On Energy Efficient Inter-Frequency Small Cell Discovery in Heterogeneous Networks

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***Abstract*—In this paper, we investigate the optimal inter-frequency small cell discovery (ISCD) periodicity for small cells deployed on carrier frequency other than that of the serving macro cell. We consider that the small cells and user terminals (UTs) positions are modelled according to a homogeneous Poisson Point Process (PPP). We utilize polynomial curve fitting to approximate the percentage of time the typical UT missed small cell offloading opportunity, for a fixed small cell density and fixed UT speed. We then derive analytically, the optimal ISCD periodicity that minimizes the average UT energy consumption (EC). Furthermore, we also derive the optimal ISCD periodicity that maximizes the average energy efficiency (EE), i.e. bit-per-joule capacity. Results show that the EC optimal ISCD periodicity always exceeds the EE optimal ISCD periodicity, with the exception of when the average ergodic rates in both tiers are equal, in which the optimal ISCD periodicity in both cases also becomes equal.**

***Index Terms*—Heterogeneous cellular network, small cell discovery, energy efficiency, energy consumption.**

I. Introduction

Over the years, mobile data traffic has continued to grow at an exponential rate [1]. With this rapid growth, it is expected that in the nearest future, the mobile data traffic demand will be about $1000\times$ the traffic experienced today [2]. Dense heterogeneous network (HetNet) deployment, which comprises of a traditional cellular network overlaid with some lower transmit power base stations (BSs) referred to as small cells, is one of the approaches aimed at meeting this demand [2]–[8]. Small cell enhancement could either be a scenario where different frequency bands are separately allocated to the small cell and macro cell layers or co-channel deployment scenario where the small cell and macro cell layers share the same carrier [3]–[5]. The former is widely favored since the small cell can operate on higher frequency bands, such as $3.5, 5, 10$ GHz, where new licensed spectrum is expected to be available for future use. Also, small cells have smaller coverage footprint, thus they do not suffer from the high propagation loss which such band causes to macro cells. In addition, cross-tier interference is avoided by operating the macro and small cells on separate frequency bands, thus leading to an improvement in spectral efficiency [5]. Hence, small cells can provide high data rate to hot spots while also offering traffic offloading opportunity, which can be boosted by incorporating range expansion bias [6], [7]. In order to achieve this, user terminals (UTs) connected to the macro cell must periodically scan for small cells in their neighborhood and perform measurement to make sure that they are able to connect to a small cell network with a higher biased signal.

The energy efficient discovery of small cell has been identified has an important issue in frequency separated deployment. Various inter-frequency small cell discovery (ISCD) mechanisms have been studied in literature. Some of the proposed solutions for enhancing ISCD include: UT speed based measurement triggering [9], [10], relaxed inter-frequency measurement gap [11], proximity based inter-frequency small cell discovery [10], small cell signal based control measurement and small cell discovery signal in macro layer [4], [12]. A common feature in all the ISCD approaches is the periodic inter-frequency scanning and measurement by the UT, which results in significant UT energy consumption (EC).

In general, for a given small cell density and UT speed, low ISCD periodicity (i.e. high scanning frequency) can result in increased small cell offloading opportunity, thus enhancing the capacity and coverage. However, this can lead to higher UT power consumption due to scanning, whereas the UT transmit power can reduce as a result of offloading to the small, where lower transmit power is required due to better coverage. On the other hand, high ISCD periodicity (i.e. low scanning frequency) can lead to the UT missing small cell offloading opportunity, thus resulting in a potential decrease in capacity improvement. Most prior work on ISCD in literature have focused only on the effect of ISCD periodicity on scanning power without evaluating the impact of UT transmit power reduction when offloading to the small cells [9]–[11]. Only recently, [13] considered UT transmit power reduction as a result of offloading to the small cell in their evaluation. However, the optimal ISCD periodicity is yet to be analyzed.

In this paper, we derive analytically the EC and the energy efficiency (EE) optimal ISCD periodicities, based on the UT transmit power and average ergodic rate in both tiers, and the knowledge of the percentage of time a random/typical UT missed small cell offloading opportunity for a given small cell density and UT speed. The rest of this paper is organized as follows: In Section II, we present the HetNet system model. In Section III, we describe ISCD and utilize a polynomial curve fitting method to approximate the percentage of time a typical UT missed small cell offloading opportunity. In Section IV, we derive the EC and EE optimal ISCD periodicities. In Section V, we present the numerical results. Our results show that UT ISCD periodicity should be set based on the target objective i.e. EC minimization or EE maximization. Finally, Section VI concludes the paper.

II. System Model

We consider a 2-tier HetNet deployment where the first tier is made up of macro cells, while the second tier is made up of small cells. We consider that each tier operates on a different carrier frequency and that each tier is identified by its pathloss exponent and, its BS transmit power and spatial density. We model the positions of BSs in the j^{th} tier according to a homogeneous PPP, Φ_j, with intensity λ_j. Furthermore, the UTs are also located according to a homogeneous PPP $\Phi^{(\mathrm{u})}$ with intensity $\lambda^{(\mathrm{u})}$, which is independent of $\Phi_j,\ \forall\ \{j = 1, 2\}$. We consider that the received signals in the j^{th} tier are subject to pathloss, which we model using the pathloss exponent $\alpha_j,\ \forall\ \{j = 1, 2\}$. The random channel variation is modelled as Rayleigh fading with unit mean. We consider that an orthogonal multiple access scheme is utilized within each cell, such that there is no intra-cell interference. Furthermore, each of the BSs in the j^{th} tier transmit the same power, i.e., $P_j,\ \forall\ \{j = 1, 2\}$, while the noise power is assumed to be σ^2.

UT Association: Given that the distance between the typical UT and the nearest BS in the j^{th} tier is denoted by $D_j,\ \forall\ \{j = 1, 2\}$. We consider that the UT is associated with a cell based on the maximum received-power (RP), i.e., the UT associates with the strongest BS in terms of the long-term averaged RP [14]. The RP by the typical UT can be expressed as

$$P_{r,j} = P_j L_0 \left(\frac{D_j}{d_0}\right)^{-\alpha_j}, \tag{1}$$

where L_0 denotes the pathloss at a reference distance d_0.

Idealistic Probability of UT Association to a Tier: In an idealistic two-tier HetNet deployment, where the UT association to the BS is based on the maximum RP, the idealistic probability that a typical UT is associated with a BS of the k^{th} tier is given in [14, Lemma 1] as

$$\mathcal{A}_k = 2\pi\lambda_k \int_0^\infty r \exp\left\{-\pi \sum_{j=1}^{2} \lambda_j \widehat{P}_j^{2/\alpha_j} r^{2/\widehat{\alpha}_j}\right\} \mathrm{d}r, \tag{2}$$

where $\widehat{P}_j \triangleq \frac{P_j}{P_k}, \widehat{\alpha}_j \triangleq \frac{\alpha_j}{\alpha_k}$. Note that $k \in \{1, 2\}$ denotes the index of the tier with which a typical UT is associated.

Idealistic Distribution of the Distance between UT and Serving BS: It has been shown in [14, Lemma 3] that the idealistic probability density function (PDF), $f_{X_k}(x)$, of the distance X_k between a typical UT and its serving BS in the k^{th} tier based on the maximum RP can be expressed as

$$f_{X_k}(x) = \frac{2\pi\lambda_k}{\mathcal{A}_k} x \exp\left\{-\pi \sum_{j=1}^{2} \lambda_j \widehat{P}_j^{2/\alpha_j} x^{2/\widehat{\alpha}_j}\right\}. \tag{3}$$

Hence, in an idealistic UT association both the probability of association of a typical UT to a tier and the PDF, $f_{X_k}(x)$, of the distance X_k between the typical UT and the serving BS are dependent on the BSs transmit powers, $P_j,\ \forall\{j = 1, 2\}$, and densities $\lambda_j,\ \forall\{j = 1, 2\}$.

III. Inter-frequency Small Cell Discovery (ISCD)

We consider a HetNet deployment where the small cell BSs transmit on a different carrier frequency from that of the macro cell BSs and the small cells' coverage overlaps with the macro cells' coverage. Consequently, the UT devices connected to the macro cell periodically scan to discover surrounding inter-frequency small cells and perform measurements to ensure that it can connect to another network when it finds a small cell with a higher RP. The energy consumed for one inter-frequency small search can be expressed as

$$E_t = P_m T_m, \tag{4}$$

where T_m is the duration of the measurement and P_m is the power consumed. For a given deployment density, $\lambda_k,\ \forall\ \{k = 1, 2\}$, having a high scanning frequency results in a faster discovery of small cells and hence, increased small cell offloading opportunity, which leads to increase in system level capacity. However, high scanning rate implies an increase in UT's power consumption. On the other hand, reducing the scanning frequency results in the UT missing small cell offloading opportunity, thus, leading to a decrease in system level capacity. Also, the typical UT can significantly reduce its transmit power when connected to the small cells. Consequently, there exists a scanning frequency, $\hat{V}^\star$, that achieves optimal performance in terms of average UT energy consumption. If the scanning frequency is less than $\hat{V}^\star$, the small cells are not discovered on time, hence excessive UT energy consumption as the UT spends more time in macro cell coverage. On the other hand, excessive energy will be consumed in the search process if the scanning frequency exceed $\hat{V}^\star$. The impact of ISCD frequency, $\hat{V}$, or ISCD periodicity, $V = \frac{1}{\hat{V}}$, can be modelled in terms of the percentage of time the UT missed small cell offloading opportunity, $\mathcal{X}$, as explained in the following.

Consider a typical UT moving according to a random direction mobility model with wrap around [15], [16]. The typical UT moves at a constant speed θ on $[0, 1)$ according to the following mobility pattern: A new direction or orientation is selected from $(0, 2\pi]$ after the UT moves in a particular direction or orientation for a duration ς, hence, the selection of the n^{th} direction initializes the n^{th} movement of the UT. The duration of each movement ς is obtained as the time duration for the UT to move (at a constant speed θ) between two farthest points in the HetNet's coverage. In order to obtain $\mathcal{X}$, for a given UT speed, small cell density and ISCD periodicity $V = \frac{1}{\hat{V}}$, we utilize the current 3GPP standard inter-frequency measurement of 40 ms as our benchmark. For the n^{th} movement with duration ς, we estimate the time duration that the UT spends in the coverage of the small cell, based on ISCD periodicity V and the standard inter-frequency measurement of 40 ms, denoted by ς_V^n and $\varsigma_{40\mathrm{ms}}^n$, respectively. Hence, the average percentage of time the UT missed small cell offloading opportunity, $\mathcal{X}$, for a fixed UT speed, θ, and small cell density λ_2, can be expressed as

$$\mathcal{X} = 1 - \mathbb{E}\left[\frac{\varsigma_V^n}{\varsigma_{40\mathrm{ms}}^n}\right], \tag{5}$$

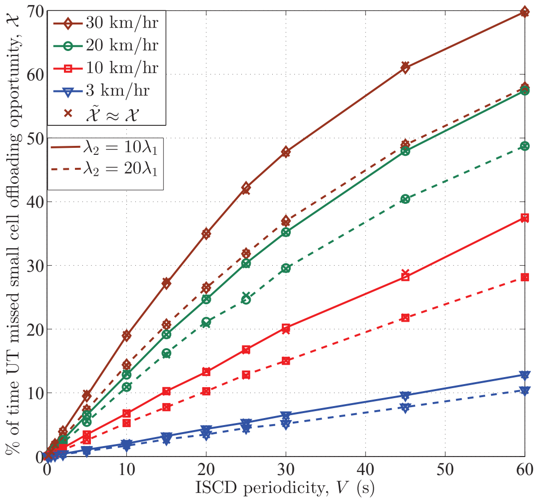

Fig. 1. *Percentage of missed small cell offloading opportunity versus ISCD periodicity for various UT speed,* $\lambda_1 = \frac{1}{\pi 400^2}$, $\lambda_2 = 10\lambda_1$ and $20\lambda_1$, $P_1 = 46$ dBm, $P_2 = 26$ dBm *and* $\alpha_1 = \alpha_2 = 4$.

where $\mathbb{E}$ is the expectation operator, ς_V^n and $\varsigma_{40\text{ms}}^n$ are the time duration that the UT spends in the small cell during the n^{th} movement based on ISCD periodicities V and 40ms, respectively.

In Fig. 1, we plot the percentage of time the UT missed small cell offloading opportunity, $\mathcal{X}$, against the ISCD periodicity, $V = \frac{1}{V}$ for UT speed, $\theta = 3, 10, 20$ and 30 km/hr, macro cell density $\lambda_1 = \frac{1}{\pi 400^2}$, small cell density $\lambda_2 = 10\lambda_1$ and $20\lambda_1$, macro cell BS transmit power $P_1 = 46$ dBm, small cell BS transmit power $P_2 = 26$ dBm and pathloss exponent $\alpha_1 = \alpha_2 = 4$. It can be seen in Fig. 1 that $\mathcal{X}$ can be approximated as a linear function of ISCD periodicity for UT speed, $\theta = 3$ km/hr. However, this is not the case for higher UT speed, hence, we generalize the approximation of $\mathcal{X}$ via a polynomial curve fitting method. The percentage of time the typical UT missed small cell offloading opportunity can be approximated as

$$\mathcal{X}(V) \approx \tilde{\mathcal{X}}(V) = \sum_{i=0}^{N} a_i V^i, \tag{6}$$

where N is the order of the polynomial, a_i is the i^{th} polynomial coefficient. The parameter N can be chosen such that the following the mean square error equation is minimized, i.e $\varepsilon_0 \ll 1$

$$\frac{\sum_{\mathbf{V}} |\mathcal{X}(V) - \sum_{i=0}^{N} a_i V^i|^2}{|\mathbf{V}|} \ll \varepsilon_0. \tag{7}$$

where $|\mathbf{V}|$ denotes the cardinality of the test vector $\mathbf{V}$. Table I gives the polynomial order and coefficient for the deployment settings with $\lambda_2 = 10\lambda_1, 20\lambda_1$ and $\theta = 3, 10, 20, 30$ km/hr. Fig. 1 shows a tight match between the exact percentage of time the UT missed small cell offloading opportunity, $\mathcal{X}$, and its approximation $\tilde{\mathcal{X}}$.

IV. Optimal ISCD Periodicity

A. Optimal ISCD Based on Energy Consumption

We consider that the UT transmit power is P_1^U when connected to the macro cell and P_2^U when connected to the small cell. In an idealistic scenario, where the typical UT connects automatically[1] to the BS with the highest RP, the average time the typical UT spend in the coverage of the macro cell and small cell can be expressed according to [17] as

$$\begin{aligned} T_1 &= \mathcal{A}_1 T \quad \text{and} \\ T_2 &= \mathcal{A}_2 T \quad , \end{aligned} \tag{8}$$

respectively, where $\mathcal{A}_k, \forall\, k = \{1, 2\}$ is defined in (2) and $T \to \infty$ is the total UT mobility time. However, in a more realistic setting, the UT misses small cell offloading opportunity as a result of the ISCD periodicity. Hence the realistic time the typical UT spend in each tier can be expressed as

$$\begin{aligned} \tilde{T}_1 &= T\left(\mathcal{A}_1 + \mathcal{X}(V)\,\mathcal{A}_2\right) \quad \text{and} \\ \tilde{T}_2 &= T\mathcal{A}_2\left(1 - \mathcal{X}(V)\right) \quad , \end{aligned} \tag{9}$$

respectively, where $\mathcal{X}(V)$ is defined in (6). Given a fixed ISCD measurement duration T_m, with ISCD periodicity V, the average number of ISCDs in the first tier can be expressed as

$$\begin{aligned} N_{ISCD} &= \frac{\tilde{T}_1}{T_m + V} \\ &= \frac{T\left(\mathcal{A}_1 + \mathcal{X}(V)\,\mathcal{A}_2\right)}{T_m + V}. \end{aligned} \tag{10}$$

The average energy consumed by a typical UT in a 2−tier HetNet, EC, is thus the sum of the average energy consumed in the first tier (macro coverage), the average energy consumed in searching the small cells, and the average energy consumed in the second tier (small cell coverage). EC in the uplink of a 2-tier HetNet can be expressed as

$$EC = \tilde{T}_1 P_1^U + N_{ISCD} T_m P_m + \tilde{T}_2 P_2^U, \tag{11}$$

which can be further simplified as a function of the ISCD periodicity

$$\begin{aligned} EC(V) = {} & TP_1^U\left(\mathcal{A}_1 + \mathcal{X}(V)\,\mathcal{A}_2\right) + \frac{TT_m P_m\left(\mathcal{A}_1 + \mathcal{X}(V)\,\mathcal{A}_2\right)}{T_m + V} \\ & + TP_2^U \mathcal{A}_2\left(1 - \mathcal{X}(V)\right). \end{aligned} \tag{12}$$

By taking $\mathcal{X}(V) \approx \tilde{\mathcal{X}}(V)$ in (6), $EC(V) \approx \tilde{EC}(V)$, which is clearly differentiable over its domain, such that $\frac{\partial \tilde{EC}(V)}{\partial V}$ can be expressed after simplification as

$$\begin{aligned} \frac{\partial \tilde{EC}(V)}{\partial V} = {} & \mathcal{A}_2\left(\Delta_p\left(T_m + V\right)^2 + T_m P_m\left(T_m + V\right)\right)\frac{\partial \tilde{\mathcal{X}}(V)}{\partial V} \\ & - T_m P_m\left(\mathcal{A}_1 + \mathcal{A}_2 \tilde{\mathcal{X}}(V)\right), \end{aligned} \tag{13}$$

[1] zero handover preparation and execution time, zero time to trigger

TABLE I
POLYNOMIAL ORDER AND COEFFICIENTS FOR VARIOUS DEPLOYMENT SETTINGS

θ	3 km/hr		10 km/hr		20 km/hr		30 km/hr	
λ_2	$10\lambda_1$	$20\lambda_1$	$10\lambda_1$	$20\lambda_1$	$10\lambda_1$	$20\lambda_1$	$10\lambda_1$	$20\lambda_1$
N	1	1	2	2	2	2	3	3
a_0	-1.27×10^{-4}	-1.5×10^{-5}	-2.38×10^{-4}	-3.55×10^{-4}	-1.489×10^{-3}	-7.75×10^{-4}	-2.440×10^{-3}	-9.97×10^{-4}
a_1	2.148×10^{-3}	1.737×10^{-3}	6.987×10^{-3}	5.378×10^{-3}	1.39×10^{-2}	1.156×10^{-2}	2.1161×10^{-2}	1.5566×10^{-2}
a_2	$-$	$-$	-1.28×10^{-5}	-1.14×10^{-5}	-7.2×10^{-5}	-5.71×10^{-5}	-1.875×10^{-4}	-1.193×10^{-4}
a_3	$-$	$-$	$-$	$-$	$-$	$-$	4.8745×10^{-7}	3.4865×10^{-7}

where $\Delta_p = P_1^U - P_2^U$. Let $V^\star$ be the solution to the equation $\frac{\partial \tilde{EC}(V)}{\partial V} = 0$. Then $\frac{\partial \tilde{EC}(V)}{\partial V} \le 0$ and $\frac{\partial \tilde{EC}(V)}{\partial V} \ge 0$ for any $V \in [0, V^\star]$ and $V \in [V^\star, +\infty]$, respectively, which in turn implies that $\tilde{EC} \approx EC$ decreases over $V \in [0, V^\star]$ and then increases over $V \in [V^\star, +\infty]$. Consequently, $EC(V)$ has a unique minimum, which occurs at $V = V^\star$. By setting $\frac{\partial \tilde{EC}(V=V^\star)}{\partial V} = 0$ and using the approximation of $\mathcal{X}(V)$ for a given speed and small cell density given in Table I in (13), we can obtain $V^\star$. For the case were $\mathcal{X}(V)$ is linear, i.e. the polynomial order $N = 1$ in (6), the optimal ISCD search based on the average energy consumed can be simplified as

$$V^\star = -T_m + \sqrt{\frac{T_m P_m \left[\mathcal{A}_2 \left(a_0 - a_1 T_m\right) + \mathcal{A}_1\right]}{\mathcal{A}_2 a_1 \Delta_p}}. \tag{14}$$

However, for the case where the polynomial order, $N > 1$, we simply use a linear search method such as Newton-Raphson method.

B. Optimal ISCD Based on UT Bit-per-Joule Capacity

The optimal ISCD periodicity in the previous subsection was based on the UT energy consumption. In this subsection, we derive the optimal ISCD based on the EE, i.e. the bit-per-joule capacity, which is the ratio of the total bit transmitted to the power consumed to do so. By considering the average ergodic rate of a typical UT in each tier, the EE in the uplink a 2-tier HetNet can be approximated as

$$EE \approx \tilde{EE} = \frac{\tilde{T}_1 \mathcal{R}_1 + \tilde{T}_2 \mathcal{R}_2}{\tilde{T}_1 P_1^U + N_{ISCD} T_m P_m + \tilde{T}_2 P_2^U} \tag{15}$$

Here, we consider that the average ergodic rate of a typical UT in the k^{th} tier, $\mathcal{R}_k$ is independent of the $\mathcal{X}$, hence, $\mathcal{R}_k$ is independent of the ISCD periodicity. The average ergodic rate of a typical user associated with a tier is obtained by finding the ergodic link rate of a user at a distance x from its serving BS in that tier. The link rate is then averaged over the distance x (i.e. over that tier) [14]. Considering a noise limited network, where interference is negligible due to the orthogonal allocation of resource, the average ergodic rate in the uplink of the k^{th} tier can be expressed as

$$\mathcal{R}_k = \int_0^\infty \mathbb{E}_{SNR_k}\left[\ln\left(1 + SNR_k\left(x\right)\right)\right] f_{X_k}(x)\mathrm{d}x, \tag{16}$$

where $SNR = \frac{h L_0 P_k^U (x/d_0)^{-\alpha_k}}{\sigma^2}$, h is i.i.d. exponentially distributed with unit mean and σ^2 is the noise power. The average ergodic rate in the k^{th} tier can thus be simplified as

$$\mathcal{R}_k = \frac{2\pi\lambda_k}{\mathcal{A}_k}\int_0^\infty -e^\beta \mathrm{Ei}\left(-\beta\right) x \exp\left\{-\pi\sum_{j=1}^{2}\lambda_j \widehat{P}_j^{2/\alpha_j} x^{2/\widehat{\alpha}_j}\right\}\mathrm{d}x, \tag{17}$$

where Ei denotes exponential integral function, $\beta = x^{\alpha_k} d_0^{-\alpha_k}\left(L_0 P_k^U\right)^{-1}\sigma^2$. Hence by substituting the expressions for $\tilde{T}_1, \tilde{T}_2$ and N_{ISCD} given in (9) and (10), respectively, into (15), the EE can be expressed solely as a function of the ISCD periodicity, V such that

$$EE = \frac{\mathcal{R}_1\left(\mathcal{A}_1 + \mathcal{X}\left(V\right)\mathcal{A}_2\right) + \mathcal{R}_2 A_2\left(1 - \mathcal{X}\left(V\right)\right)}{P_1^U(\mathcal{A}_1 + \mathcal{X}(V)\mathcal{A}_2) + \frac{T_m P_m(\mathcal{A}_1 + \mathcal{X}(V)\mathcal{A}_2)}{T_m + V} + P_2^U \mathcal{A}_2(1 - \mathcal{X}(V))} \tag{18}$$

Similar to the EC case, the EE is differentiable over its domain and the ISCD periodicity the maximizes the EE, $V^{\star\star}$, can be obtained by setting $\frac{\partial \tilde{EE}(V=V^{\star\star})}{\partial V} = 0$, which simplifies as

$$\begin{aligned}\frac{\partial \tilde{EE}(V = V^{\star\star})}{\partial V} &= 0 \\ &= \tilde{EC}(V)\mathcal{A}_2(\mathcal{R}_1 - \mathcal{R}_2)\frac{\partial \tilde{\mathcal{X}}(V)}{\partial V} \\ &\quad - \left(\sum_{k=1}^{2}\mathcal{A}_k\mathcal{R}_k + (\mathcal{R}_1 - \mathcal{R}_2)\mathcal{A}_2\tilde{\mathcal{X}}(V)\right)\frac{\partial \tilde{EC}(V)}{\partial V}\end{aligned} \tag{19}$$

Note that the optimal ISCD periodicity based on energy consumption EC, $V^\star$, and energy efficiency EE, $V^{\star\star}$, are equivalent when the ergodic rate in both tiers are equal, since $\frac{\partial \tilde{EE}(V=V^{\star\star})}{\partial V} = \frac{\partial \tilde{EC}(V)}{\partial V}$ in (19), when $\mathcal{R}_1 = \mathcal{R}_2$.

V. NUMERICAL RESULTS

We consider a two tier HetNet with fixed small cell density and fixed UT speed. We utilize a pathloss at reference distance, $d_0 = 1$, of $L_0 = -38.5$ dB and noise power $\sigma^2 = -104$ dBm. In Fig. 2, we plot the optimal ISCD periodicity against the UT transmit power in the small cell for a fixed UT transmit power in the macro cell $P_1^U = 1.5$ W, ISCD power $P_m = 1$ W, UT speed $\theta = 3$ and 10 km/hr, and small cell density $\lambda_2 = 10\lambda_1$ and $20\lambda_1$. The upper graph shows the impact of varying of UT speed on the optimal ISCD periodicity, while the lower graph shows the impact of varying the small cell density. The upper graph clearly shows that as the UT speed increases, the ISCD periodicities required to achieve optimal EC and EE performances reduces. On the other hand, the lower graph shows that increasing the small cell density reduces the ISCD

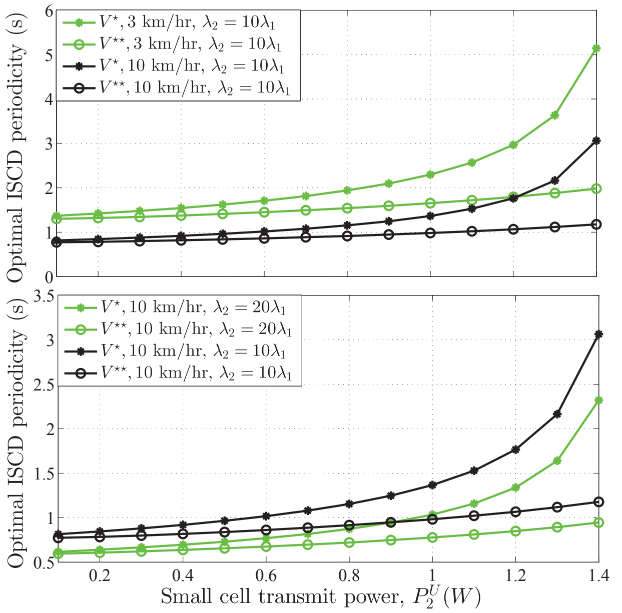

Fig. 2. *Optimal ISCD periodicity for various UT transmit power in small cell , small cell densities, $\lambda_2 = 10\lambda_1, 20\lambda_1$, and UT speed, $\theta = 3, 10$ km/hr, ISCD power, $P_m = 1$ W and UT transmit power in macro cell, $P_1^U = 1.5$ W.*

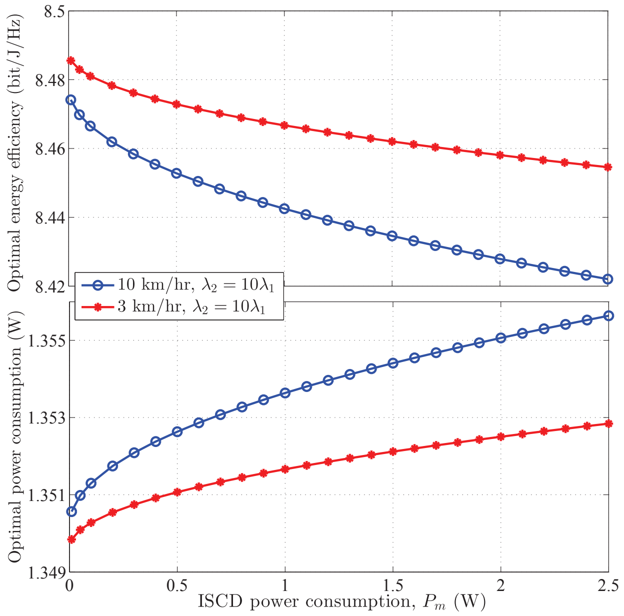

Fig. 3. *Average power consumption and EE based on optimal ISCD periodicity, for small cell density, $\lambda_2 = 10\lambda_1$, and UT speed, $\theta = 3, 10$ km/hr, UT transmit powers, $P_1^U = 1.5$ W and $P_2^U = 1.2$ W.*

periodicities required to achieve optimal EC and EE performances. Furthermore, Fig. 2 clearly shows that increasing the transmit power of the UT when connected to the small cell results in the increase in the ISCD periodicity required to achieve the optimal performance in terms of both EC and EE. Though UT power consumption is lower when UT is connected to the small cell, however, additional power is spent

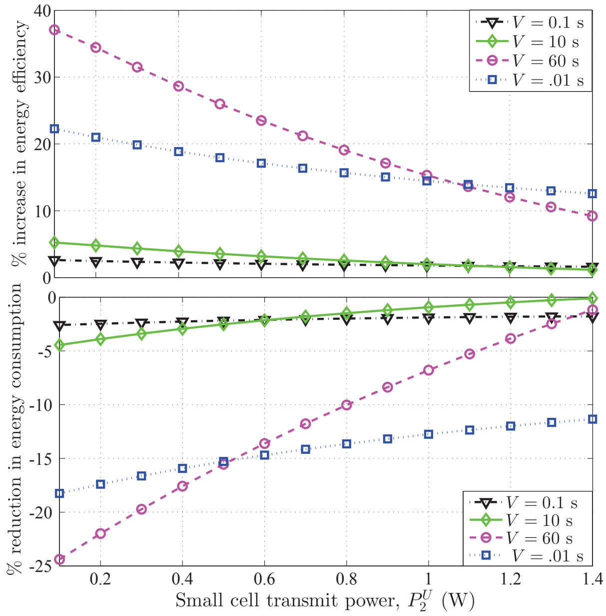

Fig. 4. *Percentage reduction in EC and percentage increase in EE achieved by using optimal ISCD periodicity over sub-optimal ISCD periodicity, for small cell densities, $\lambda_2 = 10\lambda_1$, UT speed, $\theta = 10$ km/hr, ISCD power, $P_m = 1$ W and UT transmit power, $P_1^U = 1.5$ W.*

in searching the small cell. Hence increasing the UT transmit power in the small cell implies an increase in the search periodicity required to achieve optimal EC performance. In terms of EE, increasing the UT transmit power in the small cell also leads to an increase in the average ergodic rate in the small cell. However the ergodic rate increase is lower (logarithmic) compared to the transmit power increase (linear). Hence the effect of the transmit power dominates, which thus leads to an increase in the ISCD periodicity required to achieve optimal EE. Fig. 2 further shows that for a fixed UT transmit power in the small cell, the ISCD periodicity required to achieve optimal EC performance always exceed the ISCD periodicity required to achieve optimal EE performance.

In Fig. 3, we plot the average UT power consumption (lower graph) and EE (upper graph) based on the optimal ISCD periodicity against the ISCD power consumption,P_m, for small cell density $\lambda_2 = 10\lambda_1$ and UT speed $\theta = 3, 10$ km/hr. As expected, increasing the ISCD power leads to an increase in the average power consumption and a reduction in the average EE. In addition, with the same network parameters, a high speed UT is less energy efficient since higher scanning frequency (i.e., lower ISCD periodicity) is required to attain optimal performance.

In Fig. 4 we plot the percentage reduction in average EC (lower graph) and the percentage increase in average EE (upper graph), respectively, that is achieved from using the optimal ISCD periodicity against using sub-optimal ISCD periodicity. Fig. 4 shows that significant amount of energy can be saved by adopting the optimal ISCD periodicity especially when there is a large deviation between the optimal and sub-optimal values. For example, the optimal ISCD periodicity for deployment setting with $\lambda_2 = 10\lambda_1, P_m = 1$ W, $P_1^U = 1.5$W and UT speed of 10 km/hr used in Fig. 4 is such that $V^\star \wedge V^{\star\star} \in [0.77\ 3.1]$ s (as shown in Fig. 2). However, using ISCD periodicity $V = 0.01, 60$ s results in larger difference compared with $V = 0.1, 10$, which are more closer to the optimal values.

VI. Conclusion

In this paper, we have derived the optimal inter-frequency small cell discovery (ISCD) periodicities for small cells deployed on carrier frequency other than that of the serving macro cell, while considering the average energy consumption (EC) and the average energy efficiency (EE). The locations of the user terminals (UTs) and small cells were modelled according to homogeneous Poison Point Process. It was revealed that using the EE or EC optimal ISCD results in significant saving in the UT energy consumption. Furthermore, EE optimal ISCD differs from the EC optimal ISCD as long as the average ergodic rate of the typical UT in both the macro and small cell coverage differs. Hence, UT ISCD periodicity should be chosen based on the target objectives such as EC minimization or EE maximization.

In future, we would extend our work to the interference limited scenario and also consider the impact of cell extension range on the optimal ISCD periodicity.

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