Feasibility of Simultaneous Information and Energy Transfer in LTE-A Small Cell Networks

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***Abstract*—Simultaneous information and energy transfer (SIET) is attracting much attention as an effective method to provide green energy supply for mobiles. However, low power level of harvested energy from RF spectrum limits application of this technique. Thanks to improvement of sensitivity and efficiency of RF energy harvesting circuit as well as dense deployment of small cell base stations, SIET becomes more practical. In this paper, we propose a unified receiver model for SIET in LTE-A small cell base station networks, formulate a feasibility problem with Poisson point process model and analyze the feasibility for a special and practical scenario. The results show that it is feasible for mobiles to charge the secondary battery with harvested energy from BSs, but it is still impractical to directly charge the primary battery or operate without any battery at all.**

I. Introduction

There are two major roles for RF energy. The most important use is for providing telecommunication services to the public, industries and governments. Non-communication use of RF energy mainly includes heating, radar and wireless power transfer (WPT). Due to shortage of fossil fuel and crisis of environment, WPT and energy harvesting have received considerable attention as methods of addressing environmental problems [1], [2]. There are two ways of transmitting information and wireless power: *single tone* and *multi-tone* methods [3]. The former uses only one carrier to transmit information and power simultaneously, while the latter transmits information and energy separately with two distinct carrier frequencies. Since spectrum resources are very limited today, people become more interested on research of simultaneous information and energy transfer (SIET) [4], [5].

As harvesting energy from ambient RF signal is free and unlimited, SIET has recently drawn a great attention. A point-to-point transfer with single antenna is studied in [4]. Their work investigates when a receiver should switch between two modes of information decoding and energy harvesting based on instantaneous channel and interference condition. In [6], a simultaneous wireless information and power transfer with MIMO broadcast system is considered. To optimize transfer strategy to achieve a tradeoff between maximal information rates and energy transfer, the boundary of rate-energy region is characterized. They also propose two practical designs for co-located receiver called *time switching* and *power splitting*. However, from the perspective of practicability, the key problem for SIET is whether the energy is strong enough to sustain mobiles. From Fig. 4 in [6], it can be found that the maximal harvested energy will not exceed $0.6mW$ for a 4×4 MIMO broadcast system, even when information rate is lowered to 0. The work of [7] proposes a more practical design for cellular networks to transfer wireless power: deploying a new type base stations called power beacons (PBs) to deliver energy to mobile devices by microwave radiation. The PBs are deployed as a homogeneous Poisson point process (PPP) with a certain density. It is proved in this work that density and transmit power of the PBs must satisfy some conditions to meet the outage constraint of mobiles. However, this scheme needs extra construction of PBs except for common base stations, which is economically infeasible. As a result of improvement of sensitivity and efficiency of RF energy harvesting circuit [8], SIET is becoming more and more practical. More importantly, with densely deployed small cell base stations (recently proposed to LTE-A) [9], closer distance to a radio emitter can greatly improve energy transfer efficiency. Besides, interference from other BSs can also contribute to energy harvesting, which means all signals in the air are useful. Motivated by observations above, we propose a practical receiver model for SIET in a homogeneous small cell network. Based on this model we focus on the feasibility study of SIET using stochastic geometry method. The main contributions of our work are listed as follows:

- Propose a unified receiver model for mobiles of PPP BS-deployed LTE-A small cell networks, which can decode information and harvest energy simultaneously. This model considers user activity level as well as a flexible power allocation factor for energy-harvesting and information-decoding.
- Formulate the distribution of energy harvested from PPP deployed base stations for the first time. Also, the definition of *efficient energy harvesting (EEH) probability* is first proposed.
- Formulate the feasibility of SIET in small cell networks as maximization of EEH probability conditioned on constraints of coverage probability, density and power limitation of BSs.

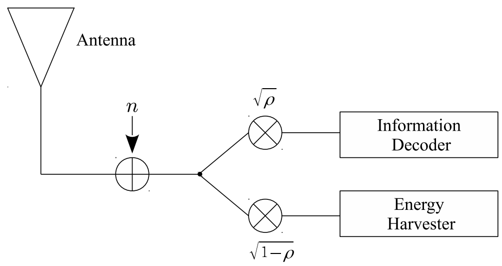

Fig. 1. Receiver Model of SIET system

- The feasibility problem for a special case which has limited interference and path loss exponent as 4 is analytically solved. The results show that it is infeasible for harvested energy to compensate basic energy consumption of a low-power mobile, but it is feasible to charge the secondary battery of a hybrid-battery supplied terminal.

In Section II, system model is proposed. Section III provides preliminaries of coverage and efficient energy harvesting. The feasibility problem is formulated and solved in Section IV, and analyzed considering real scenario in Section V. The conclusion and future research directions are given in Section VI.

II. System Model

We consider a homogeneous small cell network with: (1) base stations arranged according to a PPP Φ of intensity λ; (2) mobile users are distributed according to an independent stationary point process, and (3) each mobile user is associated with the closest base station (denoted as b_c).

In this paper, we focus on SIET on the downlink. For simplicity and tractability, we assume that all base stations (BS) transmit at the same power P. The standard power loss propagation model with path loss exponent $\alpha > 2$ along with a Rayleigh fading gain is considered. The received power at a typical mobile user with distance r from its corresponding base station is $hr^{-\alpha}$ where the random variable h follows exponential distribution with mean P.

We employ a receiver model as shown in Fig. 1. The received raw power is split into two streams. One stream is fed into information decoder while the other one is fed into the energy harvester. The power splitting factor is denoted as ρ and the white Gaussian noise introduced by the receiving antenna $n \sim \mathcal{CN}(0, \sigma^2)$.

Obviously the receiver has two states in the downlink direction. One state is that the user is active and scheduled by the BS. In this state, the receiver has to decode information and harvest energy simultaneously. Alternately, when the user is inactive, the receiver can solely harvest energy from the ambient RF signals as there is no information to be decoded. To maximize utilization of RF energy, we suppose that the power splitting factor (ρ) can be adjusted in light of the user's state. We model the user activity as a two state Markov process and assume the probabilities of user being active and idle are ϵ and $1-\epsilon$, respectively. Thus, the adaptive power splitting factor can be described as $\rho \cdot \mathbf{1}(\text{user is active})$, where $\mathbf{1}(x)$ represents the indicator function.

The received power P_0 at a typical user location the origin before power splitting corresponds to:

$$P_0 = \begin{cases} hr^{-\alpha} + \sum_{i\in\Phi/b_c} hR_i^{-\alpha} + \sigma^2 & \text{user is active,} \\ \sum_{i\in\Phi} hR_i^{-\alpha} + \sigma^2 & \text{user is idle,} \end{cases} \tag{1}$$

where, R_i denotes the distance from the i^{th} base station to a typical user located at the origin. In the next section, we will discuss the preliminary results related to coverage and energy harvesting in the system described above.

III. Preliminaries

A. Coverage

Definition 1. A user is *in coverage* when its SINR from its nearest BS is larger than some threshold T, and it is dropped from the network when SINR falls below T.

According to definition 1, the coverage probability of a homogeneous network is

$$p_c(T, \lambda, P, \alpha, \rho) \triangleq \mathbb{P}[\text{SINR} > T]. \tag{2}$$

The SINR of a mobile user at a random distance r from its associated base station can be expressed as:

$$\text{SINR} = \frac{\rho h r^{-\alpha}}{\sigma^2 + \rho \sum_{i\in\Phi/b_c} hR_i^{-\alpha}}. \tag{3}$$

1) Average Coverage Probability: In order to calculate the average coverage probability, we first restate a known result from stochastic geometry theory [10]. Then this result is employed to derive complementary cumulative distribution (ccdf) of SINR for a typical user.

Corollary 1. *For homogeneous cellular networks of which BSs' positions follow PPP with intensity λ, the interference at the origin from those base stations at least r away can be formulated as:*

$$I(r) = \sum_{i:R_i>r} hR_i^{-\alpha}, \tag{4}$$

where h follows exponential distribution with parameter μ and is independent of the distance $\{R_i\}$.

Then the Laplace Transform of $I(r)$ for any $s > 0$ is

$$\mathcal{L}_{I(r)}(s) = \exp[-\pi\lambda(s/\mu)^{2/\alpha} G(r^2(s/\mu)^{-2/\alpha})], \tag{5}$$

where

$$G(y) = \int_y^\infty \frac{dx}{1+x^{\frac{\alpha}{2}}} = \begin{cases} \pi/2 - \arctan y, & \alpha = 4, \\ {}_2F_1(1, \frac{2}{\alpha}; 1+\frac{2}{\alpha}; -x^{\frac{\alpha}{2}})x|_y^\infty, & \alpha \neq 4, \end{cases} \tag{6}$$

and ${}_2F_1(a,b;c;z)$is the hypergeometric function.

For special case with $r = 0$, $\mathcal{L}_{I(0)}(s) = \exp[-\frac{2\pi^2\lambda}{\alpha}\left(\frac{s}{\mu}\right)^{\frac{2}{\alpha}} \csc\left(\frac{2\pi}{\alpha}\right)]$

Proof: This corollary is derived from Corollary 1 in [10] by substituting X_i with h and μ with $1/\mu$ for consistency with our notation custom. □

Lemma 1. *To examine overall coverage performance of the network, the average coverage probability over the plane corresponds to:*

$$\mathcal{P}_c(T,\lambda,P,\alpha,\rho)=2\pi\lambda\int_{r>0}e^{-\pi\lambda r^2-Tr^\alpha\sigma^2/\rho P}\mathcal{L}_{I(r)}(\frac{Tr^\alpha}{P})rdr \tag{7}$$

where, $\mathcal{L}_{I(r)}(s)$ *is the Laplace transform of random variable* $I(r)$ *evaluated at* s *conditioned on the distance to the closest BS from the origin.*

Proof: Substituting (3) into (2) follows:

$$\begin{aligned} p_c(T,\lambda,P,\alpha,\rho) &= \mathbb{P}[\frac{\rho h r^{-\alpha}}{\sigma^2+\rho I(r)}>T|r] \\ &= \mathbb{E}_{I(r)}[\mathbb{P}[h>T\rho^{-1}r^\alpha(\sigma^2+\rho I(r))|r,I_r] \\ &\overset{(a)}{=} \mathbb{E}_{I(r)}[\exp(-T(\rho P)^{-1}r^\alpha(\sigma^2+\rho I(r))|r] \\ &= e^{-Tr^\alpha\sigma^2/\rho P}\mathcal{L}_{I(r)}(Tr^\alpha/P), \end{aligned}$$

where (a) follows from $h\sim\exp(1/P)$. The average coverage probability over the plane can be expressed as

$$\mathcal{P}_c(T,\lambda,P,\alpha,\rho)=\int_{r>0}p_c(T,\lambda,\alpha)f_r(r)dr, \tag{8}$$

where $f_r(r)$ is the pdf of r (distances to the nearest BS). Since the BS are distributed according to $PPP(\lambda)$, we know that $f_r(r)e^{-2\pi r^2}2\pi\lambda r$ [11]. Substituing it into (8), we can get

$$\mathcal{P}_c(T,\lambda,P,\alpha,\rho)=2\pi\lambda\int_{r>0}e^{-\pi\lambda r^2-\frac{Tr^\alpha\sigma^2}{\rho P}}\mathcal{L}_{I(r)}(\frac{Tr^\alpha}{P})rdr \tag{9}$$

Then we obtain the result. □

B. Efficient Energy Harvesting

Definition 2. Efficient Energy Harvesting (EEH): A user is able to harvest usable energy from ambient RF only if its received energy is larger than certain threshold Θ due to the limitations imposed by the energy harvesting circuitry.

Then EEH probability $p_{\text{eeh}}(\Theta,\lambda,\alpha,\rho)$ of a typical user located at the origin can be defined as:

$$p_{\text{eeh}}(\Theta,\lambda,P,\alpha,\rho)\triangleq\mathbb{P}[E_h>\Theta], \tag{10}$$

Averaging EEH probability over distance as well as the user state we can derive

$$\mathcal{P}_{\text{eeh}}(\Theta,\lambda,P,\alpha,\rho)\triangleq\mathbb{E}_{r,us}[\mathbb{P}[E_h>\Theta|r,us]]. \tag{11}$$

Lemma 2. *The average probability of efficient energy harvesting of a typical randomly located user in small cell networks is*

$$\mathcal{P}_{\text{eeh}}(\Theta,\lambda,P,\alpha,\rho)=1-\epsilon F_{I(0)}(\Theta-\sigma^2)-(1-\epsilon)F_{I(0)}(\Theta-\sigma^2), \tag{12}$$

where $F_{I(0)}(x)=\mathcal{L}_s^{-1}\left\{\frac{1}{s}\exp[-\frac{2\pi^2\lambda}{\alpha}\left(\frac{s}{\mu}\right)^{\frac{2}{\alpha}}\csc\left(\frac{2\pi}{\alpha}\right)]\right\}(x).$

Proof: For energy harvesting, there is no difference between cases with active state and idle state, respectively. Since a energy harvester does not need to extract information from its corresponding BS, we can treat harvested energy on both cases as interference from all base stations. According to definition of (4), harvested energy before power splitting can be expressed as $I(0)+\sigma^2$ and does not depend on distance r. Note that distance r is only used for deciding which base station should be connected, not the entire interference in the plane. Now (11) can be rewritten as

$$\begin{aligned} &\mathcal{P}_{\text{eeh}}(\Theta,\lambda,P,\alpha,\rho) \\ =&\mathbb{E}_{us}[\mathbb{P}[E_h>\Theta]] \\ =&\epsilon\mathbb{P}[(I(0)+\sigma^2)(1-\rho)>\Theta]+(1-\epsilon)\mathbb{P}[I(0)+\sigma^2>\Theta] \\ =&\epsilon\mathbb{P}[I(0)>\frac{\Theta-\sigma^2}{1-\rho}]+(1-\epsilon)\mathbb{P}[I(0)>\Theta-\sigma^2] \\ =&\epsilon(1-F_{I(0)}(\frac{\Theta-\sigma^2}{1-\rho}))+(1-\epsilon)(1-F_{I(0)}(\Theta-\sigma^2)) \\ =&1-\epsilon F_{I(0)}(\frac{\Theta-\sigma^2}{1-\rho})-(1-\epsilon)F_{I(0)}(\Theta-\sigma^2) \end{aligned}, \tag{13}$$

where, $F_{I(0)}(x)$ is cdf of $I(0)$. There is no closed-form expression for the cdf (pp97, [11]), but we can recover the cdf via inverse Laplace transform of $I(0)$ as:

$$\begin{aligned} F_{I(0)}(x) &= \mathcal{L}_s^{-1}\left\{\frac{\mathcal{L}_{I(0)}(s)}{s}\right\}(x) \\ &= \mathcal{L}_s^{-1}\left\{\frac{1}{s}\exp[-\frac{2\pi^2\lambda}{\alpha}\left(\frac{s}{\mu}\right)^{\frac{2}{\alpha}}\csc\left(\frac{2\pi}{\alpha}\right)]\right\}(x). \end{aligned}$$

This proves Lemma 2. □

IV. Problem Formulation

In this paper, our goal is to study feasibility of SIET in small cell networks. Intuitively, the denser the BS deployments, the more power users can harvest, thereby increasing the feasibility of SIET. However, denser BSs will not result in better link quality due to increase in interference. So, we consider a density-limited small cell networks with concurrent transmission of information and energy harvesting. Our goal is to maximize the efficient energy harvesting probability under constraints of (1) coverage probability; (2) BS's transmit power, and (3) BS-deployment density. The resulting optimization problem can be stated as:

$$\begin{aligned} \mathbf{P1}:\max_{p,\lambda}\quad & \mathcal{P}_{eeh}(\Theta,\lambda,P,\alpha,\rho) && (14) \\ \mathbf{s.t.}\quad & \mathcal{P}_c(T,\lambda,P,\alpha,\rho)\geqslant\mu && (15) \\ & P\leqslant P_{\max} && (16) \\ & \lambda\leqslant\lambda_{\max}, && (17) \end{aligned}$$

for given threshold of SINR (T) and energy harvesting threshold (Θ). Here μ is the minimum coverage probability; P_{max}

and λ_{max} are maximum transmit power of small cell BSs and maximum BS-deployment density of the networks, respectively. The setting of EEH threshold Θ and SNR threshold is based on different service quality requirements. Unfortunately, problem (14) is intractable due to the lack of closed form expression for $\mathcal{P}_c(T, \lambda, P, \alpha, \rho)$ and inverse Laplace transform based expression for $\mathcal{P}_{eeh}(\Theta, \lambda, P, \alpha, \rho)$. In the remaining part of this paper, we simplify the problem to a special case with $\alpha = 4$ and $\sigma^2 = 0$, where it leads to closed-form expressions for $\mathcal{P}_{\rm c}$ and $\mathcal{P}_{\rm eeh}$. Note that we intend to gain an insight into the feasibility of SIET in small cell networks, thereby this simplification does not weaken the focus of this paper.

A. *Interference Limit Case with $\alpha = 4$*

When we set $\alpha = 4$ and $\sigma^2 = 0$, the Laplace transform of $I(r)$ in (5) simplifies to

$$\mathcal{L}_{I(r)}(s) = e^{-\pi\lambda\sqrt{sP}(\frac{\pi}{2} - \arctan\frac{r^2}{\sqrt{sP}})}. \tag{18}$$

Introducing (18) into (8), we can get

$$\mathcal{P}_c(T) = \frac{1}{1+\sqrt{T}(\frac{\pi}{2} - \arctan\frac{1}{\sqrt{T}})}, \tag{19}$$

where the coverage probability does not depend on λ or ρ. This means that constraint (15) can be removed in this case.

Next we introduce these special α and $shi\sigma^2$ into (12) and simplify the average effective energy harvesting probability $\mathcal{P}_{\rm eeh}$ to

$$\mathcal{P}_{\rm eeh}(\Theta, \lambda, P, \rho) = \epsilon\,\mathrm{erf}(\frac{\pi^2\lambda}{4}\sqrt{\frac{P(1-\rho)}{\Theta}}) + (1-\epsilon)\mathrm{erf}(\frac{\pi^2\lambda}{4}\sqrt{\frac{P}{\Theta}}), \tag{20}$$

where $\mathrm{erf}(x) = 2/\sqrt{\pi}\int_0^x e^{-t^2}dt$ is the standard error function.

Proof: Introducing $\alpha = 4$ into (14) follows:

$$\begin{aligned} F_{I(0)}(x) &= \mathcal{L}_s^{-1}\left\{\frac{1}{s}\exp[-\frac{\pi^2\lambda}{2}\sqrt{Ps}]\right\}(x) \\ &\overset{(a)}{=} \mathrm{erfc}(\frac{\pi^2\lambda}{4}\sqrt{\frac{P}{x}}), \end{aligned}$$

where (a) comes from the fact that $\mathrm{erfc}(\frac{a}{\sqrt{x}})$'s Laplace transform is $s^{-1}e^{-2a\sqrt{s}}$ [12]. Substituting this $F_{I(0)}(x)$ into (13) we can get the result as (20). □

B. *Solution in Special Case*

Using the simplified expression of EEH probability $\bar{p}_{eeh}$ and removing constraint (15), problem (14) simplifies to

$$\begin{aligned} \mathbf{P2}: \max_{p,\lambda} \quad & \mathcal{P}_{\rm eeh}(\Theta, \lambda, P, \rho) & (21)\\ \text{s.t.} \quad & P \leqslant P_{\rm max} & (22)\\ & \lambda \leqslant \lambda_{\rm max}. & (23) \end{aligned}$$

By carefully looking at (20) we can find that given EEH threshold Θ , energy splitting factor ρ and user active probability ϵ, efficient energy harvesting probability $\mathcal{P}_{\rm eeh}$ increases monotonically with $\lambda\sqrt{P}$. This implies that from the perspective of harvesting energy, quadratic increase of transmit power equivalent to linear increase of network density, which coincides with the result of interference analysis in [11]. The curve of $\bar{\mathcal{P}}_{\rm eeh}$ with regard to $\lambda\sqrt{P}$ is depicted in Fig. 2, assuming $\epsilon = 0.3$ and $\Theta = 1\text{mw}$. With this observation, solution of (21) is straightforward and the optimal value of EEH probability is achieved when P and λ take their maximum values synchronously. Due to the equivalence of effects of λ and $\sqrt{P}$ on energy-harvesting, we can set transmit power P as a typical constant value and study the maximum EEH probability with distinct BS-deployment densities. For most small cell base stations, the transmit power would not exceed $1W$. Therefore, we set $P = 1W$. And BS density λ under such assumption is defined as *standard base station density*.

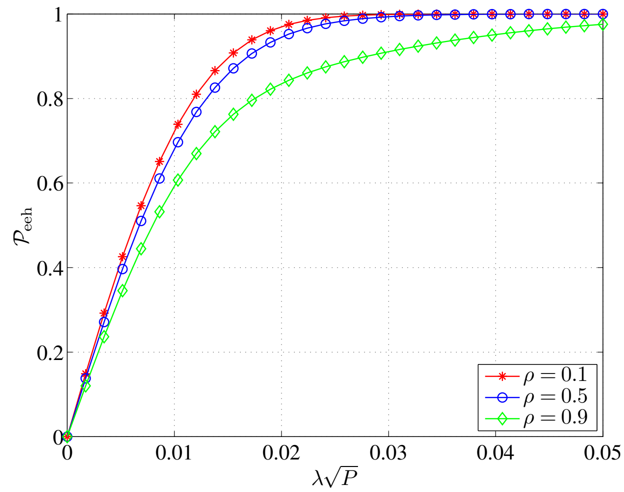

Fig. 2. Curve of $\mathcal{P}_{\rm eeh}$ over $\lambda\sqrt{P}$ with different power splitting factors, $\epsilon = 0.3$ and $\Theta = 1\text{mw}$.

Definition 3. Standard base station density (λ_s): For a homogeneous PPP cellular network, if transmit power of all base stations is 1W, density of the PPP cellular networks is called standard base station density.

It is worth noting that standard base station density is defined for easing the analysis of energy-harvesting and interference. Due to the equivalent effect of density and transmit power on P_{eeh}, the result with standard density can be readily extended to a non-unit-transmit-power case. With definition 3, the problem (21) can be further simplified as follows:

$$\begin{aligned} \mathbf{P3}: \max_{\lambda_s} \quad & \mathcal{P}_{\rm eeh}(\Theta, \lambda_s) & (24)\\ \text{s.t.} \quad & \lambda_s \leqslant \lambda_{\rm max}. \end{aligned}$$

where

$$\mathcal{P}_{\rm eeh}(\Theta, \lambda_s) = \epsilon\,\mathrm{erf}(\frac{\pi^2\lambda_s}{4}\sqrt{\frac{1-\rho}{\Theta}}) + (1-\epsilon)\mathrm{erf}(\frac{\pi^2\lambda_s}{4\sqrt{\Theta}}). \tag{25}$$

The objective function is an increasing function of λ_s. Therefore, the EEH probability can be maximized when $\lambda_s = \lambda_{max}$ and the corresponding value is $\mathcal{P}^*_{\rm eeh}(\Theta, \lambda_{\rm max})$.

V. Feasibility Analysis

For analyzing the feasibility of simultaneous information and energy transforming, the most important parameter is Θ, or, the threshold received power that is needed for sustaining the circuitry of the wireless terminal. This threshold is closely related to converter efficiency of RF energy harvester and the lowest needed power for maintaining operation of a terminal. From the perspective of energy supply, there are different ways in which harvested energy may be used:

Mode 1) *Charging the secondary battery*: The harvested energy can charge the built-in battery and prolong stand-by time of the device. For example, the wireless device can have a hybrid-battery power supply system. That is, the primary battery is charged by the grid and the secondary battery is charged by RF energy harvester. In such a case, the needed power from energy harvester can be lower than the maintenance power of the device.

Mode 2) *Sustaining the basic system*: The harvested energy can completely compensate power consumption of the device when it does not have communication or other computational tasks. To deal with such computational tasks. it is necessary to build a grid-charged battery in the system. Compared with Mode 1, the benefit is the ability to use a smaller battery, which means smaller volume and lighter weight device.

Mode 3) *Battery-free:* If harvested energy is large enough, the device can be battery-free and the energy needed to support all the tasks of the device entirely comes from the ambient energy.

As the power consumption of devices varies significantly, it is impossible to find a unified standard for all kinds of user terminals. If we assume the maintenance power is $p_{\rm m}$ and the*availability factor* is ζ, then we can use $\zeta p_{\rm m}$ to describe the needed power for the three models above. Specifically, power level for (1) charging the secondary battery can be represented as $\zeta p_{\rm m}$ with $0 < \zeta < 1$; (2) sustaining the basic system is ζp_m with $\zeta = 1$, and (3) battery-free is ζp_m with $\zeta \gg 1$. Larger ζ implies more availability of RF energy from small cell base stations. Integrating the above discussions, the threshold for harvested energy before converter can be calculated as:

$$\Theta = \frac{\zeta p_{\rm m}}{\eta}, \tag{26}$$

where η is the converter efficiency. According to recent development efforts in RF energy harvester [13], the achievable peak efficiency is 60% and achievable average efficiency is 40% in $840 - 975$ MHz band. As the converter efficiency for higher frequency (e.g. the frequency over which the cellular communication operates) is not clear till now, we will study the effects of different η on the feasibility of SIET only within the $840 - 975$ MHz range. For the other key parameter $p_{\rm m}$, experimental measurements show that the typical maintenance power for a smart phone is as much as $0.02W$ (3G) or $0.03W$ (GSM) [14]. The maintenance power of LTE-A, which is the system of interest in this paper, is believed to not exceed $0.02W$. In view of this observation, we set $p_{\rm m} = 0.02W$ for the mobile terminal of small cell networks. It is noteworthy that the maintenance power is greatly dependent on hardware and operating system of the mobile, e.g. a smartphone with ARM920T CPU and Android 1.5 operating system will cost $0.068W$ for sustaining the basic system [15]. However, since our goal is to investigate the feasibility of SIET in cellular communications, the lowest maintenance power is considered in this work. In the following subsections, we study the feasibility of SIET for 2 different densities of BSs ($\lambda_{max} = 10^{-4}$ and 10^{-2}). Additionally, we also study the relationship between the maximum BS-deployment density and availability factor conditioned on constant average EEH probability.

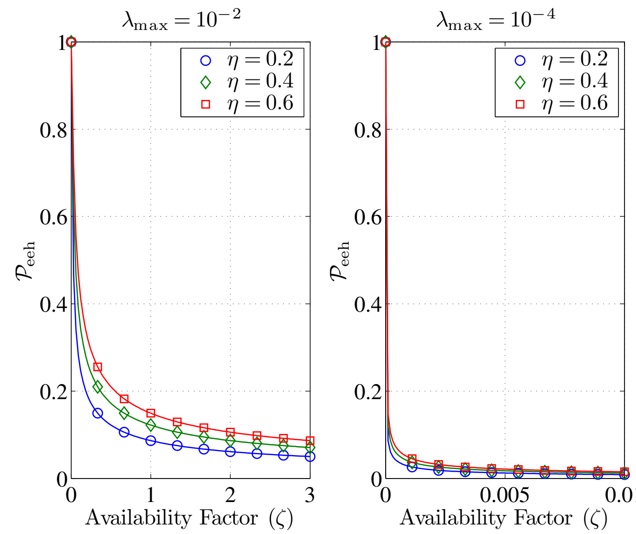

Fig. 3. Maximal average EEH probability over availability factor, which is computed using (25) with $\epsilon = 0.3$, $\rho = 0.1$ and $p_m = 0.02W$

A. Average EEH probability - Availability Factor Region

To study the feasibility of SIET on different BS density, we depict the average EEH probability and availability factor region in Fig. 3. From this figure, it can be seen that when $\lambda_{\rm max} = 10^{-2}$ (which represents a type of dense small cell networks), the average EEH probability only reaches 0.2 for feasible availability factors, even with the converter efficiency as much as 0.6. For a practical application scenario, the average EEH probability $\mathcal{P}_{\rm eeh}$ should be at least larger than 0.5 where the corresponding availability factor is $\zeta \in (0, 1)$. That means even with a very dense BS-deployment, harvested energy from BSs can only charge the secondary battery for a hybrid-battery powered device. Energy harvesting cannot sustain Mode 2 and Mode 3 even in this case.

For a more practical scenario with small cell BS density $\lambda_{\rm max} = 10^{-4}$, the availability will not be larger than 0.01 even though the average EEH probability is far less than 0.2, as shown in the right part of Fig. 3. So in this case, harvesting energy from small cell BSs is not useful under current converter efficiency of harvesters and power consumption of cell phones.

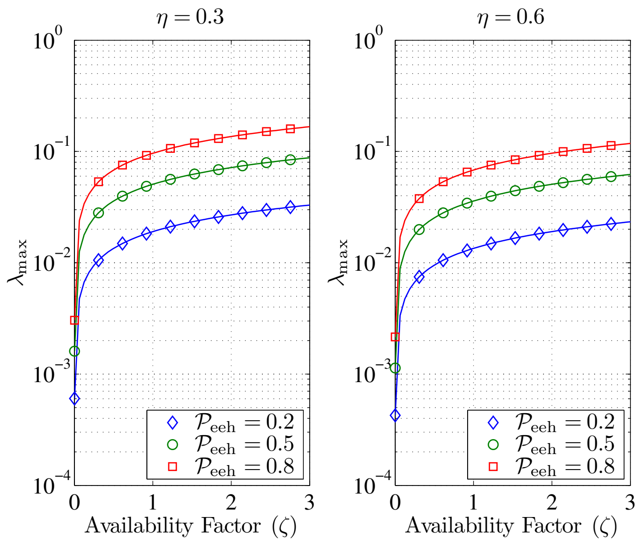

Fig. 4. Maximal BS-deployment density over availability factor, with $\epsilon = 0.3$, $\rho = 0.1$ and $p_m = 0.02W$

B. Maximal BS-deployment density over availability under constant $\mathcal{P}_{\rm eeh}$

We depict curves of $\lambda_{\max}$ over ζ with constant $\mathcal{P}_{\rm eeh}$ in Fig. 4. The converter efficiency is set to 0.3 and 0.6. The goal of this figure is to show how dense the small cell BSs should be in order to meet the requirement of average EEH probability and availability factor. It is easy to see that $\lambda_{\max}$ increases with the objective $\mathcal{P}_{\rm eeh}$ and the availability factor. It is evident that to achieve the objective of $\mathcal{P}_{\rm eeh} = 0.8$ and ζ=1 (corresponding to level 2) with $\eta = 0.3$, the needed BS density will be as much as 10^{-1}. Obviously, it is too dense compared with current LTE-A standards. Even if converter efficiency η is improved to 0.6, the *density requirement is still impractical.* In conclusion, the simultaneous information and energy transfer for small cell LTE-A networks can only provide very limited energy for mobile terminals. That does not mean SIET is infeasible. It means that SIET is possible if energy harvested from BSs can charge a secondary battery to prolong life time of terminals.

VI. Conclusion

In this paper we study the feasibility of simultaneous information and energy transfer in homogeneous small cell LTE-A networks. By using tools from stochastic geometry, we formulate an optimization problem to maximize average efficient-energy-harvesting (EEH) probability conditioned on constraints of coverage probability, deployment density and transmit power of BSs. The solution for the special case ($\alpha = 4$) shows that average EEH probability is increased with larger BS-deployment density if other parameters like converter efficiency, energy harvesting threshold, power splitting factor and user activity level are given. The numerical results reveals that under current BS-deployment of LTE-A standard, harvesting energy from BSs to charge the secondary battery of a hybrid-battery powered terminal is feasible; but to sustain the radio system purely based on energy harvested energy is infeasible.

In this paper, only single-tier small cell networks is considered, we will study the feasibility of SIET in multi-tier small cell networks in the future. The tradeoff between harvested energy and interference is also an interesting problem and needs further study.

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