Analysis of Energy-Efficiency in Ultra-Dense Networks: Determining FAP-to-UE Ratio via Stochastic Geometry

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Abstract

Femtocells are envisioned as a key solution to embrace the ever-increasing high data rate and thus are extensively deployed. However, the dense and random deployments of femtocell access points (FAPs) induce severe intercell inference that in turn may degrade the performance of spectral efficiency. Hence, unrestrained proliferation of FAPs may not acquire a net throughput gain. Besides, given that numerous FAPs deployed in ultra-dense networks (UDNs) lead to significant energy consumption, the amount of FAPs deployed is worthy of more considerations. Nevertheless, little existing works present an analytical result regarding the optimal FAP density for a given User Equipment (UE) density. This paper explores the realistic scenario of randomly distributed FAPs in UDN and derives the coverage probability via Stochastic Geometry. From the analytical results, coverage probability is strictly increasing as the FAP-to-UE ratio increases, yet the growing rate of coverage probability decreases as the ratio grows. Therefore, we can consider a specific FAP-to-UE ratio as the point where further increasing the ratio is not cost-effective with regards to the requirements of communication systems. To reach the optimal FAP density, we can deploy FAPs in line with peak traffic and randomly switch off FAPs to keep the optimal ratio during off-peak hours. Furthermore, considering the unbalanced nature of traffic demands in the temporal and spatial domain, dynamically and carefully choosing the locations of active FAPs would provide advantages over randomization. Besides, with a huge FAP density in UDN, we have more potential choices for the locations of active FAPs and this adds to the demand for a strategic sleeping policy.

Keywords: Spectral Efficiency, Energy Efficiency, Ultra-Dense Networks, Stochastic Geometry

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1. Introduction

Having been experiencing an explosion of data traffic usage in recent years, the wireless industry is now facing an even bigger challenge, an astounding 1000-fold data traffic increase in a decade [1]. Massive deployment of small cells is expected as an essential way to meet this challenge. Some studies have suggested that, with this trend, the density of FAPs will potentially reach, or ever exceed, the density of UEs, hence introducing the notion of UDN [2-4].

One may ask whether the denser deployment of FAPs will induce the better performance. When the FAP density becomes larger, users may connect to FAPs located more nearby while experience stronger intercell interference. We know that these two effects are canceled out equally in terms of the Signal-to-Interference-plus-Noise-Ratio (SINR) threshold in dense deployments [5]. At first glance, it seems that we have no need to increase FAP density in dense deployments. However, with a lower FAP to UE ratio, the FAP may not have enough resources to serve so many UEs as more UEs may access a single FAP simultaneously. Therefore, we should further discuss how many FAPs are needed to satisfy UE demands as only considering the SINR threshold is not enough.

However, little existing work has presented analytical results on this issue. Though the Monte Carlo simulations could serve as a substitute, they onerous to construct and run. Moreover, they can seldom inspire the "optimal" or creative new algorithms. There are some works in related fields. In [6], the author established a first-order analysis of the amount of energy that can be saved via sleep mode, yet the analysis is too rough such that a thorough analysis is needed. Recent work showed that the Poisson Point Process (PPP) model was as accurate as the traditional hexagonal grid model [5]. Modeling the distribution of base stations (BSs) as a PPP, the work presented in [7] presented the tradeoffs between energy efficiency and spectral efficiency. The authors in [8] studied the coverage probability in relay-assisted networks via Stochastic Geometry. The work in [9] investigated the coverage probability and energy efficiency of several sleeping strategies, involving random sleep and strategic sleep, in sparse deployments. The impact of system parameters was examined in [10], such as access point density and bandwidth partitioning on the performance of randomly deployed, interference-limited, dense wireless networks. An accurate approximation is obtained in [11] for the achievable SINR and user capacity in the downlink of a finite-area network with a fixed number of access points. The work in [12] jointly optimized the BS density, the number of antennas and spectrum allocation to minimize the network energy consumption. In this paper, however, we will analyze the effects of FAP density on coverage probability in UDN. Besides, we desire to provide several fundamental guidelines for the design of sleeping algorithms in UDN.

Moreover, although originally envisioned as low-power BSs, FAPs are now consuming significant energy even without transmission due to their sheer number. As a result, energy efficiency will also be a critical performance requirement for future green communications, especially when small cells are densely deployed to enhance the user's quality ofexperience [13]. In [14], cooperative energy efficiency is modelled and analysed under different cooperative transmission scenarios, interference levels and wireless channel conditions based on the cooperative outage probability model and a cooperative block error rate model. A joint energy efficiency (EE) and spectrum efficiency (SE) trade-off analysis is presented in [15] as a multi-objective optimization problem (MOP) in the uplink of multi-user multi-carrier two-tier orthogonal frequency division multiplexing access heterogeneous networks subject to users' maximum transmission power and minimum rate constraints. The authors in [16] apply a reformulation–relaxation technique and Taylor's theorem to propose a new convex optimization solution methodology for the energy efficiency optimization problem. The work in [17] identified energy efficiency related open problems in ultra-dense network. There have been many researches on green cellular networks with a broad range of techniques presented [18], among which this paper mainly focus on boosting energy efficiency via sleep mode. As the cellular networks are supposed to provide higher peak data rate, we can switch off some FAPs to save huge energy during off-peak hours. The authors in [19] addressed the problem of how many small cells can be turned off in a theoretical way under a separation architecture.With latest FAP sleep mode, dynamic switching on/off becomes possible.

In this paper, we consider a realistic scenario of randomly distributed FAPs, in which we explore a problem of minimizing the total power consumption while satisfying the QoS requirements for all userss in the network. To this end, we first apply Stochastic Geometry to derive the coverage probability. From analytical results, we determine the optimal FAP density and analyze the effects of several parameters. Having calculated the optimal density, we present several guidelines for the design of a self-configured FAP framework.

The rest of this paper is organized as follows. Section II describes our system model. Section III analyzes the optimal density of FAPs for a given density of UEs in terms of spectral and energy efficiency. In Section IV, we present simulation results for the analyses. Finally, we conclude the paper in Section V.

2. System Model

2.1 Network Model

In this paper, we study heterogeneous networks with macro-cells and FAPs deployed in separate carrier frequencies when traffic is not at its peak. FAPs and UEs are located according to independent homogeneous PPPs Θ_f and Θ_u with densities λ_f and λ_u, respectively, in the Euclidean plane. Since the macro-cells and FAPs are allocated orthogonal resources, the co-tier interference is not addressed. This is consistent with the self-autonomy envisioned for small cells with respect to macro cells and also accords with 3GPP from practical perspective [20]. Detailed notations are summarized in **Table 1**.

Table 1. Notations summary

Notations	Description
p_i^n	FAP i transmit power at the sub-channel n
α	path-loss exponent
$d_{i,k}$	The distance between UE k and FAP i
$h_{i,k}^n$	The channel gain between UE k and FAP i at the sub-channel n
$\mathcal{F}$	The set of FAPs
η	The thermal noise
R_k^n	The achievable rate of UE k at the sub-channel n
W	The bandwidth
$\lambda(x,t)$	The demand of UE located at x at time t
$\mu_i(x,t)$	The service rate of FAP i at x at time t

A_i	The cell area of FAP i
$\rho_i(t)$	The system load
ρ_{th}	The threshold of the traffic load
δ	The ratio of the available bandwidth to the user's demand
σ	The reuse factor

2.2 Signal-to-Interference-plus-Noise-Ratio (SINR)

We assume that active FAPs will listen to the control channel and reference signals of neighboring FAPs and subsequently measures the path loss from them. Furthermore, each FAP receives the SINR reports periodically from their associated UEs. Therefore, the FAPs have the knowledge of channel state information. The signal strength observed by UE k from FAP i is determined by:

$$S_{i,k}^n = p_i^n d_{i,k}^{-\alpha} \mid h_{i,k}^n \mid^2, \tag{1}$$

The corresponding SINR that UE k experiences at the channel n is derived by:

$$\mathrm{SINR}_{i,k}^n = \frac{S_{i,k}^n}{\sum_{j\in\mathcal{F}\setminus\{i\}} S_{j,k}^n + \eta}, \tag{2}$$

2.3 FAP Load

Downlink SINR is used to define the achievable user data rate on each sub-channel as shown:

$$R_k^n = W\log_2\left(1+\mathrm{SINR}_{i,k}^n\right), \tag{3}$$

where W is the bandwidth.

Furthermore, we derive system load in a bid to guarantee the QoS of the user. We assume an FAP should assign a certain amount of resource (e.g., time or frequency) depending on UEs' traffic load as well as its service rate. From the perspective of system, the system load of FAP i at time t is defined as the fraction of resource to serve the total traffic load in its coverage:

$$\rho_i(t) = \int_{x\in A_i} \frac{\lambda(x,t)}{\mu_i(x,t)} dx, \tag{4}$$

where $\lambda(x,t)$ is the demand of UE located at x at time t, and $\mu_i(x,t)$ $u_i(x,t)$ is the service rate of FAP i at x at time t. To maintain the QoS constraint, $\rho_i(t)$ should generally be less than 1. When a UE associates with an FAP, the service rate is evaluated by the user data rate. We suppose that when an FAP is fully loaded, i.e. $\rho_i = 1$, it has used all of its available bandwidth. For the simplicity of the algorithm, we discretize Equ. (4) in both spatial and temporal domain, and for a specific snapshot, we obtain:

$$\rho_i = \sum_{j\in\mathcal{U}_i} \frac{\lambda_j}{W_f \log_2\left(1+\mathrm{SINR}_{i,j}\right)}, \tag{5}$$

where W_f is the bandwidth an FAP could exploit, which is a constant.

2.4 Coverage Probability

We define the sum of the cell areas, whose bearing cell can guarantee the certain requirement of QoS as the coverage area, which is written as:

$$A_c = \sum_{\rho_i<\rho_{th}} A_i. \tag{6}$$

Where ρ_{th} is the threshold of the traffic load.

Accordingly, the coverage probability in terms of QoS requirement is the coverage area to the total area ratio, which is formulated as:

$$p_c = A_c / A_{total}. \tag{7}$$

Therefore, our aim is to minimize the energy consumption while maintain the same level of the coverage probability p_c. Here, we will further explain why we choose this metric. According to queuing theory, the QoS parameters, such as delay, will significantly degrade when the load increases. Hence, when the load ρ_f in an FAP exceed the threshold ρ_{th}, it is reasonable to assert that all attached UEs are suffering from bad QoS such that all services, especially real-time stream media, cannot continue. There are two possible scheduling strategies. The first is to degrade the quality of experience of all users in the cell, for example, switch from high-resolution videos to low-resolution videos, in which case the quality of experience degrades in the whole cell area. The second is to only guarantee UEs with good channel quality while reject the remaining UEs. Since the UE arrives according to a Poisson Process, the possibility of a UE locating in an overloaded FAP is proportional to the cell area. In both cases, all existing and potential UEs in the cell coverage area are affected. In other words, the larger cell area an overloaded FAP has, the bigger influence it will cause. In conclusion, we calculate the overloaded area rather than simply count the number of overloaded FAPs.

2.5 Algorithm Design

In this paper, we also aim at proposing an FAP switching algorithm that minimizes the total energy expenditure in cellular networks during T, whilst maintaining the same QoS parameters as that in the optimal density, which is the same as related papers [7]. Our objective function is given by:

$$\begin{aligned} \min_{\mathbf{a}} \quad & \sum_{f\in\mathcal{F}} \int_0^T \mathcal{E}_f \mathbf{a}(t)\, dt \\ s.t. \quad & p_c = p_o, \forall t \in [0,T) \end{aligned}, \tag{8}$$

where $\mathcal{E}_f$ is the energy consumption of one active FAP and p_o is the coverage probability when the FAP density reaches the optimum; $a_f(t) \in \{0,1\}$ is the activity indicator of FAP f at time $t \in [0,T)$, which is determined by FAP switching strategy, and $\mathbf{a} = (a_f)$ is a vector of the activity indicators of all FAPs during T.

Note that we introduce a system load constraint (as defined in Equ. (6) where $\rho_i < \rho_{th}$) to strike trade-offs between the QoS and the energy efficiency. For example, with a low threshold value, FAPs operate in a conservative manner with a low system load on average. As a result, users would experience less delay and better QoS. We can also expect less call dropping probability since the system becomes more robust to burst traffic arrivals. In contrast, with a high threshold value, more energy saving could be achieved at the cost of slight performance reduction.

Without the load constraint, we could model the problem as a minimum Set Cover Problem (SCP). Specifically, We consider the UE set $\mathcal{U}$ as the universal set and therefore all UEs that can associate with FAP i represent a subset $\mathcal{U}_i$ of the UE set $\mathcal{U}$. To serve all UEs, we should find a subset $\mathcal{F}_s$ of the FAP set $\mathcal{F}$, subject to that the union set $\bigcup_i^n \mathcal{U}_i$ equals to $\mathcal{U}$ and the cardinal number of $\mathcal{F}_s$ is minimal, which is formulated as follows:

$$\begin{aligned} \min \quad & |\mathcal{F}_s| \\ s.t. \quad & \bigcup_{i \in \mathcal{F}_s} \mathcal{U}_i = \mathcal{U} \end{aligned} \tag{9}$$

Accordingly, the energy minimization problem is modeled as an SCP with load constraint, which is an NP-complete problem. The idea to solve this problem is that we first solve an SCP and then check if the load constraint is satisfied. As illustrated in **Fig. 1**, we presents a cluster-based framework that is computationally efficient to minimize energy consumption. The macrocell serves to group FAPs into clusters based on traffic of each FAP and interference among FAPs. In one cluster, an active FAP is selected as cluster header to determine which FAP should sleep. Clusters also allow UEs to keep the same resources when performing handovers between intra-cluster FAPs.

Finally, we make several assumptions to ensure that the algorithm can be implemented in reality. The assumption is that macrocells serve as center controllers and FAPs offer data service to UEs. Additionally, it is assumed that the network will request the mobile terminals to scan for inter-frequency cells with a configured periodicity, or terminals can autonomously decide the scanning periodicity. Terminals will sort the detected cells in terms of Reference Signal Received Power (RSRP) and report the list to the macro-cell periodically.

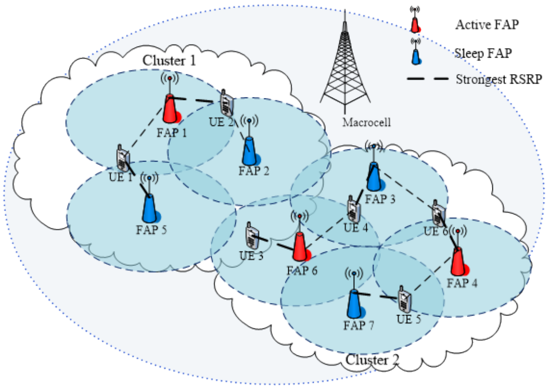


Fig. 1. Illustration of clustering and sleeping strategy in ultra-dense scenarios. Take UE1 as an example. Traditionally UE1 should connect to FAP5 as FAP5 provides best RSRP. However, UE1 detects that FAP1 can sustain its service according to RSRP, and thus UE1 can associate with FAP1 after switching off FAP5.

3. Analysis of Optimal density

In this section, we will answer the question whether we can satisfy the same amount of UE with sleep mode and provide guidelines for the sleeping polices with the optimal density of FAPs λ_f. Specifically, with more FAPs in a given area, the average distance between FAP and UE is smaller, which means a lower path loss that in turn makes both signal and interference strong. In other words, too little FAPs may result in signal strength falling below the threshold that impedes the communication while too much FAPs may introduce strong interference that degrades the system performance.

3.1 Coverage Probability

Since the FAP with its load higher than the threshold ρ_{th} could not satisfy the demand of userss under its coverage area, using Equ. (6) we derive the coverage area for a given area as:

$$A_c = \sum_i A_i P\left(\sum_{j\in\mathcal{U}_i} \rho_j < \rho_{th} \mid A_i\right), \tag{10}$$

where $P\left(\sum_{j\in\mathcal{U}_i} \rho_j < \rho_{th} \mid A_i\right)$ is the probability that an FAP with the cell area A_i has its load lower than ρ_{th}.

From the perspective of probability, Equ. (7) can be stated as:

$$p_c = \frac{\int_0^\infty AP(A)P\left(\sum_{j=0}^{n} \rho_j < \rho_{th} \mid A\right)dA}{\int_0^\infty AP(A)dA}, \tag{11}$$

where $P(A)$ equals to the probability that the cell area of an FAP in a given area is A and n is the number of users in the cell.

For simplicity, we assume that for a cell with n users, each user has a relative load lower than ρ_{th}/n. Note that this simplification can be seen as the average load of users, which reduces the coverage probability yet will not influence the results, especially for a lower threshold ρ_{th}. Thus, we could obtain a lower bound:

$$p_c = \int_0^\infty AP(A)\sum_{n=0}^{\infty} \chi(n)P(N = n \mid A)dA, \tag{12}$$

where $\chi(n) = P(\rho(d) < \rho_{th}/n \mid n, d) f(d)$. Since the distribution of FAPs follows a PPP, $f(d) = 2\pi\lambda_f d\exp(-\lambda_f \pi d^2)$ is the distribution of distance d between a UE and its designated FAP and $P(N = n \mid A) = e^{-\lambda_u A}(\lambda_u A)^n / n!$ is the probability that the number of UEs equals to n in a given cell with cell area A. Since the left of Equ. (12) is probability, which ranges between 0 and 1, the infinite series must converge. Besides, as every item of the series is positive, the infinite series converge absolutely. Thus, we could exchange the order of summation and integral. Assuming that the cell area $A \sim \exp(-\lambda_f A)$ and we acquire:

$$p_c = \sum_{n=0}^{\infty} \chi(n)\int_0^\infty \lambda_f \lambda_u^n A^{n+1} e^{-(\lambda_f+\lambda_u)A} / n! dA. \tag{13}$$

Since

$$\int_0^\infty A^{n+1} e^{-(\lambda_f+\lambda_u)A} dA = (n+1)\int_0^\infty A^n e^{-(\lambda_f+\lambda_u)A} dA / (\lambda_f + \lambda_u), \tag{14}$$

Using the recursive method, we could obtain:

$$\int_0^\infty A^{n+1} e^{-(\lambda_f+\lambda_u)A} dA = \frac{(n+1)!}{(\lambda_f + \lambda_u)^{n+2}}. \tag{15}$$

Substituting Equ. (15) into Equ. (13), we have:

$$p_c = \sum_{n=0}^{\infty} \chi(n)\frac{(n+1)\lambda_f^2 \lambda_u^n}{(\lambda_f + \lambda_u)^{n+2}}, \tag{16}$$

Assuming all users have the same demand, for example, all users have the same type of service, we know from Equ. (5) the load a specific UE adds on its serving BS is:

$$\frac{1}{\delta \log_2(1+\mathrm{SINR}_{i,j})}, \tag{17}$$

where $\delta = W_f / \lambda$ is the ratio of the available bandwidth to the user's demand, which we term as the resource-to-demand ratio. Substituting Equ. (17) into Equ. (16) and using simple algebraic manipulations, we have:

$$\chi(n) = P(\text{SINR}(d) > T \mid n, d) f(d), \tag{18}$$

where the SINR threshold $T = 2^{n/(\delta\rho_{th})} - 1$.

The work in [5] presented the detailed result of $P(\text{SINR} > T) f(d)$. However, given the purpose of this paper, we only adopt a special case, where the path-loss exponential $\alpha = 4$:

$$P(\text{SINR} > T) f(d) = \frac{\pi^{3/2}\lambda_f}{\sqrt{T/\text{SNR}}} \exp\left(\frac{(\pi\lambda_f \kappa(T))^2}{4T/\text{SNR}}\right) Q\left(\frac{\pi\lambda_f \kappa(T)}{\sqrt{2T/\text{SNR}}}\right),$$

Where $\kappa(T) = 1 + \sqrt{T}\left(\pi/2 - \arctan\left(1/\sqrt{T}\right)\right)/\sigma$ and σ is the frequency reuse factor. Let x be $\lambda_f \pi \kappa(T)/\sqrt{2T/\text{SNR}}$. When $n \to \infty$, $T \to \infty$. For large T,

$$\kappa(T) = \frac{\pi\sqrt{T}}{2\sigma}. \tag{19}$$

Substituting Equ. (19) into x, we have

$$x = \frac{\sqrt{2}\pi^2 \lambda_f \sqrt{\text{SNR}}}{4\sigma}, \tag{20}$$

which is independent of n. Furthermore, for large n,

$$T(n) = 2^{n/(\delta\rho_{th})} - 1 \approx 2^{n/(\delta\rho_{th})}. \tag{21}$$

Due to the results of Equ. (20) and Equ. (21), the coverage probability can be written as the summation of two terms:

$$\begin{aligned} p_c = \; & \sum_{n=0}^{N} x e^{x^2/2} Q(x) \frac{\sqrt{2\pi}}{\kappa(T)} \frac{(n+1)\lambda_f^2 \lambda_u^n}{(\lambda_f + \lambda_u)^{n+2}} + \\ & \sigma x e^{x^2/2} Q(x) \sum_{n=N+1}^{\infty} \frac{2\sqrt{2\pi}(n+1)\lambda_f^2 \lambda_u^n}{\pi 2^{n/(2\delta\rho_{th})} (\lambda_f + \lambda_u)^{n+2}}. \end{aligned} \tag{22}$$

Calculating the infinite geometric series of the second term, we have:

$$\sum_{n=N+1}^{\infty} \frac{2\sqrt{2\pi}(n+1)\lambda_f^2 \lambda_u^n}{\pi 2^{n/(2\delta\rho_{th})} (\lambda_f + \lambda_u)^{n+2}} = \frac{2\sqrt{2\pi}\lambda_f^2}{\pi(\lambda_f + \lambda_u)^2} \frac{\xi^{N+1}}{(1-\xi)^2}, \tag{23}$$

where $\xi = \dfrac{\lambda_u}{2^{1/(2\delta\rho_{th})}(\lambda_f + \lambda_u)}$. Since $\xi < 1$, $\xi^{N+1} \to 0$ when $N \to \infty$. Therefore, $\forall \varepsilon > 0$, $\exists N > 0$, s.t.

$$\sigma x e^{x^2/2} Q(x) \frac{2\sqrt{2\pi}\lambda_f}{\pi(\lambda_f + \lambda_u)} \frac{\xi^{N+1}}{(1-\xi)^2} < \varepsilon. \tag{24}$$

The solution of Equ. (24) is:

$$N > \log_\xi \frac{\sqrt{2\pi}\varepsilon(\lambda_f + \lambda_u)(1-\xi)^2}{4\sigma x e^{x^2/2} Q(x) \lambda_f} - 1. \tag{25}$$

To sum up, when N is large enough, we can conclude:

$$p_c = \sum_{n=0}^{N} x e^{x^2/2} Q(x) \frac{\sqrt{2\pi}}{\kappa(T)} \frac{(n+1)\lambda_f^2 \lambda_u^n}{(\lambda_f + \lambda_u)^{n+2}}. \tag{26}$$

We will state another reason for doing this. That we choose a large enough N rather than infinite is consistent with reality as the number of UEs a FAP can serve is limited. Therefore, given that $Q(x)$ is easy to compute in modern calculator, it is reasonable to state that the coverage probability is written in quasi-closed form.

Moreover, we then further assume the network is interference-limited, i.e. thermal noise can be ignored. It is reasonable to make this assumption in dense deployments as the distance between FAPs is small, which makes interference the key limitation compared to thermal noise. As a result, when $\mathrm{SNR} \to \infty$, $x \to \infty$ and thus we obtain:

$$\lim_{x \to \infty} x e^{x^2/2} Q(x) = 1/\sqrt{2\pi}. \quad (27)$$

Substituting Equ. (27) into Equ. (26), we have:

$$p_c = \sum_{n=0}^{N} \frac{(n+1)\lambda_f^2 \lambda_u^n}{\kappa(T)(\lambda_f + \lambda_u)^{n+2}}. \quad (28)$$

Besides, [5] has proved that thermal noise is not an important consideration, i.e. thermal noise has only minor effects on the coverage probability, and hence we use Equ. (28) to calculate the coverage probability in the following passage.

Here, we will make a further remark about Equ. (28). When the UE density is set, it is easy to notice that the coverage probability is independent of the FAP density λ_f and the UE density λ_u. The FAP density affects the coverage probability only when we take into account the thermal noise, i.e. $xe^{x^2/2}Q(x)$ will increase when the FAP density λ_f increases. However, the SINR would stay the same if the noise is ignored, as both the signal and the interference are affected to the same extent when the density of FAP changes. Accordingly, the coverage probability will stay the same. To be more explicit, we let $\lambda_f / \lambda_u = r$, which we terms as the FAP-to-UE ratio, and we can re-write Equ. (28) as:

$$p_c = \sum_{n=0}^{N} \frac{(n+1)r^2}{\kappa(T)(1+r)^{n+2}}. \quad (29)$$

Corollary: the coverage probability p_c is a monotone increasing function of the r.

Proof: We have $p_c = f(r) = \sum_{n=0}^{N} \frac{(n+1)r^2}{\kappa(T)(1+r)^{n+2}}$, thus, we can get

$$f(r) = \sum_{n=0}^{N} \frac{(n+1)}{\kappa(T(n))} \cdot \frac{r^2}{(1+r)^{n+2}} \triangleq \sum_{n=0}^{N} h_1(n) h_2(n,r).$$

We obtain

$$\sum_{n=0}^{N} h_2(n,r) = \frac{r[(r+1)^{N+1} - 1]}{(r+1)^{N+2}} \xrightarrow{N \to +\infty} \frac{r}{1+r}$$

$$\sum_{n=0}^{N} \frac{\partial h_2(n,r)}{\partial r} = \frac{1}{(1+r)^2} > 0$$

By calculating the first derivative of $h_2(n,r)$, we know that $\frac{\partial h_2(n,r)}{\partial r}$ is strictly monotone decreasing with n increasing and has the zero point. Hence, we assume $(\frac{\partial h_2(N,r)}{\partial r})(\frac{\partial h_2(N+1,r)}{\partial r}) < 0$. We will rewrite $\sum_{n=0}^{\infty} \frac{\partial h_2(n,r)}{\partial r} = \sum_{n=0}^{N} \frac{\partial h_2(n,r)}{\partial r} + \sum_{n=0}^{N+1} \frac{\partial h_2(n,r)}{\partial r}$. We can obtain the first derivative of $f(r)$, that is

$$f'(r) = \sum_{n=0}^{\infty} h_1(n) \frac{\partial h_2(n,r)}{\partial r} > \sum_{n=0}^{N} h_1(N) \frac{\partial h_2(n,r)}{\partial r} + \sum_{n=N+1}^{\infty} h_1(N) \frac{\partial h_2(n,r)}{\partial r}$$

$$> h_1(N) \frac{1}{(1+r)^2} > 0$$

We know that the $p_c(r)$ is a monotone increasing function of the r. Hence, the inverse function of $p_c(r)$ exists. Therefore, given the coverage probability p_c, we can get the value of r by calculating the inverse function.

Apparently, the coverage probability only depends on the FAP-to-UE ratio, which can be considered as the average number of UEs attached to an FAP, when the system parameters are set. That this conclusion is accurate rests on the assumption that the network is interference-limited, i.e. the FAPs are, at least, densely distributed. In light of this, we will be more confident to apply this conclusion to UDN for the reason that the assumption can still be satisfied even if we switch off many FAPs.

3.2 Sleeping Policies

Before giving more detailed analyses, we will first explore two sleeping strategies: random sleeping and strategic sleeping. In **Fig. 2(a)**, we show the scenario of all FAPs turning on. It is easy to notice that many FAPs have no UE attached, and it is reasonable to turn off those FAPs. As shown in **Fig. 2(b)**, each FAP choose to activate or sleep independently for random sleeping policy. Specifically, an FAP has the probability of q to activate and accordingly $1-q$ to sleep. Apparently, the active FAPs are the marked PPP of the original all FAPs. Therefore, the distribution of active FAPs is a PPP with the density of $q\lambda_f$, where $q \in (0,1)$. However, with randomization, some FAPs with are still active, and some FAPs become overloaded.

Rather than a random sleeping policy, we can also use some more complex strategies, which we terms as strategic sleeping policy. Using strategic sleeping algorithms, we will sleep underutilized FAPs, i.e. we switch on and off FAPs based on load, or FAPs that cause severe interference, as shown in **Fig. 2(c)**. Besides, the load from sleeping FAPs will be transferred to active FAPs nearby and this mechanism is illustrated in **Fig. 1**. Different from [9], we take into account the cooperation between FAPs, which will mitigate interference. To sum up, we intends to properly schedule UEs such that we can sleep as many FAPs as possible while maintaining the coverage probability. In the future, we will analyze theoretically for the strategic sleeping policy.

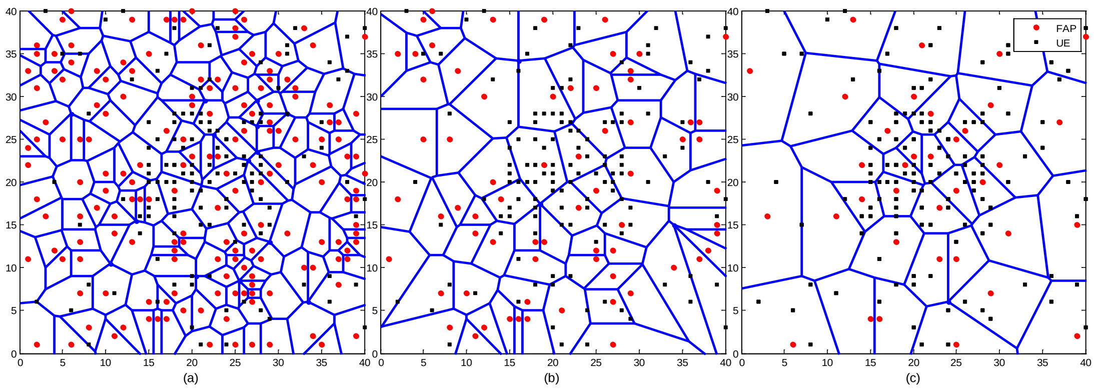


Fig. 2. The distribution of FAPs follows a PPP with UEs associating with the nearest FAP in (a). Each FAP randomly sleeps with a probability of 0.5 in (b), which follows a marked PPP (c) shows that FAPs adopt a strategic sleeping policy based on load and interference.
Cell boundaries are shown in blue to form a Voronoi tessellation.

3.2 Optimal Density

To find out the optimal density, we consider the FAP density as the independent variable and calculate the first derivative of Equ. (28). Thus, we have:

$$\frac{\partial p_c}{\partial \lambda_f} = \sum_{n=0}^{N} \frac{\lambda_f \lambda_u^n (n+1)(2\lambda_u - n\lambda_f)}{\kappa(T)(\lambda_f + \lambda_u)^{n+3}}. \tag{30}$$

For a given UE density λ_u, if the optimal FAP density exists, i.e. there is an FAP density maximizing the coverage probability, the FAP density must be subjected to $\frac{\partial p_c}{\partial \lambda_f} = 0$. However, this point does not exist. Accordingly, we can conclude that the coverage probability is a strictly monotone increasing function of the FAP density. To prove this theorem, we should notice that $\frac{\partial p_c}{\partial \lambda_f} = 0$ only when $\lambda_f = 0$ and $\lambda_f = +\infty$. For every $\lambda_f \in (0, +\infty)$, $\frac{\partial p_c}{\partial \lambda_f} > 0$. Therefore, if we decrease the density of FAP, which is equivalent to using random sleeping strategy, the coverage probability decreases as well. Accordingly, we can conclude that we cannot save energy without decreasing the coverage probability via random sleeping strategy.

To facilitate further analyses, we would need to know the difference of the coverage probability Δp_c with a small change of the FAP density $\Delta \lambda_f$. We again let $\lambda_f / \lambda_u = r$, and using Equ. (30) we obtain:

$$\Delta p_c = \frac{\partial p_c}{\partial \lambda_f} \Delta \lambda_f = \frac{\Delta \lambda_f}{\lambda_f} \sum_{n=0}^{N} \frac{(n+1)(2-nr)r^2}{\kappa(T)(1+r)^{n+3}}. \tag{31}$$

From Equ. (31), we can discover that the coverage probability only depends on the FAP-to-UE ratio with the same relative change of the FAP density. For instance, if the product of the FAP density and the first derivative of the coverage probability $\lambda_f \frac{\partial p_c}{\partial \lambda_f} = 1$, a 1% increase in the FAP density would lead to a 1% increase in the coverage probability. For the simplicity of illustration, we term $\lambda_f \frac{\partial p_c}{\partial \lambda_f}$ as the relative growing rate and denote it as γ. In terms of the absolute value, the larger the FAP density is, the more energy we can save. Accordingly, we can conclude that sleeping strategies in the UDN would be more effective. Furthermore, it is easy to notice that when the FAP-to-UE ratio r becomes larger, the first derivative of the coverage probability $\lambda_f \frac{\partial p_c}{\partial \lambda_f}$ decreases. Therefore, we could find a point that the first derivative of the coverage probability is small enough such that further increasing the density of FAPs would be rather inefficient given the increased energy consumption. Therefore, we could sleep the FAPs to this density. Since both the coverage probability and the first derivative of the coverage probability are only dependent on the FAP-to-UE ratio.

To find such a point, we let

$$\sum_{n=0}^{N} \frac{(n+1)(2-nr)r^2}{\kappa(T)(1+r)^{n+3}} = c, \tag{32}$$

where c is a constant that determines on the system requirement. In other words, that increasing coverage probability at a rate below c is inefficient, where the specific value of c may depend on the requirement of the communication system. However, solving Equ. (32) symbolically is difficult. For example, even we set $N = 3$, we would acquire a sixth order equation system. Thus, we would use numeric methods to solve the equation. Note that, we omit the density of FAPs here, which will make the results more general.

The conclusions obtained via numeric methods will be further discussed in the numerical evaluation section. Whatever the specific value of r is, we can conclude that the FAP-to-UE ratio should be the same for a given c, though. Therefore, a linear relationship between the UE density and the FAP density is assumed for a given communication system. Since the density of UEs varies in a day, we should use sleeping strategy to make the FAPs keep pace with the UEs.

From the above analysis, we know that we could save huge energy with only the slightly decreased coverage probability via random sleeping strategy. Furthermore, it is reasonable to assume that a strategic sleeping strategy would have better performance than a random sleeping strategy. Hence, it is possible that we could save energy with even slighter performance loss or without performance loss via a strategic sleeping strategy.

In brief, it is possible to save huge energy by switching off some underutilized FAPs during off-peak times as FAPs are typically deployed on the basis of peak traffic volume and stayed turned-on irrespective of traffic load.

3.2 Effects of Parameters

In this section, we will discuss how the parameters, δ and σ, affect the performance of a communication system. Assuming the available system bandwidth W_s is fixed and the bandwidth is equally divided into σ frequency bands, $W_s = \sigma W_f$. Accordingly, the product $\delta\sigma$ is fixed when λ is set. Therefore, we will also discuss how should we set δ and σ to maximize the coverage probability under this constraint.

To make the relationship more explicit, we first make the following transform. Since the coverage probability mainly depends on the first several terms, as mentioned above, we mainly consider the cases when T is small. For example, T^2 is lower than 0.1 for the first four terms of T, which can be ignored, and thus Equ. (33) is approximately equal to Equ. (34). Therefore, for small T, we have:

$$\begin{aligned}\kappa(T) &= 1+\sqrt{T}\left(\pi/2-\arctan\left(1/\sqrt{T}\right)\right)/\sigma \\ &=1+\sqrt{T}\arctan\left(\sqrt{T}\right)\sigma=1+T/\sigma+o\left(T^2\right)\end{aligned} \tag{33}$$

$$\kappa(T) = \approx 2^{n/(\delta\rho_{th})-\log_2\sigma}. \tag{34}$$

From Equ. (34), we could explicitly see the effects of the resource-to-demand ratio δ and the reuse factor σ. Specifically, the coverage probability increases as the resource-to-demand ratio δ or the number of orthogonal frequency bands σ increase.

Furthermore, we can conclude that we should adopt a factor-one frequency reuse scheme for the purpose of energy saving. As stated above, the product $\delta\sigma$ is usually fixed. Besides, δ is usually set as an integer bigger than one, since one FAP usually can serve more than one user. Therefore, with the above analyses, we can easily prove that $\kappa(T)$ decreases as σ increases. Combining Equ. (30) with Equ. (34), we can notice that the optimal UE-to-FAP ratio decreases as σ increases. Since we want a larger UE-to-FAP ratio, increasing the resource-to-demand ratio δ would be more effective than increasing the number of orthogonal frequency bands σ. This is consistent with our common sense: the FAP will be more flexible to the fluctuations of traffic if we allow one FAP to use all resources. In conclusion, since $\sigma \ge 1$, we should set $\sigma = 1$.

However, we should emphasize that this does not mean the reuse factor must stay right as 1. In fact, some communications adopt orthogonal resource allocation strategy in nearby FAPs to meet the requirement of some QoS-aware services [21] or to avoid that the SINR threshold of some edge UEs go down below the SINR threshold.

4. Numeric Results

In this section, we will run Matlab Monte Carlo simulations based on Vienna LTE System Level Simulator [22] with the simulation parameters derived from 3GPP standard, which is similar to related papers [23] as summarized in **Table 2.** The results obtained from simulations would be compared to those from analytical analyses.

Table 2. Simulation parameters

Cell Radius	50m
FAP transmission power	20dBm
Bandwidth	20MHz
Path Loss Model	$PL\text{ (dB)} = 127 + 40\log_{10}(d/1000)$
FAPs per km^2	500

Note that, both the coverage probability and the derivative of the coverage probability can be independent of the absolute value of the density, which is conducive to the comparison between analytical analyses and simulation. Furthermore, an effective scheduling algorithm should keep the FAP-to-UE ratio smaller than 1 as a bigger than 1 ratio means that there must be, at least, an FAP has no attached UEs, which we are able to turn off. Actually, it is possible that even the nearest FAP cannot bear the service of theuser, in which case increasing FAPs can shrink the overloaded area and thus can increase the coverage probability. However, we consider it as a waste of energy. We will first see the density effects on the coverage probability using Equ. (28) and Equ. (30), which is illustrated in **Fig. 3**. The UE density in **Fig. 3** left is as ten times as that in **Fig. 3** right. However, it is easy to notice that the trend is same. The difference comes from the x-scale and y-scale.

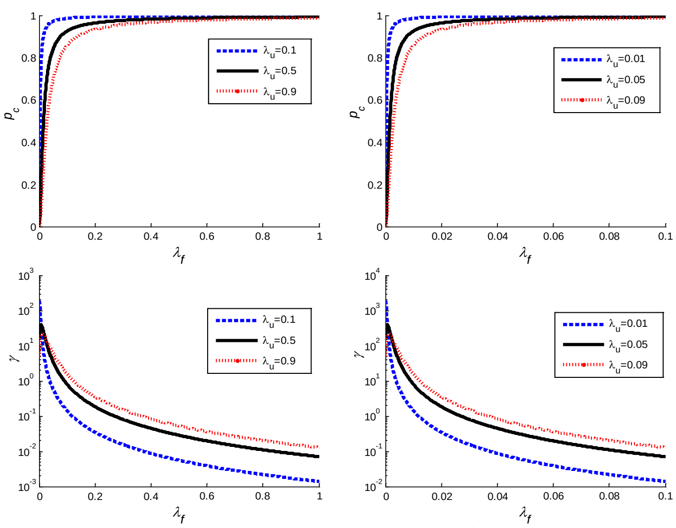


Fig. 3. The effects of density of FAPs

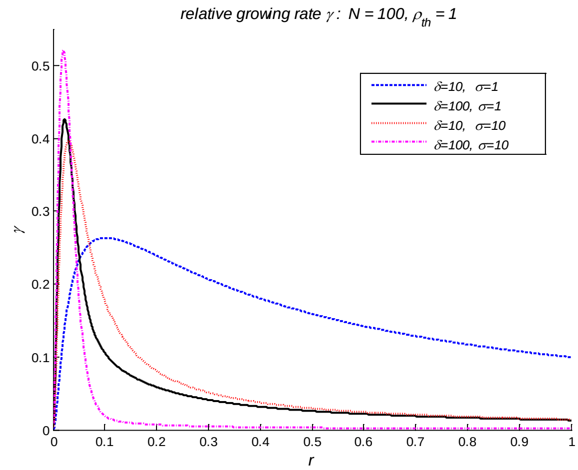
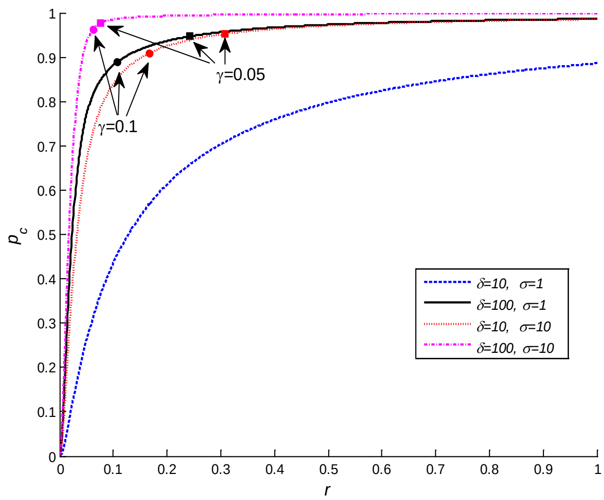
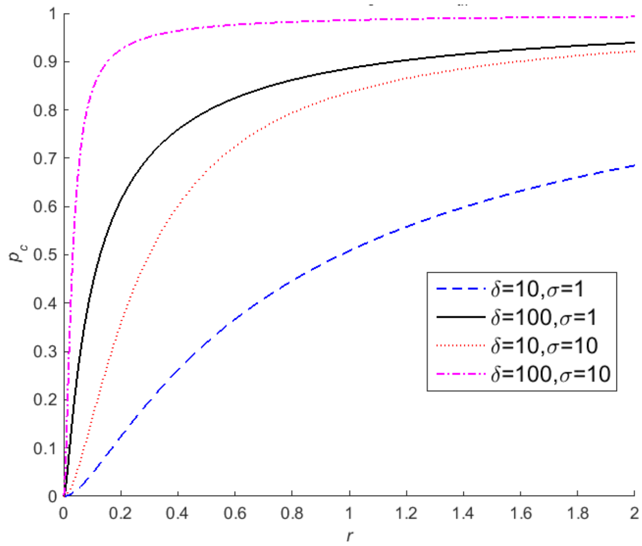


Fig. 4. The relative growing rate versus the FAP-to-UE ratio

Fig. 4 presents the relative growing rate γ under different settings of parameters. We choose two bars, i.e. 0.1 and 0.05 as the point where further increasing FAPs would not be cost-effective. Apparently, Equ. (32) would generate two real number solutions, of which we need the bigger one. As mentioned above, the solution should be less than 1 for an effective sleeping strategy. From **Fig. 4**, we understand that the more system resources, the larger FAP-to-UE ratio. In other words, we can save more energy if we have more spectra for a given amount of UEs. Besides, as we mentioned above, increasing the resource-to-demand ratio δ in an FAP would be more effective than increasing the reuse factor σ. **Fig. 5 (a)** shows the coverage probability with a mark of critical points, where the relative growing rate is 0.1 or 0.05. **Fig. 5 (b)** shows the coverage probability when $\rho_{th} = 1$. From **Fig. 5**, we know that the load threshold ρ_{th} will influence the optimal density ratio since the decreasing of the load threshold requires more FAPs to keep the same coverage probability.



(a) Coverage probability p_c : N=100, $\rho_{th} = 1$



(b) Coverage probability p_c : $N=100$, $\rho_{th} = 0.1$

Fig. 5. The coverage probability versus the FAP-to-UE ratio.

Fig. 6 uses numerical results to further illustrate Equ. (34). Assuming the product $\delta\sigma$ is a constant, we reach the same conclusion that we should adopt a factor-one reuse scheme and this conclusion is the same as the previous analysis.

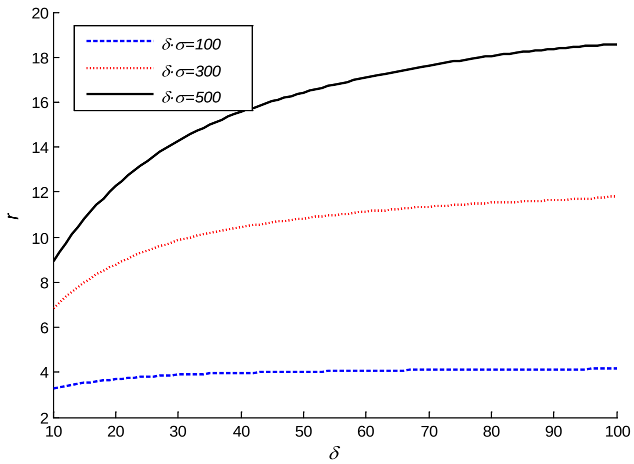


Fig. 6. The UE-to-FAP ratio versus the reuse factor and the resource-to-demand ratio, $\gamma = 0.05$

Fig. 7 presents the comparison between simulation results and analytical results. Note that we have used some approximation in the analytical results, which causes the error between analytical results and simulation results. However, it has little influence on the FAP-to-UE ratio, on which we focus most, as the trend is the same. Generally, the simulation results have higher coverage probability as we assumed each user has a relative load $\rho_i \le \rho_{th} / n$ for a cell with n users. However, when the network becomes denser, the coverage probability obtained from simulations can be lower than the analytical results, which may result from more intense interference. In light of this, the simulations also support our idea of sleeping FAP as increasing FAP beyond an extent is inefficient in UDN.

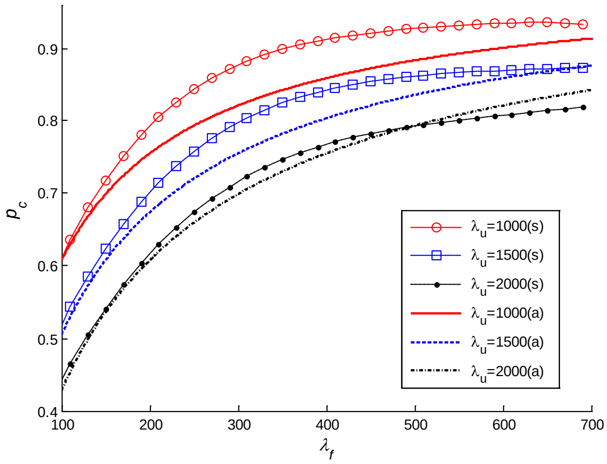


Fig. 7. The coverage probability versus the FAP density under different UE densities, where s stands for simulation and a represents analytical results.

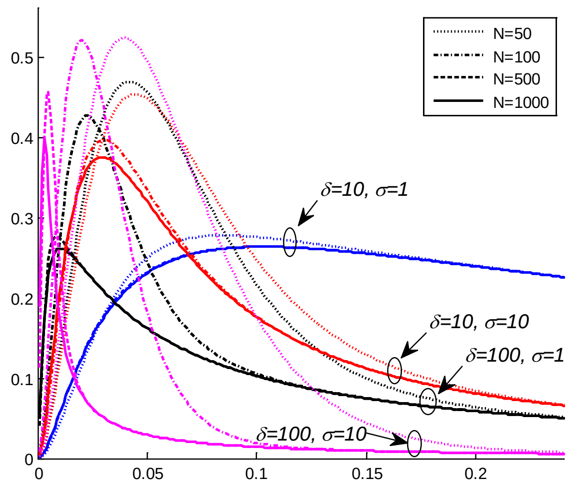


Fig. 8. Effect of N on accuracy of the relative growing rate, $\rho_{th} = 1$.

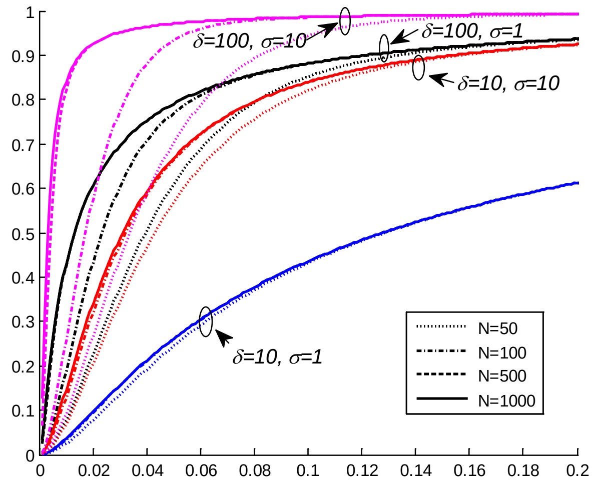


Fig. 9. Effect of N on accuracy of the coverage probability, $\rho_{th} = 1$.

In the final analysis, we will briefly illustrate the effects of the maximum UE number N of a FAP on the coverage probability and state how we choose the value of N. From **Fig. 8** and **Fig. 9**, we discover that the proper value of N mainly depends on the resource-to-demand ratio δ. It affects the value of N in two ways. First, that $2^{n/(\delta\sigma)}-1 \approx 2^{n/(\delta\sigma)}$ requires $n/(\delta\sigma)$ to be large enough, and thus with a larger δ, we need a larger N. Secondly, δ is a key factor in Equ. (25), which determines the smallest value of N. In contrast, the reuse factor σ has little effects on the accuracy. Because Equ. (25) is independent of σ when we assume the network is interference-limited.

Note that even $\delta = 100$, the $N = 500$ case has little difference from the $N = 1000$ case, and thus we can conclude the $N = 1000$ case presents exact results. For a typical FAP in UDN, the system bandwidth is 5MHz or 20MHz. If we assume the demand of a UE is 1Mbps, then δ is 5 or 20. Though the $N = 100$ case differs from $N = 1000$ case initially, they then converge, especially when we choose the threshold 0.1 and 0.05 (the red line and the blue line). Besides, since N is the maximum number of UEs an FAP can bear, a maximum number of 100 UEs in an FAP is reasonable. To sum up, we choose 100 as a proper value for N, which is still computationally efficient.

5. Conclusion

In this paper, we derived the coverage probability using a stochastic geometry based model. Several important conclusions were achieved from analytical results. First, although previous works proved that the SINR distribution is independent of FAP density in dense deployments, a specific FAP-to-UE ratio is needed to satisfy traffic demands, i.e. FAPs may not be able to provide enough resources to the attached UEs with a low FAP density. Second, we can save huge energy with only a small system performance loss even using a random sleeping policy. Moreover, we found the tradeoff between two main resources in modern communication systems: energy and bandwidth, i.e. we can save more energy with more system bandwidth. Also, we concluded that we should use employ the factor-one resource reuse scheme to switch off more FAPs. Finally, numerous FAPs in UDN provided an extended set of FAP locations for active FAP selection and thus we could devise a strategic sleeping policy that gains advantages over simply putting fewer FAPs.

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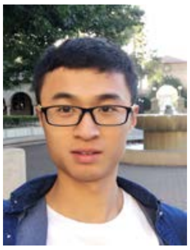

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