Energy Efficiency of Relay Aided D2D Communications Underlaying Cellular Networks

Rui Zhang*, Yongzhao Li*[1], Cheng-Xiang Wang†, Yuhan Ruan*, and Hailin Zhang*
*State Key Laboratory of Integrated Service Network, Xidian University, Xi'an, 710071, China
†School of Engineering and Physical Science, Heriot-Watt University, Edinburgh, EH14 4AS, UK
E-mail:{rui_zhang_xd@163.com, Cheng-Xiang.Wang@hw.ac.uk, ryh911228@163.com, hlzhang@xidian.edu.cn}
[1]Corresponding author: yzhli@xidian.edu.cn

***Abstract*—Given the fact that the relay contributes to higher data rate or more reliable transmission at the expense of extra power consumption, we investigate the performance of relay aided Device-to-Device (D2D) communications from the perspective of energy efficiency (EE). Firstly, a closed-form expression for the EE of the considered network over Nakagami-m fading channels is derived. Then, taking into account the effects of practical modulation and coding schemes, we propose a channel quality indicator (CQI) based power control approach to maximize the EE of relay aided D2D communications while guaranteeing the interference limitation. The proposed scheme could avoid unnecessary power increment and is applicable in real time resource allocation. Simulation results demonstrate the validity of the theoretical analysis and illustrate that the CQI based scheme can improve EE.**

I. Introduction

Enabling users in proximity to communicate with each other directly by sharing cellualr spectrum resource in an underlay mode, D2D communications have a great potential to improve spectral efficiency (SE) and alleviate the traffic load of base stations (BSs) [1]. However, the envisioned advantages of D2D communications may be limited by poor quality of D2D links and interference between D2D and cellular communications. Therefore, the relay aided D2D communication is introduced to serve as a candidate paradigm to enhance the performance of D2D communications without extra construction and maintenance costs [2], [3].

Recently, the relay aided D2D communication has attracted tremendous attentions. The authors in [4] and [5] investigated the outage probability and achievable capacity of the relay aided D2D communication, respectively. Except for the performance analysis, interference and resource management schemes have also attracted numerous attentions since the mutual interference caused by resource reuse may degrade the system performance. An iterative Hungarian method was proposed in [6] to maximize the throughput with joint relay selection and related subchannel-power allocation. The authors in [7] proposed a mode selection scheme to maximize the capacities of relay aided D2D and cellular systems. The authors in [8] proposed three relay selection schemes and investigated the corresponding capacities. A heuristic green relay assignment algorithm to maximize the minimum data rate of the D2D link was provided in [9]. These aforementioned researches analyzed or optimized the performance of the relay aided D2D communication from the perspective of capacity and reliability.

Whereas, the relay contributes to higher data rate or more reliable transmission at the expense of extra transmit power and circuit power, which starts to dominate when the transmit power is reduced in short distance transmission. Thus, the consideration of EE, an important metric for 5G networks [10], for relay aided D2D communications has attracted increasing attentions. In this regard, the authors in [11] utilized EE as an incentive parameter in D2D cooperative communications. In the scenario where users act as relays in cellular uplink transmission, the authors in [12] proposed a mobile association scheme to maximize the EE while guaranteeing the quality-of-service requirement of users. The authors in [13] studied the average EE and SE of multi-hop D2D communications operating in dedicated radio resources.

To best of our knowledge, the EE of relay aided D2D communications in the underlay mode, where the mutual interference between D2D and cellular communications exists, has not been well studied. To fill this research gap, we investigate the EE in relay aided D2D communications and propose an EE maximized power control scheme in this paper. We firstly derive a closed-form expression for the EE over Nakagami-m fading channels. Based on the theoretical analysis, we present a power control scheme maximizing the EE of D2D communications while guaranteeing the interference limitations imposed by cellular communications. Moreover, taking into account the effects of practical modulation and coding schemes, we modify the power control approach based on CQI, which is the quantization of signal-to-interference-plus-noise ratio (SINR) [14].

II. System Model

We consider a single cell scenario consisting of one cellular user (CU), one D2D pair and one relay user (RU) (the extension to multiple relays is left for future work).

978-1-5386-3531-5/17/$31.00

The D2D source user (SU) will communicate with the D2D destination user (DU) with the assistance of the RU, sharing the same radio resources as the CU used in uplink transmissions. The RU and DU are interfered by the CU and the BS is also interfered by the SU and RU. We assume that the radio resource of the CU can only be shared by one D2D pair. Besides, each user equipment is equipped with a single antenna and amplify-and-forward (AF) protocol is adopted at the RU. We denote $h_{\rm sr}$, $h_{\rm rd}$, $h_{\rm sb}$, $h_{\rm rb}$, $h_{\rm cr}$, and $h_{\rm cd}$ as the channel coefficients of SU→RU, RU→DU, SU→BS, RU→BS, CU→RU, and CU→DU links, respectively.

One relay aided transmission consists of two orthogonal time phases. In the first phase, SU transmits signal to RU and the signal received at RU can be written as

$$y_{\rm sr} = \sqrt{P_{\rm s}} h_{\rm sr} x + \sqrt{P_{\rm c}} h_{\rm cr} z + n_1 \tag{1}$$

where x is the desired signal from the SU, z is the interfering signal from the CU, n_1 is the noise at RU in the first phase, and $P_{\rm s}$ and $P_{\rm c}$ are the transmit powers of the SU and CU, respectively. It is assumed that all the noises in this paper are complex additive white Gaussian noises (AWGNs) with distribution $\mathcal{CN}(0, N_0)$. After receiving signal from the SU, the RU employs AF strategy to multiply the received signal $y_{\rm sr}$ with a multiplication factor ρ and then forward it to the DU, where $\rho = 1 \Big/ \sqrt{P_{\rm s}|h_{\rm sr}|^2 + P_{\rm c}|h_{\rm cr}|^2 + N_0}$ is the energy normalized factor to satisfy the average transmit power constraint. By denoting $P_{\rm r}$ as the transmit power of the RU, the signal received at the DU in second phase is

$$y_{\rm d} = \sqrt{P_{\rm r}} h_{\rm rd} \rho y_{\rm sr} + \sqrt{P_{\rm c}} h_{\rm cd} z + n_2 \tag{2}$$

where n_2 is the noise at the DU. By substituting (1) into (2), the received SINR at the DU can be expressed as $\gamma_{\rm d} = \frac{\Psi_1 \Psi_2}{\Psi_1 + \Psi_2 + 1}$ where $\Psi_1 = \frac{\bar{\gamma}_{\rm s}|h_{\rm sr}|^2}{\bar{\gamma}_{\rm c}|h_{\rm cr}|^2 + 1}$ and $\Psi_2 = \frac{\bar{\gamma}_{\rm r}|h_{\rm rd}|^2}{\bar{\gamma}_{\rm c}|h_{\rm cd}|^2 + 1}$. Here, $\bar{\gamma}_{\rm s} = P_{\rm s}/N_0$, $\bar{\gamma}_{\rm r} = P_{\rm r}/N_0$, and $\bar{\gamma}_{\rm c} = P_{\rm c}/N_0$ denote the average signal-to-noise ratio (SNR).

We assume that the amplitude of all links follows the Nakagami-m distribution. In this case, the probability density function (PDF) of $|h|^2$ is given by a gamma distribution, i.e., $\mathcal{G} \sim (m, \lambda)$, and can be written as

$$f_{|h|^2}(x) = \frac{1}{\Gamma(m)\lambda^m} x^{m-1} e^{-\frac{x}{\lambda}}, \; x > 0, m \geq 0.5 \tag{3}$$

where m and λ are the shape and scale parameters, $\lambda = \Omega/m$ with Ω as the average local power. We denote (m_1, λ_1) for interfering links and (m_2, λ_2) for communication links.

III. Theoretical Analysis of EE

In this section, we theoretically analyze the EE performance of the AF relay aided D2D communications. Considering the interference received at the RU and DU in underlay mode, we firstly derive the PDFs of the SINRs for the relay forward and backward links. Then, employing the moment generating function (MGF) based method, a closed-form expression for the EE is obtained.

Energy efficiency (EE, in bits/Hz/Joule) is defined as the ratio of the spectral efficiency ($C_{\rm d}$, in bits/s/Hz) to the total power consumption (P, in Watt). The EE for the relay aided D2D communication can be expressed as

$$EE = \frac{C_{\rm d}}{P} \tag{4}$$

where $P = \frac{1}{2}(\varepsilon P_{\rm s} + \varepsilon P_{\rm r} + 2(P_0^{\rm C} + P_0^{\rm S}))$ denotes the total power consumption. Note that the coefficient 1/2 accounts for the fact that the entire relay aided D2D communication occurs during two phases. Here, $\varepsilon P_{\rm s}$ and $\varepsilon P_{\rm r}$ are the radio-frequency power of SU and RU, respectively, with $1/\varepsilon \in (0, 1]$ denoting the drain efficiency of power amplifier. Besides, $P_0^{\rm C}$ is the circuit power and $P_0^{\rm C}$ is the static power of each transmitter. For notation simplicity, we use $P_0 {=} P_0^{\rm C} + P_0^{\rm S}$ in the following. By denoting $C_{\rm d}$ as the instantaneous mutual information of D2D communications, we have

$$C_{\rm d} = \frac{1}{2}\mathbb{E}\left[\log_2(1 + \gamma_{\rm d})\right] \tag{5}$$

where $\mathbb{E}\{\cdot\}$ is the statistical expectation. The key procedure to obtain the theoretical result of (4) is to derive a closed-form expression of $C_{\rm d}$. From (5), we have

$$\begin{aligned} C_{\rm d} &= \frac{1}{2}\mathbb{E}\left[\log_2\left(\frac{(\Psi_1 + 1)(\Psi_2 + 1)}{\Psi_1 + \Psi_2 + 1}\right)\right] \\ &= \frac{1}{2}\sum_{i=1}^{2}\mathbb{E}[\log_2(1+\Psi_i)] - \frac{1}{2}\mathbb{E}\left[\log_2(1+\Psi_3)\right] = \sum_{i=1}^{2} C_i - C_3 \end{aligned} \tag{6}$$

where $\Psi_3 = \Psi_1 + \Psi_2$ and $C_i = \frac{1}{2}\mathbb{E}\left[\log_2(1 + \Psi_i)\right](i = 1, 2, 3)$. Then, the problem is transformed into the derivation of $C_i \, (i = 1, 2, 3)$.

For $i = 1, 2$, C_i can be written with the PDF of Ψ_i as

$$C_i = \frac{1}{2\ln 2}\int_0^\infty \ln(1 + x) f_{\Psi_i}(x)\, dx. \tag{7}$$

The C_1 and C_2 can be derived as

$$\begin{aligned} C_1 = &\frac{1}{2\ln 2}\sum_{i=0}^{m_2}\binom{m_2}{i}\frac{(\lambda_1\bar{\gamma}_{\rm c})^i}{\Gamma(m_1)\Gamma(m_2)}\sum_{j=0}^{L}\frac{(-1)^j}{j!(\lambda_2\bar{\gamma}_{\rm s})^b} \\ &\times G_{33}^{32}\left[\frac{\lambda_1\bar{\gamma}_{\rm c}}{\lambda_2\bar{\gamma}_{\rm s}}\,\middle|\, \begin{matrix} -b, -a+1, -b+1 \\ -b, -b, 0 \end{matrix}\right] \end{aligned} \tag{8}$$

and

$$\begin{aligned} C_2 = &\frac{1}{2\ln 2}\sum_{i=0}^{m_2}\binom{m_2}{i}\frac{(\lambda_1\bar{\gamma}_{\rm c})^i}{\Gamma(m_1)\Gamma(m_2)}\sum_{j=0}^{L}\frac{(-1)^j}{j!(\lambda_2\bar{\gamma}_{\rm r})^b} \\ &\times G_{33}^{32}\left[\frac{\lambda_1\bar{\gamma}_{\rm c}}{\lambda_2\bar{\gamma}_{\rm r}}\,\middle|\, \begin{matrix} -b, -a+1, -b+1 \\ -b, -b, 0 \end{matrix}\right]. \end{aligned} \tag{9}$$

The details of derivation can be found in Appendix A.

Then, we focus on deriving of C_3. Due to the fact that a closed-form expression for the PDF of $\Psi_3 = \Psi_1 + \Psi_2$ is difficult to derive, C_3 can not be calculated using methods similar to those for C_1 and C_2. Thus, we use the method in [17, Eq. (7)] and express C_3 in (6) as

$$C_3 = \frac{1}{\ln 2}\int_0^{\infty} \mathrm{Ei}\left(-s\right) M_{\Psi_3}^{(1)}\left(s\right) ds \tag{10}$$

where $\mathrm{Ei}\left(-s\right) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt$ is the exponential integral function [15, Eq. (8.211.1)]. Here, $M_{\Psi_3}^{(1)}\left(s\right)$ represents the first-order derivative of $M_{\Psi_3}(s)$, where $M_{\Psi_3}(s) = \mathbb{E}\left\{e^{-s\Psi_3}\right\} = \int_0^{\infty} e^{-sx} f_{\Psi_3}\left(x\right) dx$. From the definition of MGF, we have

$$M_{\Psi_3}\left(s\right) = M_{\Psi_1}\left(s\right) M_{\Psi_2}\left(s\right) \tag{11}$$

where $M_{\Psi_1}\left(s\right)$ and $M_{\Psi_2}\left(s\right)$ are the MGFs of Ψ_1 and Ψ_2, respectively. Rewriting $e^{-\left(s+\frac{1}{\lambda_2\bar{\gamma}_{\mathrm{s}}}\right)}$ into series expansion with L terms, we have

$$\begin{aligned} M_{\Psi_1}\left(s\right) = &\sum_{i=0}^{m_2}\binom{m_2}{i}\frac{(m_1)_i\bar{\gamma}_{\mathrm{c}}^i}{\Gamma\left(m_2\right)\lambda_1^{m_1}(\lambda_2\bar{\gamma}_{\mathrm{s}})^{m_2}}\sum_{l=0}^{L}\frac{\left(-1\right)^l}{l!} \\ &\times\left(s+\frac{1}{\lambda_2\bar{\gamma}_{\mathrm{s}}}\right)^l\int_0^{\infty}x^{c-1}\left(\frac{1}{\lambda_1}+\frac{\bar{\gamma}_{\mathrm{c}}x}{\lambda_2\bar{\gamma}_{\mathrm{s}}}\right)^{-a}dx \end{aligned} \tag{12}$$

where $c = m_2 + l$. Using [15, Eq. (3.194.3)] we can get

$$M_{\Psi_1}\left(s\right) = \varphi_l(1+\lambda_2\bar{\gamma}_{\mathrm{s}}s)^l \tag{13}$$

$$\varphi_l = \sum_{i=0}^{m_2}\binom{m_2}{i}\frac{(m_1)_i}{\Gamma\left(m_2\right)}\sum_{l=0}^{L}\frac{\left(-1\right)^l}{l!}\left(\lambda_1\bar{\gamma}_{\mathrm{c}}\right)^{i-c}B\left(c,a-b\right)$$

where $B\left(u,v\right) = \frac{\Gamma(u)\Gamma(v)}{\Gamma(u+v)}$. Similarly, we have $M_{\Psi_2}\left(s\right) = \varphi_k(1+\lambda_2\bar{\gamma}_{\mathrm{r}}s)^k$. Then, $M_{\Psi_3}^{(1)}\left(s\right)$ can be expressed as

$$M_{\Psi_3}^{(1)}\left(s\right) = M_{\Psi_1}^{(1)}\left(s\right) M_{\Psi_2}\left(s\right) + M_{\Psi_1}\left(s\right) M_{\Psi_2}^{(1)}\left(s\right). \tag{14}$$

Then, $M_{\Psi_3}^{(1)}\left(s\right)$ can be written as

$$M_{\Psi_3}^{(1)}\left(s\right) = \varphi_l\varphi_k\lambda_2^{k+l}\bar{\gamma}_{\mathrm{s}}^l\bar{\gamma}_r^k\left(l+k\right)s^{l+k-1}. \tag{15}$$

By substituting (15) into (10) and employing the identity [15, Eq. (6.223)], C_3 can be deduced as

$$C_3 = -\frac{1}{\ln 2}\varphi_l\varphi_k\lambda_2^{k+l}\bar{\gamma}_{\mathrm{s}}^l\bar{\gamma}_{\mathrm{r}}^k\Gamma\left(l+k\right). \tag{16}$$

The closed-form expression of C_{d} can be obtained with (8), (9), and (16), so is the expression of EE in (4).

IV. Energy Efficiency Maximized Power Control

In the following, we present a power control scheme maximizing the EE of D2D communications while restricting the interference caused by D2D communications to an acceptable level, i.e., the interference power received at the BS remains below the predefined threshold I_{th}. As our objective is to investigate the EE of D2D communications where the relay transmission is adopted, we assume that the transmit power of SU has been given. Then, the optimization problem can be formulated as

$$\begin{array}{ll} \underset{P_{\mathrm{r}}}{\text{maximize}} & EE \\ \text{subject to} & 0 \le P_{\mathrm{r}} \le P_M \\ & \frac{1}{2}(I_{\mathrm{sb}}+I_{\mathrm{rb}}) \le I_{\mathrm{th}} \end{array} \tag{17}$$

where $I_{\mathrm{sb}} = P_{\mathrm{s}}\left|h_{\mathrm{sb}}\right|^2$, $I_{\mathrm{rb}} = P_{\mathrm{r}}\left|h_{\mathrm{rb}}\right|^2$, and P_M is the maximum transmit power. We perform an exhaustive search for the optimal value of P_{r}. However, in practice, the implementation of this approach may be limited due to: i) even slight fluctuation of SINR will lead to frequent transmit power adjustment, resulting in large control overhead when the power control function is applied to resource block (RB); ii) in the LTE cellular network, the SE is determined by CQI instead of SINR, which means that increase of SINR does not necessarily bring higher SE; iii) all RBs allocated to one user must use the same modulation and coding scheme [14], further increasing the unnecessary power under continues power allocation.

It is unprofitable that extra transmit power only result in SINR increase rather than CQI level, in which case the SE remains constant. We expect that more transmit power could achieve higher SE and even can achieve higher EE. Therefore, we propose a CQI based power control scheme regarding to the disadvantages mentioned above. Specifically, according to different CQI levels [14], we discretize the continuous transmit power to a finite number of discrete values. Then, the problem above can be modified as

$$\begin{array}{ll} \underset{\mathbb{P}_{\mathrm{r}_i}}{\text{maximize}} & EE \\ \text{subject to} & 0 \le \mathbb{P}_{\mathrm{r}_i} \le P_M \\ & \frac{1}{2}(I_{\mathrm{sb}}+\mathbb{I}_{\mathrm{rb}}) \le I_{\mathrm{th}} \end{array} \tag{18}$$

where $\mathbb{P}_{\mathrm{r}_i}$ is the minimum required transmit power of the RU at each CQI level CQI_i. Similarly, $\mathbb{I}_{\mathrm{rb}} = \mathbb{P}_{\mathrm{r}_i}\left|h_{\mathrm{rb}}\right|^2$ holds. In the proposed scheme, we avoid unnecessary power increment and adjustment while guaranteeing the SE, in which way a higher EE can be achieved. Moreover, exhaustive search for the discrete values can effectively reduce the computation complexity, which is more practical in real time resource allocation.

V. Results and Analysis

In this section, we verify the theoretical analysis and evaluate the proposed schemes. The BS is located at the center of cell with radius $r = 0.5$ Km. The SU, RU, and DU are in a straight line and the RU is at the midpoint. The distance between RU and BS is $0.5r$ and d_{SD} denotes the distance between SU and DU. The pathloss model between BS and users is $\mathrm{PL} = 128.1 + 37.6\log_{10}(D$ [in Km]$)$ and the pathloss model between users is $\mathrm{PL} = 148.1 + 40\log_{10}(D$ [in Km]$)$. We set $N_0 = -174$ dBm/Hz, $m_1 = 1$, and $\Omega = 1$. The mapping relation between SNR and CQI level is presented in [18].

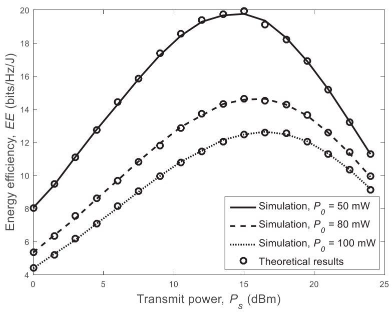

Fig. 1. EE of relay aided D2D communications with different circuit power consumptions ($I_{\rm th} = \infty$, $d_{\rm SD} = 0.5r$, $P_{\rm c} = 23$ dBm, $m_2 = 3$).

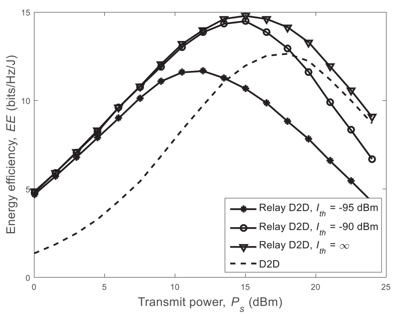

Fig. 2. Simulated EE of D2D communications with different interference thresholds ($P_0 = 50$ mW, $d_{\rm SD} = 0.6r$, $P_{\rm c} = 23$ dBm, $m_2 = 3$).

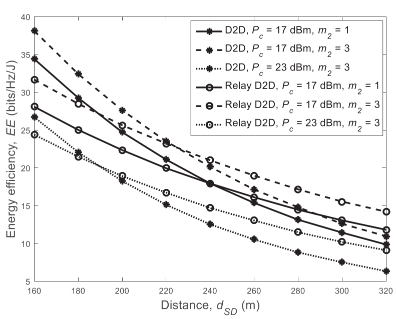

Fig. 3. Simulated EE of D2D communications versus the distance between S and D ($P_0 = 80$ mW, $P_{\rm s} = 13$ dBm, $I_{\rm th} = -90$ dBm).

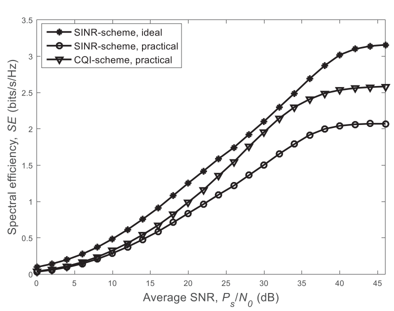

Fig. 4. Simulated SE with different power control approaches ($P_0 = 50$ mW, $P_{\rm c} = 23$ dBm, $d_{\rm SD} = 0.5r$, $I_{\rm th} = -90$ dBm, $m_2 = 3$).

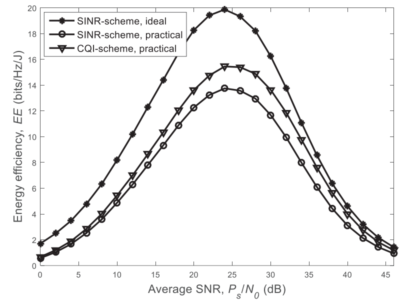

Fig. 5. Simulated EE with different power control approaches ($P_0 = 50$ mW, $P_{\rm c} = 23$ dBm, $d_{\rm SD} = 0.5r$, $I_{\rm th} = -90$ dBm, $m_2 = 3$).

Fig. 2 performs the EE of relay aided D2D communications with different circuit power consumptions, P_0. As expected, the larger the circuit power is, the smaller the EE becomes. For each P_0, the EE increases in the beginning and deteriorates afterwards as $P_{\rm s}$ increases. Moreover, the theoretical curves plotted with $L = 30$ agree well with the Monte Carlo simulations, confirming the accuracy of the theoretical analysis and simulations.

Fig. 3 presents the EE with different interference thresholds, where the EE of direct transmission is taken as a baseline. As observed, compared with the transmission without interference threshold ($I_{\rm th} = \infty$), the transmission under interference power limitations could achieve almost the same EE when $P_{\rm s}$ is small, while lower EE as $P_{\rm s}$ increases. This is due to that when $P_{\rm s}$ is small, the optimal $P_{\rm r}$ maximizing the EE is small. Meanwhile, although the maximum permitted $P_{\rm r}$ is constrained by the interference limitations, the optimal $P_{\rm r}$ can be obtained as well. Moreover, the looser the interference constraint is, i.e., $I_{\rm th}$ gets larger, the higher the EE is, indicating that there is a balance between the performance of D2D and cellular communications.

Fig. 4 depicts the EE of D2D and relay D2D versus the distance between S and D in three cases: case 1, $P_{\rm c} = 17$ dBm, $m_2 = 3$; case 2, $P_{\rm c} = 17$ dBm, $m_2 = 1$; case 3, $P_{\rm c} = 23$ dBm, $m_2 = 3$. As the distance between D2D pair increases, all the EE clearly decreases. For each case, the EE of direct transmission is superior to the relay aided transmission in the beginning and deteriorates afterwards. Comparing case 1 and case 2, we observe that a higher EE can be achieved with a better link quality (as m_2 increases). Comparing case 1 and case 3, we find that the advantage of relay aided D2D in resisting interference is more obvious as $P_{\rm c}$ increases.

As illustrated in Fig. 5 and Fig. 6, we compare the SE and EE of different power control schemes. Here, the ideal one corresponds to the theoretical analysis, while the practical one takes the practical decoding/demodulation threshold into account. It is clear that the CQI based scheme outperforms the SINR based scheme in terms of both SE and EE when practical decoding/demodulation threshold is conducted. Besides, since the upper bound of SE in the LTE cellular network is restricted by the practical modulation and coding scheme, the SE maintains a stable value at the end of the curves, although the SINR keeps increasing.

VI. Conclusions

We have studied the EE of underlaying relay aided D2D communications. Simulation results have shown that relay aided D2D communications could achieve higher EE than one hop D2D communications when the distance between SU and DU is large or the D2D link experiences serve fading.

Acknowledgement

The authors gratefully acknowledge the support from the National Key Research and Development Program of China (2016YFB1200202), Natural Science Foundation of Shaanxi Province (2017JZ022), 111 Project in Xidian University of China (B08038), EU H2020 RISE TESTBED project (No. 734325), EU FP7 QUICK project (No. PIRSES-GA-2013-612652), and EPSRC TOUCAN project (No. EP/L020009/1).

Appendix A

From (3), $f_{\Psi_i}(x)\,(i=1,2)$ can be expressed as

$$f_{\Psi_1}(x)=\int_0^{\infty}\frac{(1+\bar{\gamma}_{\rm c}y)}{\bar{\gamma}_{\rm s}}f_{|h_{\rm cr}|^2}(y)f_{|h_{\rm sr}|^2}\left(\frac{x\,(1+\bar{\gamma}_{\rm c}y)}{\bar{\gamma}_{\rm s}}\right)dy \tag{19}$$

$$f_{\Psi_2}(x)=\int_0^{\infty}\frac{(1+\bar{\gamma}_{\rm c}y)}{\bar{\gamma}_{\rm r}}f_{|h_{\rm cd}|^2}(y)f_{|h_{\rm rd}|^2}\left(\frac{x\,(1+\bar{\gamma}_{\rm c}y)}{\bar{\gamma}_{\rm r}}\right)dy. \tag{20}$$

Considering $f_{\Psi_1}(x)$ and $f_{\Psi_2}(x)$ are similar in expression, we take the derivation of $f_{\Psi_1}(x)$ as an example in the following. By substituting (4) into (20), we have

$$\begin{aligned} f_{\Psi_1}(x) &= \frac{e^{-x/(\lambda_2\bar{\gamma}_{\rm s})}x^{m_2-1}}{\Gamma(m_1)\Gamma(m_2)\lambda_1^{m_1}(\lambda_2\bar{\gamma}_{\rm s})^{m_2}} \\ &\quad\times\int_0^{\infty}(1+\bar{\gamma}_{\rm c}y)^{m_2}y^{m_1-1}e^{-\left(\frac{1}{\lambda_1}+\frac{\bar{\gamma}_{\rm c}x}{\lambda_2\bar{\gamma}_{\rm s}}\right)y}dy. \end{aligned} \tag{21}$$

Then, applying binomial expansion and [15, Eq. (3.381.3)], we can further obtain

$$f_{\Psi_1}(x)=\sum_{i=0}^{m_2}\binom{m_2}{i}\frac{(m_1)_i\bar{\gamma}_{\rm c}^i x^{m_2-1}e^{-\frac{x}{\lambda_2\bar{\gamma}_{\rm s}}}}{\Gamma(m_2)\lambda_1^{m_1}(\lambda_2\bar{\gamma}_{\rm s})^{m_2}}\left(\frac{1}{\lambda_1}+\frac{\bar{\gamma}_{\rm c}x}{\lambda_2\bar{\gamma}_{\rm s}}\right)^{-a} \tag{22}$$

where $a=m_1+i$ and $(u)_v=\frac{\Gamma(u+v)}{\Gamma(u)}$ is a pochhammer symbol. By substituting (22) into (8) and rewrite $e^{-\frac{x}{\lambda_2\bar{\gamma}_{\rm s}}}$ into series expansion with L terms, C_1 can be written as

$$\begin{aligned} C_1 &= \frac{1}{2\ln 2}\sum_{i=0}^{m_2}\binom{m_2}{i}\frac{(m_1)_i\bar{\gamma}_{\rm c}^i}{\Gamma(m_2)\lambda_1^{m_1}}\sum_{j=0}^{L}\frac{(-1)^j}{j!(\lambda_2\bar{\gamma}_{\rm s})^b} \\ &\quad\times\int_0^{\infty}\ln(1+x)\,x^{b-1}\left(\frac{1}{\lambda_1}+\frac{\bar{\gamma}_{\rm c}x}{\lambda_2\bar{\gamma}_{\rm s}}\right)^{-a}dx \end{aligned} \tag{23}$$

where $b=m_2+j$. To solve the integral, we first express $\ln(1+x)$ and $\left(\frac{1}{\lambda_1}+\frac{\bar{\gamma}_{\rm c}x}{\lambda_2\bar{\gamma}_{\rm s}}\right)^{-m_1-i}$ in terms of Meijer-G function according to [16, Eq. (10) and (11)], i.e., $\ln(1+x) = G_{22}^{12}\left[x\,\middle|\,\begin{matrix}1,1\\1,0\end{matrix}\right]$ and $\left(\frac{1}{\lambda_1}+\frac{\bar{\gamma}_{\rm c}x}{\lambda_2\bar{\gamma}_{\rm s}}\right)^{-a} = \frac{\lambda_1^a}{\Gamma(a)}G_{11}^{11}\left[\frac{\lambda_1\bar{\gamma}_{\rm c}}{\lambda_2\bar{\gamma}_{\rm s}}x\,\middle|\,\begin{matrix}-a+1\\0\end{matrix}\right]$. Then, using the identity [15, Eq. (7.811.1)], the expression of C_1 can be written as in (9). Similarly, C_2 can be written as in (10) by replacing $\bar{\gamma}_{\rm s}$ with $\bar{\gamma}_{\rm r}$.

References

[1] A. Asadi, Q. Wang, and V. Mancuso, "A survey on Device-to-Device communication in cellular networks," *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, Fourthquarter 2014,.

[2] Y. Cao, T. Jiang, and C. Wang, "Cooperative device-to-device communications in cellular networks," *IEEE Wireless Commun.*, vol. 22, no. 3, pp. 124–129, June 2015.

[3] M. Hasan, E. Hossain, and D. I. Kim, "Resource allocation under channel uncertainties for relay-aided Device-to-Device communication underlaying LTE-A cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2322–2338, Apr. 2014.

[4] Y. Ni *et al.*, "Outage probability of device-to-device communication assisted by one-way amplify-and-forward relaying," *IET Commun.*, vol. 9, no. 2, pp. 271– 282, Jan. 2015.

[5] Z. Lin, *et al.*, "Stochastic geometry analysis of achievable transmission capacity for relay-assisted Device-to-Device networks," in *Proc. IEEE ICC'14*, Sydney, Australia, June 2014, pp. 2251–2256.

[6] T. Kim and M. Dong, "An iterative Hungarian method to joint relay selection and resource allocation for D2D communications," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 625–628, Dec. 2014.

[7] L. Wang, T. Peng, Y. Yang, and W. Wang, "Interference constrained D2D communication with relay underlaying cellular networks," in *Proc. IEEE VTC'13-Fall*, Las Vegas, USA, Sep. 2013, pp. 1–5.

[8] H. Feng, H. Wang, X. Chu, and X. Xu, "On the tradeoff between optimal relay selection and protocol design in hybrid D2D networks," in *Proc. IEEE ICC'15 Workshop on D2D Commun. Cellular and Wireless Networks*, London, June 2015, pp. 705–711.

[9] T. Han and N. Ansari, "Heuristic relay assignments for green relay assisted device to device communications," in *Proc. IEEE GLOBECOM'13*, Atlanta, USA, Dec. 2013, pp. 468–473.

[10] C.-X. Wang *et al.*, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[11] Q. Sun, L. Tian, Y. Zhou, J. Shi, and X. Wang, 'Energy efficient incentive resource allocation in D2D cooperative communications," in *Proc. IEEE ICC'15*, London, UK, June 2015, pp. 2632–2637.

[12] S. Xiao *et al.*, "Energy-efficient mobile association in heterogeneous networks with Device-to-Device communications," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5260–5271, Aug. 2016.

[13] Wei L *et al.*, "Energy efficiency and spectrum efficiency of multihop Device-to-Device communications underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 367–380, Jan. 2016.

[14] 3GPP, "Physical layer procedures evolved universal terrestrial radio access," Third Generation Partnership Project, TS 36.213, Oct. 2013.

[15] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. Academic Press, 2000.

[16] V. S. Adamchik and O. I. Marichev, "The algorithm for calculating integrals of hypergeometric type functions and its realization in reduce systems" in *Proc. Int. Conf. Symp. Algebraic Comput.*, Tokyo, Japan, 1990, pp 212–224.

[17] M. Di Renzo, *et al.*, "Channel capacity cver generalized fading channels: a novel MGF-based approach for aerformance analysis and design of wireless communication systems," *IEEE Trans. Veh. Technol.*, vol. 59, no. 1, pp. 127–149, Jan. 2010.

[18] C. Mehlf *et al.*, "Simulating the long term evolution physical layer," in *Proc. European Signal Process. Conf.'09*, Glasgow, UK, Aug. 2009, pp. 1471–1478.