Energy Efficient Sleep Strategy for Decoupled Uplink/Downlink Access in HetNets

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***Abstract*—In dense and heterogeneous networks, the decoupled uplink/downlink (UL/DL) access (DUDA) design has drawn great attentions for improving system performance. Energy efficiency (EE) becomes a major concern for densely deployed heterogeneous cellular networks (HetNets). In this paper, we theoretically analyze the energy efficient sleep strategy for DUDA HetNets. Through using stochastic geometry theory, we first examine the applicability of conventional sleep strategy to DUDA networks and design a new DUDA sleep strategy. We then formulate the energy consumption minimization problem and EE optimization problem, and derive the optimal BS sleep probability. Numerical results reveal that conventional sleep strategy may provide inaccurate guidance for sleep design in DUDA networks, which may lead to excessive sleeps and decrease system EE. Meanwhile our DUDA sleep strategy can effectively reduce network energy consumption. We also find that the dense deployment of small cells may generally increase network EE, but this improvement saturates as the BS density further increases.**

I. Introduction

With the explosive growth of mobile traffic, the paradigm of cellular networks has been shifting from single-tier homogeneity to multi-tier heterogeneity. Extremely dense and heterogeneous base station (BS) deployment is expected to be a worldwide architectural design for the next generation mobile communication systems (5G) [1]. Decoupled UL/DL access (DUDA) design, as a promising architectural technique for 5G, has been proposed to alleviate the UL/DL asymmetry and thus improve load balancing and system throughput [3]-[9].The performance gain of DUDA design has been validated through simulations based on experimental data of Vodafones LTE field trial network [5]. Based on the experimental results of [5] as well as theoretical results of [6], the authors of [7] identify and explain arguments of DUDA design and indicate the feasible changes from 4G LTE/LTE-A to 5G for realizing DUDA design. In [8], we conduct an analytical comparison of system performance between conventional coupled UL/DL access (CUDA) and DUDA designs and evaluate the performance gain brought by DUDA design. The analytical justification of DUDA design is also presented in [9]. However, thus far little attention has been paid to the energy efficiency (EE) design for DUDA networks.

On the other hand, reducing energy consumption of cellular networks has attracted increasing attention recently [2]. Since the electricity bill of cellular networks mainly comes from energy consumption in BSs [14], sleep strategy has been recognized as one of the most effective energy efficient technologies [2] [11] [12]. Apparently, sleep strategies should be addressed without compromising system performance, especially the coverage performance [10]- [12]. In contrary to conventional CUDA networks, the UL and DL coverage of a BS in DUDA networks are independent, and thus the conventional DL coverage indicator may lead to biased coverage evaluation for sleep operation in DUDA networks. Therefore, it is essential to carefully examine the applicability of existing sleep strategies to DUDA networks, which can further indicate the necessity to develop new sleep strategy for DUDA networks. To the best of our knowledge, so far no research focuses on this issue. Furthermore, previous research has indicated benefits of DUDA networks, in terms of load balance, performance gain, etc. It is interesting to understand impact of DUDA sleep operation on EE aspect.

In this paper, we evaluate the impact of random sleep strategy on EE aspect in a two-tier DUDA HetNet by using stochastic geometry theory. We first investigate the applicability of conventional sleep strategies, and then design a new sleep strategy for DUDA networks. By formulating the energy consumption minimization and EE optimization problems, the optimal BS active/sleep state is determined. Numerical results reveal that the conventional sleep strategy may lead to excessive sleeps, and thus decreased system throughput and EE. In comparison, our DUDA sleep strategy can effectively reduce the network energy consumption, without compromising other benefits brought by DUDA mode. Furthermore, we find that the dense deployment may generally increase the network EE, but saturates with the increasing BS density.

The rest of this paper is organized as follows. Section II presents the system model. The analytical sleep strategy modelling and energy consumption minimization problem are analyzed in Section III. Simulation and numerical results are discussed in Section IV. Section V concludes this paper.

II. System Model

A. Network Model

We consider a two-tier HetNet composed by macro BSs (MBSs) and small BSs (SBSs). The locations of MBSs and SBSs are distributed according to independent homogeneous Poisson Point Process (PPP) Φ_v with intensity λ_v, where v=M for MBSs, v=S for SBSs. Let P_v be the transmit power of BS

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$v \in \{M, S\}$, $P_v \leq P_{MAX,v}$. The total energy consumption $P_{tot,v}$ of an active BS *v* is given by $P_{tot,v}{=}P_{v0}{+}\gamma_v P_v$ [14], where P_{v0} is the static power expenditure, and γ_v is the slope of transmit power. The dynamic transmit power can be used to avoid the coverage hole caused by sleep strategies. Users are located according to an independent PPP Φ_U with intensity λ_U. The standard path loss model over a distance x is expressed by $l\left(x\right) = \left\|x\right\|^{-\alpha}$, $\alpha{>}2$, where α is the path loss factor. The Rayleigh fading is employed where the fading coefficients are independent and identically distributed random variables with unit mean. All BSs share the same frequency spectrum, and apply universal frequency reuse in both UL and DL transmissions, where the bandwidth is equally allocated among all users [6] [12].

Let R_v be the distance between a user and its geographically nearest BS $v{\in}\{M,S\}$. The probability distribution function (PDF) of R_v can be derived by the null probability of a two dimensional PPP, which is given by

$$f_{R_v}\left(r\right) = 2\pi\lambda_v r\exp\left(-\lambda_v\pi r^2\right). \tag{1}$$

B. Decoupled UL and DL Access HetNets

In a typical DUDA HetNet scenario, a user accesses to the geographically nearest BS in UL transmission and the BS with the maximum reference signal receiving power (RSRP) in DL transmission [8] [9]. Fig.1 illustrates a simple case of coverage in conventional CUDA (a) and DUDA networks (b). In the DUDA networks, since the service for users in the shadow area is provided by both MBS and SBS, the sleep state of either MBS or SBS will lead to coverage hole for these users. Different from sleep operation in conventional CUDA network, DUDA sleep strategy should take both UL and DL coverage into account. Therefore, it is necessary to evaluate the applicability of conventional sleep strategy with DL coverage indicator in DUDA networks. Based on this investigation, we specifically propose a more accurate coverage indicator, which concerns both UL and DL coverage simultaneously, named joint UL/DL coverage, for DUDA sleep operation.

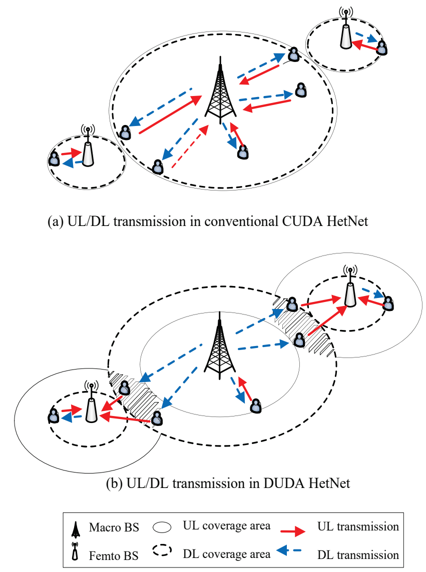
According to different access rules, the associated tier of UL and DL transmissions can be respectively given by $\kappa^{\mathrm{UL}}{=}\arg\min\limits_{v} R_v$ and $\kappa^{\mathrm{DL}} = \arg\max\limits_{v} P_v(R_v)^{-\alpha}$, $v \in \{M,S\}$. The probability that a user is associated with tier *v* in UL and DL transmissions is respectively given by $A_v^{UL}{=}\lambda_v/(\lambda_M + \lambda_S)$ and $A_v^{DL}{=}\lambda_v P_v^{2/\alpha}\Big/\left(\lambda_M P_M^{2/\alpha}{+}\lambda_S P_S^{2/\alpha}\right)$, and the proof can refer to Lemma 1 of [15].

C. Analysis of Random Sleep Strategy in DUDA Networks

We analyze the random sleep strategy for SBSs, where the transmit power of an SBS in sleep state can be given by P_{sleep}.The power consumption of an SBS is given by

$$P_{tot,S} = \begin{cases} P_{S0}{+}\gamma_S P_S,\ P_S{\leq}P_{MAX,S}, & \text{Active} \\ P_{sleep}, & \text{Sleep.} \end{cases} \tag{2}$$

The state of an SBS continues to be active with probability *q*, and to be sleep with probability 1-*q*. To maintain the coverage performance at a reasonable level, we employ the coverage probability $\Re\left(\theta\right)$ [10]- [12], i.e. $\Re\left(\theta\right) = \Pr\left[\mathrm{SINR} > \theta\right]$ as network performance indicator, where θ is the received signal-to-interference-plus-noise (SINR) threshold. Conventional sleep strategies are based on DL coverage constraint [10]- [12]; our DUDA sleep strategy is based on the joint UL/DL coverage constraint.



(a) UL/DL transmission in conventional CUDA HetNet

(b) UL/DL transmission in DUDA HetNet

Fig. 1. Illustration of UL and DL coverage for a two-tier HetNet in DUDA and CUDA scenarios respectively.

To evaluate the performance of sleep strategy, we employ the network energy consumption (EC) and the network EE. The network EC can be given by

$$EC = \lambda_M P_{tot,M} + q\lambda_S P_{tot,S} + \left(1-q\right)\lambda_S P_{sleep}. \tag{3}$$

The network EE can be defined as the average network throughput per Joule energy consumption [12]. We are focused on EE of DL transmission for sleep analysis, where the network throughput can be given by $\Pr\left(\mathrm{SINR} > \theta\right)\ln\left(1+\theta\right)$ [9] [12]. Thus, the EE can be expressed as

$$EE{=}\frac{\left(\lambda_M{+}q\lambda_S\right)\Pr\left(\mathrm{SINR}^{\mathrm{DL}}{>}\theta^{\mathrm{DL}}\right)\ln\left(1{+}\theta^{\mathrm{DL}}\right)}{\lambda_M P_{tot,M} + q\lambda_S P_{tot,S} + \left(1{-}q\right)\lambda_S P_{sleep}}. \tag{4}$$

III. Optimal Random Sleep Strategy for Energy Consumption Minimization in DUDA Networks

In this section, we theoretically analyze sleep strategies in DUDA HetNets. Different from conventional sleep strategies for CUDA networks, we derive the joint UL/DL coverage probability as the coverage indicator in our DUDA sleep strategy. To validate the necessity of our DUDA sleep strategy, we formulate the energy consumption minimization problem subject to coverage constraint.

A. Statistical Distance from a User to the Serving BSs

Without loss of generality, we analyze a typical user located at the origin. Denoted by X_v^{UL} and X_v^{DL} the distance from this user to its serving BS of tier $v \in \{M,S\}$ of UL and DL transmissions respectively. The PDF of X_v in UL and DL transmissions is respectively given by

$$f_{X_v^{UL}}\left(x\right) = 2\pi\left(\lambda_M + \lambda_S\right)xe^{-\pi\left(\lambda_M+\lambda_S\right)x^2},$$

and

$$f_{X_v^{DL}}(x)=\frac{2\pi\left(\lambda_M P_M^{2/\alpha}+\lambda_S P_S^{2/\alpha}\right)}{P_v^{2/\alpha}}x\mathrm{e}^{-\frac{\pi\left(\lambda_M P_M^{2/\alpha}+\lambda_S P_S^{2/\alpha}\right)}{P_v^{2/\alpha}}x^2},$$

and the proof can be referred to Lemma 3 of [15]. For the joint PDF of distance to UL and DL serving BSs, since there are four possible combinations for choosing the UL and DL access points in a two-tier HetNet, we derive this PDF based on the four cases.

Lemma 1. *The joint PDF of the distance between a user and its UL and DL serving BSs, is given by*

$$f_{X^{UL},X^{DL},\kappa^{\mathrm{UL}}=v,\kappa^{\mathrm{DL}}=t}(x,y)$$
$$=\begin{cases} 2\pi\lambda_M x\exp\left(-\pi(\lambda_M+\lambda_S)x^2\right), \\ \qquad\qquad x=y,\ \kappa^{UL}=\kappa^{DL}=\mathrm{MBS} \\ 2\pi\lambda_S x\exp\left(-\pi\lambda_M\left(\frac{P_M}{P_S}\right)^{\frac{2}{\alpha}}x^2-\pi\lambda_S x^2\right), \\ \qquad\qquad x=y,\ \kappa^{UL}=\kappa^{DL}=\mathrm{SBS} \\ 4\pi^2\lambda_M\lambda_S xy\exp\left(-\pi\lambda_M y^2-\pi\lambda_S x^2\right), \\ \qquad\qquad \left(\frac{P_S}{P_M}\right)^{\frac{1}{\alpha}}y<x<y,\ \kappa^{UL}=\mathrm{SBS},\ \kappa^{DL}=\mathrm{MBS} \\ 0, \qquad\qquad otherwise. \end{cases} \tag{5}$$

Proof: See Appendix 1. ■

B. Coverage Probabilities

In conventional CUDA networks, the DL coverage probability is widely applied as the performance indicators for sleep analysis [10]- [12]. According to the RSRP access rule, the DL coverage probability is given by

$$\Re^{\mathrm{DL}}=\pi Q\int_0^\infty \mathrm{e}^{-Q\left(1+2\theta^{\mathrm{DL}}{}_2F_1\left[1,1-\frac{2}{\alpha};2-\frac{2}{\alpha};-\theta^{\mathrm{DL}}\right]\right)x}\mathrm{e}^{-\theta^{\mathrm{DL}}\sigma^2x^{\frac{\alpha}{2}}}\mathrm{d}x, \tag{6}$$

where σ^2 represents the additive noise power; ${}_2F_1[\cdot]$ denotes the Gauss hypergeometric function; $Q=\sum_{t\in\{M,S\}}\lambda_t P_t^{2/\alpha}$; θ^{DL} is the DL received SINR threshold which is the same in each tier. The Laplace function of DL interference I^{DL} can be given by

$$L_{I^{DL}}(s)=\prod_{l\in\{M,m\}}\exp\left(-\frac{2\pi\lambda_l P_l s y^{2-\alpha}}{\alpha-2}{}_2F_1\left[1,1-\frac{2}{\alpha};2-\frac{2}{\alpha};-\frac{sP_l}{y^\alpha}\right]\right). \tag{7}$$

However, in DUDA HetNets, the coverage probability of UL transmission is different from that of DL transmission. According to the geographically closest access rule, the UL coverage probability is derived in Lemma 2.

Lemma 2. *The UL coverage probability with the geographically closest access rule is given by*

$$\Re^{\mathrm{UL}}=2\pi\lambda_{BH}\int_0^\infty L_{I_v^{UL}}(s)\cdot\mathrm{e}^{-\frac{\theta^{\mathrm{UL}}x^\alpha}{P_U}\cdot\sigma^2}xe^{-\pi\lambda_{BH}x^2}\mathrm{d}x, \tag{8}$$

where θ^{UL} is the UL received SINR threshold, which is the same in all BSs. $s=\theta^{\mathrm{UL}}x^\alpha/P_U$, and the Laplace function of UL interference I^{UL} is given by

$$L_{I_v^{UL}}(s)=\exp\left(-\pi\lambda_{BH}s^{2/\alpha}P_U^{2/\alpha}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right). \tag{9}$$

where P_U is the transmit power of each user.

Proof: See Appendix 2. ■

In our DUDA sleep strategy, we propose to use the joint UL/DL coverage probability as the coverage indicator. According to the definition of coverage probability, the joint UL/DL coverage probability is defined by

$$\Re^J=\Pr\left[\mathrm{SINR}^{\mathrm{UL}}>\theta^{\mathrm{UL}},\ \mathrm{SINR}^{\mathrm{DL}}>\theta^{\mathrm{DL}}\right]. \tag{10}$$

which can be theoretically derived in Theorem 1.

Theorem 1. *The joint UL/DL coverage probability of a two-tier HetNet is given by*

$$\Re^J=\sum_{v\in\{M,S\}}\sum_{t\in\{M,S\}}\int_0^\infty\int_0^\infty L_{I_v^{UL}}\left(\frac{x^\alpha\theta^{\mathrm{UL}}}{P_U}\right)L_{I^{DL}}\left(\frac{y^\alpha\theta^{\mathrm{DL}}}{P_t}\right)$$
$$\times f_{X^{\mathrm{UL}},X^{\mathrm{DL}}\kappa^{\mathrm{UL}}=v,\kappa^{\mathrm{DL}}=t}(x,y)\,\mathrm{e}^{-\sigma^2\left(\frac{x^\alpha\theta^{\mathrm{UL}}}{P_U}+\frac{y^\alpha\theta^{\mathrm{DL}}}{P_t}\right)}\mathrm{d}x\mathrm{d}y, \tag{11}$$

where $L_{I_v^{UL}}\left(x^\alpha\theta^{\mathrm{UL}}/P_U\right)$ and $L_{I^{DL}}\left(y^\alpha\theta^{\mathrm{DL}}/P_t\right)$ are Laplace functions respectively derived in (7) and (9). The joint distance PDF $f_{R^{\mathrm{UL}},R^{\mathrm{DL}},\kappa^{\mathrm{UL}}=v,\kappa^{\mathrm{DL}}=t}(x,y)$ is derived in Lemma 1.

Proof: According to the four combinations of UL/DL access points in a two-tier HetNet, we respectively analyze $\Re^J$ in the four cases. For each case, where $\kappa^{\mathrm{UL}}=v$ and $\kappa^{\mathrm{DL}}=t$, $v,t\in\{M,S\}$, based on the definition in (10), the joint UL/DL coverage probability can be given by

$$\Pr\left(\mathrm{SINR}^{\mathrm{UL}}>\theta^{\mathrm{UL}},\mathrm{SINR}^{\mathrm{DL}}>\theta^{\mathrm{DL}},\kappa^{\mathrm{UL}}=v,\kappa^{\mathrm{DL}}=t\right)$$
$$=\Pr\left(\frac{P_U h_x\|x\|^{-\alpha}}{I_v^{\mathrm{UL}}+\sigma^2}>\theta^{\mathrm{UL}},\frac{P_t h_y\|y\|^{-\alpha}}{I^{\mathrm{DL}}+\sigma^2}>\theta^{\mathrm{DL}}\right)$$
$$=\Pr\left[h_x>\left(I_v^{\mathrm{UL}}+\sigma^2\right)\left(\frac{x^\alpha\theta^{\mathrm{UL}}}{P_U}\right),h_y>\left(I^{\mathrm{DL}}+\sigma^2\right)\left(\frac{y^\alpha\theta^{\mathrm{DL}}}{P_t}\right)\right]$$
$$\overset{(a)}{=}\int_0^\infty\int_0^\infty L_{I_v^{\mathrm{UL}}}\left(\frac{x^\alpha\theta^{\mathrm{UL}}}{P_U}\right)\mathrm{e}^{-\frac{\theta^{\mathrm{UL}}\sigma^2}{P_U}x^\alpha}L_{I^{\mathrm{DL}}}\left(\frac{y^\alpha\theta^{\mathrm{DL}}}{P_t}\right)\mathrm{e}^{-\frac{\theta^{\mathrm{DL}}\sigma^2}{P_t}y^\alpha}$$
$$\times f_{X^{\mathrm{UL}},X^{\mathrm{DL}},\kappa^{\mathrm{UL}}=v,\kappa^{\mathrm{DL}}=t}(x,y)\,\mathrm{d}x\mathrm{d}y,$$

where (a) comes from both the independence assumption of fading variant and UL/DL interference [6]. Since the expression of Theorem 1 is too complicated, we do not expand the joint UL/DL coverage probability. ■

C. Energy Consumption Minimization Problem

Based on the modeling of DUDA HetNets, we formulate energy consumption minimization problem as follows:

$$\begin{aligned}&\min_q EC\\ &s.t.\ \Re(q\lambda_S)\geq\varepsilon, 0\leq q\leq 1,,\end{aligned} \tag{12}$$

where the constraints respectively indicate the performance maintenance for network coverage and reasonable sleep fraction. Note that the coverage constraint of our DUDA sleep strategy is different from that of conventional sleep strategy. Specifically, the DL coverage probability of (6) is employed in conventional sleep strategy, and the joint UL/DL coverage probability (11) is employed in our DUDA sleep strategy. According to the EC definition of (3), the optimal q^* comes from the lowest q which satisfies these constrains. In the conventional sleep strategy presented in [12], the DL coverage probability increases with q, and thus $\Re^{\mathrm{DL}}(q^*\lambda_S)=\varepsilon$.

TABLE I
System Parameters

Parameter	value
Intensity of MBSs, SBSs(/km^2), λ_M, λ_S	1, 10
Intensity (/km^2), λ_U	40
Path loss factor, α	4
Transmit power of a user (W), P_U	0.2
Max transmit power of an MBS/SBS (W), P_M, P_S	20,6.3
MBS/SBS static power expenditure(W), P_{M0}, P_{S0}	130, 56
Slope of the MBS/SBS transmit power, γ_M, γ_S	4.7, 2.6
Energy consumption of a sleep SBS (W), P_{sleep}	39
Total BS bandwidth (MHz), W	20
Noise power spectral density (dBm/Hz), N_0	-174

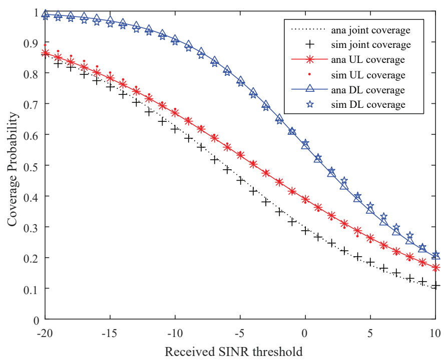


Fig. 2. Comparison of UL, DL and joint UL/DL coverage probabilities.

In our DUDA sleep strategy, since the joint UL/DL coverage probability in Theorem 1 involves four UL/DL access cases, the energy consumption minimization problem becomes much more complicated. Since (11) is generally mathematically intractable, we investigate the optimal q^* in the interference-limited scenario as shown in Theorem 2. The general case will be investigated by numerical calculations in Section IV.

Theorem 2. *The optimal sleep probability q^* of our DUDA sleep strategy in interference-limited scenarios can be given by $q^* = 0$, when $\varepsilon \le \frac{1}{(A+B+1)}$; $q^* = x_2 \big/ \lambda_{S/M}^0$, when $\varepsilon > \frac{1}{(A+B+1)}$, and the expression of x_2 is given in (17).*

Proof: See Appendix 3. ■

IV. Evaluation for Energy Efficient DUDA

In this section, we evaluate the performance of a two-tier DUDA HetNet with conventional and our designed sleep strategies in terms of energy consumption and EE. The default system parameters in our evaluations are given in Table I, where the parameters of energy model refer to [12][14]. For validating the correctness and accuracy of our analytical models, we also perform Monte Carlo simulations with 5000 independent realizations in a square area of 2km×2km.

Fig.2 shows the UL, DL and joint UL/DL coverage probability as a function of the received SINR threshold. In determining the joint UL/DL coverage probability, the identical UL and DL received SINR threshold is used. We can observe that under the same receiving criteria, the DL coverage probability is the highest, while the joint UL/DL coverage probability is the lowest. This is because that the joint UL/DL coverage needs to satisfy both UL and DL receiving criterion. Moreover,

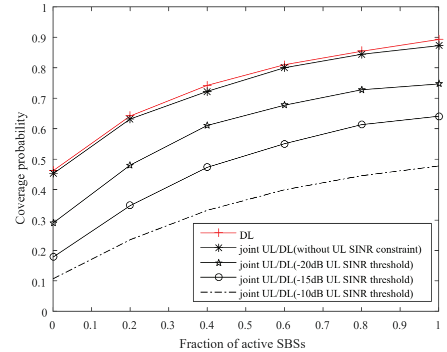


Fig. 3. Comparison of coverage performance based on DL and joint UL/DL receiving criteria.

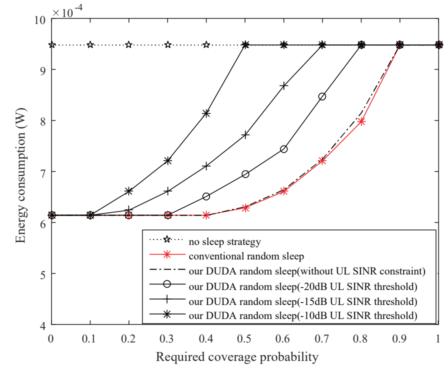


Fig. 4. Comparison of energy consumption for conventioanl and our designed DUDA sleep strategies.

the gap between UL and joint UL/DL coverage probability increases with the required SINR threshold. Therefore, neither UL nor DL coverage probability can instead the joint UL/DL coverage probability, and the conventional random sleep strategy using DL coverage probability may lead to the biased evaluation for sleep operations in DUDA networks. Indeed, the joint UL/DL coverage probability exactly matches the independent UL and DL coverage characteristic of DUDA networks. Simulation results further validate the accuracy of our analytical model.

Next, we validate the effectiveness of our designed DUDA sleep strategy and further examine the applicability of conventional sleep strategy to DUDA HetNets. Fig. 3 shows the DL and joint UL/DL coverage probabilities as a function of active SBSs fraction q, where the DL coverage threshold is set to -10dBm, and all BSs apply the maximum transmit power. We can observe that the joint UL/DL coverage probabilities increase when the UL SINR threshold decreases. When we do not set UL received SINR threshold (without UL receiving requirement), the joint UL/DL coverage probability is nearly identical to the DL coverage probability. It implies that under certain coverage probability requirement, fewer SBSs need to be activated when using lower UL SINR threshold, and the conventional sleep strategy would be more inaccurate under higher UL receiving criteria. In extreme case, all SBSs are turned off by using conventional sleep strategy, when the required coverage probability is lower than 0.45. The excessive sleeps brought by conventional sleep strategy will severely affect normal communications of DUDA networks. Indeed from the results we can also know that the conventional sleep strategy is applicable to DUDA networks only when we do not set UL received SINR threshold. To further demonstrate the effect of conventional and our designed sleep strategies on energy consumption, Fig.4 shows the energy consumption as a function of required DL coverage probability, where the system setting is identical to that of Fig.3. We can observe that in most circumstances, where a certain UL received SINR requirement is set, the energy consumption of our DUDA sleep strategy is lower than that of conventional sleep strategy. Thus, the conventional sleep strategy also leads to a biased energy consumption assessment. Fig. 4 also shows that under a reasonable required coverage probability, the corresponding of our designed DUDA sleep strategy leads to lower energy consumption. In addition, when the UL received SINR threshold becomes lower, the energy saving will be more significant. Therefore, our designed DUDA sleep strategy can effectively reduce energy consumption, which is based on more accurate joint UL/DL coverage probability evaluation (compared with biased coverage probability evaluation in conventional random sleep strategy), without compromising other benefits brought by the DUDA technique.

V. Conclusion

In this paper we have theoretically analyzed energy efficient sleep strategy in a two-tier DUDA HetNet. Using stochastic geometry theory, we have investigated the applicability of conventional sleep strategy for DUDA scenarios. Based on our findings, we have specifically designed a DUDA sleep strategy subject to the joint UL/DL coverage constraint, where the joint UL/DL coverage probability exactly matches the independent UL and DL coverage characteristic of DUDA networks. We are focused on random sleep strategy and formulate the energy consumption minimization and EE optimization problems to determine the optimal sleep probability. Numerical results have demonstrated the necessity and effectiveness of our DUDA sleep design. Moreover, the conventional sleep strategy will lead to inaccurate sleep operation for BSs and biased network performance assessment, which reduces system EE. In addition, our designed DUDA sleep strategy can effectively reduce energy consumption without compromising other benefits brought by DUDA technique, in terms of load balance and system throughputs, etc. Furthermore, the densely deployed small cells may bring benefits on EE but with the cost of increased BS density. Simulation results have further validated the accuracy of our analytical model.

Appendix 1: Proof of Lemma 1

In a two-tier HetNet, there are four access cases for a user. The probability of Case 1, where a user accesses to MBS in both UL and DL transmissions, is given by

$$\begin{aligned}
&\Pr\left[R^{UL}=R^{DL}>x,\kappa^{UL}=\kappa^{DL}=\mathrm{MBS}\right]\\
&=\Pr\left\{\left(P_M R_M^{-\alpha}>P_S R_S^{-\alpha}\right)\cap(R_M<R_S)\cap(R_M>x)\right\}\\
&=E_{R_M>x}\left[\Pr\left[R_S>R_M\right]\right]\\
&=\textstyle\int_x^\infty \mathrm{e}^{-\pi\lambda_S r^2}\cdot 2\pi\lambda_M r\cdot \mathrm{e}^{-\pi\lambda_M r^2}\mathrm{d}r,
\end{aligned}$$

and thus the joint distance PDF of Case 1 is given by

$$f_{R^{UL},R^{DL},\kappa^{UL}=\kappa^{UL}=\mathrm{MBS}}(x)=2\pi\lambda_M x\exp\left(-\pi(\lambda_M+\lambda_S)x^2\right).$$

Similarly, we can derive the probability of Case 2, where the UL and DL serving BSs are SBSs, which is given by

$$\begin{aligned}
&\Pr\left[R^{UL}=R^{DL}>x,\kappa^{UL}=\kappa^{DL}=\mathrm{SBS}\right]\\
&=\Pr\left\{\left(P_M R_M^{-\alpha}<P_S R_S^{-\alpha}\right)\cap(R_M>R_S)\cap(R_S>x)\right\}\\
&=\textstyle\int_x^\infty \mathrm{e}^{-\pi\lambda_M(P_M/P_S)^{\frac{2}{\alpha}}r^2}2\pi\lambda_S r\mathrm{e}^{-\pi\lambda_S r^2}\mathrm{d}r.
\end{aligned}$$

In Case 3, the probability that a user accesses to MBS in UL transmission and SBS in DL transmission is given by

$$\begin{aligned}
&\Pr\left(R^{UL}>x,R^{DL}>y,\kappa^{UL}=\mathrm{MBS},\kappa^{DL}=\mathrm{SBS}\right)\\
&=\Pr\left\{(R_M<R_S)\cap\left(P_S R_S^{-\alpha}>P_M R_M^{-\alpha}\right)\cap(R_M>x)\cap(R_S>y)\right\}\\
&=0.
\end{aligned}$$

In Case 4, the probability that a user accesses to SBS in UL transmission and MBS in DL transmission is given by

$$\begin{aligned}
&\Pr\left(R^{UL}>x,R^{DL}>y,\kappa^{UL}=\mathrm{S},\kappa^{DL}=\mathrm{M}\right)\\
&=\Pr\left\{(R_S<R_M)\cap\left(P_M R_M^{-\alpha}>P_S R_S^{-\alpha}\right)\cap(R_S>x)\cap(R_M>y)\right\}\\
&\overset{(a)}{=}\textstyle\int_y^\infty\int_{\max\left\{x,(P_S/P_M)^{1/\alpha}r\right\}}^r f_{R_M,R_S}(r,l)\,\mathrm{d}l\mathrm{d}r\\
&=4\pi^2\lambda_M\lambda_S yx\exp\left(-\pi\lambda_M y^2-\pi\lambda_S x^2\right),\ x>(P_S/P_M)^{\frac{1}{\alpha}}y,
\end{aligned}$$

where the joint PDF of R_M and R_S in (a) is given by

$$\begin{aligned}
f_{R_M,R_S}(r,l)&=\frac{\mathrm{d}\left[1-\Pr\left(R_M>r,R_S>l\right)\right]}{\mathrm{d}r\mathrm{d}l}\\
&=4\pi^2\lambda_M\lambda_S rl\exp\left(-\pi\lambda_M r^2-\pi\lambda_S l^2\right),
\end{aligned}$$

Finally we can derive Lemma 1.

Appendix 2: Proof of Lemma 2

Without loss of generality, we analyze the UL transmission from a typical user located at x to its serving BS located at the origin in tier $v\in\{M,S\}$. The SINR of UL transmission is given by

$$\mathrm{SINR}_v^{\mathrm{UL}}=\frac{P_U h_x\|x\|^{-\alpha}}{\sum_{u\in\Phi_{I,v}^{UL}}P_U h_u\|u\|^{-\alpha}+\sigma^2},$$

where P_U is the transmit power of the user; $\Phi_{I,v}^{\mathrm{UL}}$ is the set of interfering users for transmission to BSs of tier v. According to the definition of coverage probability, the UL coverage probability of tier v can be given by

$$\begin{aligned}
\Re_v^{\mathrm{UL}}&\triangleq\Pr\left[\mathrm{SINR}^{\mathrm{UL}}>\theta^{\mathrm{UL}}\right]\\
&=\Pr\left[h_y>\theta^{\mathrm{UL}}\left(I_v^{\mathrm{UL}}+\sigma^2\right)/\left[P_U\|x\|^{-\alpha}\right]\right]\\
&=\int_0^\infty L_{I_v^{UL}}\left(\theta^{\mathrm{UL}}x^\alpha/P_U\right)L_{\sigma^2}\left(\theta^{\mathrm{UL}}x^\alpha/P_U\right)f_{X_v^{UL}}(x)\,\mathrm{d}y,
\end{aligned}$$

where $L_{I_v^{\mathrm{UL}}}(s)$ is the Laplace function of interference with $s=\theta^{\mathrm{UL}}y^\alpha/P_U$, which can be given by

$$\begin{aligned}
&L_{I_v^{UL}}(s)=\mathrm{E}_{I_v^{UL}}\left[e^{-sI_v^{UL}}\right]\\
&=\mathrm{E}\left[\exp\left(-s\textstyle\sum_{k\in\{M,S\}}\sum_{u\in\Phi_{I,v_k}^{UL}}P_U h_u u^{-\alpha}\right)\right]\\
&=\textstyle\prod_{k\in\{M,S\}}\exp\left[-2\pi\lambda_k\int_0^\infty\left(1-1/\left(1+sP_U u^{-\alpha}\right)\right)u\mathrm{d}u\right]\\
&=\exp\left[-\pi\lambda_{BH}s^{2/\alpha}P_U{}^{2/\alpha}(2\pi/\alpha)/\sin(2\pi/\alpha)\right],
\end{aligned}$$

and thus the UL coverage probability can be given by

$$\Re^{\mathrm{UL}}=\sum\nolimits_{v\in\{M,S\}}A_v^{\mathrm{UL}}\Re_v^{\mathrm{UL}}.$$

APPENDIX 3: PROOF OF THEOREM 2

Using transformations $\lambda_{S/M}=q\lambda_S/\lambda_M$ and $P_{M/S}=P_M/P_S$ in (12) yields

$$\begin{aligned}&\min\ \lambda_{S/M}\\&s.t.\ \Re^J_{\sigma^2=0}\left(\lambda_{S/M}\right)\geq\varepsilon, 0\leq\lambda_{S/M}\leq\lambda^0_{S/M},\end{aligned}\tag{13}$$

where $\lambda^0_{S/M}$ is the origin ratio between intensity of SBS to that of MBS, and $\Re^J_{\sigma^2=0}\left(\lambda_{S/M}\right)$ can be derived as follows

$$\begin{aligned}&\Re^J_{\sigma^2=0}\left(\lambda_{S/M}\right)=\\&\left(1-\frac{1}{A\lambda^{-1}_{S/M}+(A+1)}\right)\frac{1}{(A+B+1)+\left(A+P^{-2/\alpha}_{M/S}B+1\right)\lambda_{S/M}}\\&+\left(1+\frac{P^{2/\alpha}_{M/S}}{\left(A+(A+1)\lambda_{S/M}\right)}\right)\frac{1}{(A+B+1)+\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\lambda^{-1}_{S/M}},\end{aligned}\tag{14}$$

where $B=\frac{2\theta^{\mathrm{DL}}}{\alpha-2}{}_2F_1\left[1,1-\frac{2}{\alpha};2-\frac{2}{\alpha};-\theta^{\mathrm{DL}}\right]$ and $A=\left(\theta^{\mathrm{UL}}\right)^{2/\alpha}\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}$. We employ a reasonable assumption that the original BS deployment can provide effective coverage, i.e. $\Re^J_{\sigma^2=0}\left(\lambda^0_{S/M}\right)\geq\varepsilon$. To derive the optimal $\lambda^*_{S/M}$ that satisfies (13), we firstly evaluate the functional feature of (14) and analyze the minimum $\lambda_{S/M}$ which satisfies (14) in $0\leq\lambda_{S/M}\leq\lambda^0_{S/M}$. And (14) can be transformed into

$$\begin{aligned}&f\left(\lambda_{S/M}\right)=\left(A+A\lambda_{S/M}\right)\left((A+B+1)+\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\lambda^{-1}_{S/M}\right)\\&+\left(A+(A+1)\lambda_{S/M}+P^{2/\alpha}_{M/S}\right)\left((A+B+1)+\left(A+P^{-2/\alpha}_{M/S}B+1\right)\lambda_{S/M}\right)\\&-\left(A+(A+1)\lambda_{S/M}\right)\left((A+B+1)+\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\lambda^{-1}_{S/M}\right)\\&\times\left((A+B+1)+\left(A+P^{-2/\alpha}_{M/S}B+1\right)\lambda_{S/M}\right)\varepsilon\geq 0,\end{aligned}\tag{15}$$

We then rewrite (15) into (16)

$$f(\lambda_{S/M})=a{\lambda_{S/M}}^3+b{\lambda_{S/M}}^2+c\lambda_{S/M}+d\geq 0,\tag{16}$$

where $a=\left(A+P^{-2/\alpha}_{M/S}B+1\right)(A+1)[1-\varepsilon\left(A+B+1\right)]$;

$$\begin{aligned}b=&(A+B+1)(2A+1)+\left(A+P^{2/\alpha}_{M/S}\right)\left(A+P^{-2/\alpha}_{M/S}B+1\right)\\&-\varepsilon\begin{bmatrix}A(A+B+1)\left(A+P^{-2/\alpha}_{M/S}B+1\right)+(A+1)(A+B+1)^2\\+(A+1)\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\left(A+P^{-2/\alpha}_{M/S}B+1\right)\end{bmatrix};\end{aligned}$$

$$\begin{aligned}c=&A\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)+\left(2A+P^{2/\alpha}_{M/S}\right)(A+B+1)\\&-\varepsilon\begin{bmatrix}A(A+B+1)^2+A\left(A+P^{-2/\alpha}_{M/S}B+1\right)\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\\+(A+1)\left(A+B+1\right)\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\end{bmatrix};\end{aligned}$$

$$d=A\left(A+P^{2/\alpha}_{M/S}B+P^{2/\alpha}_{M/S}\right)\left[1-\varepsilon\left(A+B+1\right)\right].$$

Since the properties of cubic function (15) is totally depended on parameters *a*, *b*, *c* and *d*, we are focused on the value of these parameters. It is obvious that the positive or negative value of both *a* and *d* is decided by that of $1-\varepsilon\left(A+B+1\right)$. The cubic function (15) is restricted into the following two types.

1) When $1-\varepsilon\left(A+B+1\right)\geq 0$, we can know that $a,d\geq 0$, and thus $f(0)=d\geq 0$. Therefore, we can derive that $q^*=\lambda^*_{S/M}/\lambda^0_{S/M}=0$;
2) When $1-\varepsilon\left(A+B+1\right)<0$, we can know that $a,d<0$, and thus $f(0)<0$. According to characteristic of cubic function, we can derive $f(-\infty)\to+\infty$ and $f(+\infty)\to-\infty$. Combined with above assumption $\Re^J_{\sigma^2=0}\left(\lambda^0_{S/M}\right)\geq\varepsilon$, i.e. $f\left(\lambda^0_{S/M}\right)\geq 0$, we can derive that the values that satisfy $f\left(\lambda_{S/M}\right)=0$ must respectively exist in the following intervals $(-\infty,0)$,$\left[0,\lambda^0_{S/M}\right]$ and $\left(\lambda^0_{S/M},\infty\right)$.Therefore, according to roots of normally cubic function [17], $\lambda^*_{S/M}$ can be given by
$$\lambda^*_{S/M}=x_2,\tag{17}$$
where $x_2=\frac{1}{3a}\left[-b+\sqrt{b^2-3ac}\left(\cos\frac{\theta}{3}-\sqrt{3}\sin\frac{\theta}{3}\right)\right]$ and $\theta=\arccos\left(\left\{2\left(b^2-3ac\right)b-3a\left(bc-9a^2\right)\right\}\Big/\left\{2\sqrt{\left(b^2-3ac\right)^3}\right\}\right)$.
Thus $q^*=\lambda^*_{S/M}\big/\lambda^0_{S/M}=x_2\big/\lambda^0_{S/M}$. When the parameters are given, the expression of x_2 can be easily derived.

Therefore, we derive Theorem 2.

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