Energy Efficiency Analysis of Energy Harvesting Relay-Aided Cooperative Networks

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***Abstract*—Cooperative relaying is a promising technology which can improve the energy efficiency of cellular networks. However, the relays' static power consumption may cancel out the energy saved by the deployed relays. Energy harvesting (EH) technique is introduced for relay nodes in cellular networks in order to deploy flexibility and reduce the energy charge. Due to the EH property, relay nodes cannot maintain a stable energy flow and keep active with a certain probability, which would degrade the benefit from relay-aided cooperative transmission. In this paper, an analytical model is proposed to investigate the energy efficiency of cellular networks aided by EH relay nodes. Meanwhile, the closed-form expressions of coverage probabilities and mean achievable rates for different links are derived. Numerical results show that EH relays bring more improvement on energy efficiency compared with non-EH relayed transmission. The influence of the density and transmit power of stations is also given through numerical simulation.**

I. INTRODUCTION

With the increasing demand for higher data rate wireless communications and the exponential growth of the numbers of base stations (BSs) and users, the operating cost and power consumption of cellular networks grow quite amazingly. Therefore, improving the energy efficiency is of great importance. Recently, relayed transmission has been regarded as a promising way to reduce the energy consumption of BSs [1], as well as to increase the capacity and reliability of wireless networks [2]. Compared with BSs in traditional cellular networks, the deployed relays which cover smaller areas with lower transmit power can provide the nearby users with higher signal-to-interference-plus-noise ratios (SINRs).

There have been some works in the literature about energy efficiency of relay-assisted networks. Most of the related works focus on traditional network deployments such as square or hexagonal. In [3], an analytical approach to derive the coverage and achievable rate in cellular networks is proposed based on a stochastic geometry model, which seems more tractable to the usual grid models. Furthermore, the combination of introducing active/sleep modes in macrocell base stations as well as deploying small cells has been considered in the heterogeneous cellular networks [4]. The relationship between base station density and energy efficiency of the relay-assisted cellular networks is studied in [5] [6]. Energy efficiency analysis of relay-assisted cellular networks which is performed on orthogonal time division multiple address (TDMA) is investigated in [7]. However, TDMA proposed to be used at relay is not scalable, so we select FDMA as our orthogonal resource sharing scheme.

Generally, the power consumed by a BS or a relay node consists of two parts, the transmit power consumption and the static power consumption. The static power consumption, which is caused by signal processing, cooling consumption and etc., occupies a significant part of the total power consumption. Therefore, the power saved by relayed transmission may not compensate for the additional power consumption of relays. An emerging solution is using energy harvesting (EH) nodes as relays. Ambient energy harvesting is a promising technique which can collect energy from renewable resources such as wind, solar energy, geothermal energy and so on [8]. EH relays are attractive as they provide sustainable energy without the need for batteries or wires, and they can be deployed flexibly. The capacity of a point-to-point link with an EH transmitter was investigated for the additive white Gaussian noise (AWGN) channel in [9]. Furthermore, the work in [10] discussed the optimal transmission protocols for two-hop communication systems with an EH source and a non-EH relay. In [11], the outage behavior benefited from cooperative transmission aided by energy harvesting relay node. In this paper, we investigate a communication system with normal non-EH BSs and EH relays. Meanwhile, this paper attempts to evaluate the energy efficiency of energy harvesting relay-aided cooperative network based on stochastic geometry approach. An on-off model is employed to describe the active/sleep modes in relay nodes. The explicit expression of energy efficiency for the proposed cooperative networks is obtained. By theoretical analysis, the effect of nodes density and transmit power on the energy efficiency is derived.

The rest of this paper is organized as follows. The system model is presented in section II, some assumptions are proposed as well. In Section III, the coverage probability and the energy efficiency expression for the downlink networks are derived. Afterwards, the simulation results and discussions are shown in Section IV. Finally, we conclude our paper in section V.

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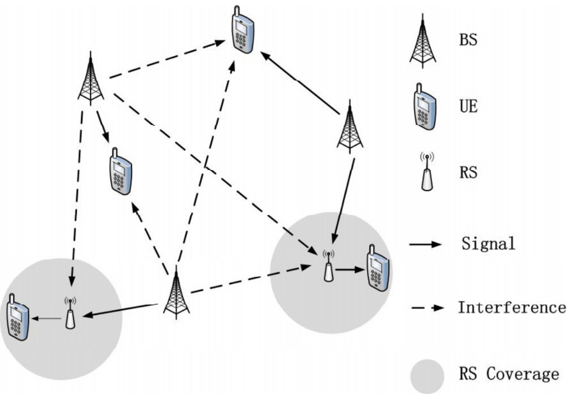

Fig. 1. The downlink relay-assisted cellular network model.

II. SYSTEM MODEL

A downlink relay-aided cellular network shown in Fig.1 is considered in this paper. The BSs and relay stations (RSs) are located in Euclidean plane according to independent homogeneous Poisson point processes (HPPPs) Φ_B and Φ_R with densities λ_B and λ_R. Suppose all RSs work in half-duplex mode and use decode-and-forward (DF) strategy. Each RS connects to the geographically closest BS and has a circular coverage with radius R_r.

Users are divided into two different types: some are served directly by the geographically closest BS and distributed according to an independent stationary point process with density λ_{DU}, namely D-UEs in this paper. The cooperative users, namely C-UEs, locate in the RSs' coverage areas and communicate with BSs via the retransmission of relays. C-UEs are arranged to another independent HPPP with intensity λ_{CU} in each circular area. Suppose the distance between D-UE or RS and its corresponding BS is r. As BSs are distributed according to HPPP with density λ_B, the probability density function (pdf) of r is $f_r\left(r\right) = 2\pi r \lambda_B \exp\left(-\pi\lambda_B r^2\right)$. Furthermore, due to the HPPP property of Φ_R, the distance between the C-UE and its targeted RS l follows the pdf $f_l\left(l\right) = 2l/R_r^2$. Since different nodes arranged to different HPPPs would interact each other and make it a huge challenge to analyse the system, two assumption are made to simplify the model. Firstly, we assume that a C-UE cannot be coverd by more than one relay at a time. The second hypothesis is that the whole coverage area of a relay is within a Voronoi area of a unique BS.

Frequency division multiple access (FDMA) is performed to handle the resource distribution of multiple users and relays. Assume that the total number of subchannels is constant M and the subchannel resources are fully used in the transmission. Information is intended to be transmitted from BSs to users. In cooperative transmission protocol, the half-duplex relays divide the transmission process into two equal sub-phrases. In the first half phrase, the BSs send data to relays and occupied M_{br} subchannels. In the second half phrase, M_{ru} subchannels are divided for each RS which have successfully decoded the data to transmit the information to C-UEs, and the number of RSs that can work simultaneously in this Voronoi cell is $\rho = M_{br}/M_{ru}$. The remainder M_{bu} subchannels are distributed to the direct link, and there exists $M_{bu} = M - M_{br} - M_{ru}$.

A. Power Consumption Model

It is assumed that BS is powered by a traditional power source with constant power P_B. In contrast, relay is powered by the energy harvesting module with average power output flow P_R. The power consumption model at each BS is given by $P_{B\_tot} = \Delta_B P_B + P_{B0}$. Where Δ_B is the slope of the load-dependent power consumption, and $1/\Delta_B$ accounts for the efficiency of the amplifier. P_{B0} denotes the static power consumption, which includes overhead of signal processing, cooling power consumption, etc.. Similarly, the power consumption for a relay P_{Rtot} in the transmission process can be given as $P_{R\_tot} = \Delta_R P_R + P_{R0}$, where P_{R0} accounts for the static power consumption of relay nodes.

B. Energy Harvesting Model

The state of renewable resources in nature may vary all the time, such as the speed of wind or the intensity of sunlight. Thus the power of harvested energy can't be stable as artificial energy source. In this study, we assume that the harvested energy flow is ergodic and stationary. The battery inside an EH relay can be used to store the harvested energy. When forwarding the received signal, the EH relay will use the energy stored in the battery. To simplify the analysis, it is assumed that the storage of a battery is big enough and there is no leakage in battery.

We constrain the process of utilizing the harvested energy as follows. When a frame of date is coming, it is necessary for the EH relay to judge whether to amplify and forward this frame because the energy may be not enough. And it will make the judgement by the rules that if there is more than $P_{R\_tot}t_0$ energy in the battery when the beginning of a frame is just received, the relay will forward this frame. Otherwise the relay will do nothing with this frame. t_0 represents the transmitting period of a frame. We define active rely is a rely with enough energy. And we model the active/sleep strategy of a relay as a Bernoulli trial. When there is no enough energy in a rely, it will sleep, during which the battery will still keep harvesting the available energy. We define γ as the probability that a relay is in active state. Thus when $\gamma = 1$, it means that the rate of harvesting energy is faster than the average rate of consuming energy. In addition, each relay has the same probability to be in active state. And probability for a relay to be sleeping is $1 - \gamma$. A relay will consume energy with a power of P_{sleep} when it is sleeping. Thus the average total power consumption of each relay is given as

$$P_{R\_tot} = \gamma(\Delta_R P_R + P_{R0}) + (1 - \gamma)P_{sleep}. \qquad (1)$$

C. UE distributions and Spectrum Allocation

In our system, suppose the area of a BS Voronoi cell is S. From the Gamma distribution $\Gamma(K) = \int_0^\infty x^{K-1}\exp(-x)dx$ with factor $K = 3.575$ [12], the pdf of S can be approximate represented as

$$f(S) = {\lambda_B}^K \frac{K^K}{\Gamma(K)} S^{K-1} \exp(-K\lambda_B S). \qquad (2)$$

Since RSs are distributed according to a HPPP Φ_R, the active relays' number N_R in a Voronoi cell with an area of S follows the Poisson distribution. Then the discrete probability density function of N_R can be written as

$$p\{N_R = k\} = \int_0^\infty \frac{(\gamma\lambda_R S)^k}{k!} exp(-\gamma\lambda_R S) f(S) dS. \quad (3)$$

The distribution of the D-UEs' average number $p\{N_{DU} = k\}$ can also be derived in the same way.

Since C-UEs are distributed according to HPPP with density λ_{CU}, the C-UEs' number in the coverage area of a relay is given by

$$p\{N_{CU} = k\} = \frac{(\lambda_{CU}\pi R_r^2)^k}{k!}\exp(-\lambda_{CU}\pi R_r^2). \quad (4)$$

The subchannels are independently selected by transmit nodes and the analytical result for a unique subchannels can be extended to others. The probability that a given subchannel in M_{bu} is used by the direct BS-to-UE link in the first phrase can be given as follows

$$p_{du} = \frac{1}{M_{bu}} \sum_{k=0}^{\infty} min(k, M_{bu1}) p\{N_{DU} = k\}. \quad (5)$$

The same expression goes for the BS-to-relay link in the first half phrase, as well as the relay-to-UE link in the second half phrase.

$$p_r = \frac{1}{\rho} \sum_{k=0}^{\infty} min(k, \rho) p\{N_R = k\}, \quad (6)$$

$$p_{cu} = \frac{1}{M_{ru}} \sum_{k=0}^{\infty} min(k, M_{ru}) p\{N_{CU} = k\}. \quad (7)$$

D. Performance metrics

According to our model, the energy efficiency of the whole network is equivalent to that of an arbitrary Voronoi cell, which can be expressed as the ratio of area spectral efficiency to the area average power consumption

$$EE = \frac{\tau}{P_{ave}} \ (bps/Hz/W). \quad (8)$$

The area spectral efficiency for the network is measured by the mean achievable rate as

$$\tau = \tau_B + \tau_R \ (bps/Hz), \quad (9)$$

where τ_B and τ_R are the area average achievable rate over all the direct links and relay links, respectively. The average network power consumption P_{ave} consists of the power consumed by both BSs and relays. The details are analyzed in the next section.

III. ENERGY EFFICIENCY ANALYSIS

In this section, the coverage probabilities for different links are derived firstly. Then, we use the mean achievable rate to measure the spectral efficiency. Finally, the energy efficiency expression is derived.

A. Coverage Probability and Mean Achievable Rate

The signal-to-interference-plus-noise ratio (SINR) experiences by the receiver is given by

$$\text{SINR} = \frac{Phr^{-\alpha}}{I + \sigma^2}, \quad (10)$$

where P represents the transmit power, and h is the channel power gain which we assume to experience the Rayleigh fading, namely $h \sim exp(\mu)$. Suppose $\mu = 1$ in this paper. I is the interference from the other active transmitters (excluding the targeted transmitter) nearby which work in the same frequency, and σ^2 is the variance of the background noise.

The coverage probability is defined as the probability that the SINR at the receiver is equal to or larger than a quality-of-service (QoS) threshold Γ and can be written as

$$P_c = \mathbb{P}\left(\text{SINR} \geq \Gamma\right). \quad (11)$$

The average ergodic achievable rate for a given subchannel is defined as

$$\begin{aligned} \tau &\triangleq \mathbf{E}[\log_2(1 + \text{SINR})] \\ &= \frac{1}{\ln 2}\mathbf{E}[\ln(1 + \text{SINR})], \end{aligned} \quad (12)$$

and the unit of τ is b/s/Hz.

According to the distribution densities of different nodes and their subchannels occupied probability, the spatial process of BSs is the independent thinning of the original PPP of BSs, denoted by a PPP with intensity $\lambda_B p_{du}$. Similarly, for the BS-RS link, the BS intensity is $\lambda_B p_r$.

1) BS-RS link: We assume the SINR threshold at the receiver is Γ_{br}, and the transmit power on one of the subchannels is given by $P_{br} = P_B/M_{br}$. I_{br} is the aggregate interference from all the other BSs working at the same time and frequency except the intended BS b_0, which is given by $I_{\text{br}} = \sum_{i\in\Phi_B\backslash\{b_0\}} P_{br} g_i r_i^{-\alpha}$. Then the coverage probability for a BS-RS link is derived as follows

$$\begin{aligned} P_{c\_\text{br}} &= \mathbb{P}(\frac{P_{br} h r^{-\alpha}}{I_{\text{br}} + \sigma^2} \geq \Gamma_{\text{br}}) \\ &= \mathbb{P}(h \geq \frac{\Gamma_{\text{br}} r^\alpha (I_{\text{br}} + \sigma^2)}{P_{br}}) \\ &= \int_{r>0} exp(\frac{-\Gamma_{\text{br}} r^\alpha \sigma^2}{P_{br}}) \mathcal{L}_{I_{\text{br}}}(\frac{\Gamma_{\text{br}} r^\alpha}{P_{br}}) f_r(r) dr. \end{aligned} \quad (13)$$

Observe that $\mathcal{L}_{I_{\text{br}}}(s)$ represents the Laplace transform of I_{br}. It can be derived from the definition of Laplace transform, evaluating at $s = \Gamma_{\text{br}} r^\alpha / P_{\text{br}}$,

$$\begin{aligned} \mathcal{L}_{I_{\text{br}}}(s) &= \mathbb{E}_{I_{\text{br}}}(\exp(-sI_{\text{br}})) \\ &= \mathbb{E}_{\Phi_B}(\prod_{i\in\Phi_B\backslash\{b_0\}} E_{h_i}(\exp(-sP_{br} h_i r_i{}^{-\alpha}))) \\ &= \mathbb{E}_{\Phi_B}(\prod_{i\in\Phi_B\backslash\{b_0\}} \frac{1}{1 + sP_{br} r_i{}^{-\alpha}}). \end{aligned} \quad (14)$$

Then, the last step can be derived from the probability generating functional (PGFL) of the PPP. For function such as $g(x)$, there exists $\mathbf{E}[\prod_{x\in\Theta} g(x)] = \exp(-\lambda \int_{\mathbb{R}^2}(1 - g(x))dx)$, where λ represents the density of the interference node. According to the whole transmission process of BS-RS-UE link, the occupied probability for a given BS-RS link is $p_r p_{cu}$. Thus the interference density received from other BSs on this subchannel is $p_r p_{cu}\lambda_B$. Equation (13) can be deduced as

$$\mathcal{L}_{I_{\mathrm{br}}}(s) = \exp(-2\pi p_r p_{cu}\lambda_B \int_{r>0} (1 \frac{1}{1+sP_{\mathrm{br}}v^{-\alpha}})vdv). \tag{15}$$

The distance r between RS and its associated BS is also the minimum distance between them, so the integration limits should be set from r to ∞. The details of the derivation can be found in [3] and we just provide some key steps in this paper.

For a positive random variable X, there exists $\mathbf{E}[X] = \int_0^\infty \mathbb{P}(X > t)dt$, equation (12) can be written as

$$\begin{aligned} \tau_{br} &= \frac{1}{\ln 2}\int_0^\infty \mathbf{E}(\ln(1+\frac{P_{\mathrm{br}}hr^{-\alpha}}{I_{\mathrm{br}}+\sigma^2}))f_r(r)dr \\ &= \frac{1}{\ln 2}\int_0^\infty\int_0^\infty \mathbb{P}(\ln(1+\frac{P_{\mathrm{br}}hr^{-\alpha}}{I_{\mathrm{br}}+\sigma^2}) > t)dtf_r(r)dr \\ &= \frac{\pi\lambda_B}{\ln 2}\int_0^\infty\int_0^\infty exp(-\pi\lambda_B v - \frac{v^{\frac{\alpha}{2}}\sigma^2(e^t-1)}{P_{\mathrm{br}}}) \\ &\quad \times \mathcal{L}_{I_{\mathrm{br}}}(\frac{v^{\frac{\alpha}{2}}(e^t-1)}{P_{br}})dtdv \end{aligned} . \tag{16}$$

According to equation (15), $\mathcal{L}_{I_{\mathrm{br}}}$ can be expressed as

$$\begin{aligned} \mathcal{L}_{I_{\mathrm{br}}}(\frac{v^{\frac{\alpha}{2}}(e^t-1)}{P_{br}}) &= exp(-\pi v\lambda_B p_r p_{cu}(e^t-1)^{2/\alpha}) \\ &\quad \times \int_{(e^t-1)^{-2/\alpha}}^\infty \frac{1}{1+x^{\alpha/2}}dx. \end{aligned} \tag{17}$$

2) BS-UE link: The derivations of the coverage probability for BS-UE link are similar to those of P_{c_br}. Suppose the SINR threshold at the UE is Γ_{bu} and the transmit power on the particular subchannel is $P_{bu} = P_B/M_{bu}$, then we can obtain the coverage probability for BS-UE link as

$$\begin{aligned} P_{c\_\mathrm{bu}} = \pi\lambda_B &\int_{v>0} exp(-\pi\lambda_B v(1+p_{du}Q(\Gamma_{\mathrm{bu}},t))) \\ &\times exp(\frac{-\Gamma_{\mathrm{bu}}v^{\alpha/2}\sigma^2}{P_{\mathrm{bu}}})dv. \end{aligned} \tag{18}$$

The mean achievable rate we derived in this link is

$$\begin{aligned} \tau_{bu} &= \frac{\pi\lambda_B}{\ln 2}\int_0^\infty\int_0^\infty exp(-\pi\lambda_B v - \frac{v^{\frac{\alpha}{2}}\sigma^2(e^t-1)}{P_{bu}}) \\ &\quad \times \mathcal{L}_{I_{\mathrm{bu}}}(\frac{v^{\frac{\alpha}{2}}(e^t-1)}{P_{bu}})dtdv \end{aligned} , \tag{19}$$

where

$$\begin{aligned} \mathcal{L}_{I_{\mathrm{bu}}}(\frac{v^{\frac{\alpha}{2}}(e^t-1)}{P_{bu}}) &= exp(-\pi v\lambda_B p_{du}(e^t-1)^{2/\alpha}) \\ &\quad \times \int_{(e^t-1)^{-2/\alpha}}^\infty \frac{1}{1+x^{\alpha/2}}dx. \end{aligned} \tag{20}$$

3) RS-UE link: There exists some differences when talking about the RS-UE link. The accuracy coverage probability function for a RS-UE link cannot be obtained, since the PDFs of the distance between R-UE and other RSs are unknown. Suppose that the whole coverage area of a RS shrinks to a single point and the distances between R-UE and the other RSs are approximated to be the distances between the targeted RS and other RSs. Approximate expressions of the coverage probability for a typical RS-UE link is obtained under the assumption. According to the discussions above, there are $P_{c\_br}p_r\rho$ RSs on average that can receive and decode the messages successfully. Considering the active probability of the EH RSs, the density of RSs on the unique subchannel for the RS-UE link is $\lambda = \gamma P_{c\_br}p_r p_{cu}\rho\lambda_{\mathbf{R}}$.

For the RS-UE link, the coverage probability is given by

$$\begin{aligned} P_{c\_\mathrm{ru}} = \frac{1}{R_r^2}&\int_0^{R_r} exp(-\pi\lambda vQ(\Gamma_{\mathrm{ru}},t)) \\ &\times exp(\frac{-\Gamma_{\mathrm{ru}}v^{\alpha/2}\sigma^2}{P_{ru}})dv, \end{aligned} \tag{21}$$

where $P_{ru} = P_R/M_{ru}$.

The mean achievable rate we derived in this link is

$$\begin{aligned} \tau_{ru} &= \frac{1}{R_r^2}\int_0^{R_r}\int_0^\infty exp(-\frac{v^{\frac{\alpha}{2}}\sigma^2(e^t-1)}{P_{bu}}) \\ &\quad \times \mathcal{L}_{I_{\mathrm{ru}}}(\frac{v^{\frac{\alpha}{2}}(e^t-1)}{P_{ru}})dtdv \end{aligned} \tag{22}$$

where

$$\begin{aligned} \mathcal{L}_{I_{\mathrm{bu}}}(\frac{v^{\frac{\alpha}{2}}(e^t-1)}{P_{ru}}) &= exp(-\pi v\lambda P_{bu}(e^t-1)^{2/\alpha}) \\ &\quad \times \int_0^\infty \frac{1}{1+x^{\alpha/2}}dx. \end{aligned} \tag{23}$$

B. Spectrum Efficiency

The throughput of one subchannel is defined as

$$T = P_c\log_2(1+\mathrm{SINR}), \tag{24}$$

where P_c represents the coverage probability of the certain subchannel.

Mean achievable rate of a certain link represents the average achievable throughput of the link. Since our system uses a non-overlapped subchannels to transmit data, multi-users are able to work simultaneously by FDMA. When we calculate the area average throughput, the occupied probability for each subchannel should be taken into consideration. The cooperative link consists of two period, and the throughput of this link is determined by the smaller one. As a result, the area average achievable throughput of the BS-UE link is given by

$$\tau_1 = P_{c\_bu}M_{bu}p_{du}\tau_{bu} \tag{25}$$

Similarly, the area average throughput of the BS-RS-UE link is

$$\tau_2 = \frac{1}{2}\rho p_r M_{ru}p_{cu}P_{c\_br}P_{c\_ru}\min\{\tau_{br},\tau_{ru}\} \tag{26}$$

The throughput of the links should be normalized at the end of the calculation, and the spectral efficiency per unit area τ is defined as follows

$$\frac{1}{M}\lambda_B(\tau_1+\tau_2)=\tau. \tag{27}$$

C. Energy Efficiency

BSs send messages to both D-UEs and RSs, the numbers of subchannels allocated for BS-UE link and BS-RS link are $M_{bu}p_{du}$ and $p_r\rho M_{ru}p_{cu}$, respectively. Thus the average power consumption for a BS during the whole process ia given by

$$P_{B\_av}=\beta_B(M_{bu}p_{du}P_{bu}+P_{br}M_{ru}p_{cu}\rho p_r)+P_{B0}. \tag{28}$$

The relay link is divided into two sub-phrases. Only when both of the sub-phrases send messages successfully, the BS-RS-UE link works. RSs which have not harvested enough energy will sleep and cost P_{sleep}. Some of the active RSs would decode the frames successfully is $P_{c\_br}p_r\rho$, while others which would not receive datas from BSs or fail to decode the frame. The average power consumption of RSs is

$$\begin{aligned}P_{R\_av}&=P_{c\_br}p_r\rho P_{R1}+(\gamma\lambda_R\backslash\lambda_B-P_{c\_br}P_{br}\rho)P_{R0}\\&+((1-\gamma)\lambda_R P_{sleep})\backslash\lambda_B.\end{aligned} \tag{29}$$

Where $P_{R1}=\beta_R P_{ru}p_{cu}M_{ru}+P_{R0}$.

Combining the above equations, the energy efficiencies for normal and EH relay-assisted cellular networks are given by.

$$\eta_{nor}=\frac{\tau}{\lambda_B(P_{R\_av}+P_{B\_av})}$$

$$\eta_{EH}=\frac{\tau}{\lambda_B P_{R\_av}}$$

IV. SIMULATION RESULTS

In this section, we present the derived analytical results through simulations. Table 1 shows the default simulation parameters of the system model. The simulations can be divided into two parts. The nodes density effect on energy efficiency, and the impact of transmit power for different nodes on energy efficiency. We also compare the differences between different γ.

TABLE I. SYSTEM PARAMETERS

Parameter	Value
λ_B, λ_R	$10^{-5}m^{-2}$, $5\times10^{-5}m^{-2}$,
λ_{CU}, λ_{DU}	$2\times10^{-3}m^{-2}$, $10^{-3}m^{-2}$
P_B, P_R	23dBm, 20dBm
R	$40m$
α	4
M_{bu}, M_{br}, M_{ru}	88, 32, 8
Γ_{bu}, Γ_{ru}, Γ_{br}	-10dB, -10dB, -10dB
σ^2	-80dBm
β_B, β_R	5.32, 4.8
P_{B0}, P_{R0}	$118.7W$, $7.5W$
P_{sleep}	$4.3W$

In this part, we evaluate the relationship between energy efficiency and nodes density. Figure 2 shows how the energy efficiency varies with the density of BSs for different active probabilities of RSs in both EH and normal systems. It can be seen from the figure that the energy efficiency increases with the density of BSs first with a fast speed then decreases, and finally reaches a convergence value. That is to say, the growth of area spectral efficiency is faster than the average network power consumption first and then the situation is reversed, so each curve has its optimal BS density for energy efficiency. Besides, the energy efficiency of EH relay-assisted networks is superior to that of ordinary networks with normal non-EH relays. Meanwhile, in the same BSs' density, the bigger the RSs' active probability, the better energy efficiency the link has. However, with the increasement of BS density, energy saved by EH adopted in RSs is negligible, and the energy efficiency for different links begin to converge.

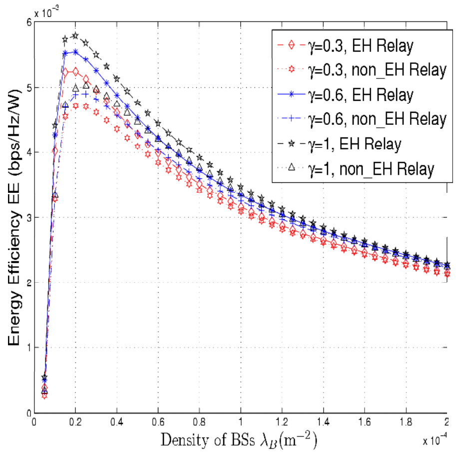

Fig. 2. Energy efficiency vs. density of BSs for different active probabilities.

Figure 3 illustrates how the energy efficiency of this system changes with density of C-UEs in various working probabilities. We observe that the energy efficiency first increase with the density then tend to keep a constant value. The reason can be explained as follows. In the very beginning, densities of the C-UEs and D-UEs are small. Subchannels allocated for UEs are sufficient, so the energy efficiency increases faster than the increase of the density of C-UEs. After reaching a top value, almost all the residual subchannels are occupied by the BSs and D-UEs, and the energy efficiency will not increase anymore. Because of the subchannels limitation, high density of RSs will lead to a increase of statistic power consumption. Since EH can avoid this problem and bring a lot of benefit, the EH links perform better than the normal links. The relationship between the density of D-UEs and energy efficiency follows the same trend.

Figure 4 displays how the energy efficiency varies with the transmit power of BS for different values of active probabilities of RSs. It can be seen that the energy efficiency increases with the transmit power first and then decrease, showing a quasi-convex trend. There exists an optimal energy efficiency. Firstly, the increase of coverage probability, which is caused by the increase of transmit power may lead to better performance in energy efficiency. However, when the power bounds to a value, the growth of spectrum efficiency cannot compensate for the growth of power consumption and the energy efficiency begin

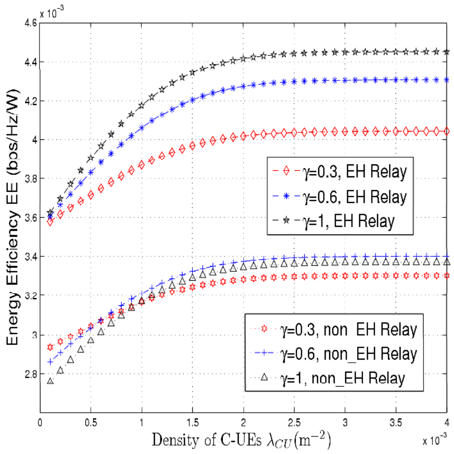

Fig. 3. Energy efficiency vs. density of R-UEs for different active probabilities.

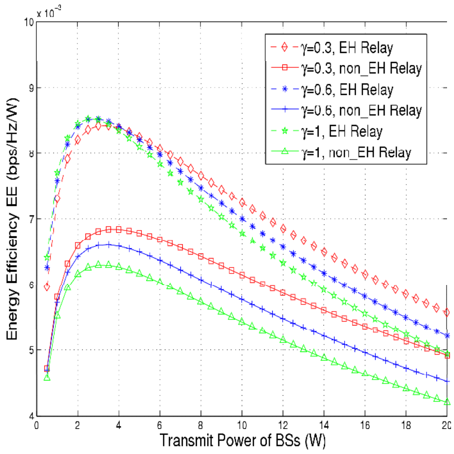

Fig. 4. Energy efficiency vs. transmit power of BSs for different active probabilities.

to decrease. EH relay system has better performance since the power consumed by relays is ignored.

The relationship between energy efficiency and transmit power of RS for different RS active probabilities is shown in Figure 5. Compared to EH Relay system, the energy efficiency of normal system will decrease with the increase of transmit power because of the increasing power consumption made by the RSs.

V. CONCLUSION

In this paper, we study the energy efficiency of downlink energy harvesting relay-assisted cellular networks and normal relay-assisted cellular networks using stochastic geometry approach instead of merely relying on system simulations. We introduce EH relays with sleeping strategy into the normal relay-assisted system to reduce the static power consumption of RSs. Expressions of the coverage probability and mean achievable rates are derived to calculate the energy efficiency. For certain network configuration, there exist optimal BSs densities and transmit power. Meanwhile, EH relay system performs better on energy efficiency.

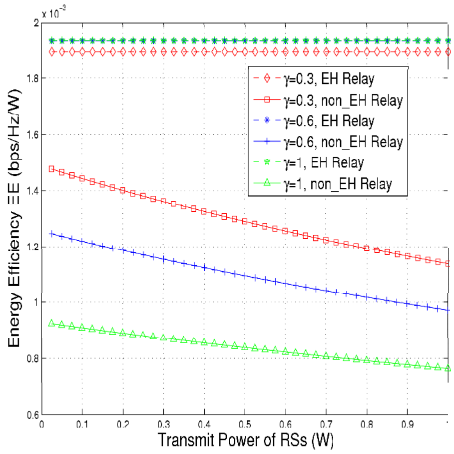

Fig. 5. Energy efficiency vs. transmit power of RSs for different active probabilities.

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