Energy-Efficient Mode Selection for D2D Communication in SWIPT Systems

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Abstract. To realized an energy-efficient mode selection, we apply simultaneous wireless information and power transfer (SWIPT) to D2D communications, so that D2D and cellular users can obtain energy from receiving information, and reduce the battery energy consumption in the communication process. We leverage the theory of stochastic geometry to analyze the ergodic energy harvesting (EEH) of D2D and cellular links in reuse, dedicated, and cellular communication modes. Based on the data transmission process, we obtain the expressions of the ergodic capacity (EC) of D2D and cellular users in three D2D communication modes with power splitting (PS) architectures of SWIPT, and based on this, we derive the system energy efficiency (EE). Finally, theoretical research is demonstrated through the simulation experiments. The mode selection mechanism is performed according to the energy-efficiency. The simulations show that the system EE is improved, especially for D2D communications in reuse mode by our proposed mode selection mechanism.

Keywords: Mode selection · Power splitting · EEH

1 Introduction

It is well-known that device-to-device (D2D) communications allow data to be transferred directly from one device to another without going through the base station. While the paradigm of D2D communications has many notable advantages such as improved spectral efficiency, enhanced system capacity, and accoladed performance [1,2], it, however, also faces some challenges. One of major challenges is the limited battery power in devices. Besides the regular routine battery replacement and/or battery recharge, on-site energy harvesting [3] is emerging as an additional effective method for resolving this energy shortage issue.

Mode selection [4] is one of the most direct and effective ways to address the energy and interference issues in D2D communication. The choice of D2D

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mode is related to the system spectrum utilization and the interference between D2D users and cellular users. D2D communications can work in: reuse mode, dedicated mode, and cellular mode. Reuse mode means that D2D users reuse uplink spectrum resources of the cellular link to communication, and this may cause interference between D2D users and cellular users, and among D2D users themselves as well. Dedicated mode refers to the case that the base station allocates the proprietary bandwidth to the D2D users, at this time, there is no interference between D2D users and cellular users. Cellular mode means that D2D users send and receive data through the base station, D2D users work in the same way as cellular users, and there is no interference. As such, the amount of interference experienced by D2D and cellular users in one mode will be different from that in another mode, which leads to different system capacities in these three modes. Therefore, the system energy consumption can be expected to be reduced by appropriately selecting a D2D communication mode.

Energy efficiency (EE) [5,6] is an important performance indicator for wireless networks. The EE of a system is essentially determined by the amount of energy consumed at the base station and at individual users in the system, both of which are aimed to be reduced. SWIPT [7] provides energy for communication devices while interacting with information between devices. In this paper, the power splitting method is used to use part of the power received by the receiver (sum of received power and interference power) for information decoding, and another part to charge the rechargeable battery, in order to reduce the energy consumption of the device during transmission, achieving the goal of improving EE and extending deceive standby time.

Currently, there is a large amount of studies dedicated to the SWIPT in wireless networks. Mohjazi [8] et al. evaluated the system throughputs for the time switching (TS) and power splitting (PS) mechanisms when the SIR is relatively low, according to outage probability and harvested energy, and by the differential modulation mechanism. Also, in [9], Mohjazi study the performance of the SWIPT relay network with non-coherent modulation and found that there is a unique PS ratio value that minimizes the systems outage probability, while this is not the case for the TS protocol. At lower SNR value, the performance of the TS protocol is superior to the PS protocol while ensuring maximum system throughput. In [10], when using the TS protocol and Non-Orthogonal Multiple Access (NOMA) technique, the outage probability expressions of all users are derived, and the system performance is evaluated by analyzing the system throughput. However, Maleki [11] et al. used amplify-and-forward EH relaying and hybrid EH protocol to obtain the systems outage probability and throughput, and computed the optimal values for TS and PS ratios that maximizes the system throughput.

When applying SWIPT to D2D communication, mode selection problem is manifested in the modeling of the channel fading for D2D users and cellular users, and more accurate mathematical calculations. In [12,13], the channel fading is always assumed to be Rayleigh no matter what communication mode the D2D and cellular users are in, however, this is not the case in practice because the distance between a D2D pair is of Los when the communication mode is in reuse mode or dedicated mode, therefore we assume that the channel fading for D2D users is Rician. Besides, the system throughput and EE computations may be inaccurate if the users distance to the base station is assumed to be a constant or the Shannon formula is directly used, as in [14]. To accurately simulate the randomness of the users, this paper uses stochastic geometry to model the users locations in a two-dimensional space, based on the distance to the energy harvesting and energy efficiency of the link for accurate calculation.

Although extensive studies have focused on interference management and EE, most studies have been largely conducted without considering SWIPT. Unlike the prior works, this paper proposes a mode selection mechanism based on PS using stochastic geometry, game theory, and SWIPT. It differs from existing studies in the following aspects: (1) Regarding the process of energy harvesting, both the PS architectures of SWIPT are considered and the corresponding closed-form formulas of the harvested energy for D2D and cellular users are derived by leveraging the theory of stochastic geometry. (2) In this paper, the channel fading of D2D links follows either Rician distribution or Rayleigh distribution, depending on whether or not the distance associated with the D2D pair is of line-of-sight (Los).

The rest of this paper is organized as follows. In Sect. 2, we introduce the system model. In Sect. 3, we analyze the EEH of all three modes under PS. In Sect. 4, we analyze the ergodic capacity of the link in the data transmission phase and propose the EE-based model selection strategy. Section 5 gives the simulation results to demonstrate the proposed model selection strategy. Section 6 concludes the paper.

2 System Model

We consider the scenario of multiple small cells. The sets of D2D users **D**, cellular users **C**, and BSs **B** are of independent and identically distributed PPP with densities λ_D, λ_C and λ_B, respectively. For any cellular user CUE and any D2D pair DTU-DRU, if the distance from CUE to the nearest BS is D_C, and the distance from DTU to DRU is D_D, then by the spatial probability of Poisson Point processes, the probability density functions of the cellular user and the D2D user are given as

$$f_{D_C}(D_C) = 2\pi\lambda_B D_C \exp(-\pi\lambda_B {D_C}^2) \tag{1}$$

and

$$f_{D_D}(D_D) = 2\pi\lambda_D D_D \exp(-\pi\lambda_D {D_D}^2) \tag{2}$$

respectively.

Since any CUE chooses to connect to its nearest BSs, there is a relative discrepancy in terms of distance from a CUE to its serving BS for all CUEs, thence all CUEs in each cell are separated into N tier. As illustrated in Fig. 1, the transmit power of CUEs in the i-th tier is $P_{C_i}(i = 1, 2, ..., N)$, with $P_{C_1} \neq$

$P_{C_2} \neq ... \neq P_{C_N}$. For the D2D link, in the case of reuse mode or dedicated mode, the difference between the distance of each D2D pair could be negligible, thus the transmit power for all DTUs is set to an average value P_D; In the cellular mode, DUEs, like CUEs, rely on BS to transmit data, so all DUEs will be stratified as well, and the transmit power of DTUs in the i-th tier is $P_{D_i}(i = 1, 2, ..., N)$. When BS becomes the transmitter as a data forwarding point in the small network, no matter which layer the receiver is on, the transmit power amplitude of BS varies slightly, so the base station transmits power is set to an average value P_B.

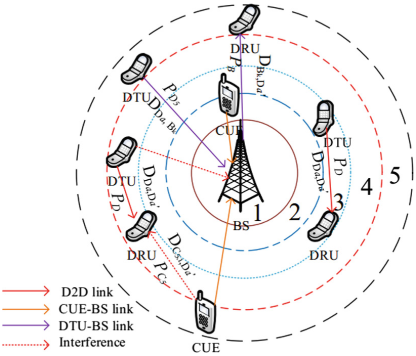

Fig. 1. Stratification model

In reuse mode, the uplink resources of CUEs are reused by DUEs, any DRU will experience both intra-cell and inter-cell interference caused by other DUEs or CUEs who are using the same spectrum used by this DRU; any CUE in one cell will experience both intra-cell and inter-cell interference caused by DUEs who are reusing the spectrum assigned to that CUE, and inter-cell interference caused by CUEs in other cells who are using the same spectrum. In dedicated and cellular modes, DUEs is interference-free to CUEs. In reuse and dedicated modes, due to the short and Los communication distance between D2D pairs, thence we assume that the D2D links follow the Rician fading. In cellular mode, DUEs, like CUEs, rely on BS to transmit data, so D2D links follow the Rayleigh fading with an exponential distribution of mean 1. In all three modes, since the distance of the transmission link from any CUE to its BS is of non-line-of-sight (NLos), thus cellular links follow the Rayleigh fading. Simultaneously, the distances of the interference links from any DTU to a non-pairing DRU, from any CUE to a DRU, and from any BS (BS does not serve the DRU in cellular mode) to a DRU are all of NLos, thus the interference links follow the Rayleigh fading. All signal largescale fading on any links can be modeled as $D^{-\alpha}$ and α is the path loss exponent for all links.

In this paper, we use PS in mode selection to extend device standby time and will analyze the two phases of energy harvesting and data transmission. In the energy harvesting phase, the receiver is subject to different interference, and the receiver acquires different energy in different modes of D2D communication. In the data transmission phase, we stipulate that the total spectrum resource in each cell is B Hz which will be split into various sub-spectrums for use by multiple CUEs. In reuse mode, D2D pairs will reuse all uplink spectrum resources of cellular users; in dedicated mode, a certain amount of bandwidth will be reserved for DUEs only, and the rest will be used by CUEs; in cellular mode, DUEs, just like CUEs, transmit all data through the BS, the cellular user can use the bandwidth B_1, and the remaining bandwidth $B_2 (B_1 + B_2 = B)$ will be evenly distributed to the D2D uplink and downlink.

3 Energy Harvesting

In the energy harvesting phase, this paper does not consider the distinction between useful signals and interference and charges all of its absorption. We assume that the energy harvested by the cellular user is EEH_C, and the energy harvested by the D2D user is EEH_D. The signal received at the receiver is split into two signal streams for energy harvesting and information decoding. Let $\kappa \in [0, 1]$ be the ratio of received power used for energy harvesting, then the energy harvested by D2D users and cellular users in all three modes is as follows.

3.1 D2D User Energy Harvesting

In reuse mode, there is co-channel interference between the cellular user and D2D user; in dedicated mode, there is no co-channel interference between cellular user and D2D user. Therefore, the total power of the signal that the receiver can receive will vary due to the size of the interference in reuse or dedicated mode of D2D communications. Also, D2D users need to forward data through the base station in cellular mode. Thus, the base station serves as the transmitter, and D2D serves as the receiver when the D2D user acquires energy.

***EEH*$_{\boldsymbol{D}}$ in Reuse Mode:** In reuse mode, a D2D link $l_{D_a,D_{a'}}$ reuses the uplink spectrum resources of the cellular link, and the signal power received by the receiver is $S_D = P_D D_{D_a,D_{a'}}^{-\alpha} g_{D_a,D_{a'}}$, where P_D is the transmit power of D2D user, $D_{D_a,D_{a'}}$ is the distance between D2D pairs, $g_{D_a,D_{a'}}$ is the Rician power fading from the transmitter to the receiver. Interference power is $I = I_{\mathbf{C},D_{a'}} + I_{\mathbf{D}_{-a},D_{a'}}$, $I_{\mathbf{C},D_{a'}} = \sum_{C_{i,j}\in\mathbf{C}} \sum_{i=1}^{N} P_{C_i} D_{C_{i,j},D_{a'}}^{-\alpha} h_{C_{i,j},D_{a'}}$, $I_{\mathbf{D}_{-a},D_{a'}} = \sum\limits_{D_{a''}\in\mathbf{D}_{-a}} P_D D_{D_{a''},D_{a'}}^{-\alpha} h_{D_{a''},D_{a'}}$, where P_{C_i} is the transmit power of cellular user, $D_{C_{i,j},D_{a'}}$ is the distance between DRU and cellular user, $h_{C_{i,j},D_{a'}}$ and $h_{D_{a''},D_{a'}}$ are respectively channel gain of the D2D link $l_{D_a,D_{a'}}$ with both $h_{C_{i,j},D_{a'}} \sim \exp(1)$ and $h_{D_{a''},D_{a'}} \sim \exp(1)$.

Theorem 1. *When D2D communications reuse the uplink resources of cellular users, the EEH of the D2D link is given by*

$$\begin{aligned} EEH_{D_a, D_{a'}} = \kappa\eta \Big\{ P_D \Big[d^{-\alpha}(-e^{-\pi\lambda_D d^2} + 1) + (\pi\lambda_D)^{\alpha/2} \Gamma\left(\tfrac{-\alpha+2}{2}, \pi\lambda_D d^2\right) \Big] \\ \cdot(1+K) + \textstyle\sum_{i=1}^{N} P_{C_i} \pi\lambda_C d^{-\alpha+2} \tfrac{\alpha}{\alpha-2} + P_D \pi\lambda_D d^{-\alpha+2} \tfrac{\alpha}{\alpha-2} \Big\}. \end{aligned} \tag{3}$$

where η is energy conversion efficiency.

Proof. $E\left(S_D + I\right) = P_D E\left(D_{D_{a,a'}}^{-\alpha}, g_{D_{a,a'}}\right) + E\left(I_{\mathbf{C},D_{a'}}\right) + E\left(I_{\mathbf{D}_{-a},D_{a'}}\right)$, where $E\left(D_{D_{a,a'}}^{-\alpha}, g_{D_{a,a'}}\right) = E\left(D_{D_{a,a'}}^{-\alpha}\right) \cdot E\left(g_{D_{a,a'}}\right)$. We have

$$\begin{aligned} E\left(D_{D_{a,a'}}^{-\alpha}\right) &= \int_0^\infty D_{D_{a,a'}}^{-\alpha} \cdot 2\pi\lambda_D D_{D_{a,a'}} \exp(-\pi\lambda_D D_{D_{a,a'}}^2) dD_{D_{a,a'}} \\ &\overset{(a)}{=} \int_0^d d^{-\alpha} \cdot 2\pi\lambda_D D_{D_{a,a'}} \exp(-\pi\lambda_D D_{D_{a,a'}}^2) dD_{D_{a,a'}} + \int_d^\infty D_{D_{a,a'}}^{-\alpha} 2\pi\lambda_D \\ &\cdot D_{D_{a,a'}} \exp(-\pi\lambda_D D_{D_{a,a'}}^2) dD_{D_{a,a'}} \\ &= d^{-\alpha}\left(-e^{-\pi\lambda_D d^2} + 1\right) + (\pi\lambda_D)^{\alpha/2} \Gamma\left(\frac{-\alpha+2}{2}, \pi\lambda_D d^2\right). \end{aligned}$$

Where step (a) is supported by the fact that when the integral range of $D_{D_{a,a'}}$ is $(0,\infty)$, $E\left(D_{D_{a,a'}}\right)$ will tend to infinity. To ensure the finiteness of the received power [15], we assume that the path loss is $d^{-\alpha}$ when $D_{D_{a,a'}} < d$ and $D_{D_{a,a'}}^{-\alpha}$ when $D_{D_{a,a'}} > d$.

$$\begin{aligned} E\left(g_{D_{a,a'}}\right) &= \int_0^\infty g_{D_{a,a'}} \cdot \exp\left(-K - g_{D_{a,a'}}\right) \sum_{k=0}^\infty \frac{\left(K g_{D_{a,a'}}\right)^k}{(k!)^2} dg_{D_{a,a'}} \\ &= \sum_{k=0}^\infty \exp\left(-K\right) \frac{K^k}{(k!)^2} \cdot \int_0^\infty {g_{D_{a,a'}}}^{k+1} \exp\left(-g_{D_{a,a'}}\right) dg_{D_{a,a'}} \\ &= \sum_{k=0}^\infty \exp\left(-K\right) \frac{K^k}{(k!)^2} \cdot (k+1)! \\ &= 1 + K, \end{aligned}$$

$$\begin{aligned}
E\left(I_{\mathbf{C},D_{a'}}\right) &= E\left(\sum_{C_{i,j}\in\mathbf{C}}\sum_{i=1}^{N}P_{C_i}D_{C_{i,j},D_{a'}}^{-\alpha}h_{C_{i,j},D_{a'}}\right)\\
&=\sum_{i=1}^{N}P_{C_i}E\left(\sum_{\substack{C_{i,j}\in\mathbf{C}\\ D_{C_{i,j},D_{a'}}>d}}D_{C_{i,j},D_{a'}}^{-\alpha}+\sum_{\substack{C_{i,j}\in\mathbf{C}\\ D_{C_{i,j},D_{a'}}<d}}D_{C_{i,j},D_{a'}}^{-\alpha}\right)\\
&=\sum_{i=1}^{N}P_{C_i}\cdot\pi\lambda_C d^{-\alpha+2}\frac{\alpha}{\alpha-2}.
\end{aligned}$$

In a similar fashion, we can get

$$E\left(I_{\mathbf{D}_{-a},D_{a'}}\right)=P_D\pi\lambda_D d^{-\alpha+2}\frac{\alpha}{\alpha-2}.$$

***EEH_D* in Dedicated Mode:** The difference in dedicated mode and reuse mode is that there is no co-channel interference between cellular user and D2D user in dedicated mode. Thus, the D2D user energy harvesting expression in dedicated mode can be given from the energy harvesting expression in reuse mode of D2D communications.

Theorem 2. *In dedicated mode, the EEH of the D2D link is given by*

$$\begin{aligned}
&EEH_{D_a,D_{a'}}=\kappa\eta\left\{P_D\left[d^{-\alpha}(-e^{-\pi\lambda_D d^2}+1)+(\pi\lambda_D)^{\alpha/2}\Gamma\left(\tfrac{-\alpha+2}{2},\pi\lambda_D d^2\right)\right]\right.\\
&\left.\cdot(1+K)+P_D\pi\lambda_D d^{-\alpha+2}\tfrac{\alpha}{\alpha-2}\right\}.
\end{aligned}\tag{4}$$

Proof. Similar to that of Theorem 1.

***EEH_D* in Cellular Mode:** In cellular mode, the communication process of the D2D user is divided into the uplink of DTU to BS and the downlink of BS to DRU. In the uplink, the base station serves as the receiver, just forward the data, so there is no energy harvesting, and in the downlink, DRU can perform data decoding and energy harvesting. In the cellular mode, the signal power received by a D2D downlink $l_{B_k,D_{a'}}$ receiver is $S_D=P_{B_k}D_{B_k,D_{a'}}^{-\alpha}h_{B_k,D_{a'}}$, interference power is $I=I_{\mathbf{B}_{-k},D_{a'}}$, $I_{\mathbf{B}_{-k},D_{a'}}=\sum_{B_{k'}\in B_{-k}}P_{B_{k'}}D_{B_{k'},D_{a'}}^{-\alpha}h_{B_{k'},D_{a'}}$, where $\mathbf{B}_{-k}=\mathbf{B}\backslash\{B_k\}$, P_{B_k} denotes the transmit power of B_k (B_k is the nearest base station to $D_{a'}$), $D_{B_k,D_{a'}}$ is the distance between B_k and $D_{a'}$, $h_{B_k,D_{a'}}$ is channel gain of the D2D link $l_{B_k,D_{a'}}$ with $h_{B_k,D_{a'}}\sim\exp(1)$, $P_{B_{k'}}$ denotes the transmit power of $B_{k'}$, $D_{B_{k'},D_{a'}}$ is the distance between $B_{k'}$ and $D_{a'}$.

Theorem 3. *In cellular mode, the EEH of the D2D downlink is given by*

$$EEH_{B_k,D_{a'}} = \kappa\eta \left\{ P_{B_k} \left[d^{-\alpha}(1 - e^{-\pi\lambda_B d^2}) + (\pi\lambda_B)^{\alpha/2} \Gamma\left(\tfrac{-\alpha+2}{2}, \pi\lambda_B d^2\right) \right] + 2\pi \right. \\ \cdot \lambda_B P_{B_{k'}} \left[d^{-\alpha+2}(\tfrac{1}{2} + \tfrac{1}{\alpha-2})(1 - e^{-\pi\lambda_B d^2}) + \tfrac{d^{-\alpha}}{2\pi\lambda_B} \left[\left(\pi\lambda_B d^2 + 1\right) e^{-\pi\lambda_B d^2} - 1 \right] \right. \\ \left. \left. + \tfrac{(\pi\lambda_B)^{\frac{\alpha}{2}-1}}{\alpha-2} \Gamma\left(\tfrac{-\alpha+4}{2}, \pi\lambda_B d^2\right) \right] \right\}. \tag{5}$$

Proof.

$$E\left(I_{\mathbf{B}_{-k},D_{a'}}\right) = E_{\mathbf{B},h}\left(\sum_{B_{k'} \in \mathbf{B}_{-k}} P_{B_{k'}} D^{-\alpha}_{B_{k'},D_{a'}} h_{B_{k'},D_{a'}} \right) \\ \overset{(a)}{=} 2\pi\lambda_B P_{B_{k'}} \int\limits_0^{\infty} \left\{ \int\limits_{D_D}^{\infty} \left[\max(D_{B_{k'},D_{a'}}, d)\right]^{-\alpha} D_{B_{k'},D_{a'}} dD_{B_{k'},D_{a'}} \right\} \\ \cdot 2\pi\lambda_B D_D \exp(-\pi\lambda_B D_D^2) dD_D \\ = 2\pi\lambda_B \cdot P_{B_{k'}} \left[d^{-\alpha+2}\left(\frac{1}{2} + \frac{1}{\alpha-2}\right)\left(1 - e^{-\pi\lambda_B d^2}\right) + \frac{d^{-\alpha}}{2\pi\lambda_B} \right. \\ \left. \cdot \left[\left(\pi\lambda_B d^2 + 1\right) e^{-\pi\lambda_B d^2} - 1 \right] + \frac{(\pi\lambda_B)^{\frac{\alpha}{2}-1}}{\alpha-2} \Gamma\left(\frac{-\alpha+4}{2}, \pi\lambda_B d^2\right) \right].$$

For step (a), since the D2D user is connected to the nearest base station, the distance between the interfering base station and the D2D user is necessarily greater than the communication distance D_D of $l_{B_k,D_{a'}}$, so the integration range of the interference link distance is $(D_D, +\infty)$.

3.2 Cellular User Energy Harvesting

In the energy harvesting phase, when the cellular user obtains energy for charging, the base station acts as the transmitter, and the cellular user acts as the receiver to implement the charging process, which occurs on the cellular downlink. However, the D2D link reuses the spectrum resources of the cellular uplink in reuse mode. Therefore, regardless of the mode communication used by D2D, the energy available to the cellular user is unchanged, and the cellular user has the same energy as the D2D user in cellular mode.

Theorem 4. *The EEH of the cellular downlink is given by*

$$EEH_{B_k,C_i} = \kappa\eta \left\{ P_{B_k} \left[d^{-\alpha}(1 - e^{-\pi\lambda_B d^2}) + (\pi\lambda_B)^{\alpha/2} \Gamma\left(\tfrac{-\alpha+2}{2}, \pi\lambda_B d^2\right) \right] + 2\pi \right. \\ \cdot \lambda_B P_{B_{k'}} \left[d^{-\alpha+2}(\tfrac{1}{2} + \tfrac{1}{\alpha-2})(1 - e^{-\pi\lambda_B d^2}) + \tfrac{d^{-\alpha}}{2\pi\lambda_B} \left(\left(\pi\lambda_B d^2 + 1\right) e^{-\pi\lambda_B d^2} - 1 \right) \right. \\ \left. \left. + \tfrac{(\pi\lambda_B)^{\frac{\alpha}{2}-1}}{\alpha-2} \Gamma\left(\tfrac{-\alpha+4}{2}, \pi\lambda_B d^2\right) \right] \right\}. \tag{6}$$

Proof. Similar to that of Theorem 3.

4 Data Transmission

4.1 Ergodic Capacity

Combined with the system ergodic capacity part of the literature [16], the system ergodic capacity under SWIPT is analyzed. In the information transmission phase, the ratio of the power received by the receiver to the information decoding is $(1-\kappa)$, so the capacity of each state of the D2D link and the cellular link in three modes is

EC in Reuse Mode: In reuse mode, when the D2D user uses the spectrum as B, the EC of D2D link is

$$\begin{aligned} EC_{D_a,D_{a'}} = (1-\kappa)B\Bigg(&\sum_{n=1}^{\infty}\sum_{m=0}^{n-1}\sum_{b=1}^{n-m}(-1)^{n-m}J\left(m,n\right)\beta_b^{n-m}\frac{\pi\lambda_D\alpha}{2}I_b \\ &+\sum_{n=0}^{\infty}J(n,n)\frac{\alpha\pi\lambda_D}{2}I_0\Bigg), \end{aligned} \tag{7}$$

where
$I_b = \int\limits_0^{\infty}\frac{t^{b+\frac{\alpha}{2}-1}dt}{(\pi\lambda_D+t)^{b+1}\left(A^{\frac{\alpha}{2}}+t^{\frac{\alpha}{2}}\right)}, b = 0,1,2\ldots, \beta_b^{n-m} = \sum\limits_{i=1}^{b}(-1)^i\binom{b}{i}\left(\frac{2i}{\alpha}\right)_{n-m}$,
$C\left(\alpha\right)=\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}$, $\mathcal{J}\left(m,n\right)=\frac{\frac{K^n m!}{e^K}\binom{n}{m}}{(n!)^2}$, $A=\pi C\left(\alpha\right)\left(\sum\limits_{i=1}^{N}\left(\frac{P_{C_i}}{P_D}\right)^{2/\alpha}\lambda_C+\lambda_D\right)$.

In reuse mode, when the cellular user uses the spectrum as B, the EC of cellular link is

$$EC_{C_i,B_k} = \int_0^{\infty}\frac{(1-\kappa)Bdt}{\frac{\lambda_C}{\lambda_B}\rho\left(e^t-1,\alpha\right)+C\left(\alpha\right)\frac{\lambda_D}{\lambda_B}\left(\frac{P_D}{P_{C_\gamma}}\left(e^t-1\right)\right)^{\frac{2}{\alpha}}+1}, \tag{8}$$

where $\rho\left(e^t-1,\alpha\right)=\sum\limits_{i=1}^{N}\int\limits_{\left(\frac{P_{C_\gamma}}{(e^t-1)P_{C_i}}\right)^{2/\alpha}}^{\infty}\frac{1}{1+u^{\alpha/2}}\cdot\left(\frac{(e^t-1)P_{C_i}}{P_{C_\gamma}}\right)^{2/\alpha}du.$

EC in Dedicated Mode: In dedicated mode, when the D2D user uses the spectrum as B_1, the EC of D2D link is

$$\begin{aligned} EC_{D_a,D_{a'}} = (1-\kappa)B_1\Bigg(&\sum_{n=1}^{\infty}\sum_{m=0}^{n-1}\sum_{b=1}^{n-m}(-1)^{n-m}J\left(m,n\right)\beta_b^{n-m}\frac{\pi\lambda_D\alpha}{2}I_b \\ &+\sum_{n=0}^{\infty}J(n,n)\frac{\alpha\pi\lambda_D}{2}I_0\Bigg), \end{aligned} \tag{9}$$

where $A=\pi C\left(\alpha\right)\lambda_D$.

In dedicated mode, when the cellular user uses the spectrum as B_2, the EC of cellular link is

$$EC_{C_i,B_k} = \int_0^{\infty} \frac{(1-\kappa)B_2 dt}{\frac{\lambda_C}{\lambda_B}\rho\left(e^t-1,\alpha\right)+1}. \tag{10}$$

EC in Cellular Mode: In cellular mode, when the D2D user uses the spectrum as B_1, the EC of D2D link is

$$EC_{D_a,D_{a'}} = \frac{(1-\kappa)B_1}{2}\int\limits_0^{\infty} \mathrm{SP}_{D_a,D_{a'}}\left(e^t-1\right)dt, \tag{11}$$

where $SP_{D_a,D_{a'}}$ is the success probability [16] of the D2D link $l_{D_a,D_{a'}}$.

In cellular mode, when the cellular user uses the spectrum as B_2, the EC of cellular link is

$$EC_{C_i,B_k} = \int\limits_0^{\infty} \frac{(1-\kappa)B_2 dt}{1+\frac{\lambda_C}{\lambda_B}\rho\left(e^t-1,\alpha\right)}. \tag{12}$$

4.2 Energy Efficiency

According to the energy harvesting of D2D user and cellular user in three modes, combined with the EC of D2D and cellular link in the data transmission part, the system energy efficiency in three modes using SWIPT can be obtained.

Theorem 5. *In reuse and dedicated modes, when cellular users are stratified into N tiers, the transmitting power of CUE at i tier is P_{C_i}, and the transmitting power of all DUEs is P_D, the system energy efficiency would be*

$$\varDelta_{EE} = \frac{\lambda_C \sum\limits_{i=1}^{N} EC_{C_i} + \lambda_D EC_D}{\lambda_C(\sum\limits_{i=1}^{N} P_{C_i} + P_{cir} - EH_C) + \lambda_D(P_D + P_{cir} - EH_D)}, \tag{13}$$

where P_{cir} denotes the average user device circuit power loss.

Theorem 6. *In cellular mode, the system energy efficiency would be*

$$\varDelta_{EE} = \frac{\lambda_C \sum\limits_{i=1}^{N} EC_{C_i} + \lambda_D \sum\limits_{i=1}^{N} EC_{D_i}}{\lambda_C(\sum\limits_{i=1}^{N} P_{C_i} + P_{cir} - EH_C) + \lambda_D(\sum\limits_{i=1}^{N} P_{D_i} + P_{cir} + P_{cir\_B} - EH_D)}, \tag{14}$$

where P_{cir-B} denotes the average BS circuit power loss.

5 Simulation Results

In this section, we conduct extensive simulations for the EEH and EE of D2D users and cellular users investigated in the previous sections. The simulation parameters are shown in Table 1.

Table 1. Parameters settings

Parameter	Value
Transmit power of BSs (P_B)	49 dBm
Transmit power of cellular users on tier 1 (P_{C_1})	27 dBm
Transmit power of cellular users on tier 2 (P_{C_2})	30 dBm
Transmit power of cellular users on tier 3 (P_{C_3})	33 dBm
Transmit power of D2D users on tier 1 in the cellular mode (P_{D_1})	20 dBm
Transmit power of D2D users on tier 2 in the cellular mode (P_{D_2})	24 dBm
Transmit power of D2D users on tier 3 in the cellular mode (P_{D_3})	28 dBm
Density of BSs λ_B (m^{-2})	$7 \cdot 10^{-6}$
Density of cellular users λ_C (m^{-2})	$4 \cdot 10^{-5}$
Density of D2D users λ_D (m^{-2})	$1 \cdot 10^{-4}$

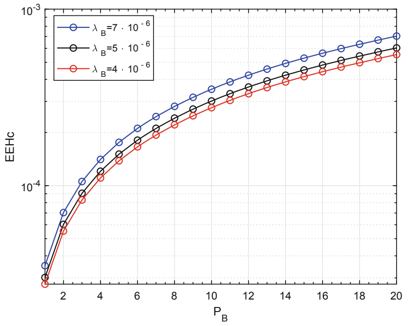

Fig. 2. Cellular users' energy harvesting

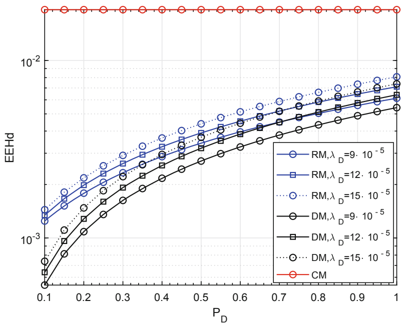

Fig. 3. D2D users' energy harvesting

As illustrated in Fig. 2, with PS, the energy harvested by the cellular user in the energy harvesting phase increases as the base station transmit power P_B and base station density λ_B. This is because when the transmission power P_B increases, the power of the receiver receiving the useful signal increases, and the co-channel interference signal increases. However, the receiver does not need to distinguish between the useful signal and the interference when acquiring the energy, and directly acquires all of them, so the harvested energy is consequently increased; when λ_B increases, the co-channel interference will be significantly enhanced, and the harvested energy will increase. Thus the cellular users energy harvesting shows an increasing trend.

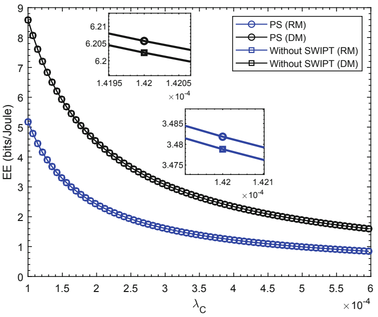

Fig. 4. λ_C vs EE in reuse and dedicated modes

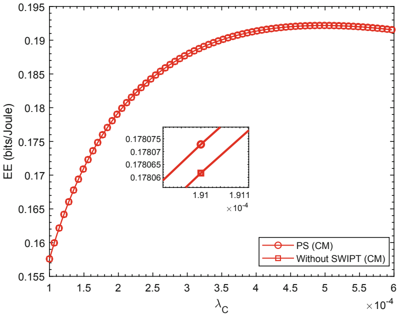

Fig. 5. λ_C vs EE in cellular mode

Figure 3 shows the EEH of D2D users with PS in three different modes. With PS, the amount of energy harvested by a D2D user receiver in three different modes have the following rank: cellular mode > reuse mode > dedicated mode. In cellular mode, DRU obtains energy from the base station, so EEH has nothing to do with both P_D and λ_D, and BS transmit power is much greater than that of D2D transmitters, so that DRU receives more energy; in reuse and dedicated modes, the co-channel interference received by DRU in dedicated mode is less than that in reuse mode. Simultaneously, when λ_D increases, the energy harvesting by DRU will increase accordingly.

Figures 4 and 5 depict the correlation between λ_C and system energy efficiency with PS and without SWIPT under the three different communication modes. In reuse and dedicated modes, the system energy efficiency decreases with the increase of cellular user density, and the system EE in reuse mode is less than that in dedicated mode; in cellular mode, the system EE will reach its maximum value when λ_C is minimal. This can be attributed to the fact that a smaller number of cellular users leads to sufficient spectrum resources and low energy consumption of devices which leads to a larger EC and then EE, but an increased λ_C will lead to insufficient spectrum resources and increasing devices energy consumption which result in a decreased EE. Finally, note that these two figures show that the system EE can be improved with SWIPT, especially for D2D communications in reuse mode.

Figure 6 indicates that EE will increase as λ_D increases in reuse and dedicated modes; and in cellular mode, the increase of λ_D results in a decrease in EE. This can be interpreted as the result of the following fact. In reuse and dedicated modes, EC would increase when the number of available spectrum increases, and subsequently, EE will increase as well. In cellular mode, the base station is used as a relay in the D2D communications, and the energy consumed by the base station in the process of forwarding data is much larger than that of the user, and the EC of the D2D link is small compared to the cellular link, resulting in the entire system link EC is low.

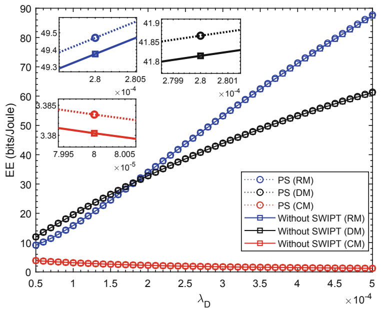

Fig. 6. λ_D vs EE

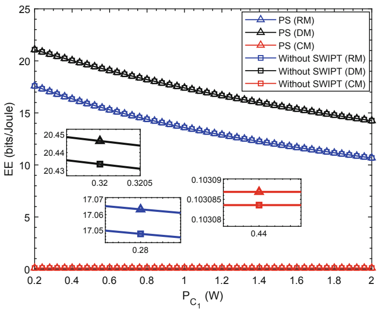

Fig. 7. PC_1 vs EE

Figure 7 demonstrate the EE of the system concerning the transmit power of cellular users with PS. In reuse and dedicated modes, the co-channel interference will increase as the value of PC_1 increases, leading to a decrease in EC and subsequently a decrease in EE as well. In cellular mode, the system EE increases over small values of PC_1 and decreases over the rest of PC_1. This owes to the fact that the transmit power of the cellular user is higher than the transmit power of the D2D user, and when the value of PC_1 is small, the interference caused between cellular users can be ignored. However, if PC_1 exceeds the threshold and continues to increase, it will affect EC due to excessive co-channel interference.

6 Conclusion

In this paper, we have investigated the mode selection for D2D communications from the perspective of energy saving. By utilizing the power splitting under SWIPT, the energy acquired by the cellular link and the D2D link can be used for communication, and energy can be effectively utilized while reducing energy consumption and extending the lifetime of the device. Then, according to DUEs and CTUs energy harvesting formulas in three modes, combined with the data transmission part, the expression of the system energy efficiency is obtained. Finally, our simulations demonstrate the impacting factors on the mode selection mechanism. In particular, ergodic energy harvesting of D2D and cellular links in-creases gradually as user transmit power increases in all three modes, and after using SWIPT, the system EE is improved, and the improvement is most obvious in reuse mode.

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