Performance Tradeoff in Relay Aided D2D-Cellular Networks

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***Abstract*—With the explosive growth of multitudinous wireless services and high-data-rate required applications, relay aided Device-to-Device (D2D) communications have attracted increasing attentions. In this correspondence, we investigate the performance tradeoff in relay aided D2D-cellular networks, where D2D users reuse the resource of cellular uplink transmissions. To optimize the performance of relay aided D2D communications, we first study the tradeoff between spectral efficiency (SE) and energy efficiency, and propose a source-relay joint power allocation scheme. The optimal transmit powers for both source and relay users are derived, based on which we further introduce a SE-variation function to explicitly evaluate the impact of enabling D2D communications on D2D-cellular networks. Theoretical analysis and simulation results demonstrate the viability of the proposed scheme and provide comprehensive insights into the coexistence of different systems.**

***Index Terms*—Device-to-Device communications, power allocation, energy efficiency, spectral efficiency, interference constraint.**

I. INTRODUCTION

Recently, relay aided Device-to-Device (D2D) communications have emerged as a promising paradigm to increase the spectral efficiency (SE) of D2D communications and alleviate the co-channel interference imposed on cellular communications without extra construction and maintenance costs [1], [2]. To achieve the envisioned advantages of resource reuse, interference and resource management strategies have attracted numerous attentions. In this context, a mode selection scheme [3] and a relay selection scheme [4] were proposed to maximize SE. The authors in [5] proposed relay selection and resource allocation schemes to maximize the network throughput. As the energy efficiency (EE) is also a crucial metric for future fifth-generation networks [6], the authors in [7] utilized EE as an incentive parameter to encourage users to relay data for others. In [8], the authors conducted theoretical analysis of EE for relay aided D2D communications. Although relay aided D2D communications undelaying cellular networks have extensively been studied, the above papers [3]–[5], [7], and [8] investigated EE and SE or capacity individually.

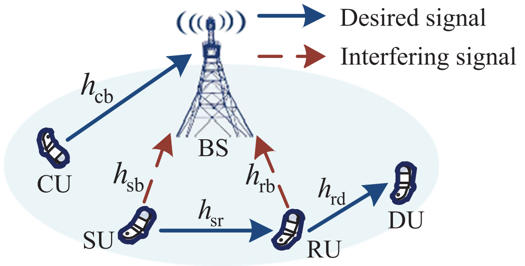

Fig. 1. Relay aided D2D communications underlaying cellular networks.

In our previous work [9], [10], we investigated the EE-SE tradeoff of D2D communications underlaying cellular networks, in which the transmit power of one single user was optimized. However, for relay aided D2D communications, the transmit powers of both source and relay users are vital for cooperative transmissions. Thus, in this paper, we propose a source-relay joint power allocation approach to optimize the performance of relay aided D2D communications. Although resource reuse between D2D and cellular communications can accommodate more users and services within the limited spectrum, it is always accompanied by co-channel interference received at cellular users. In this case, the impact of enabling D2D communications on cellular networks is a worthwhile research topic in terms of holistic performance. To achieve better coexistence of different systems, performance trade-off between D2D and cellular communications is also investigated.

We highlight the contributions of this paper as follows:

1) A composite fading channel model is considered. Taking both shadowing fading and multipath fading into account, we model the fading links in D2D-cellular networks as generalized-K fading, which characterizes a more realistic communication environment than only considering multipath fading [4], [7], and [8].
2) Optimal transmit powers of both source and relay users are derived. To optimize the performance of D2D communications, a power allocation scheme is proposed, in which the SE of D2D users is maximized while the EE requirement of D2D communications is guaranteed without violating the interference constraint. Based on the obtained solutions, we also analyze the impact of EE threshold on the optimal transmit power.
3) A SE-variation function is introduced to evaluate the trade-off between D2D and cellular communications. Providing quantitative analysis of the impact of enabling D2D communications on cellular networks, the SE-variation function is employed to facilitate the determination of interference threshold, which plays a decisive role in the performance of D2D-cellular networks.

II. SYSTEM MODEL

As illustrated in Fig. 1, we take a D2D communication unit, which consists of one base station (BS), one D2D pair, and one cellular user

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(CU), as an example to investigate the power allocation.[1] In one D2D pair, the source user (SU) communicates with the destination user (DU) with the assistance of the relay user (RU), sharing the same radio resources with the CU in uplink transmissions. In this case, the cellular communication is interfered by the SU and RU. Since the CU is always far away from D2D users who reuse its resources, the received interference of D2D users is relative inferior and is regarded as additive white Gaussian noise accounting for the worst case [12]. The BS and each user are equipped with a single antenna and decode-and-forward (DF) protocol is adopted at the RU. We denote h_{sr}, h_{rd}, h_{cb}, h_{sb}, and h_{rb} as the channel coefficients of SU→RU, RU→DU, CU→BS, SU→BS, and RU→BS links, respectively. Considering a composite multipath/shadowing fading environment, we assume that all links follow the generalized-K fading because of its relatively simple mathematical form that enables an integrated analysis of cellular networks [11]. The probability density function (PDF) of $|h_i|^2\,(i = \mathrm{sr}, \mathrm{rd}, \mathrm{cb}, \mathrm{sb}, \mathrm{rb})$ is given by

$$f_{|h_i|^2}(x) = \frac{2b^{\varphi_i+\varepsilon_i} x^{\left(\frac{\varphi_i+\varepsilon_i}{2}\right)-1}}{\Gamma(\varepsilon_i)\,\Gamma(\varphi_i)} K_{\varphi_i-\varepsilon_i}\left(2b\sqrt{x}\right), x > 0 \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, $K_{\varphi_i-\varepsilon_i}(\cdot)$ is the modified Bessel function of the second kind with order $(\varphi_i - \varepsilon_i)$, $b = \sqrt{\frac{\varphi_i\varepsilon_i}{\Omega_i}}$,$\varepsilon_i \geq 0.5$ is the multipath parameter, $\varphi_i \geq 0$ is the shadowing parameter, and Ω_i is the mean of the received local power.

As the SU communicates with the DU with the assistance of the RU, one complete transmission consists of two time phases. In the first phase, the SU transmits signal to the RU. After receiving signal from the SU, the RU employs DF protocol to forward the signal to the DU. According to [5] and [12], the instantaneous capacity of DF relay aided two-hop D2D communications can be written as $C^{\mathrm{D}} = \frac{W}{2}\log_2\left(1 + \min\left(\gamma_{\mathrm{sr}}, \gamma_{\mathrm{rd}}\right)\right)$, where W is the bandwidth, $\gamma_{\mathrm{sr}} = \frac{P_{\mathrm{s}}|h_{\mathrm{sr}}|^2}{N_0}$ and $\gamma_{\mathrm{rd}} = \frac{P_{\mathrm{r}}|h_{\mathrm{rd}}|^2}{N_0}$ are the received signal-to-noise ratios (SNRs) at RU and DU, respectively. Here, P_{s} and P_{r} denote the transmit powers of SU and RU, respectively, and N_0 is the noise power. By denoting $\mathbb{E}\{\cdot\}$ as the statistical expectation, the average SE can be expressed as $\Phi_{\mathrm{SE}}^{\mathrm{D}} = \frac{\mathbb{E}\left\{C^{\mathrm{D}}\right\}}{W}$. Then, the average EE can be expressed as $\Phi_{\mathrm{EE}}^{\mathrm{D}} = \frac{\Phi_{\mathrm{SE}}^{\mathrm{D}}}{\mathbb{E}\{P\}}$, where $P = \frac{1}{2}(\rho P_{\mathrm{s}} + \rho P_{\mathrm{r}} + 2(P_0^{\mathrm{c}} + P_0^{\mathrm{s}}))$ denotes the total power consumption of relay aided transmission, consisting of radio-frequency power $\rho P_{\mathrm{s/r}}$, circuit power P_0^{c}, and static power P_0^{s} of each transmitter, with $1/\rho \in (0, 1]$ denoting the drain efficiency of the power amplifier [13].

III. EE-SE TRADE-OFF IN D2D COMMUNICATIONS

In this section, we propose a power allocation scheme for the EE-SE trade-off in relay aided D2D communications. The optimal transmit powers for the SU and RU are firstly derived, based on which we further analyze the impact of EE threshold on the trade-off performance.

A. Power Allocation in Relay Aided D2D Communications

As demonstrated in [3]–[5], employing a RU can increase SE of D2D communications. Whereas, the relay contributes to higher data rate or more reliable transmission at the expense of extra power consumption, which may degrade the EE performance. Meanwhile, although the D2D users can reuse the resource of cellular users, they must ensure that D2D transmissions do not adversely interfere with conventional cellular communications. Therefore, we formulate the power allocation scheme as an optimization problem maximizing SE subject to both EE requirement and interference constraints. By denoting Θ_{EE} as the EE requirement of D2D communications and I_{th} as the interference threshold of the BS, the optimization problem can by expressed as

$$\begin{aligned} \underset{P_{\mathrm{s}}, P_{\mathrm{r}}}{\text{maximize}} \quad & \Phi_{\mathrm{SE}}^{\mathrm{D}} \\ \text{subject to} \quad & \mathrm{C1}: \Phi_{\mathrm{EE}}^{\mathrm{D}} \geq \Theta_{\mathrm{EE}} \\ & \mathrm{C2}: P_{\mathrm{s}}|h_{\mathrm{sb}}|^2 \leq I_{\mathrm{th}} \\ & \mathrm{C3}: P_{\mathrm{r}}|h_{\mathrm{rb}}|^2 \leq I_{\mathrm{th}}. \end{aligned} \quad (2)$$

When $P_{\mathrm{s}}|h_{\mathrm{sr}}|^2 = P_{\mathrm{r}}|h_{\mathrm{rd}}|^2$, the maximum SE can be achieved [14]. Thus, the problem in (2) can be equalized as

$$\begin{aligned} \underset{P_{\mathrm{s}}, P_{\mathrm{r}}}{\text{maximize}} \quad & \mathbb{E}\left\{\log_2\left(1 + \gamma_{\mathrm{sr}}\right)\right\} \\ \text{subject to} \quad & \mathrm{C1}: \frac{\mathbb{E}\left\{\log_2\left(1 + \gamma_{\mathrm{sr}}\right)\right\}}{\mathbb{E}\left\{\rho\left(1 + \nu\right)P_{\mathrm{s}} + 2P_0\right\}} \geq \Theta_{\mathrm{EE}} \\ & \mathrm{C2}: P_{\mathrm{s}}|h_{\mathrm{sb}}|^2 \leq I_{\mathrm{th}} \\ & \mathrm{C3}': P_{\mathrm{s}}\nu|h_{\mathrm{rb}}|^2 \leq I_{\mathrm{th}} \end{aligned} \quad (3)$$

where $P_0 = P_0^{\mathrm{c}} + P_0^{\mathrm{s}}$ and $\nu = \frac{|h_{\mathrm{sr}}|^2}{|h_{\mathrm{rd}}|^2}$.

In the following, we first settle the problem without interference constraints C2 and C3′. The objective function is logarithmic function with respect to P_{s} and thus, it is concave according to [15]. Note that the objective function is differentiable, so it is Pseudo-concavity in P_{s}. On the other hand, since the denominator of the constraint C1 is affine, C1 is quasi-concave in P_{s}. Thus, the feasible set defined by constraint C1 is a convex set. Therefore, the Karush-Kuhn-Tucker conditions are both sufficient and necessary for the optimality of (3) according to [15]. The partial Lagrangian of problem (3) is given by

$$\begin{aligned} L(P_{\mathrm{s}},\ell) = {} & \ell\left(\mathbb{E}\{\log_2(1 + \gamma_{\mathrm{sr}})\} - \Theta_{\mathrm{EE}}\mathbb{E}\{(\rho(1+\nu)P_{\mathrm{s}} + 2P_0)\}\right) \\ & + \mathbb{E}\left\{\log_2\left(1 + \gamma_{\mathrm{sr}}\right)\right\} \end{aligned} \quad (4)$$

where $\ell \geq 0$ is the Lagrange multiplier associated with constraint C1. The solution for the optimal power should satisfy $\frac{\partial L(P_{\mathrm{s}},\ell)}{\partial P_{\mathrm{s}}} = 0$, i.e.,

$$\frac{(1+\ell)\,|h_{\mathrm{sr}}|^2}{\ln 2\left(N_0 + P_{\mathrm{s}}|h_{\mathrm{sr}}|^2\right)} - \rho\ell\Theta_{\mathrm{EE}}\left(1 + \nu\right) = 0. \quad (5)$$

From (5), we have

$$P_{\mathrm{s}}' = \left[\frac{\alpha}{\Theta_{\mathrm{EE}}\left(1+\nu\right)} - \frac{N_0}{|h_{\mathrm{sr}}|^2}\right]^+ \quad (6)$$

with $\alpha = \frac{1+\ell}{\ln 2\rho\ell}$ and $[x]^+$ denoting $\max(0, x)$.

If C1 is satisfied with strict inequality, ℓ must be zero. Otherwise, the value of ℓ can be obtained by substituting (6) into C1 and setting the inequality to equality, i.e.,

$$\mathbb{E}\left\{\log_2\left(1 + \gamma_{\mathrm{sr}}\left(P_{\mathrm{s}}'\right)\right)\right\} - \Theta_{\mathrm{EE}}\mathbb{E}\left\{\rho\left(1+\nu\right)P_{\mathrm{s}}' + 2P_0\right\} = 0. \quad (7)$$

The involved mean values can be derived as (8) and (9) shown at the bottom of the next page. Derivation details can be found in Appendix A.

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[1] We assume that the relay selection and frequency band allocation have been accomplished and the revelent methods can refer to [3]–[5]. Similar to [5] and [7], we assume that the resource of one CU can only be shared by one D2D pair. In this case, the system with multiusers is a sum of D2D communication units. The proposed schemes in this paper can easily be extended to multiuser scenarios.

To this end, we have obtained the solution for interference unconstrained case. When the interference constraints C2 and C3' are considered, utilizing the result obtained above, the optimal transmit power can be divided into two parts:

1) $P_{\mathrm{s}}' \leq \min\left(|h_{\mathrm{sb}}|^2, \nu|h_{\mathrm{rb}}|^2\right)$: In this situation, the transmit power that maximizes SE with EE constraint is lower than the maximum transmit power bounded by interference constraints. Thus, C2 and C3' does not affect the optimal solution and hence, the optimal power with C2 and C3' is the same as written in (6).
2) $P_{\mathrm{s}}' > \min\left(|h_{\mathrm{sb}}|^2, \nu|h_{\mathrm{rb}}|^2\right)$: In this case, the transmit power obtained without C2 and C3' is beyond the acceptable interference allowed by cellular communications. Then, it is invalid for practical D2D-cellular networks. Since SE function is a monotone increasing function in P_{s}, the optimization problem in (2) with both EE and transmit power constrains can be simplified into a power constrained SE maximization problem. If $\Phi_{\mathrm{EE}}\left(P_{\mathrm{M}}'\right) \leq \Theta_{\mathrm{EE}}$, there is no feasible solution for (2), since the transmit power is too small to satisfy the EE requirement. Here, P_{M}' is the transmit power bounded by interference constraint. If $\Phi_{\mathrm{EE}}\left(P_{\mathrm{M}}'\right) \geq \Theta_{\mathrm{EE}}$, we have $P_{\mathrm{s}}^* = \min\left(|h_{\mathrm{sb}}|^2, \nu|h_{\mathrm{rb}}|^2\right)$.

In summary, the optimal solution for (2) can be written as

$$P_{\mathrm{s}}^* = \begin{cases} 0 & \text{if}\, \Phi_{\mathrm{EE}}^{\mathrm{D}}\left(P_{\mathrm{s}}\right) < \Theta_{\mathrm{EE}} \\ \min\left(\left[\frac{\alpha}{\Theta_{\mathrm{EE}}(1+\nu)} - \frac{N_0}{|h_{\mathrm{sr}}|^2}\right]^+, \frac{I_{\mathrm{th}}}{|h_{\mathrm{sb}}|^2}, \frac{I_{\mathrm{th}}}{\nu|h_{\mathrm{rb}}|^2}\right) & \text{else} \end{cases} \tag{10}$$

and $P_{\mathrm{r}}^* = \nu P_{\mathrm{s}}^*$.

B. The Impact of Θ_{EE} on Optimal Transmit Powers

From (10), we can see that the transmit power P_{s}^* and P_{r}^* are dependent on the interference constraint I_{th}, the channel gains $|h_{\mathrm{sr}}|^2$, $|h_{\mathrm{rd}}|^2$, $|h_{\mathrm{sb}}|^2$, and $|h_{\mathrm{sb}}|^2$, and the EE threshold Θ_{EE}, among which Θ_{EE} is the decisive parameter in terms of the trade-off between EE and SE. In the following, we focus on discussing the impact of Θ_{EE} on P_{s}^*, where Θ_{EE} can be divided into three regions:

- When $\Theta_{\mathrm{EE}} < \min\left(f\left(h_{\mathrm{sb}}\right), f\left(h_{\mathrm{rb}}\right)\right)$, where $f\left(h_{\mathrm{sb}}\right) = \frac{\beta|h_{\mathrm{sb}}|^2}{N_0|h_{\mathrm{sb}}|^2 + I_{\mathrm{th}}|h_{\mathrm{sr}}|^2}$ and $f\left(h_{\mathrm{rb}}\right) = \frac{\beta|h_{\mathrm{rb}}|^2}{N_0|h_{\mathrm{rb}}|^2 + I_{\mathrm{th}}|h_{\mathrm{rd}}|^2}$ with $\beta = \frac{\alpha|h_{\mathrm{sr}}|^2|h_{\mathrm{rd}}|^2}{|h_{\mathrm{sr}}|^2 + |h_{\mathrm{rd}}|^2}$, Θ_{EE} is too small to be an active constraint, the transmit power maximizing SE equals to the maximum value bounded by interference constraints, i.e., $P_{\mathrm{s}}^* = \min\left(I_{\mathrm{th}}/|h_{\mathrm{sb}}|^2, I_{\mathrm{th}}/\nu\left|h_{\mathrm{rb}}\right|^2\right)$.
- When $\min\left(f\left(h_{\mathrm{sb}}\right), f\left(h_{\mathrm{rb}}\right)\right) < \Theta_{\mathrm{EE}} < \frac{\beta}{N_0}$, we have $P_{\mathrm{s}}^* = \frac{\alpha}{\Theta_{\mathrm{EE}}(1+\nu)} - \frac{N_0}{|h_{\mathrm{sr}}|^2}$. In this case, we should adapt the transmit power according to channel fading under the given threshold Θ_{EE}.
- When $\Theta_{\mathrm{EE}} > \frac{\beta}{N_0}$, we have $P_{\mathrm{s}}^* = 0$, indicating that the D2D communication will be terminated because Θ_{EE} is too high that it cannot be satisfied by the acceptable transmit power. In this case, the RU for D2D communications can be reallocated to increase the quality of relay transmissions. Alternatively, D2D users can reduce the requirement of EE to increase access probability.

IV. TRADE-OFF BETWEEN D2D AND CELLULAR SYSTEMS

To this end, we have obtained the optimal transmit powers for both SU and RU, and analyzed the impact of Θ_{EE} on the optimal transmit power. Except for the EE requirement, the transmit power is also determined by the interference constraint, which can greatly affect the cellular performance. Whereas, how to determine the interference threshold is still an open issue in terms of the viability of D2D-cellular networks and has not been well studied in previous work. Thus, to optimize the performance of the whole network, we investigate the performance trade-off between D2D and cellular systems with respect to the interference threshold I_{th}.

From (10), we can observe that the larger I_{th} is, the larger the potential capacity of D2D communications can be achieved. However, a large I_{th} will also result in server interference to cellular communications. To evaluate the variation of network SE when enabling relay aided D2D communications in cellular networks, we define a SE-variation function for a D2D communication unit and it can be written as

$$\Delta\left(I_{\mathrm{th}}\right) = \delta_{\mathrm{D}}^+ - \delta_{\mathrm{C}}^- \tag{11}$$

where δ_{D}^+ is the SE increment of D2D communications and $\delta_{\mathrm{C}}^- = \Phi_{\mathrm{SE}}^{\mathrm{C}} - \Phi_{\mathrm{SE}}^{\mathrm{C\text{-}D}}$ is the SE decrement of cellular communications. Here, $\Phi_{\mathrm{SE}}^{\mathrm{C}}$ is the cellular SE in absence of D2D communications and $\Phi_{\mathrm{SE}}^{\mathrm{C\text{-}D}}$ is the cellular SE when D2D users reuse the resource of cellular uplink transmissions.

Proposition 1: The SE loss of cellular communications δ_{C}^- is upper bounded by $\frac{I_{\mathrm{th}}}{\ln 2N_0}$.

Proof: The proof is presented in Appendix B. ■

$$\mathbb{E}\left\{(1+\nu)P_{\mathrm{s}}'\right\} = \frac{\eta_{\mathrm{rd}}^{m_{\mathrm{sr}}} e^{-\frac{N_0}{a\eta_{\mathrm{sr}}}}}{\Gamma\left(m_{\mathrm{sr}}\right)\Gamma\left(m_{\mathrm{rd}}\right)} \left[\sum_{p=0}^{m_{\mathrm{sr}}-1} \frac{1}{p!} \sum_{l=0}^{p} \binom{p}{l} \frac{N_0^{p-m_{\mathrm{sr}}-l}}{\eta_{\mathrm{sr}}^{p-l} a^{p-m_{\mathrm{sr}}-l-1}} G_{21}^{12}\left[\frac{\eta_{\mathrm{rd}}a}{N_0}\middle| \begin{matrix} -m_{\mathrm{sr}}-l+1, -m_{\mathrm{sr}}-m_{\mathrm{rd}}+1 \\ 0 \end{matrix}\right]\right.$$
$$\left. - \frac{\Gamma\left(m_{\mathrm{sr}}-1\right)}{\Gamma\left(m_{\mathrm{sr}}\right)} \sum_{q=0}^{m_{\mathrm{rd}}-2} \frac{1}{q!} \sum_{n=0}^{q+1} \binom{q+1}{n} \frac{N_0^{q+1-m_{\mathrm{sr}}-n}}{\eta_{\mathrm{sr}}^{q+1-n} a^{q-m_{\mathrm{sr}}-n}} G_{21}^{12}\left[\frac{\eta_{\mathrm{rd}}a}{N_0}\middle| \begin{matrix} -m_{\mathrm{sr}}-n+1, -m_{\mathrm{sr}}-m_{\mathrm{rd}}+1 \\ 0 \end{matrix}\right]\right]. \tag{8}$$

$$\mathbb{E}\left\{\log_2\left(1+\gamma_{\mathrm{sr}}\left(P_{\mathrm{s}}'\right)\right)\right\} = \frac{\eta_{\mathrm{rd}}^{m_{\mathrm{sr}}} e^{-\frac{N_0}{a\eta_{\mathrm{sr}}}}}{\eta_{\mathrm{sr}}^{m_{\mathrm{sr}}}\Gamma^2\left(m_{\mathrm{sr}}\right)\Gamma\left(m_{\mathrm{rd}}\right)} \left[\sum_{k=1}^{L} \frac{1}{k} \sum_{s_1}^{k} \binom{k}{s_1} \Gamma\left(m_{\mathrm{sr}}+s_1\right) \sum_{s_2=0}^{m_{\mathrm{sr}}+s_1-1} \frac{(-1)^{2k-s_1-1}}{s_2!} \left(\frac{N_0}{a\eta_{\mathrm{sr}}}\right)^{s_2-s_1-s_3-m_{\mathrm{sr}}}\right.$$
$$\left. \times \sum_{s_3}^{s_2-s_1} \binom{s_2-s_1}{s_3} G_{21}^{12}\left[\frac{\eta_{\mathrm{rd}}a}{\eta_{\mathrm{sr}}}\middle| \begin{matrix} -s_3-m_{\mathrm{sr}}+1, -m_{\mathrm{sr}}-m_{\mathrm{rd}}+1 \\ 0 \end{matrix}\right]\right]. \tag{9}$$

TABLE I
GENERALIZED-K CHANNEL PARAMETERS [18]

Shadowing	σ_i	φ_i	ε_i
Infrequent light shadowing (ILS)	0.115	75.1155	3
Average shadowing (AS)	0.345	7.9115	2
Frequent heavy shadowing (FHS)	0.806	1.0931	1

According to Proposition 1, the maximum SE loss of cellular communications is determined by $I_{\rm th}$. We can set a maximum value of $I_{\rm th}$ to guarantee the minimum data rate of conventional cellular users. In the following, we focus on discuss the impact of interference threshold on the effectiveness of spectrum utilization in each D2D communication unit.

Remark 1: When $\Delta\left(I_{\rm th}\right) < 0$, D2D users should not be allowed to reuse the resource of cellular communications. When $\Delta\left(I_{\rm th}\right) \geq 0$, the optimal value of interference threshold is $I_{\rm th}^{*} = \arg\max \Delta\left(I_{\rm th}\right)$.

Here, $\Delta\left(I_{\rm th}\right) < 0$ accounts for that resource reuse between D2D and cellular systems will result in degradation of SE in D2D communication unit, which may come up as the SU/RU is quite close to the cellular receiver. In this case, the SE increase of resource reuse cannot offset the SE decrease resulted by co-channel interference. Thus, to safeguard the efficiency of spectrum utilization, we prefer to prohibit D2D users to reuse cellular resources. When $\Delta\left(I_{\rm th}\right) \geq 0$, the resource reuse can indeed improve the spectral efficiency of D2D communication unit. Thus, through maximizing the SE-variation function, we can find out the optimal interference threshold that maximizes the SE in each D2D communication unit.

V. RESULTS AND ANALYSIS

In this section, Monte-Carlo simulations are conducted to evaluate the scheme described in previous sections. To provide accurate evaluation of the system with various locations of users, the simulation scenario is described as follows. The BS is assumed to locate at the center of one cell with the radius R and the CU is randomly dropped at each simulation trial. The SU is randomly distributed in an annular area with outer radius R and inner radius $d_{\rm I}$, which is the minimum distance between the SU and the BS to protect cellular communications from severe interference. The DU is randomly distributed around the SU with distance $d_{\rm sd}$. Unless specifically stated, the RU is randomly distributed in a region where $\max(d_{\rm sr}, d_{\rm rd}) \leq d_{\rm sd}$.

The pathloss model between BS and each user is $\mathrm{PL} = 128.1 + 37.6\log_{10}(\mathrm{d}\ [\text{in Km}])$, while the pathloss model between users is $\mathrm{PL} = 148.1 + 40\log_{10}(\mathrm{d}\ \ [\text{in Km}])$. For generalized-$K$ distributions with $\Omega_i = 1$, detailed channel parameters are given in Table I, where σ_i is the standard deviation of the log-normal shadowing and increases as the amount of fading increases. According to [18], the parameter φ_i can be linked to $\varphi_i = \frac{1}{e^{\sigma_i^2}-1}$. We assume that $h_{\rm cb}$, $h_{\rm sb}$, and $h_{\rm rb}$ experience AS fading and "X-Y" represents the fading of "$h_{\rm sr}$-$h_{\rm rd}$" links, which undergoes ILS fading unless specifically stated. Besides, we set $N_0 = -174$ dBm/Hz, $W = 10$ MHz, $P_{\rm c} = 23$ dBm, $\rho = 1.3$, and $P_0 = 120$ mW.

Fig. 2 depicts the SE versus interference threshold for different EE thresholds. As observed, the looser the interference constraint is, i.e., $I_{\rm th}$ gets larger, the higher SE it can achieve. It can also be seen that due to the existence of EE constraints, the SE of D2D communications becomes saturated eventually. Moreover, since the optimal transmit power decreases as $\Theta_{\rm EE}$ increases, the SE performance deteriorates and gets saturated earlier. In addition, the proposed joint source-relay power allocation scheme in this paper, referred as "Proposed scheme", is compared with two existing schemes presented in [5] and [8], referred as "Ref. scheme in [5]" and "Ref. scheme in [5]", respectively. These schemes are all pursue SE maximization of relay-D2D communications. Specifically, in [8], only the transmit power of the relay node is optimized, while in [5], the transmit power of the source and the relay nodes are separately optimized and the one with the maximum rate is finally selected. From Fig. 3 we can observe that, at low interference threshold region, the proposed scheme performs similar to "Ref. scheme in [8]" and "Ref. scheme in [5]". While at high interference threshold region, the proposed scheme significantly outperforms existing schemes, which implies joint power allocation is necessary and can bring significant performance gain.

Fig. 3 illustrates $P_{\rm s}$ and $P_{\rm r}$ versus the location of the RU for different shadowing conditions. Here, the horizontal axis is ratio of $d_{\rm sr}$ to $d_{\rm sd}$

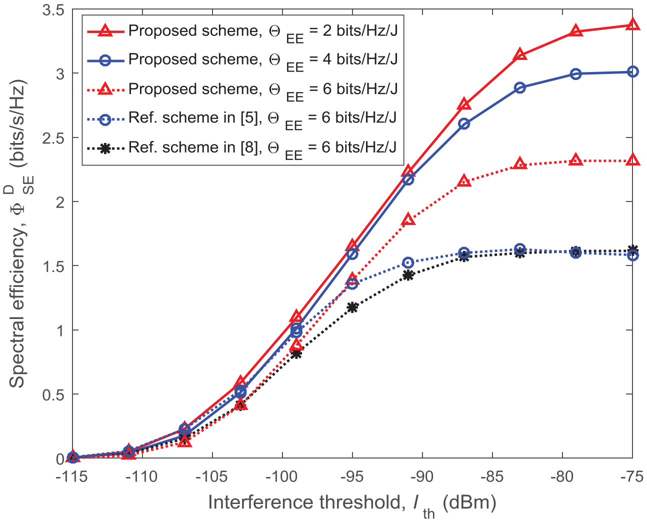

Fig. 2. SE versus interference threshold with different EE thresholds ($d_{\rm sd} = 200$ m).

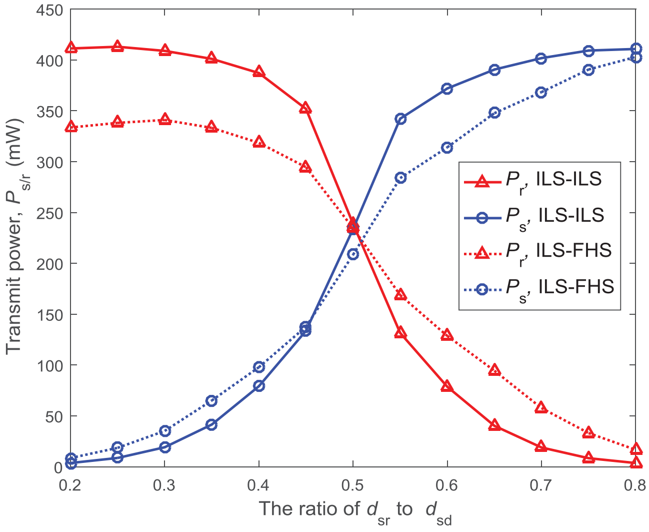

Fig. 3. Transmit powers of SU and RU versus location of the RU with different shadowing conditions ($d_{\rm sd} = 200$ m, $\Theta_{\rm EE} = 2$ bits/Hz/J, $I_{\rm th} = -90$ dBm).

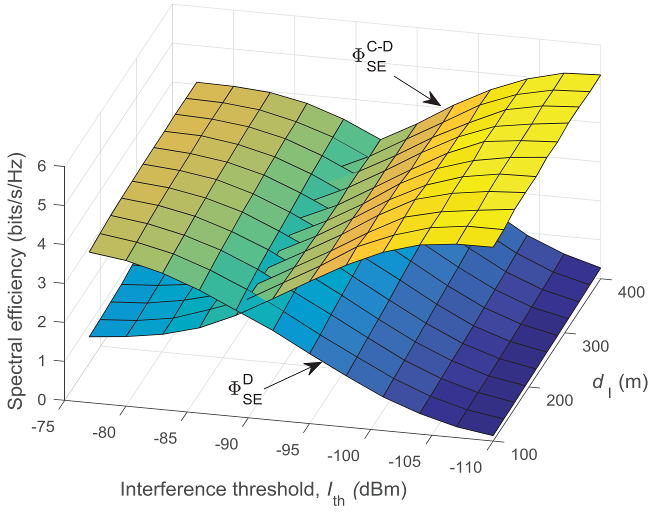

Fig. 4. Spectral efficiency of D2D system and cellular system with D2D communications ($\Theta_{\rm EE} = 2$ bits/Hz/J, $d_{\rm sd} = 150$ m).

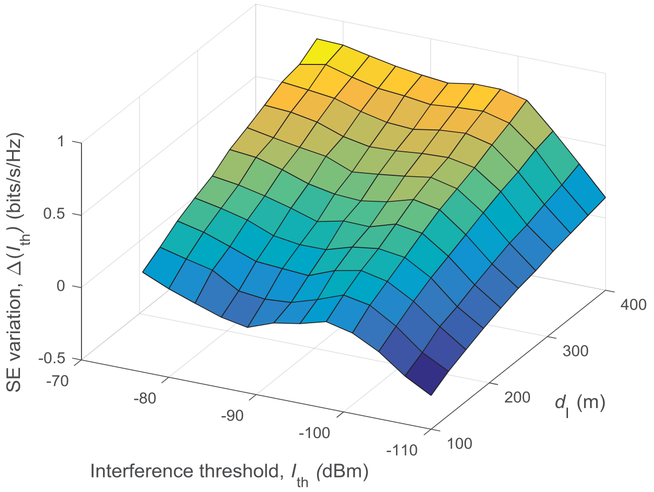

Fig. 5. Spectral efficiency variation ($\Theta_{\rm EE} = 2$ bits/Hz/J, $d_{\rm sd} = 150$ m).

with the RU randomly distributed. It can be seen that as the RU moves towards the DU, $P_{\rm s}$ maximizing SE increases and $P_{\rm r}$ decreases. This is because more transmit power is required when the corresponding link distance gets large. Moreover, when $h_{\rm rd}$ experiences severer fading, the variation trends of the $P_{\rm s}$ and $P_{\rm r}$ depend on the ratio of $d_{\rm sr}$ to $d_{\rm sd}$. When the RU is close to the SU, the optimal transmit power of $P_{\rm s}$ increases slightly and $P_{\rm r}$ decreases obviously. However, the total transmit power decreases due to the existence of EE constraints. When the RU locates nearby the DU, owing to the properties of min-function in DF protocol, the performance of the D2D relay communication is constrained by the quality of $h_{\rm rd}$ link. Thus, more $P_{\rm r}$ is required to combat the severer fading conditions.

To illustrate the impact of enabling D2D communications on cellular networks in an underlay manner, we present the system SE in Fig. 4 and SE variation in Fig. 5, respectively. Fig. 4 plots SE of D2D communications and cellular communications with resource reusing by D2D users. As $d_{\rm I}$ increases, the interference power received at the BS decreases and the permitted transmit power of D2D communications increases. Thus, for a given interference threshold, larger SE can be achieved for both D2D and cellular communications with larger $d_{\rm I}$. Moreover, as $I_{\rm th}$ increases, the SE of cellular communications decreases in the beginning and becomes saturated eventually, which is contrary to SE of D2D communications observed in Fig. 2.

Fig. 5 depicts SE variation $\Delta(I_{\rm th})$ versus $I_{\rm th}$ and $d_{\rm I}$. It can be seen that for a given $I_{\rm th}$, the larger $d_{\rm I}$ is, the larger $\Delta(I_{\rm th})$ can be achieved, implying that larger distance between the SU and the BS can increase the SE of cellular-D2D network. In addition, as $I_{\rm th}$ increases, $\Delta(I_{\rm th})$ increases then decreases and increases afterwards. When $I_{\rm th} \leq -85$ dBm, the SE decrease of cellular communications is less than 40%. In this situation, there exists an optimal $I_{\rm th}$ around -100 dBm that maximizes $\Delta(I_{\rm th})$, as discussed in Section IV. When $I_{\rm th} > -85$ dBm, $\Delta(I_{\rm th})$ increases with $I_{\rm th}$ increasing. In this case, since the interference constraint imposed by cellular communications is rather loose that the SE of cellular communications significantly decreases. Whereas, the nature of short distance communications enables significant increase in SE of D2D communications. As a result, $\Delta(I_{\rm th})$ is still increasing. It is worthy noting that $\Delta(I_{\rm th})$ falls below zero at some regions. This phenomenon implies that the SE increment of D2D communications cannot compensate the SE degradation of cellular communications caused by co-channel interference. In this case, the resource reuse should be terminated to guarantee the effectiveness of spectrum utilization in D2D communication unit.

VI. CONCLUSION

In this paper, we have investigated the EE-SE trade-off in relay aided D2D communications underlaying cellular networks. Firstly, we have derived a joint relay-source power allocation for D2D users and analyzed the impact of EE threshold on the transmit power. Further, to evaluate efficiency of resource reuse, a SE-variation function has been introduced. By maximizing the SE-variation function, we could determine the value of $I_{\rm th}$ that maximizes the SE of a D2D communication unit.

APPENDIX A
DERIVATION OF (8) AND (9)

From (6), we can get

$$\begin{aligned}\mathbb{E}\{(1+\nu)P_{\rm s}'\} &= \int_0^\infty \int_{\frac{N_0}{a}(y+1)}^\infty \left(a - \frac{N_0(y+1)}{x}\right) f_{|h_{\rm sr}|^2}(x) f_\nu(y) dx dy \\ &= \int_0^\infty \underbrace{\int_{\frac{N_0}{a}(y+1)}^\infty a f_{|h_{sr}|^2}(x)\, dx\, f_\nu(y) dy}_{J_1} \\ &\quad - \int_0^\infty \int_{\frac{N_0}{a}(y+1)}^\infty \frac{N_0(y+1)}{x} f_{|h_{\rm sr}|^2}(x)\, f_\nu(y)\, dx dy\end{aligned} \tag{12}$$

with $a = \frac{\alpha}{\Theta_{\rm EE}}$. We denote Ξ_1 and Ξ_2 as the first and second integral items, respectively, i.e., $\mathbb{E}\{(1+\nu)\, P_{\rm s}'\} = \Xi_1 - \Xi_2$.

For the convenience of derivations, we rewrite the PDF of Generalized-K into a gamma distributed format with a shape parameter m_i and a scale parameter η_i, where $m_i = \frac{\varphi_i \varepsilon_i}{\varphi_i + \varepsilon_i + 1}$ and $\eta_i = m_i / \Omega_i$ [11], i.e.,

$$f_{|h_i|^2}(x) = \frac{x^{m_i - 1} e^{-\frac{x}{\eta_i}}}{\Gamma(m_i)\, \eta_i^{m_i}},\ x > 0. \tag{13}$$

Then, J_1 can be calculated as

$$J_1 = a e^{-\frac{N_0(y+1)}{a\eta_{\rm sr}}} \sum_{p=0}^{m_{\rm sr}-1} \frac{N_0^p (y+1)^p}{(a\eta_{\rm sr})^p p!}. \tag{14}$$

To obtain Ξ_1, we need to calculate $f_\nu(x)$ firstly. From $\nu = \frac{|h_{\rm sr}|^2}{|h_{\rm rd}|^2}$, we can get

$$f_\nu(x) = \int_0^\infty y f_{|h_{\rm rd}|^2}(y) f_{|h_{\rm sr}|^2}(xy)\, dy. \tag{15}$$

By substituting (1) and (13) into (15), we can obtain

$$f_\nu(x) = \frac{\Gamma(m_{\rm sr}+m_{\rm rd})\, x^{m_{\rm sr}-1}}{\Gamma(m_{\rm sr})\Gamma(m_{\rm rd})\, \eta_{\rm sr}^{m_{\rm sr}} \eta_{\rm rd}^{m_{\rm rd}}} \left(\frac{1}{\eta_{\rm rd}} + \frac{x}{\eta_{\rm sr}}\right)^{-m_{\rm sr}-m_{\rm rd}}. \tag{16}$$

Then, by substituting (14) and (16) into (12), Ξ_1 can be expressed as

$$\Xi_1 = \frac{\Gamma(m_{\rm sr}+m_{\rm rd})\, e^{-\frac{N_0}{a\eta_{\rm sr}}}}{\Gamma(m_{\rm sr})\Gamma(m_{\rm rd})\, \eta_{\rm sr}^{m_{\rm sr}} \eta_{\rm rd}^{m_{\rm rd}}} \sum_{p=0}^{m_{\rm sr}-1} \frac{N_0^p}{\eta_{\rm sr}^p a^{p-1} p!} \times \int_0^\infty y^{m_{\rm sr}-1}(y+1)^p e^{-\frac{N_0}{a\eta_{\rm sr}}y} \left(\frac{1}{\eta_{\rm rd}} + \frac{y}{\eta_{\rm sr}}\right)^{-m_{\rm sr}-m_{\rm rd}} dy. \tag{17}$$

By extending the binomial expression, expressing $\left(\frac{1}{\eta_{\rm rd}} + \frac{y}{\eta_{\rm sr}}\right)^{-m_{\rm sr}-m_{\rm rd}}$ into Meijer-G function [16, (10)], and using [17, (7.813.1)], we can calculate Ξ_1 as the first term shown in (8). Similarly, we have Ξ_2 as the second term shown in (8).

Moreover, from (6), we also have

$$\begin{aligned} \mathbb{E}\{\log_2(1+\gamma_{\rm sr}(P_{\rm s}'))\} &= \mathbb{E}\left\{\log_2\left(\frac{a|h_{\rm sr}|^2}{(\nu+1)N_0}\right)\right\} \\ &= \int_0^\infty \int_{\frac{N_0}{a}(y+1)}^\infty \log_2\left(\frac{ax}{(\mathrm{y}+1)N_0}\right) \\ &\quad f_{|h_{\rm sr}|^2}(x)\, dx\, f_\nu(y)\, dy. \end{aligned} \tag{18}$$

By extending log function into L series and with the similar derivations as above, the analytical expression of $\mathbb{E}\{\log_2(1+\gamma_{\rm sr}(P_{\rm s}'))\}$ can be obtained as shown in (9).

APPENDIX B
PROOF OF PROPOSITION 1

When D2D users reuse the cellular resource, the SE of cellular communications can be written as

$$\begin{aligned} \Phi_{\rm SE}^{\text{C-D}} &= \frac{1}{2}\left(\log_2\left(1+\frac{P_{\rm c}|h_{\rm cb}|^2}{P_{\rm s}|h_{\rm sb}|^2+N_0}\right) + \log_2\left(1+\frac{P_{\rm c}|h_{\rm cb}|^2}{P_{\rm r}|h_{\rm rb}|^2+N_0}\right)\right) \\ &\geq \frac{1}{2}\left(\log_2\left(\frac{P_{\rm c}|h_{\rm cb}|^2+N_0}{P_{\rm s}|h_{\rm sb}|^2+N_0}\right) + \log_2\left(\frac{P_{\rm c}|h_{\rm cb}|^2+N_0}{P_{\rm r}|h_{\rm rb}|^2+N_0}\right)\right) \\ &= \frac{1}{2}\left(2\Phi_{\rm SE}^{\rm C} - \log_2\left(1+\frac{P_{\rm s}|h_{\rm sb}|^2}{N_0}\right) - \log_2\left(1+\frac{P_{\rm r}|h_{\rm rb}|^2}{N_0}\right)\right). \end{aligned} \tag{19}$$

Referring to the fact that $x\log_2(e) \geq \log_2(1+x)$ for $x \geq 0$, we have

$$\Phi_{\rm SE}^{\text{C-D}} \geq \frac{1}{2}\left(2\Phi_{\rm SE}^{\rm C} - \frac{P_{\rm s}|h_{\rm sb}|^2}{\ln 2N_0} - \frac{P_{\rm r}|h_{\rm rb}|^2}{\ln 2N_0}\right). \tag{20}$$

According to interference constraints in (2), we have

$$\Phi_{\rm SE}^{\text{C-D}} \geq \frac{1}{2}\left(2\Phi_{\rm SE}^{\rm C} - \frac{I_{\rm th}}{\ln 2N_0} - \frac{I_{\rm th}}{\ln 2N_0}\right) = \Phi_{\rm SE}^{\rm C} - \frac{I_{\rm th}}{\ln 2N_0}. \tag{21}$$

According to (21), we have $\delta_{\rm C}^- \leq \frac{I_{\rm th}}{\ln 2N_0}$. To this end, we complete the proof of Proposition 1.

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