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

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Abstract—Simultaneous information and energy transfer is attracting much attention as an effective method to provide green energy supply for mobiles. However, the very low power level of the harvested energy from RF spectrum limits the application of such technique. Thanks to the improvement of sensitivity and efficiency of RF energy harvesting circuit as well as the dense deployment of small cells base stations, the SIET becomes more practical. In this paper, we propose a unified receiver model for SIET in LTE-A small cell base station networks, formulate the feasibility problem with Poisson point process model and analysis 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 infeasible 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 among them is in providing telecommunications services to the public, industry and government. The non-communications uses of RF energy mainly include heating, radar and wireless power transfer (WPT). Due to the shortage of fossil fuels and the crisis of environment, WPT and energy harvesting have received considerable attention as methods addressing environmental problems[1, 2]. There are two ways for transmitting information and wireless power: single tone and multi-tone methods[3]. The former uses only one carrier to transmit information and power simultaneously; the latter method transmits the information and energy separately with two distinct carrier frequencies. Since the spectrum resources is also very limited today, people spend more energy on the research of simultaneous information and energy transfer (SIET)[4, 5].

As harvesting energy from ambient RF signal is free and unlimited, the SIET has recently drawn a great attention. A point-to-point transfer with single antenna is studied in [4], their work investigates when the receiver should switch between the two modes of information decoding and energy harvesting based on the instantaneous channel and interference condition. In [6], a simultaneous wireless information and power transfer with MIMO broadcast system is considered. To optimise the transfer strategy to achieve tradeoffs for maximal information rates versus 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 practicalbility, the key problem for SIET is whether the energy is strong enough to sustain the 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 though the information rate is lowered to 0. The work of [7] propose 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 the density and transmit power of the PBs must satisfy some condition to meet the outage constraint of the mobiles. However, this scheme needs extra construction of PBs except for common base stations and it is economically infeasible.

Thanks to the improvement of sensitivity and efficiency of RF energy harvesting circuit[8], the simultaneous information and energy transfer (SIET) is becoming more and more practical. More importantly, with densely deployed small cells base stations (recently proposed to LTE-A) [9], the closer distance to the radio emitter can greatly improve the energy transfer efficiency. Besides, the interference from other BSs can also contribute to the energy harvesting, which means all signals in the air is useful. Encouraged by above observation, we propose a practical receiver model for SIET in a homogeneous small cell networks. Based on this model we focus on the feasibility study of the SIET using stochastic geometry method. The main contributions of our work are 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. Such model considers the user activity level as well as a flexible power allocation factor for energy-harvesting and information-decoding.
- Formulate the distribution of the energy harvested from a 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 the EEH probability conditioned on...
constraints of coverage probability and density and power limitation of BSs.

- The feasibility problem for a special case which has limited interference and path loss exponent as 4 is analytically solved. The result shows that it is still infeasible for the harvested energy to compensate the 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, the system model is proposed. Section III provide the preliminary of coverage and efficient energy harvesting. The feasibility problem is formulated and solved in section IV and considering real scenario the feasibility is analysed in section V. The conclusion and future research direction is given in section VI.

II. SYSTEM MODEL

We consider a homogeneous small cells networks with base stations arranged according to Possion point process (PPP) $\Phi$ of intensity $\lambda$. We also assume the mobile users located according to some independent stationary point process and each mobile user is associated with the closest base station notated as $b_c$.

For simplicity and tractability, we set the base station and associated mobile user experience fading channel with mean 1. The standard power loss propagation model is used with path loss exponent $\alpha > 2$. Besides, all the base stations transmit power is set to be $P$. Then the received power at a typical mobile user with a distance $r$ from its corresponding base station is $hr^{-\alpha}$ where the random variable $h$ follows exponential distribution with mean $P$, i.e., $h \sim \exp(1/P)$.

We employ a receiver model as figure 1. The received raw power is splitted into two streams, one stream is fed into the information decoder while the other into the energy harvester. The power splitting factor is denoted as $\rho$. The white Gaussian noise introduced by the receiving antenna is represented as $n$, here $n \sim CN(0, \sigma^2)$.

III. PRELIMINARY

A. Coverage

Definition 1. Coverage: 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 for SINR below $T$.

According to definition 1, the coverage probability of homogenous network can be formulated as

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

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

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

1) Distance to Nearest base Station: The probability density function(pdf) of $r$ can be derived using the fact that the null probability of a 2-D Possion process in an area $A$ is $\exp(-\lambda A)$

$$\mathbb{P}[r > R] = \mathbb{P}[\text{No BS closer than } R] = e^{-\lambda \pi R^2}$$

Then the pdf of $r$ is found as:

$$f_r(r) = e^{-\lambda \pi r^2} 2\pi\lambda r$$

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

Corollary 1. For a homogeneous cellular networks of which the BS’s positions follow PPP with intensity $\lambda$, the interference at the origin from those base stations at least $r$ away from the user can be formulated as:

$$I(r) = \sum_{i : R_i > r} h R_i^{-\alpha}$$
where \( h \) follows exponential distribution with parameter \( \mu \) and independent of the distance \( \{R_i\} \). Then the Laplace Transform of \( I(r) \) at any \( s > 0 \) is

\[
\mathcal{L}_I(r)(s) = \exp[-\pi \lambda (s/\mu)^{2/\alpha} G(r^2(s/\mu)^{-2/\alpha})],
\]

(6)

where

\[
G(y) = \int_0^\infty \frac{dx}{1 + x^2} = \left\{ \begin{array}{ll}
\frac{\pi}{2} - \arctan y, & \text{if } \alpha = 4, \\
2F_1(1, \frac{\alpha}{2}, 1 + \frac{\alpha}{2}; -x^2) & \text{if } \alpha \neq 4,
\end{array} \right.
\]

and \( 2F_1(a, b; c; z) \) is the hypergeometric function.

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

Proof: The corollary is straightforward from Corollary 1 in \([10]\) by substituting \( X_i \) with \( h \) and \( \mu \) with \( 1/\mu \) for consistency with our notation convention.

\[ \square \]

**Lemma 1.** To examine the overall coverage performance of the network, the average coverage probability over the plane can be presented as:

\[
P_c(T, \lambda, P, \alpha, \rho) = 2\pi \lambda \int_{r>0} e^{-\pi \lambda r^2} - T r^{\alpha} \sigma^2/\rho P \mathcal{L}_I(r)(T r^{\alpha}/P) r^{\alpha} dr.
\]

(8)

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: Substitute (6) into (8) follows:

\[
p_c(T, \lambda, P, \alpha, \rho) = \mathbb{P}\left[ h > T \rho^{-1} \sqrt{T \rho + \rho I(r)} \right] = \mathbb{E}_I(r)\left[ \mathbb{E}[h > T \rho^{-1} \sqrt{T \rho + \rho I(r)} | r, I_r] \right] = e^{-T r^{\alpha} \rho^{-2} \rho^{\alpha} \mathcal{L}_I(r)(T r^{\alpha}/P)}.
\]

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

\[
P_c(T, \lambda, P, \alpha, \rho) = \int_{r>0} p_c(T, \lambda, \alpha) fr(r) dr = 2\pi \lambda \int_{r>0} e^{-\pi \lambda r^2} - T r^{\alpha} \sigma^2/\rho P \mathcal{L}_I(r)(T r^{\alpha}/P) r^{\alpha} dr.
\]

(11)

Then we obtain the result. \[ \square \]

**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 a certain threshold \( \Theta \) due to the constraint of energy harvesting circuit.

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

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

(10)

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

\[
P_{eeh}(\Theta, \lambda, P, \rho) \triangleq \mathbb{E}_r,us[\mathbb{P}[E_h > \Theta | r, us]].
\]

(11)

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

\[
P_{eeh}(\Theta, \lambda, P, \alpha, \rho) = 1 - e F_{I(0)}(\Theta - \sigma^2) - (1 - e) F_{I(0)}(\Theta - \sigma^2),
\]

(12)

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

Proof: For energy harvesting, there is no difference between the cases with active state and idle state. Since the energy harvester does not need to extract information from its corresponding BS, we can treat the harvested energy on both cases as interference from all the baseline stations. According to the definition of (8), the harvested energy before power splitting can be expressed as \( I(0) + \sigma^2 \) and does not depend on the distance \( r \). Note that the distance \( r \) only affects which BS should be connected but not the whole interference in the plane. Now (11) can be rewritten as

\[
P_{eeh}(\Theta, \lambda, P, \alpha, \rho) = \mathbb{E}_r,us[\mathbb{P}[E_h > \Theta]] = e \mathbb{P}[I(0) + \sigma^2 > \Theta] + (1 - e) \mathbb{P}[I(0) + \sigma^2 > \Theta]
\]

\[
= e \mathbb{P}[I(0) > \Theta - \sigma^2] + (1 - e) \mathbb{P}[I(0) > \Theta - \sigma^2]
\]

\[
= e(1 - F_{I(0)}(\Theta - \sigma^2)) + (1 - e)(1 - F_{I(0)}(\Theta - \sigma^2))
\]

(13)

where \( F_{I(0)}(x) \) is the cdf of \( I(0) \). There is no close-form expression for the cdf (pp97, [11]), but we can recover the cdf by inverting the Laplace transform of \( I(0) \) as following:

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

Then Lemma 2 is proved. \[ \square \]

**IV. PROBLEM FORMULATION**

In this paper, we mainly study the feasibility of the SIET in small cell networks. Intuitively, the denser the BSs are deployed, the more power the user can harvest and then the feasibility of SIET is increased. However for communication purpose, excessive denser BSs will not bring better link quality but more severe interference. So we consider an density-limited small cell networks with ability of concurrent transmission of energy and information. That is to maximize
the Efficient Energy Harvesting probability under constraint of coverage probability, BS’s transmit power and BS-deployment density. The problem is formulated as below:

\[
P_1: \max_{\rho, \lambda} \quad P_{\text{eeh}}(\Theta, \lambda, P, \alpha, \rho) \quad (14)
\]

s.t.
\[
P_c(T, \lambda, P, \alpha, \rho) \geq \mu \quad (15)
\]
\[
P \leq P_{\text{max}} \quad (16)
\]
\[
\lambda \leq \lambda_{\text{max}}, \quad (17)
\]

for given thresholds of SINR($T$) and energy harvesting threshold ($\Theta$), where $\mu$ is the minimum coverage probability, $P_{\text{max}}$ and $\lambda_{\text{max}}$ is the maximum transmit power of the small cell BSs and the maximum BS-deployment density of the networks, respectively. The setting of EEH threshold $\Theta$ and SNR threshold is based on different service quality requirement. Unfortunately, the problem (14) is intractable due to integration form of $P_c(T, \lambda, P, \alpha, \rho)$ and inverse Laplace transform expression of $P_{\text{eeh}}(\Theta, \lambda, P, \alpha, \rho)$. 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 a closed-form expressions for $P_c$ and $P_{\text{eeh}}$. 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 (6) is simplified to

\[
L_{I(r)}(s) = e^{-\pi \lambda \sqrt{s T}(\frac{T}{2} - \arctan \frac{2}{\sqrt{s T}})}. \quad (18)
\]

Introducing (18) into (9) can get

\[
P_c(T) = \frac{1}{1 + \sqrt{T}(\frac{T}{2} - \arctan \frac{1}{\sqrt{T}})}, \quad (19)
\]

where the coverage probability does not depend on $\lambda$ or $\rho$. This means that the constraint (15) can be removed in such case.

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

\[
P_{\text{eeh}}(\Theta, \lambda, P, \rho) = \epsilon \text{erf}(\frac{\pi^2 \lambda}{4} \sqrt{\frac{P(1 - \rho)}{\Theta}}) + (1 - \epsilon) \text{erf}(\frac{\pi^2 \lambda}{4} \sqrt{\frac{P}{\Theta}}) \quad (20)
\]

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

Proof: Omitted due to page limit. \ \Box

B. Solution in Special Case

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

\[
P_2: \max_{\rho, \lambda} \quad P_{\text{eeh}}(\Theta, \lambda, P, \rho) \quad (21)
\]

s.t.
\[
P \leq P_{\text{max}} \quad (22)
\]
\[
\lambda \leq \lambda_{\text{max}}. \quad (23)
\]

By carefully looking at (20) we can find that given the EEH threshold $\Theta$, the energy splitting factor $\rho$ and the user active probability $\epsilon$, the Efficient Energy Harvesting probability is monotonously increased with $\lambda \sqrt{P}$. This implies that from the perspective of harvesting energy, quadratic increasing of transmit power is equivalent to linear increasing of network density, which coincides with the result of interference analysis in [11]. The curve of $P_{\text{eeh}}$ with regard to $\lambda \sqrt{P}$ is depicted in figure (2), assuming $\epsilon = 0.3$ and $\Theta = 1\text{mw}$. With above observation, the solution of (21) is straightforward and the optimal value of EEH probability is achieved when $P$ and $\lambda$ take their maximum values synchronously. Due to the equivalence of effects of $\lambda$ 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 density. For most small cell base stations, the transmit power would not exceed $1\text{W}$, then it is reasonable to set $P = 1\text{W}$. And the BSs density $\lambda$ under such assumption is defined as standard base station density.

\[
\begin{align*}
&\text{P2: max } P_{\text{eeh}}(\Theta, \lambda, P, \rho) \\
&\text{s.t. } P \leq P_{\text{max}} \\
&\text{and } \lambda \leq \lambda_{\text{max}}.
\end{align*}
\]

\[
\begin{align*}
P_2: & \max_{\rho, \lambda} \quad P_{\text{eeh}}(\Theta, \lambda, P, \rho) \\
&\text{s.t. } P \leq P_{\text{max}} \\
&\text{and } \lambda \leq \lambda_{\text{max}}.
\end{align*}
\]

![Fig. 2. Curve of $P_{\text{eeh}}$ over $\lambda \sqrt{P}$ with different power splitting factors $\epsilon = 0.3$ and $\Theta = 1\text{mw}$.](image)

Definition 3. Standard base station density ($\lambda_s$): For a homogeneous PPP cellular network, if the transmit power of all the base stations is $1\text{W}$, then the 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. Since the equivalence among the variation of density and transmit power, the result with standard density can be readily extended to non-unit-transmit-power case. With
sustaining the circuit of the wireless terminal. This threshold or the threshold that the received power could be useful for energy transforming, the most important parameter is energy.

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

2) Sustaining the basic system: the harvested energy can completely compensate the power consumption of the device when it has not communication or other computation task. To deal with such computation tasks, it is necessary to build a grid-charged battery in the system. Compared with level 1, the improvement is less battery, more necessary to build a grid-charged battery in the system. Compared with level 1, the improvement is less battery, which means smaller volume and lighter weight of the device, and longer lasting power.

3) Battery-free: if the 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 spectrum.

As the power consumption of distinct devices is greatly varied, it is impossible to find a unified standard for all kinds of terminals. If we assume the maintenance power is $p_m$, the availability factor is $\zeta$, then we can use $\zeta p_m$ to describe the needed power for above three levels. More specifically, power level of charging the secondary battery can be represented by $\zeta p_m$ with $0 < \zeta < 1$, sustaining the basic system with $\zeta = 1$ and battery-free with $\zeta \geq 1$. Larger $\zeta$ implies more availability of the RF energy from the small cell base stations. Integrating above analysis the threshold of harvested energy before converter can be calculated as:

$$\Theta = \frac{\zeta p_m}{\eta}, \quad (26)$$

where $\eta$ is the converter efficiency. According the recent development of the RF energy harvester [12], the peak efficiency can achieve 60% and average efficiency 40% in the 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 $\eta$ on the feasibility of SIET. For the other key parameter $p_m$, experimental measurement shows that the typical maintenance power for a smart phone is as much as 0.02W (3G) or 0.03W (GSM) [13]. The maintenance power of the LTE-A, which is concerned in this paper, is believed not to exceed 0.02W. In view of this observation, we set $p_m = 0.02W$ for the mobile terminal of small cell networks in the remaining part. It is noteworthy that the maintenance power is greatly dependent on the hardware and operating system of the mobile, e.g. an smartphone with ARM920T CPU and Android 1.5 operating system will cost $0.068W$ for sustaining the basic system [13]. However, we only concern the feasibility of SIET in cellular communication and thus the lowerest maintenance power is considered in this work. Next we discuss two types of small cell networks according to different density of the distribution of BSs: the small cell networks with $\lambda_{\text{max}} = 10^{-4}$ and the dense small cell networks with $\lambda_{\text{max}} = 10^{-2}$. We also studied the relationship between the maximum BS-deployment density and availability factor conditioned on constant average EEH probability.

### A. Average EEH probability - Availability Factor Region

To study the feasibility of SIET on different BSs density, we depict the average EEH probability and availability factor region as figure 4. From the figure it can be found that when $\lambda_{\text{max}} = 10^{-2}$, which represents a type of dense small cell networks, the average EEH probability only reaches 0.2 for feasible availability factor, even with the converter efficiency as much as 0.6. For a practical application scenario, the average EEH probability $P_{\text{eeh}}$ 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, the harvested energy from the BSs can only charge the secondary battery for a hybrid-battery powered device. And the charging efficiency is proportional to the availability factor.

For a more practical scenario with small cell BS density $\lambda_{\text{max}} = 10^{-4}$, 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 figure 4. So in this case harvesting energy from small cell BSs is impossible under current converter efficiency of the harvesters and power consumption of cell phones.

### B. Maximal BS-deployment density over availability under constant $P_{\text{eeh}}$

We depict curves of $\lambda_{\text{max}}$ over $\zeta$ with constant $P_{\text{eeh}}$ as figure 4. The left part sets the converter efficiency as 0.3 and
LTE-A networks. By stochastic geometry tools, we formulated constraints of coverage probability, deployment density and the feasibility as maximization the available average efficient-problem to a special case with path loss exponent transmit power of the BSs. For tractability, we simplified the activity level is given. The numerical results reveals that under noise variance that the average EEH probability is increased with larger BS-energy harvesting threshold, power splitting factor and user activity level.

In conclusion, in light of above analysis the simultaneous information and energy transfer for small cell LTE-A networks can only provide very limited energy for the mobile terminals. That dose not mean the SIET is infeasible, but the energy harvested from the BSs can charge the secondary battery to prolong the lasting-time of terminals. Besides, only the BS-deployment density can reach $10^{-1}$ or higher can the harvested energy and the interference is also an interesting problem and needs further study.

VI. CONCLUSION

In this paper we studied the feasibility of simultaneous information and energy transfer in homogeneous small cell LTE-A networks. By stochastic geometry tools, we formulated the feasibility as maximization the available average efficient-energy-harvesting(EEH) probability problem conditioned on constraints of coverage probability, deployment density and transmit power of the BSs. For tractability, we simplified the problem to a special case with path loss exponent $\alpha = 4$ and noise variance $\sigma^2 = 0$. The solution for the special case shows that the 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 is 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 basic system with or without other computation tasks is infeasible.

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

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