by:

$$EE = \frac{\lambda_M (1 - \varepsilon_M) \log_2 (1 + SINR_M) + \lambda_F \pi r_M^2 (1 - \varepsilon_F) \log_2 (1 + SINR_F)}{\underbrace{\lambda_M \Big(E\{s\}(P_{MO} + \Delta M \beta P_{MBS}) + \lambda_M (1 - E\{s\}) P_{sleep} \Big)}_{macro-tier}}$$

$$+ \underbrace{\pi r_M^2 \Big(\lambda_F \Big(E\{s\}(P_{FO} + \Delta F \beta P_{MBS}) + \lambda_F (1 - E\{s\}) P_{sleep} \Big) \Big)}_{femto-tier}.$$

(24)

Similar way, the network energy efficiency is expressed as the numerator in Eq. (24) of the total average throughput achieved by all the users in the two-tier network and the denominator of the total power consumption use of Eqs. (22) and (23).

4.3. Optimization problem

To solve the following multi-objective optimization problem [14]:

$$\max_{\lambda_F} \ EE(\lambda_F)$$

$$s.t. \quad 1-\mathbb{P}\Big(B_M \ln(1 + SINR_M) > T_M\Big) \leq \varepsilon_M, \tag{25}$$

$$1-\mathbb{P}\Big(B_F \ln(1 + SINR_F) > T_F\Big) \leq \varepsilon_F$$

where ε_M and ε_F denote the outage objectives guaranteeing a minimum target throughput for each user in the macro and femto tier, respectively. The optimal femto tier BS density λ_F^* that maximizes the energy efficiency of network subject to the downlink outage constraints is given by λ_F^*

$$\lambda_F^* = \begin{cases} [\lambda_{EE,F}] & \text{for } \mu_M^* = 0, \ \mu_F^* = 0 \ \text{(both inactive)} \\ \lambda_M(1-q)\zeta^{-1} & \text{for } \mu_M^* > 0, \ \mu_F^* = 0 \ \text{(macro active \& femto inactive)} \\ \lambda_F - \lambda_M q \zeta^{-1} & \text{for } \mu_M^* = 0, \ \mu_F^* > 0 \ \text{(macro inactive \& femto active)} \\ \lambda_F(1-q) & \text{for } \mu_M^* > 0, \ \mu_F^* > 0 \ \text{(both active)} \end{cases}, \tag{26}$$

where μ_M^* and μ_F^* are the Lagrange multipliers and $\zeta = (P_F/P_M)^{2/\alpha}$ is power ratio of BSs. The optimization problem in Eq. (25) is determined by satisfying the KKT conditions as follows:

$$\mathcal{L}(\lambda_{EE}, \mu_M, \mu_F, \lambda_F) = EE(\lambda_F) - \mu_M[1-\mathbb{P}\Big(B_M \ln(1 + SINR_M) > T_M\Big) - \varepsilon_M].$$
$$-\mu_F[1-\mathbb{P}\Big(B_F \ln(1 + SINR_F) > T_F\Big) - \varepsilon_F] \tag{27}$$

The KKT conditions are then listed as follows:

$$\frac{\partial \mathcal{L}(\lambda_F^*)}{\partial \lambda_F} = 0,$$

$$1-\mathbb{P}\Big(B_M \ln(1 + SINR_M) > T_M\Big) \leq \varepsilon_M \tag{28}$$

$$1-\mathbb{P}\Big(B_F \ln(1 + SINR_F) > T_F\Big) \leq \varepsilon_F$$

$$\mu_M^*[1-\mathbb{P}\Big(B_M \ln(1 + SINR_M) > T_M\Big) - \varepsilon_M] = 0.$$
$$\mu_F^*[1-\mathbb{P}\Big(B_F \ln(1 + SINR_F) > T_F\Big) - \varepsilon_F] = 0 \tag{29}$$
$$\mu_M^* > 0, \ \mu_F^* > 0$$

Based on the listed KKT conditions, evaluating each possible scenario for which μ_M^* and μ_F^* are either active or inactive gives the optimal femto tier BS density λ_F^*.

5. Combined coordinated multi-point (CoMP) transmission and BS sleeping scheme

In this section, we also evaluate the performance of the combined CoMP and BS sleeping scheme in a two-tier HCNs. The first tier is deployed as MBSs with a density of λ_M, and the second tier is deployed as FBSs with a density of λ_F.

5.1. BS cooperation

BS sleeping has been proved to be an effective technique for saving energy consumption in cellular networks. However, BSs in sleeping mode might cause coverage holes, which have a negative impact on the connectivity of the network. We conduct a stochastic geometry analysis to evaluate the performance of the proposed combined CoMP and BS sleeping scheme in HCNs for energy efficiency [10]. We apply CoMP to avoid coverage holes when the target SINR cannot be reached. Applying stochastic geometry tools, we formulate and compare the coverage probability and the energy efficiency in HCN scenarios with and without CoMP.

The cooperative set is composed of the closest BSs in each network tier to the user. The density of CoMP is the same as the tier contains BSs with the lowest density. The probability of CoMP happens is equal to the probability of awake MBSs q, and its density is $q\lambda_M$. We assume that the awake MBSs can always cooperate with FBSs to transmit, so that $n = K = 2$. Here, n is the number of cell cooperatives. The following lemma gives the coverage probability of the combined CoMP and BSs sleeping control.

Theorem [10]: In two-tier HCNs with CoMP and BSs sleeping, the coverage probability of a randomly located user is given by:

$$p_{c\_CoMP} = 4\pi^2 q^2 \lambda_M \lambda_F \int \exp\left(-2\pi q \lambda_M s_1^{2/\alpha} F(r_1 s_1^{-1/\alpha})\right) \times$$

$$\exp\left(-2\pi q \lambda_F s_2^{2/\alpha} F(r_2 s_2^{-1/\alpha})\right) \times \exp\left(-\pi q(\lambda_M r_1^2 + \lambda_F r_2^2)\right) r_1 r_2 dr_1 r_2, \tag{30}$$

where $s_i = \frac{TP_i}{P_1 r_1^{-\alpha} + P_2 r_2^{-\alpha}}$ for $r_i \geq 0$, $i = \{1, 2\}$ and $F(x) = \int_x^\infty \frac{r}{1+r^\alpha} dr$.

The energy efficiency of the networks for BS cooperation

$$EE = \frac{\lambda_M p_{c\_CoMP} \log_2(1 + SINR_M) + \pi r_M^2 \lambda_F p_{c\_CoMP} \log_2(1 + SINR_F)}{\underbrace{\lambda_M q_M(P_{M0} + \Delta M \beta P_M) + \lambda_M(1 - q_M)P_{sleep}}_{macro-tier}}.$$

$$+\pi r_M^2 \underbrace{\left(\lambda_F(P_{F0} + \Delta F \beta P_F) + \lambda_F(1 - q_F)P_{sleep}\right)}_{femto-tier} \tag{31}$$

From Eq. (31), we can see that the energy efficiency is related to the coverage probability and the power consumption of whole networks.

5.2. BS non-cooperation

The typical user only connects to the nearest BS, which belongs to first tier in a non-CoMP scenario [10]. Then, the coverage probability in the case of BS non-cooperation is given by:

$$p_{c\_Non-CoMP} = \frac{1}{1 + T^{2/\alpha}2F(T^{-1/\alpha}) + \frac{T^{2/\alpha}}{\sin c(2/\alpha)}\frac{q\lambda_F}{q\lambda_M}\frac{P_2^{2/\alpha}}{P_1^{2/\alpha}}}. \tag{32}$$

Thus, the energy efficiency of the networks for BS non-cooperation is given by:

$$EE = \frac{\lambda_M p_{c\_Non-CoMP}\log_2(1 + SINR_M) + \pi r_M^2 \lambda_F p_{c\_Non-CoMP}\log_2(1 + SINR_F)}{\underbrace{\lambda_M q_M(P_{M0} + \Delta M\beta P_M) + \lambda_M(1-q_M)P_{sleep}}_{macro-tier} + \pi r_M^2 \underbrace{\left(\lambda_F(P_{F0} + \Delta F\beta P_F) + \lambda_F(1-q_F)P_{sleep}\right)}_{femto-tier}}. \tag{33}$$

From Eqs. (30) and (32), we can see that the coverage probability depends on both the sleep strategy and BSs density ratio.

6. Markovian wireless networks

The BS can be in either of the two operational states: ON or OFF. If BS is ON, the energy increases with the energy harvesting rate and decreases according to the number of users served by that BS. However, if the BS is OFF, it does not serve any users.

6.1. Uncoordinated

In this class of strategies, the decision to toggle the operational state, that is, turn a BS ON or OFF, is taken by the BS independently of the operational states of the other BSs.

6.2. Coordinated

In this class of strategies, the decision to toggle the state of a particular BS is dependent upon the states of the other BSs.

6.3. Energy efficiency of two-cell cellular networks

To investigate the basic energy efficiency performance of two-cell cellular network, in this case, a user's channel of two-cell cellular network is modeled into good and bad states due to channel conditions [15]. Moreover, a transition from one state to the next state only depends on the current state with the state space $\{0, 1\}$, where '0' corresponds to a good state and '1' corresponds to a bad state in **Figure 4**. Based on properties of Markovian processes, a channel transition probability matrix is given by:

$$q^{(n)} = \begin{bmatrix} q_{00}^{(n)} & q_{01}^{(n)} \\ q_{10}^{(n)} & q_{11}^{(n)} \end{bmatrix} = \begin{bmatrix} q_{00} & q_{01} \\ q_{10} & q_{11} \end{bmatrix}^{(n)}, \tag{34}$$

where $q_{i,j}$, i and $j \in \{0, 1\}$, is a one-step transition probability from the state i into the state j, and $q_{i,j}^{(n)}$, i and $j \in \{0, 1\}$, is a probability from the initial state i into the state j after n steps transition. The energy efficiency for multicell cellular networks is given by:

$$EE_{multicell} = \sum_{i=1}^{K} \log_2 \left(1 + \frac{P_i \| h_i \|_F^2}{\sigma_i^2 + \sum_{j=1, \ i\neq j} P_j \| h_{i,j} \|_F^2} \right) \bigg/ \sum_{i=1}^{K} P_i. \tag{35}$$
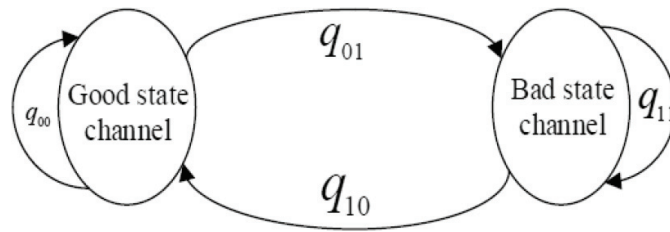

Figure 4. State transition diagram of two-state Markovian wireless channel.

The wireless channels of multicell cellular network are assumed as two-state Markovian wireless channels, due to the memory-less property of two-state Markovian wireless channel model [15]. Furthermore, after an n steps state transition in two-state Markovian wireless channels, a model of energy efficiency of multicell cellular network is given by:

$$EE_{multicell} = \frac{\sum_{i=1}^{K} \left\{ \log_2 \left(1 + \frac{P_i \| h_i^{good} \|_F^2}{\sigma_i^2 + \sum_{j=1, \ i\neq j} P_j \| h_{i,j}^{good} \|_F^2} \right) q_{00}^{(n)} + \log_2 \left(1 + \frac{P_i \| h_i^{bad} \|_F^2}{\sigma_i^2 + \sum_{j=1, \ i\neq j} P_j \| h_{i,j}^{bad} \|_F^2} \right) q_{01}^{(n)} \right\}}{\sum_{i=1}^{K} P_i}. \tag{36}$$

To analyse the impact of cell number on the energy efficiency of multicell cellular networks; for a good state channel, $h_i^{good} = 0.9$ and $h_{i,j}^{good} = 0.1$; for a bad state channel, $h_i^{bad} = 0.6$ and $h_{i,j}^{bad} = 0.4$; n steps transition probabilities of two-state Markovian channels are fixed as $P_{00}^{(n)} = 0.8$ and $P_{01}^{(n)} = 0.2$; and the noise is $\sigma_i^2 = 0.1$. Moreover, an initial state transition probability matrix of two-state Markovian chain channels is shown as:

$$q = \begin{bmatrix} q_{00} & q_{01} \\ q_{10} & q_{11} \end{bmatrix} = \begin{bmatrix} 0.8 & 0.2 \\ 0.6 & 0.4 \end{bmatrix} = \begin{bmatrix} 4/5 & 1/5 \\ 3/5 & 2/5 \end{bmatrix}. \tag{37}$$

7. Numerical results

In this section, we present numerical evaluations of the integral expressions for the coverage probability and energy efficiency performance. We focus on the two network tiers consisting of a macro tier overlaid with a femto tier. The assumed parameter values for two-tier HCNs are based on the values used in **Table 1**. We assume that $\alpha = 4$ and that the first tier has spatial intensity $\lambda_1 = (500^2\pi)^{-1}$ and available power $P_1 = 25$, while the second tier has spatial intensity $\lambda_2 = 5\lambda_1$ and available power $P_2 = P_1/25$.

Figure 5 illustrates the effect of the SINR threshold T on the coverage probability. By comparing the performance of the cooperative scheme to the baseline of no cooperation scheme, we observe that around 0 dB cooperation yields relative gains in coverage probability of up to about 30% compared to non-cooperative. The coverage probability can be directly related to the ergodic rate of communication from the cooperating BSs to the typical receiver.

Figure 6 plots the coverage probability versus noise σ^2 for different sleeping strategies. The sleeping strategy is modeled as 0 and 1, respectively. As shown in **Figure 6**, in strategic

Symbol	Description	Value
B	Bandwidth	180 kHz
α	Path loss exponent	4
T_M	SINR threshold for macro	8 dB
T_F	SINR threshold for femto	5 dB
P_{MBS}	Macro BS transmit power	20 W
P_{FBS}	Femto BS transmit power	2 W
r_M	Macro range	300 m
r_F	Femto range	15 m
P_{MO}	Static power MBS	130 W
P_{FO}	Static power FBS	4.8 W
ΔM	Slope of MBS	4.7
ΔF	Slope of FBS	8
$P_{M-sleep}$	Sleeping power MBS	75 W
$P_{F-sleep}$	Sleeping power FBS	5 W
λ_M	Density of MBS	$1 \times 10^{-4}\ m^{-2}$
λ_F	Density of FBS	$1 \times 10^{-2}\ m^{-2}$

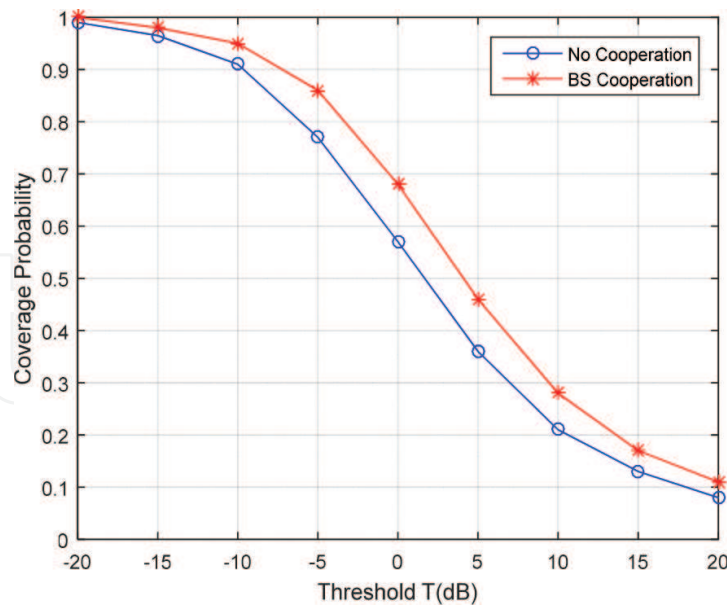**Table 1.** Network parameter values.

Figure 5. Comparison of the coverage probabilities for BS cooperation and no cooperation against the threshold in dB.
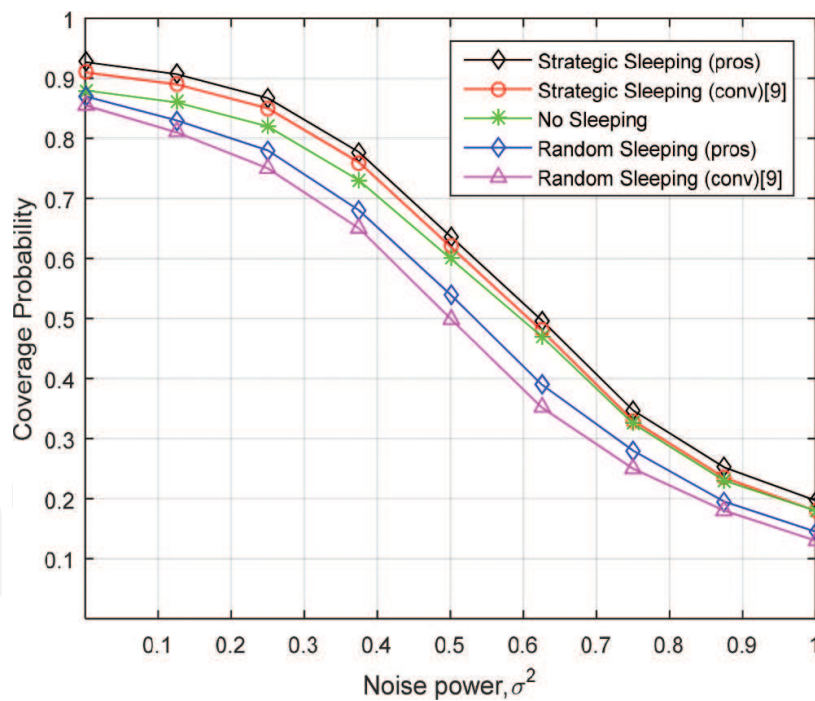

Figure 6. Coverage probabilities for different sleeping strategies.

sleeping mode, the coverage probability is marginally better than no sleeping mode. It can also be said that strategic sleeping has a bigger margin of improvement over no sleeping when $\sigma^2 \to 0$. Finally, it can be seen that strategic sleeping is always better than random sleeping for the same fraction of sleeping MBSs and FBSs.

Figure 7 shows the maximum two-tier achieved energy efficiency versus density. The assumed parameter values for the two-tier HCNs are based on the values used in **Table 1**. In general, the maximum two-tier energy efficiency decreases with increasing density. Note that, we show the
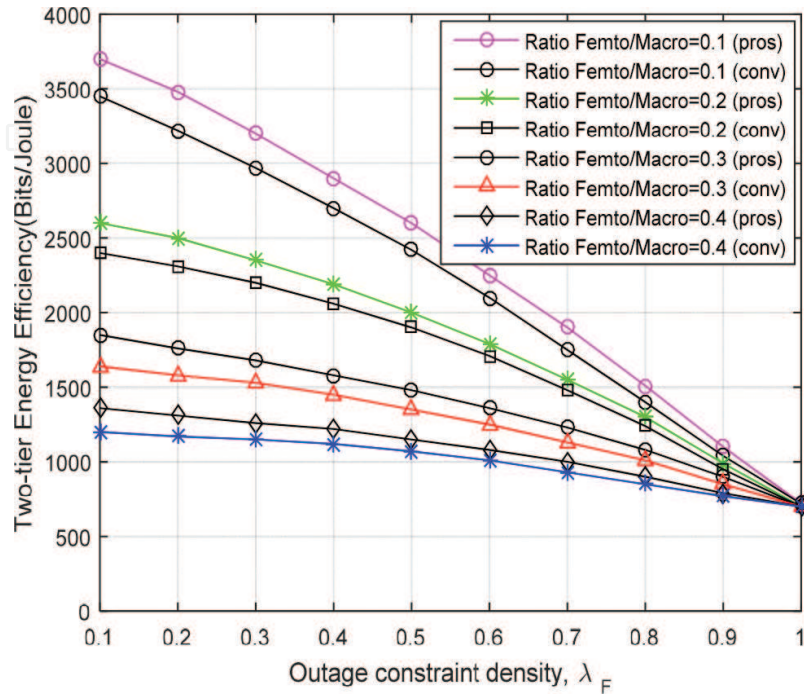
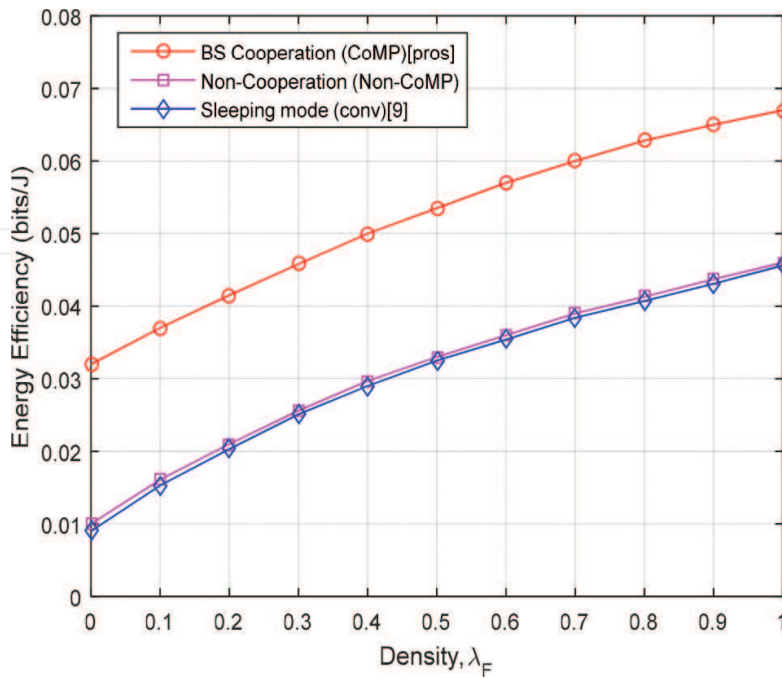**Figure 7.** Two-tier network energy efficiency versus density.

Figure 8. Energy efficiency versus density for the CoMP and non-CoMP.

energy efficiency curves close to the points for $P_{FBS}/P_{MBS} = 0.1,\ 0.2,\ 0.3$ and 0.4. The observations made from **Figure 7** underscore the impact of the femto-to-macro BS power consumption factor on the ability to maximize the two-tier energy efficiency while satisfying the outage objectives.

Figure 8 shows the energy efficiency of the CoMP and non-CoMP schemes versus density. It is observed that the energy efficiency improves according to the density. The proposed scheme of combined CoMP and BSs sleeping mode is increased by 2% of energy efficiency from non-CoMP schemes. Numerical results confirm that the combined CoMP and BS sleeping can improve the energy efficiency as well as increase the coverage probability compared with implementing BS sleeping only. Moreover, the performance of non-CoMP is almost same as the macro BS sleeping only [9].

8. Conclusion

In this chapter, we provide energy efficiency of two-tier network through deploying sleeping strategy in MBSs and FBSs. The MBS and FBS are switching off/on systems, that is, it reduces power consumption and interference and improves the energy efficiency of HCNs. Power consumption is formed into optimization problems, which is determined by the optimal density of femto tier BS. BSs in sleeping mode might cause coverage holes, which have a negative impact on the connectivity of the network. Thus, we proposed combined CoMP and BS sleeping scheme in HCNs for energy efficiency to avoid coverage holes. Numerical results show that the proposed sleeping strategy can effectively increase energy efficiency. We also analyze the energy efficiency performance of cellular network based on two-state Markovian wireless channels.

Acknowledgements

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