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Power-Spectrum Trading for Full-Duplex D2D Communications in Cellular Networks

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***Abstract*—Device-to-device (D2D) communications allows two adjacent mobile terminals transmit signal directly without going through base stations, which has been considered as one of the key technologies for future mobile networks. As full-duplex (FD) communications can improve the performance (*i.e.*, throughput, energy efficiency (EE)) of communications systems, it is commonly used in practical D2D communications scenarios. However, FD-enabled D2D communications also results in self-interference. To fully realize the potential benefits of FD-enabled D2D communications, an effective resource allocation mechanism is critical to avoid not only the self-interference of FD-enabled D2D communications but also the interference between D2D users (DUs) and cellular users (CUs). In this paper, we investigate the resource allocation issue for FD-enabled DUs and traditional CUs. Considering the asymmetry of energy and spectrum resources of DUs and CUs, we propose a power-spectrum trading mechanism to achieve mutual benefits for both types of users. A concave-convex procedure algorithm is employed to solve the optimization problem of power allocation, and then a maximum weighted bipartite matching based method is proposed to select proper D2D pairs to maximize the overall system throughput. Numerical results show that the proposed scheme can remarkably improve the overall throughput and EE of FD-enabled D2D communications system.**

***Index Terms*—D2D communications, full-duplex communications, resource allocation, maximum weighted bipartite matching**

I. INTRODUCTION

Since the beginning of the 21st century, with the development of electronic information technology, intelligent terminals, (*i.e.*, mobile phones), have become indispenable products in human life. According to the Ministry of Industry and Information Technology of China, in 2019, the consumption of mobile Internet access traffic in China reached 122 billion Gigabits, among which the mobile phone Internet accounts for 99.2% of the total traffic [1]. The rapidly increasing number of intelligent terminals brings great convenience to the society, but it also poses huge challenges to the design of the future wireless networks. Specifically, two of the fundamental challenges that need to be addressed ared: (1) How to use the limited spectrum resources to serve the increasing number of mobile users; (2) How to use less energy consumption of mobile devices when communicating with each other since the development of mobile phone battery technology has always been relatively slow [2]. Therefore, improving network performance with the limited spectrum and energy resources effectively has become s critical yet challenging issue for future wireless networks [3]–[5].

In recent years, device-to-device (D2D) communications, which enables two adjacent terminals to communicate directly without going through base stations (BSs) [6], has been proposed and attracted much attention. It brings three additional gains, *i.e.*, channel gain, hop gain, and multiplexing gain, compared with traditional cellular communications [7]. Two-way data transmission is commonly used in practical D2D communications scenarios since full-duplex (FD) communications can reduce latency and increase system throughput [8]. However, FD-enabled D2D communications also result in severe interference including the self-interference and the interference between D2D users (DUs) and cellular users (CUs) [9], [10]. If there is no efficient interference management scheme, the performance of networks can heavily deteriorate. Efficient resource allocation is the key to solve the communications interference problem and therefore is one of the key issues to fully realize the potential benefits of FD-enabled D2D communications.

There has been much work on resource allocation in D2D communications. To reduce the interferences between D2D links and cellular links, a multi-cell resource allocation algorithm based on dynamic interference constrained domain is proposed in [11]. In [12], a two-hop D2D communications resource allocation scheme for the fifth generation (5G) cellular network is proposed. In [13]–[17], the authors considered joint power control and channel allocation to improve the system throughput while guaranteeing the QoS of the users. In [18] and [19], interference control schemes have been investigated to ensure the coexistence of D2D communications and cellular systems. In [20] and [21], resource allocation for two-way D2D communications has been investigated. In particular, a spectrum sharing protocol has been proposed in [20], which

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allows D2D users to communicate in both directions and assists two-way communications between cellular users. In [21], the authors have adopted a two-way interference sensing algorithm to guarantee that there is no serious interference caused by the spectrum reuse between cellular users and D2D users. In [22], a spectrum-energy trading scheme has been proposed to maximize the weighted sum energy efficiency (EE) of DUs. These works have shown that D2D communications can achieve great potential gains in network throughput, EE and spectrum efficiency (SE), etc. However, these works only focus on half-duplex(HD)-enabled D2D communications. In fact, compared with HD-enabled D2D communications, FD-enabled D2D communications can potentially double the SE, achieve more flexible spectrum allocation and reduce end-to-end delay.

In [23]–[25], resource allocation in FD-enabled D2D communications has been investigated. The authors in [23] mainly focus on FD relay aided D2D systems. The authors of [24] consider both perfect channel state information (CSI) and statistical CSI scenarios and study the resource allocation for multi-user full-duplex D2D communications. In [25], the authors have studied the optimal allocation scheme for an FD D2D relay working in the amplify and forward mode to assist cellular uplink transmission. References [26]–[29] are works of spectrum and power allocation based on D2D communication. The authors of [26] have studied the joint spectrum sharing and power allocation problem of device to device (D2D) communication based on cellular network, and proposed two methods, centralized and decentralized, in the case of uplink resource sharing with D2D link. In [27], the authors solve the resource allocation problem of uplink D2D communication in 5G network. The research focus of this paper is to maximize the overall throughput of the system and increase the number of participating D2D pairs while ensuring the QoS defined by the target SINR and reducing the power consumption. The authors of [28] propose a channel access method for D2D-U pairs on unlicensed channels, and design a decentralized joint spectrum and power allocation scheme to minimize the power consumption of D2D-U pairs. The authors in [29] propose a joint spectrum and power allocation framework based on pricing, which realizes the decentralized interference coordination between device to device (D2D) communication and cellular user. However, these works do not consider any cooperation between DUs and CUs.

Based on D2D communications, every user in the network is a natural relay. With the help of D2D relays, the transmission rate and service experience of cell-edge users or users in a deep fading state can be greatly improved. However, in the actual system, the battery capacity of user is limited, and in the FD-D2D relay communications, the user needs to consume more energy due to the elimination of self-interference. Therefore, if there is no appropriate incentive mechanism, D2D users will lack incentives to serve another user. For cell edge users who need to be relayed, due to the long distance from the base station, the signal fading is large and will be in a low signal-to-noise ratio state. At this time, compared with spectrum resources, a large amount of power consumption is the bottleneck restricting its data transmission rate. However, for D2D relay users, due to the relatively short transmission distance, they often work in a high signal-to-noise ratio state. At this time, compared with power consumption, spectrum resources are the bottleneck restricting its own data transmission. Therefore, this paper first comprehensively considers the asymmetry between spectrum and energy resources between users, and proposes a power-spectrum trading mechanism for D2D users and cellular user.

In this paper, we develop a novel power-spectrum trading mechanism in FD-enabled D2D communications system to maximize the total throughput of both D2D pairs and CUs. The proposed power-spectrum trading mechanism takes into account the QoS requirement of users and the limitation of transmission power. According to the channel conditions and the fairness of obtained resource, we establish a maximization model of the overall utility of the network. For solving the power resource allocation problem, we use a concave-convex procedure (CCCP) algorithm to transfer the original nonconvex problem into a sequence of convex programs. After obtaining the optimal resource allocation of cooperative communications based on power-spectrum trading, we propose a maximum weight bipartite matching based scheme to obtain the optimal pairing strategy for multi-user cooperative communications. Simulation results show that compared with direct transmission, the proposed scheme can greatly improve the overall throughput and EE of the FD-enabled D2D communications system.

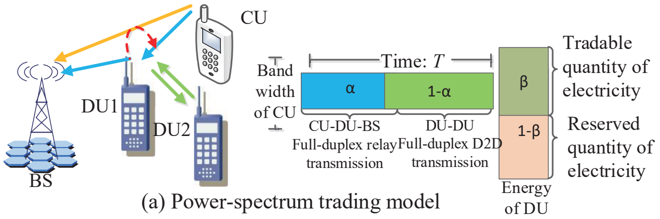
The rest of this paper is organized as follows. In Section II, we describe the system model and formulate the optimization problem. To solve the problem, we develop our resource allocation algorithm in Section III. Then we present simulation results in Section IV. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

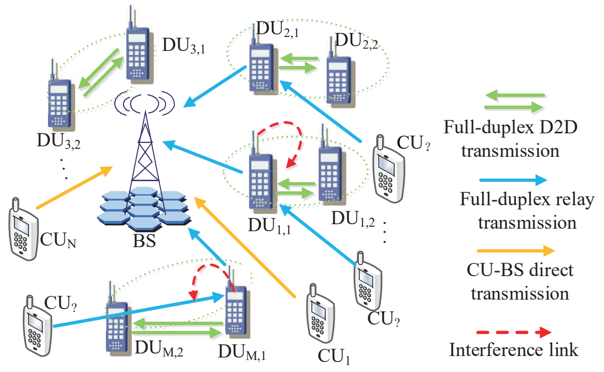
In this section, we first introduce the system model and then formulate an optimization problem for a single cell communication system including FD-enabled D2D communications and cellular uplink transmission.

A. System Model

The terminal equipments are mobile. In the process of moving, obstacles such as buildings will affect the communication quality of the equipments. Secondly, when the user moves to the edge of the base station coverage, the communication quality will be greatly damaged. Therefore, considering the mobility of users, our research is based on the demand of users moving in the edge area. The system model of FD-enabled D2D communications is shown in Fig.1, where Fig.1(a) is a power-spectrum trading model for a D2D pair and a CU and Fig.1(b) shows a case of mutil-users. Specially, the CUs are located around the cell-edge area while the DUs are near to the base station (BS) and operate in FD mode for two-way data exchanging. We denote that the sets of CUs and D2D pairs as $C = \{1, \cdots, N\}$ and $D = \{1, \cdots, M\}$ respectively. The DUs of the j-th D2D pair are denoted as j_1 and j_2. To overcome the deep fading of CUs, DUs can work



(a) Power-spectrum trading model for single pairing user



(b) Power-spectrum trading model for multiple CUs and multiple pair of D2D users.

Fig. 1: System model of power-spectrum trading for FD-enabled D2D communications.

as relay nodes to assist the uplink transmission of CUs. As compensation, CUs can also provide the DUs with their own dedicated spectrum/time resources. Without loss of generality, we assume DU j_1 is chosen as the relay node for CU i, which works in FD decoded-and-forward (DF) mode. In addition, we assume the BS has the perfect channel-state-information (CSI) of all involved channels and can schedule proper resources for each user according to the requirement, such as power, spectrum, etc. In a practical system, when a potential D2D transmitter sends a discovery beacon to a neighbor node, the CSI of the D2D channel can be estimated [30], and when a D2D connection request is sent, the BS can obtain the CSI. As suggested in [31], the D2D user can estimate the CSI of the interference channel from CUs to the DUs by measuring the power level of the uplink pilot received from the CU, and then feed it back to the BS through the control channel.

As shown in Fig. 1, the power gains of the channels from CU i to DU j_1, DU j_1 to the BS, DU j_1 to DU j_2, DU j_2 to DU j_1, and SI channel are denoted as $h_{i,j_1}, h_{j_1,B}, g_{j_{1,2}}, g_{j_{2,1}}$, and η, respectively. The bandwidth and the noise power are denoted as W and σ^2 respectively. If CU i is assigned a percentage α_i of the total transmission time T for its uplink transmission, the collaborative benefit of CU i can be expressed as

$$U_{i,j}^{c}=\alpha_i TW\log_2\left(1+\min\left(\frac{h_{i,j_1}P_i^c}{\sigma^2+\eta P_{j_1}^r},\frac{h_{j_1,B}P_{j_1}^r}{\sigma^2}\right)\right), \tag{1}$$

where P_i^c is the transmit power of CU i. $P_{j_1}^r$ is the transmit power of DU j_1 to help CU i. W is the channel bandwidth.

For the D2D pair j, they are assigned a percentage $(1-\alpha_i)$ of the total transmission time T for their two-way data exchanging. Therefore, the collaborative benefit of D2D pair j can be expressed as

$$\begin{aligned}U_{i,j}^{d}=(1-\alpha_i)TW&\left(\log_2\left(1+\frac{g_{j_{1,2}}P_{j_1}^d}{\sigma^2+\eta P_{j_2}^d}\right)\right.\\&\left.+\log_2\left(1+\frac{g_{j_{2,1}}P_{j_2}^d}{\sigma^2+\eta P_{j_1}^d}\right)\right),\end{aligned} \tag{2}$$

where $P_{j_1}^d$ and $P_{j_2}^d$ are the transmit powers of DU j_1 and j_2 for their own data transmission, respectively.

B. Problem Formulation

In this paper, we aim to maximize the total throughput of CUs and DUs via proper power and spectrum trading. Let P_{max}^c and P_{max}^d denote the maximum power of CUs and DUs respectively. E_d is the total energy of the DU. Then the resource allocation problem can be expressed as

$$\max_{\rho_{i,j},\alpha_i,\beta_j,P_{j_1}^d,P_{j_1}^r,P_{j_2}^d}\sum_{i\in N}\sum_{j\in M}U_{i,j}^c+U_{i,j}^d, \tag{3}$$

$$\text{s.t. } \rho_{i,j}=\begin{cases}1,\text{when CU } i \text{ collaborates with DU } j_1\\ 0, \qquad\qquad\qquad\qquad \text{Otherwise}\end{cases}, \tag{3a}$$

$$\alpha_{min}<\alpha_i\le 1,\forall i\in C, \tag{3b}$$

$$0\le P_i^c\le P_{max}^c,\forall i\in C, \tag{3c}$$

$$0\le P_{j_1}^d,P_{j_1}^r\le P_{max}^d,\forall j\in D, \tag{3d}$$

$$0\le P_{j_2}^d\le P_{max}^d,\forall j\in D \tag{3e}$$

$$\alpha_i T\left(P_{j_1}^r+P_0\right)\le\beta_j E_d, \tag{3g}$$

where Constraint (3a) is an indicator function for cooperative communication between CUs and DUs, Constraint (3b) is the transmit time constraint to guarantee the QoS of CUs, constraint (3c) is the transmit power for the CUs, Constraint (3d) is the transmit power for DU j_1, Constraint (3e) is the transmit power for DU j_2, Constraints (3g) is the supply energy limit and loss power limit for DU j_1. Particularly, P_0 denotes the circuit power. $\alpha_{\min}$ denotes the minimum transmission time allowed by CUs.

Problem (3) is a non-convex optimization problem, which is difficult to solve in general. Additional, considering that in the actual application scenario, only when the user has enough energy, the relay user would assist the neighboring CU. Therefore, to make it trackable, we assume that the energy of DU j_1 is large enough to support the transmission of itself and CU i. In our future work, we will consider the general case that without the ideal assumption of DU energy. At this point, the original problem can be simplified as

$$\max_{\rho_{i,j},\alpha_i,\beta_j,P^d_{j_1},P^r_{j_1},P^d_{j_2}} \sum_{i\in N}\sum_{j\in M} U^c_{i,j}+U^d_{i,j}, \tag{4}$$

$$\text{s.t. } \rho_{i,j}=\begin{cases}1,\text{when CUs collaborate with DUs}\\ 0, \qquad\qquad\qquad\qquad \text{Otherwise}\end{cases}, \tag{4a}$$

$$\alpha_{min}<\alpha_i\le 1,\forall i\in C, \tag{4b}$$

$$0\le P^c_i\le P^c_{max},\forall i\in C, \tag{4c}$$

$$0\le P^d_{j_1},P^r_{j_1}\le P^d_{max},\forall j\in D, \tag{4d}$$

$$0\le P^d_{j_2}\le P^d_{max},\forall j\in D. \tag{4e}$$

III. OPTIMAL RESOURCE ALLOCATION

In the following, we propose the optimal resource allocation algorithm to solve problem (4). First, we introduce the optimal resource allocation algorithm for the scenario of one CU and one D2D pair. Then, we obtain the optimal resource allocation for the scenario of multiple CUs and D2D pairs. Finally, the optimal pairing strategy is proposed for multi-user cooperative communications.

A. Optimal Resource Allocation for the Scenario of one CU and one D2D Pair

To solve the optimization problem in (4), we first introduce the solution to the scenario of one CU and one D2D pair. Suppose that a D2D pair m coexists with CU n, where DU m_1 serves as a relay to assist the uplink transmission of CU n. The optimization problem in (4) can be rewritten as

$$\max_{\alpha_n,P^d_{m_1},P^r_{m_1},P^d_{m_2}} U^c_{n,m}+U^d_{n,m}, \tag{5}$$

$$\text{s.t. } \alpha_{min}<\alpha_n\le 1,\forall n\in C, \tag{5b}$$

$$0\le P^c_n\le P^c_{max},\forall n\in C, \tag{5c}$$

$$0\le P^d_{m_1},P^r_{m_1}\le P^d_{max},\forall m\in D, \tag{5d}$$

$$0\le P^d_{m_2}\le P^d_{max},\forall m\in D. \tag{5e}$$

First, we derive the optimal power allocation for the relay-aided cooperative communications. Since the SINR of CU-to-DU and DU-to-BS are equal to ensure the transmission efficiency, we need to calculate two transmit powers (for CU n and relay user m_1) in collaborative communications.

Let $\mathbf{P}_{m_1}=[P^c_n,P^r_{m_1}]$. From (1), we observe that the optimal $\mathbf{P}^*_{m_1}$ should satisfy

$$\frac{h_{n,m_1}P^c_n}{\sigma^2+\eta P^r_{m_1}}=\frac{h_{m_1,B}P^r_{m_1}}{\sigma^2}. \tag{6}$$

Thus, we have

$$\overline{P}^r_{m_1}=\frac{-h_{m_1,B}\sigma^2+\sqrt{(h_{m_1,B}\sigma^2)^2+4\eta\sigma^2P^c_nh_{m_1,B}h_{n,m_1}}}{2\eta h_{m_1,B}}. \tag{7}$$

If $\overline{P}^r_{m_1}\le P^d_{\max}$,

$$\mathbf{P}^*_{m1}=\begin{cases}P^c_n=P^c_{\max}\\ P^r_{m_1}=\bar{P}^r_{m_1}\end{cases}, \tag{8}$$

If $\overline{P}^r_{m_1}>P^d_{\max}$,

$$\mathbf{P}^*_{m1}=\begin{cases}P^r_{m_1}=P^d_{\max}\\ P^c_n=\frac{P^r_{m_1}h_{m_1,B}(\sigma^2+\eta P^r_{m_1})}{h_{n,m_1}\sigma^2}\end{cases}. \tag{9}$$

Then, we give the optimal power allocation for the D2D communications. For $\mathbf{P}_{m_2}=[P^d_{m_1},P^d_{m_2}]$, it can be solved from the following optimization problem:

$$\max_{\mathbf{P}_{m_2}} R_d(\mathbf{P}_{m_2})=U_{cav}\left(\mathbf{P}_{m_2}\right)+U_{vex}\left(\mathbf{P}_{m_2}\right), \tag{10}$$

$$s.t.\ \ 0\le P^d_{m_1}\le P^d_{\max},\forall m\in D, \tag{10a}$$

$$0\le P^d_{m_2}\le P^d_{\max}.\forall m\in D, \tag{10b}$$

where $U_{cav}(\mathbf{P}_{m_2})=\log(\sigma^2+\eta P^d_{m_2}+g_{m_{1,2}}P^d_{m_1})+\log(\sigma^2+\eta P^d_{m_1}+g_{m_{1,2}}P^d_{m_2})$ and $U_{vex}(\mathbf{P}_{m_1})=-\log(\sigma^2+\eta P^d_{m_2})-\log(\sigma^2+\eta P^d_{m_1})$.

We have that $U_{cav}(\mathbf{P}_{m_2})$ is strictly concave and $U_{vex}(\mathbf{P}_{m_2})$ is strictly convex. Meanwhile, constraints (10a) and (10b) are linear in $\mathbf{P}_{m_2}$. Thus, the above problem is a difference of convex function (D.C.) problem, which can be solved by the CCCP algorithm [32], [33].

CCCP is a majorization-minimization algorithm which transforms the D.C. problem to a sequence of convex problems. More specifically, at each iteration, it first finds a feasible point as the fixed point(*i.e.*, $\mathbf{P}^k_{m_2}$), and then initializes the convex part of the problem by using the Taylor expansion at the fixed point. At last, the optimal solution at the iteration is obtained by solving a simplified convex optimization problem. The update process is given as follows

$$\mathbf{P}^{k+1}_{m_2}=\arg\max_{\mathbf{P}_{m_2}\in\Omega}\ U_{cav}+\bigtriangledown U_{vex}(\mathbf{P}^k_{m_2})\mathbf{P}^T_{m_2}, \tag{11}$$

where $\bigtriangledown U_{vex}(\mathbf{P}^k_{m_2})$ is the gradient of U_{vex} at point $\mathbf{P}^k_{m_2}$, and $\mathbf{P}^T_{m_2}$ is the transpose of $\mathbf{P}_{m_2}$. The convex optimization problem can be solved efficiently by well known interior point method. The above process of the optimal power allocation for a D2D pair is showed in Algorithm 1. Furthermore, the convergence of the algorithm is proved in [16].

The computational complexity of this algorithm depends upon the number of iterations required and the computational complexity in each iteration. In Algorithm 1, each iteration is convex and solved by the interior point method with the computational complexity of $O(K^3)$, where K is the number of variables in (11). Otherwise, since U_{cav} and U_{vex} are convex piecewise linear, the linearity of the constrained CCCP algorithm is at least converged to $O(log(1/\delta))$, where δ is the convergence accuracy of the Algorithm. Therefore, the complexity of algorithm 1 is $O(K^3log(1/\delta))$.

After the optimal power allocations of the relay-aided cooperative communications and D2D communications are performed, the transmission time allocation can be obtained as follows. Once the optimal values of $\mathbf{P}^*_{m_1}$ and $\mathbf{P}^*_{m_2}$ are given, α_n can be obtained from:

$$\max_{\alpha_n}\ \alpha_nTWR_c\left(\mathbf{P}^*_{m_1}\right)+(1-\alpha_n)\,TWR_d\left(\mathbf{P}^*_{m_2}\right), \tag{12}$$

$$s.t.\ \ \alpha_{\min}\le\alpha_n\le 1,\forall n\in C, \tag{12a}$$

Algorithm 1 Optimal Power Allocation Algorithm

```
Initialization
Iteration index $k = 0$, and tolerance $\epsilon > 0$;
$\mathbf{P}^0_{m_2} = [\frac{P^d_{max}}{2}, \frac{P^d_{max}}{2}]$;
Repeat
    $\mathbf{P}^{k+1}_{m_2} = \arg \max_{\mathbf{P}_{m_2} \in \Omega} U_{cav} + \triangledown U_{vex}(\mathbf{P}^k_{m_2})\mathbf{P}^T_{m_2}$;
    Adopting CCCP Algorithm to solve the D.C. Convex optimization problem of Problem (10);
    Adopting interior point method to solve the Convex optimization problem of Problem (11);
    k=k+1;
Until
    $\|\mathbf{P}^{k+1}_{m_2} - \mathbf{P}^k_{m_2}\| < \varepsilon$;
$\mathbf{P}_{m_2} = \mathbf{P}^{k+1}_{m_2}$.
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where $R_c\left(\mathbf{P}^*_{m_1}\right) = \log\left(1 + \min\left(\frac{h_{n,m_1}P^c_n}{\sigma^2 + \eta P^r_{m_1}}, \frac{h_{m_1,B}P^r_{m_1}}{\sigma^2}\right)\right)$ and R_d is defined in (10).

It is easy to see that the value of α_n depends on $R_c(\mathbf{P}^*_{m_1})$ and $R_d(\mathbf{P}^*_{m_2})$. That is

$$\alpha^*_n = \left\{ \begin{array}{l} \alpha_{\min}, \textbf{if } R_c\left(\mathbf{P}^*_{m_1}\right) \leq R_d\left(\mathbf{P}^*_{m_2}\right) \\ \;\;1 \;\;\;\;, \textbf{if } R_c\left(\mathbf{P}^*_{m_1}\right) > R_d\left(\mathbf{P}^*_{m_2}\right) \end{array} \right. . \tag{13}$$

Thus, we can obtain the solution of the non-convex optimization problem in (5).

B. Optimal Resource Allocation for the Scenario of Multiple CUs and D2D Pairs

After the optimal resource allocation for the scenario of one CU and one D2D pair is obtained, we now consider the optimal resource allocation for the scenario of multiple users. The problem is given as follows

$$\max_{\alpha_i, P^d_{j_1}, P^r_{j_1}, P^d_{j_2}} \sum_{i \in N} \sum_{j \in M} U^c_{i,j} + U^d_{i,j}, \tag{14}$$

$$\text{s.t. } \alpha_{min} < \alpha_i \leq 1, \forall i \in C, \tag{14b}$$

$$0 \leq P^c_i \leq P^c_{max}, \forall i \in C, \tag{14c}$$

$$0 \leq P^d_{j_1}, P^r_{j_1} \leq P^d_{max}, \forall j \in D, \tag{14d}$$

$$0 \leq P^d_{j_2} \leq P^d_{max}, \forall j \in D. \tag{14e}$$

In the relay-aided cooperative communications, let $\mathbf{P}_1 = \{\mathbf{P}_{11}, \mathbf{P}_{21}, \cdots, \mathbf{P}_{j_1}, \cdots, \mathbf{P}_{M_1}\} = \{[P^c_{11}, P^r_{11}], [P^c_{21}, P^r_{21}], \cdots, [P^c_{i_1}, P^r_{j_1}], \cdots, [P^c_{N_1}, P^r_{M_1}]\}$, from (6)-(9), we can show that if $\overline{P}^r_{j_1} \leq P^d_{\max}$,

$$\mathbf{P}^*_{j_1} = \left\{ \begin{array}{l} P^c_i = P^c_{\max} \\ P^r_{j_1} = \bar{P}^r_1 \end{array} \right. , \tag{15}$$

if $\overline{P}^r_{j_1} > P^d_{\max}$,

$$\mathbf{P}^*_{j_1} = \left\{ \begin{array}{l} P^r_{j_1} = P^d_{\max} \\ P^c_i = \frac{P^r_{j_1} h_{j_1,B}(\sigma^2 + \eta P^r_{j_1})}{h_{i,j_1}\sigma^2} \end{array} \right. . \tag{16}$$

For FD-enabled D2D communications, let $\mathbf{P}_2 = \{\mathbf{P}_{12}, \mathbf{P}_{22}, \cdots, \mathbf{P}_{j_2}, \cdots, \mathbf{P}_{M_2}\} = \{[P^d_{11}, P^d_{12}], [P^d_{21}, P^d_{22}], \cdots, [P^d_{j1}, P^d_{j2}], \cdots, [P^d_{M_1}, P^d_{M_2}]\}$, , the optimization problem becomes:

$$\max_{\mathbf{P}_{j_2}} R_d(\mathbf{P}_{j_2}) = U_{cav}\left(\mathbf{P}_{j_2}\right) + U_{vex}\left(\mathbf{P}_{j_2}\right), \tag{17}$$

$$s.t. \;\; 0 \leq P^d_{j_1} \leq P^d_{\max}, \forall j \in D, \tag{17a}$$

$$0 \leq P^d_{j_2} \leq P^d_{\max}, \forall j \in D. \tag{17b}$$

The optimization problem (17) can then be solved by Algorithm 1.

Once the optimal values of $\mathbf{P}^*_1$ and $\mathbf{P}^*_2$ are given, $\boldsymbol{\alpha} = \{\alpha_1, \alpha_2, \cdots, \alpha_i, \cdots, \alpha_N\}$ can be obtained according to (13), namely:

$$\alpha^*_i = \left\{ \begin{array}{l} \alpha_{\min}, \textbf{if } R_c\left(\mathbf{P}^*_{j_1}\right) \leq R_d\left(\mathbf{P}^*_{j_2}\right) \\ \;\;1 \;\;\;\;, \textbf{if } R_c\left(\mathbf{P}^*_{j_1}\right) > R_d\left(\mathbf{P}^*_{j_2}\right) \end{array} \right. . \tag{18}$$

C. Optimal Pairing Strategy

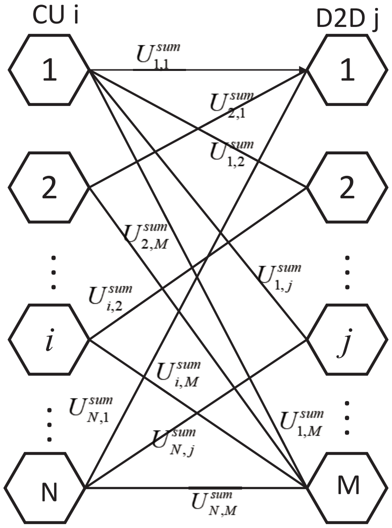


Fig. 2: Bipartite graph for optimal paring.

After we derive the resource allocation for each user, we propose an optimal pairing strategy for multi-user cooperative communications based on a maximum weight matching algorithm.

When CU i cooperates with D2D pair j, the maximum achievable sum throughput $U^{sum}_{i,j}$ can be expressed as

$$U^{sum}_{i,j} = \alpha^*_i TWR_c(\mathbf{P}^*_{j_1}) + (1 - \alpha^*_i)TWR_d(\mathbf{P}^*_{j_2}), \tag{19}$$

where α^*_i, $\mathbf{P}^*_{j_1}$ and $\mathbf{P}^*_{j_2}$ are obtained from equation (6), (10) and (12), respectively. The optimal collaborative user pair is represented as follow

$$(i^*, j^*) = \arg \max_{i \in N, j \in M} \rho_{i,j} U^{sum}_{i,j}. \tag{20}$$

By now, we have obtained the resource allocation solution for each user and its potential pairing user. When there are multiple users, they need to find the best pairing partner, that

Table I Simulation Parameters

Parameter	**Value**
Uplink bandwidth	5 MHz
Noise power (σ^2)	-114 dBm/MHz
Pathloss exponent (λ)	3 and 4
Pathloss constant	10^{-2}
Maximum CU Tx power (P^c_{max})	24 dBm
Transmission time and minimum time ratio of CU (T,α)	$T = 1s$, $\alpha_{min} = 0.5$
Maximum DU Tx power (P^d_{max})	21 dBm
Cellular user SINR (ξ^c_{min})	Uniform distributed in [0,25] dBm
DU SINR (ξ^d_{min})	Uniform distributed in [0,25] dBm
D2D cluster radius (r)	20,40,60,...,120 (m)
D2D cluster location	Uniform distributed in [R/3,2R/3]
Location of CUs	On the edge of a cell
User circuit power consumption (P_0)	100 mW
Rayleigh fading	Exponential distribution with unit mean
Shadowing	Log-normal distribution with standard deviation of 8 dB

is, the problem becomes a maximum weight bipartial matching problem, which can be expressed as

$$\max \sum_{i \in N, j \in M} \rho_{i,j} U^{sum}_{i,j}, \tag{21}$$

$$\text{s.t. } \rho_{i,j} = \begin{cases} 1, \text{when CUs collaborates with DUs} \\ 0, \qquad\qquad\qquad\qquad \text{Otherwise} \end{cases}, \tag{21a}$$

where $\rho_{i,j}$ indicates the existence of the cooperative communications.

We can adopt the Kuhn-Munkres (KM) algorithm to solve the non-convex optimization problem (21). The KM algorithm converts the problem of maximum weight matching into a perfect matching problem by giving each vertex a label(called the top tag). In the first step, it initializes the value of the feasible top mark. The second step is to use the Hungarian algorithm to find the complete matching. In the third step, if the complete match cannot be found, then the value of the feasible top mark will be modified. Repeating step two and step three until a complete match of the equal subgraph is found. In the KM algorithm, the complexity is $O(K^3)$, where K is the larger of the number of vertices on both sides of the bipartite graph. In our work, since N is equal to M, the algorithm complexity of the KM algorithm is $O(N^3)$. Fig. 2 explains the maximum weight bipartite matching problem in (21), where the numbers of CUs and D2D pairs form two sets of vertexes, respectively. The utility $U^{sum}_{i,j}$ is considered as the weight of each link path.

In the scenario of one CU and one D2D pair, we first obtain the optimal power allocation for the relay-aided cooperative communications. Then we adopt the CCCP algorithm to solve the optimization problem for D2D communications. Transmission time factor α_i is also easy to obtain. Finally, we adopt a maximum weight bipartite matching based scheme for multi-user cooperative communications. Therefore, we can determine the solution of the non-convex optimization Problem (4). All algorithms are implemented at BS, which has strong processing and computing power. Particularly, our work only provides a solution close to the upper limit. In the actual system, due to the influence of environmental factors and actual equipment limitations, the user's throughput will also be affected by the modulation and coding scheme (MCS), link adaptation, hybrid automatic repeat request (HARQ) and so on.

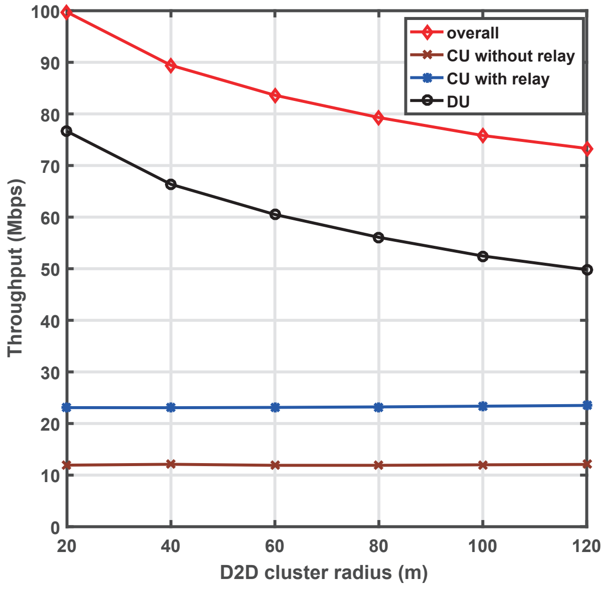
IV. SIMULATION RESULTS AND ANALYSIS

In this section, we conduct simulations to evaluate the performance of the proposed resource allocation mechanism. We consider a single cell scenario with ten CUs and ten D2D pairs and assume that the radius of the cell is $R = 0.5$ km. CUs are located at the edge of the cell and D2D pairs are close to the BS. D2D pairs are distributed within the cell as a cluster with radius r. Additionally, two performance metrics, namely, the total throughput and energy efficiency (EE) of all users in the cell, are evaluated in this paper. For the EE, we use the same defination as in [16], [34], which considers both the transmit power and circuit poewer consumtions. The simulation parameters are illustrated in Table I [17].

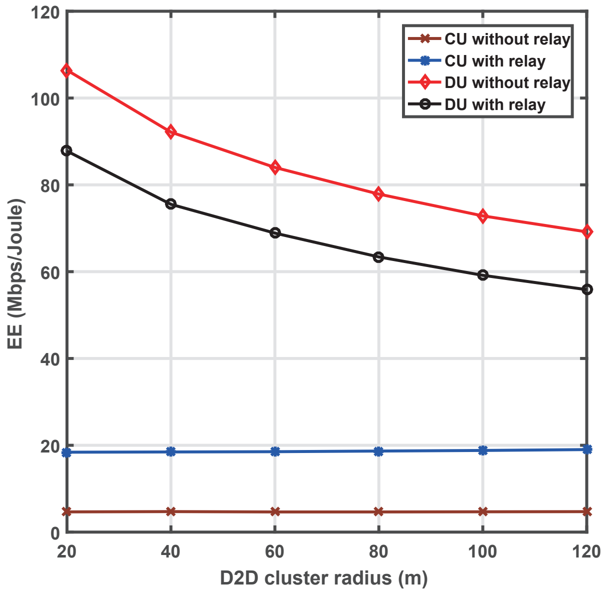
Fig. 3(a) illustrates the overall throughput of FD-enabled D2D communications systems, the throughput of CUs with and without relay, and the throughput of DUs with respect to D2D cluster radius. It can be seen that the overall throughput and the throughput of DUs decreases with D2D cluster radius. This is because when the D2D cluster radius increases, the channel gains of D2D links become smaller. By comparing the throughput of the CUs with and without relay, we can see that CUs can obtain throughput gain with the help of DU relay. Fig. 3(b) illustrates the EE of CUs and DUs with and without relay. It can be seen that the EE of DUs without relay is better than that with relay. This is because in the relay transmission, DUs spend its own energy to help the transmission of CUs.

In Fig. 4, we evaluate the effect of different values of the time partition for the relay transmission $\alpha_{\min}$ on throughput and EE. It is shown that when the time allocated to relay is less than 0.2, the throughput and EE of CUs are reduced since less transmission resource is allocated to CU transmission. In contrast, the throughput and EE of DUs are increased as more transmission resourece is given to the FD D2D transmissions.

Fig. 5 shows the impact of the number of users in the cell on throughput and EE. In the simulations, we assume that the number of CUs is equal to the number of D2D pairs. As can be seen from the figure, when the number of D2D pair increases, the bandwidth allocated to each user will decrease, thus the throughput of users changes little. At the same time, as the number of D2D pairs increases, the power consumption



(a) Throughput of users versus D2D cluster radius.

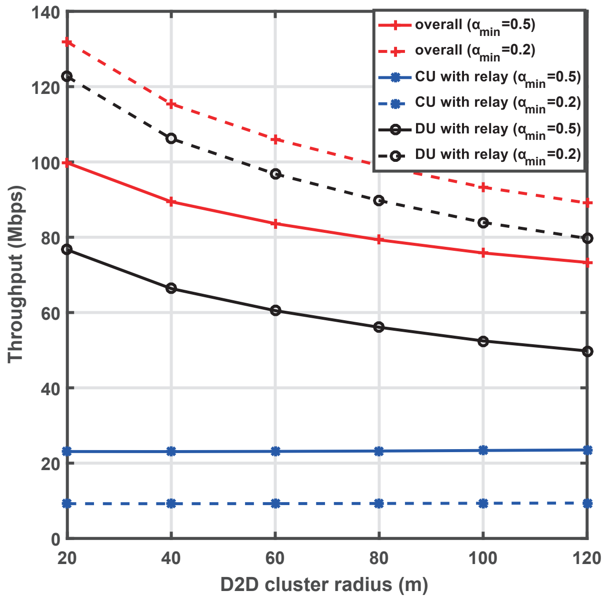


(b) EE of users versus D2D cluster radius.

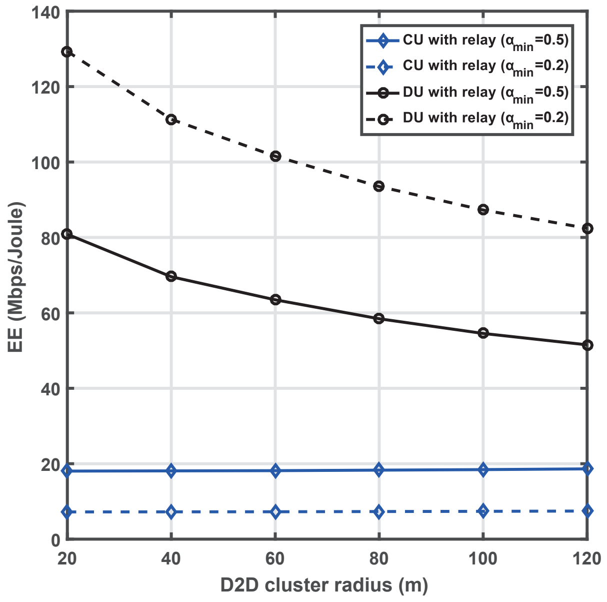
Fig. 3: Throughput and EE versus D2D cluster radius, where $\alpha_{\min} = 0.5$, $P^c_{\max} = 24$dBm.

increases rapidly. As a result, we can see that the EE curves of CU and DU with and without relay have declined.

In Fig.6, we compare throughput as well as EE under different maximum power of CUs. We assume that the maximum transmit power of CUs is twice as that of DUs. It can be seen that the change of the maximum transmit power has little effect on the throughput of users. This is because the bandwidth is limited. At the same time, with the maximum transmit power increasing, the power consumption of users increases, thus the EE constantly decreases.



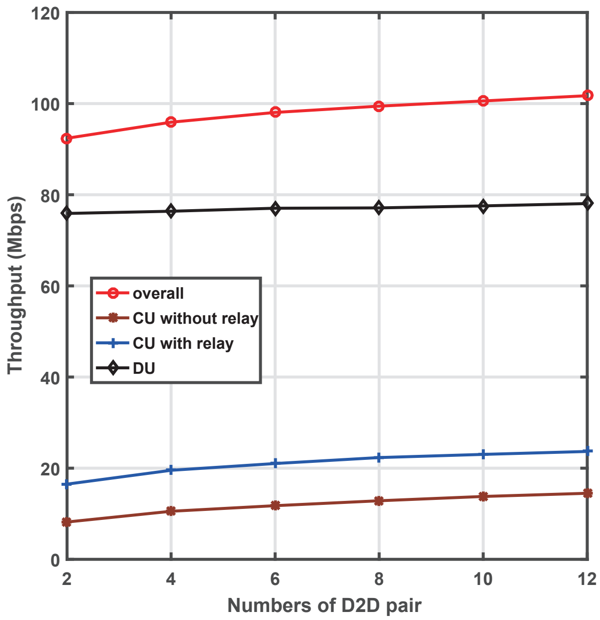
(a) Throughput of users versus D2D cluster radius.



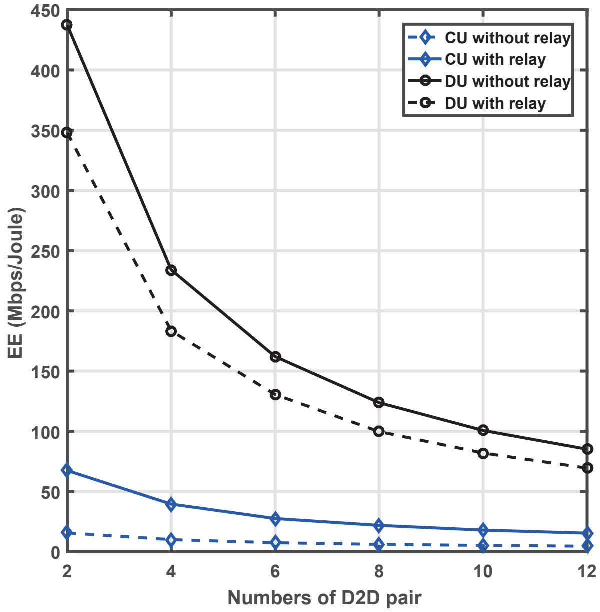
(b) EE of users versus D2D cluster radius.

Fig. 4: Throughput and EE versus D2D cluster radius, where $\alpha_{\min} = 0.2, 0.5$, $P^c_{\max} = 24$dBm.

Fig. 7 shows the simulation results of EE and througput versus D2D cluster radius when the cell radius changes. It can be seen that the throughput of DUs is almost unchanged when the cell radius is changed. This is because full duplex D2D communications does not pass through the base station and is only related to the radius of its user cluster. The overall throughput of the system and the throughput of CUs with relay decrease with the increase of cell radius. At the same time, when the cell radius increases, more transmission power

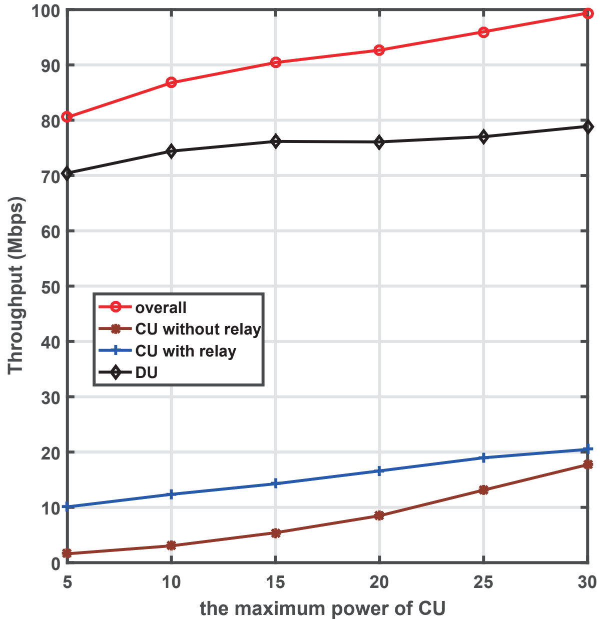


(a) Throughput of users versus D2D cluster radius.

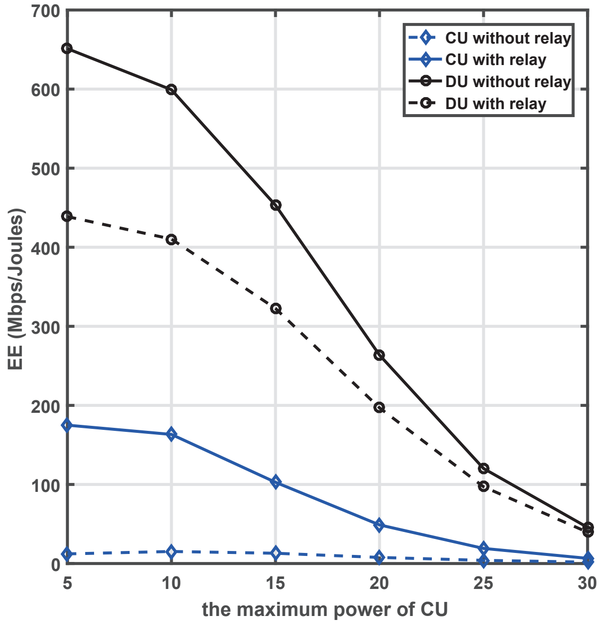


(b) EE of users versus D2D cluster radius.

Fig. 5: Throughput and EE versus Numbers of D2D pair, where $\alpha_{\min} = 0.5$, $r = 60$m, $P^c_{\max} = 24$dBm.



(a) Throughput of users versus D2D cluster radius.

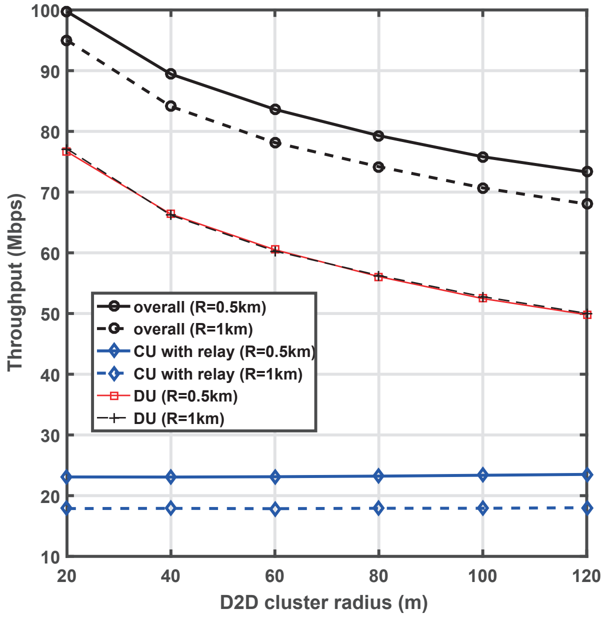


(b) EE of users versus D2D cluster radius.

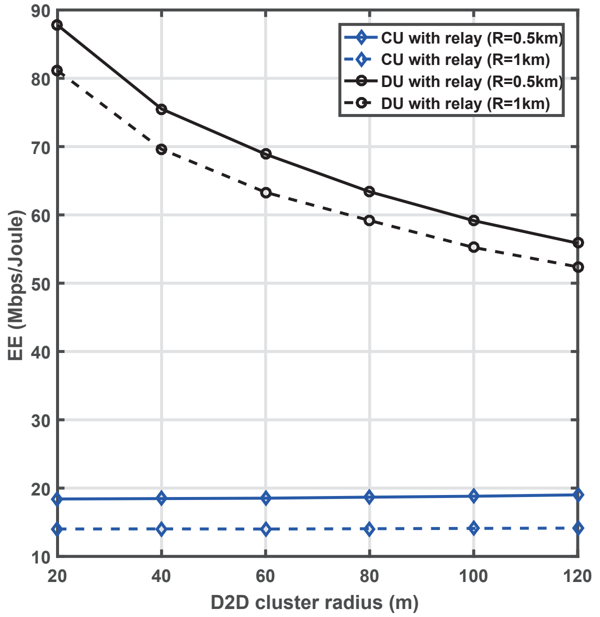
Fig. 6: Throughput and EE versus the maximum power of CUs, where $\alpha_{\min} = 0.5$, $r = 60$m, $P^d_{max} = P^c_{max}/2$.

needs to be consumed, and the EE of DUs and CUs with relay decrease. For DUs, they also need to consume energy for the uplink transmission of CUs. Therefore, the descending arc of these curves is obvious.

Fig. 8 shows the relationship between EE and circuit power (which will affect the actual EE of the system). It is shown that with the increase of circuit power, the EE will decrease since the circuit power will produce energy consumption, which in turn affects EE. Therefore, when optimizing EE in communication systems, circuit power is an essential factor for the accuracy of the results. If only the transmit power consumption is considered without considering the fixed circuit power, the EE obtained will have a large deviation from the actual EE of the system. A lot of work has neglected the relationship between circuit power and EE, which needs to be attended.



(a) Throughput of users versus D2D cluster radius.



(b) EE of users versus D2D cluster radius.

Fig. 7: Throughput and EE versus D2D cluster radius, where $\alpha_{\min} = 0.5$, $P^c_{\max} = 24\text{dBm}$.

V. CONCLUSION

In this paper, we study the resource allocation problem of the shared uplink resources between the FD-enabled D2D pairs and the cell edge users. By considering the asymmetry of the spectrum and energy resources between D2D users and CUs, we propose a power-spectrum trading mechanism to maximize the overall throughput of the system. Since the maximization problem is non-convex, which is difficult to solve in general, we simplify the problem by taking some assumptions. We then solved the problem in three steps. First, we proposed the optimal resource allocation algorithm for the scenario of one CU and one D2D pair by using the CCCP algorithm. Second, we derived the optimal resource allocation algorithm for all CUs and D2D pairs based on the solution obtained from the first step. Finally, we proposed an optimal pairing strategy for multi-user cooperative communications. Simulation results show that both CUs and DUs can obtain benefits from the power-spectrum trading mechanism and the overall throughput can also be improved. In the next research work, we will further refine our scientific problems in combination with the latest standards and requirements of the future network, and consider them more comprehensively, so as to better meet the research trend of the future communication network.

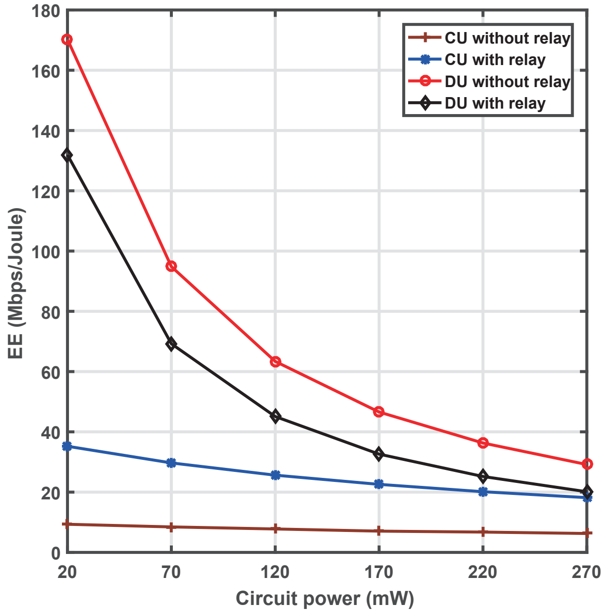


Fig. 8: EE versus circuit power, where $\alpha_{\min} = 0.5$, $r = 60\text{m}$, $P^c_{\max} = 24\text{dBm}$.

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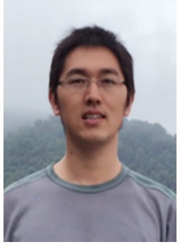

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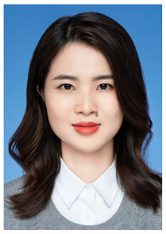

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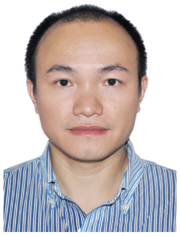

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