# A Matching Approach for Power Efficient Relay Selection in Full Duplex D2D Networks

Bojiang Ma, Hamed Shah-Mansouri, and Vincent W.S. Wong
Department of Electrical and Computer Engineering
The University of British Columbia, Vancouver, Canada
e-mail: {bojiangm, hshahmansour, vincentw}@ece.ubc.ca

***Abstract*—Full duplex relaying, which allows relays to transmit and receive signals simultaneously, can improve the spectrum efficiency and extend the range of device-to-device (D2D) communications. Due to the limited battery of mobile devices, it is essential to design a power-efficient relay selection scheme which can reduce the power consumption of devices and extend their lifetime. In this paper, we consider multiple D2D user pairs utilize full duplex relays to communicate using directional antennas. We formulate the power-efficient relay selection problem as a combinatorial optimization problem to minimize the power consumption of the mobile devices. Using a matching approach, we transform the problem into a one-to-one weighted bipartite matching problem. We then propose a power-efficient relay selection algorithm for relay-assisted D2D networks called PRS-D2D based on the Hungarian method to obtain the optimal solution in polynomial time. Simulation results show that our proposed algorithm improves the total power consumption of mobile devices by up to $32\%$ comparing to an existing relay selection scheme in the literature.**

## I. INTRODUCTION

Device-to-device (D2D) communications, which allow the mobile devices to communicate with each other directly, can provide high data rates for nearby devices and offload data traffic from cellular base stations [1]. Relays can assist connection establishment among devices, extend the range of D2D communication, and improve the quality of data transmission [2]. By using full duplex relaying in D2D communication, where the relays operate in full duplex mode, the data rate can further be improved over traditional half duplex relaying systems. Full duplex technique allows wireless devices to simultaneously transmit and receive signals by employing self interference cancellation.

Relay selection and resource allocation for full duplex relaying systems have been studied in several existing works. Jimenez Rodriguez *et al.* in [3] proposed an optimal power allocation scheme to improve the data rate in a two-hop full duplex relaying system. In [4], Han *et al.* proposed a successive interference cancellation method to fully exploit the link diversity of full duplex relaying. Riihonen *et al.* in [5] studied the transmission power adaption problem in a hybrid full duplex and half duplex relaying system.

In addition, the benefits of relay-assisted communication in D2D networks have been shown in [6]–[8]. Hasan *et al.* studied a multi-user relay-assisted D2D network in [6] and formulated a robust optimization problem, which considers the channel uncertainties. They showed that relay-assisted communications can significantly improve the aggregate data rate. Zhang *et al.* in [7] proposed a power allocation scheme to maximize the data rate of D2D users in a relay-assisted D2D network, which is underlaying the cellular system. A resource allocation scheme, which maximizes the sum rate of relay-assisted D2D networks, is proposed in [8] based on the matching theory. However, the power efficiency of the battery-operated mobile devices is not considered in [6]–[8]. A power-efficient relay selection algorithm is proposed in [9], which considers relay-assisted communication among devices. However, to overcome the computational complexity of relay selection, the algorithm sacrifices the power efficiency and cannot achieve the optimal solution.

Although full duplex relay-assisted D2D communication has great potentials for future fifth generation (5G) systems, the limited battery capacity of mobile devices has become a major barrier to obtain the aforementioned benefits of such system. In order to fully exploit the potentials of full duplex relay-assisted D2D communication, an efficient relay selection scheme that can reduce the power consumption of devices and extend their battery lifetime is essential. However, most of the previous related studies either do not consider the power efficiency in relay-assisted D2D communications (e.g., [6]–[8]) or fail to obtain an optimal power-efficient solution (e.g., [9]).

In this paper, we study relay-assisted D2D communications for 5G wireless cellular networks, in which devices are equipped with directional millimeter wave (mm-wave) technology. We consider the relays have full duplex capability and can assist device discovery, connection establishment, and data transmission. We also consider the practical case that the self-interference cannot be fully eliminated due to imperfect self channel estimation and hardware constraints. The main contributions of this paper are summarized as follows:

- We formulate the relay selection problem as a combinatorial optimization problem, which aims to minimize the total transmission power of the mobile devices.
- We transform the combinatorial optimization problem into a many-to-one matching problem. By introducing virtual relays, we further transform the problem into a one-to-one weighted matching problem, which can be solved optimally in polynomial time.
- We propose a Power-efficient Relay Selection algorithm

for relay-assisted D2D networks, which is called PRS-D2D, to obtain the optimal relay selection.

- Through numerical studies, we evaluate the performance of our proposed algorithm with different network settings. Simulation results show that PRS-D2D outperforms an existing algorithm proposed in [9] in terms of power consumption by up to 32%.

The rest of this paper is organized as follows. In Section II, we present the system model and formulate the power-efficient relay selection problem. In Section III, we transform the problem into a one-to-one weighted matching problem and propose PRS-D2D. Simulation results are presented in Section IV. Conclusion is given in Section V.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider an mm-wave cellular network with full duplex relay-assisted D2D communications as shown in Fig. 1. The D2D users require relays to assist communication due to blockage or poor direct link quality. The cellular base station delivers short control messages among D2D users and relays. We denote the set of relays as $\mathcal{R}$. The set of source and destination devices are denoted as $\mathcal{S}$ and $\mathcal{D}$, respectively, where $\mathcal{S} \bigcap \mathcal{D} = \emptyset$. We further denote the set of source-destination user pairs as $\mathcal{L}$. The $i^{\text{th}}$ source device $s_i \in \mathcal{S}$ and the $i^{\text{th}}$ destination device $d_i \in \mathcal{D}$ form source-destination user pair $l_i = (s_i, d_i) \in \mathcal{L}$. For the sake of simplicity, we assume that each D2D user pair can be assisted by one relay. However, each relay is allowed to assist multiple D2D communication pairs using different subchannels. Each relay is equipped with two sets of antennas that enable full duplex operation. One set of antennas is used to receive signals and the other set is used to transmit signals. Decode-and-forward protocol is employed by the relays. The D2D user pairs communicate based on orthogonal frequency division multiple access (OFDMA), so that each D2D user pair is allocated a non-overlapping subchannel.

### A. Channel Model

The future mm-wave cellular system will operate on the frequency of 28 or 38 GHz [10]. The channel model of mm-wave communication is different from current cellular channel model. In this paper, we consider a cellular system that operates on the frequency of 38 GHz and adopt the channel model introduced in [11]. This model is specifically proposed for mm-wave cellular system. The path loss function $L(z)$ is

$$L(z) = \overline{L(z_0)} + 10\alpha \log(z) + Z_\sigma, \tag{1}$$

where $\overline{L(z_0)}$ is the free-space path loss at reference distance $z_0$, $\alpha$ is the path loss exponent, and $Z_\sigma$ is a zero-mean Gaussian random variable with variance $\sigma^2$ that models the shadowing effect. We use a sectored antenna model proposed in [12], in which the antennas achieve a constant high gain in the main lobe and a constant low gain in the side lobe. The transmitting and receiving antenna gains are as follows:

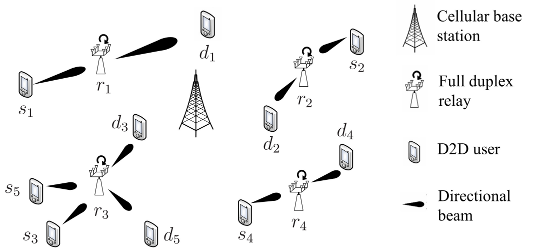


Fig. 1. Relay-assisted mm-wave D2D network. The relays operate in full duplex mode and the devices use directional transmissions.

$$G^t(\Theta^t) = \begin{cases} M^t, & 0^\circ \le \Theta^t \le \Theta^t_{\text{HPBW}}, \\ m^t, & \Theta^t_{\text{HPBW}} < \Theta^t \le 180^\circ, \end{cases} \tag{2}$$

$$G^r(\Theta^r) = \begin{cases} M^r, & 0^\circ \le \Theta^r \le \Theta^r_{\text{HPBW}}, \\ m^r, & \Theta^r_{\text{HPBW}} < \Theta^r \le 180^\circ, \end{cases} \tag{3}$$

where $M^t, M^r, m^t, m^r, \Theta^t_{\text{HPBW}}, \Theta^r_{\text{HPBW}}$ are the main lobe gain, side lobe gain, and half power beamwidth for the transmitting and receiving antennas, respectively. Moreover, $\Theta^t$ and $\Theta^r$ represent the angles of departure and arrival of signals, respectively. The antenna gain between devices $i$ and $j$ is denoted as $G_{i,j} = G^t(\Theta^t_{i,j})G^r(\Theta^r_{j,i})$, where $\Theta^t_{i,j}$ is the angle of departure of signal from transmitter $i$ to receiver $j$ and $\Theta^r_{j,i}$ is the angle of arrival of signal in receiver $j$ transmitted from $i$. Note that if $i$ and $j$ belong to a pair of communicating devices, $\Theta^t_{i,j}$ and $\Theta^r_{j,i}$ are $0^o$, since we assume the transmitting and receiving antennas are accurately aligned. The total gain (including channel and antenna gains) between devices $i$ and $j$ can be represented as $h_{i,j} = \frac{G_{i,j}}{L(z_{i,j})}$, where $z_{i,j}$ is the distance between the corresponding devices.

### B. Data Rate of a User Pair

To obtain the data rate of user pair $l_i = (s_i, d_i) \in \mathcal{L}$, which is assisted by relay $r_j$, we first define $P_{s_i,r_j}$ as the transmission power of source device $s_i$ to relay $r_j$. We further denote the transmission power of relay $r_j$ to destination device $d_i$ as $P_{r_j,d_i}$. The signal to interference plus noise ratio (SINR) from source $s_i$ to relay $r_j$ is given by [5]

$$\text{SINR}_{s_i,r_j} = \frac{P_{s_i,r_j} h_{s_i,r_j}}{N_0 + P_{r_j,d_i} h_{LI}}, \tag{4}$$

where $N_0$ is the noise power, $h_{LI}$ is the loop-interference gain for the full duplex relay, and $P_{r_j,d_i} h_{LI}$ represents the self interference received by full duplex relay $r_j$. Note that the mutual interference among different user pairs is avoided since each user pair is allocated an orthogonal subchannel. Similarly, the SINR from relay $r_j$ to destination device $d_i$ is

$$\text{SINR}_{r_j,d_i} = \frac{P_{r_j,d_i} h_{r_j,d_i}}{N_0 + P_{s_i,r_j} h_{s_i,d_i}}, \tag{5}$$

where $P_{s_i,r_j} h_{s_i,d_i}$ is the interference induced by device $s_i$. In a full duplex relaying system using decode-and-forward protocol, the data rate of user pair $l_i \in \mathcal{L}$ through relay $r_j \in \mathcal{R}$

can be represented as follows [5]:

$$B \min \left(\log_2(1+\mathrm{SINR}_{s_i,r_j}), \log_2(1+\mathrm{SINR}_{r_j,d_i})\right), \quad (6)$$

where $B$ is the bandwidth of each subchannel.

### C. Problem Formulation

Since the relays are assumed to be plugged into the power source and have sufficient power supply, our objective is to minimize the total transmission power of the transmitting D2D devices by selecting relays efficiently, while satisfying the data rate requirements. We define matrix $\boldsymbol{X} = (x_{s_i,r_j})_{s_i\in\mathcal{S},r_j\in\mathcal{R}}$ to indicate the relay selection for source devices, where binary variable $x_{s_i,r_j} = 1$ if source device $s_i$ selects relay $r_j$. Otherwise, $x_{s_i,r_j} = 0$. We further define $\boldsymbol{P}_s = (P_{s_i,r_j})_{s_i\in\mathcal{S},r_j\in\mathcal{R}}$ as the transmission power matrix, where entry $P_{s_i,r_j}$ is the transmission power from source device $s_i$ to relay $r_j$. Similarly, matrix $\boldsymbol{P}_r = (P_{r_j,d_i})_{r_j\in\mathcal{R},d_i\in\mathcal{D}}$ denotes the transmission power from the relays to the destination devices. For full duplex relays, a higher relay transmission power increases the received power in the destination devices. However, it induces a higher self interference at the same time.

We denote $C_{l_i}^{\min}$ as the minimum data rate requirement for D2D user pair $l_i$, $N_{r_j}$ as the number of subchannels that relay $r_j$ can use, $P_s^{\max}$ as the maximum transmission power of each D2D device, and $P_r^{\max}$ as the maximum transmission power of relays. Formally, the relay selection problem to minimize the total power consumption can be formulated as follows:

$$\underset{\boldsymbol{X},\boldsymbol{P}_s,\boldsymbol{P}_r}{\text{minimize}} \quad \sum_{s_i\in\mathcal{S}}\sum_{r_j\in\mathcal{R}} x_{s_i,r_j} P_{s_i,r_j} \qquad (7a)$$

$$\text{subject to} \quad \sum_{r_j\in\mathcal{R}} x_{s_i,r_j} B \min\left( \log_2\left(1+\frac{P_{s_i,r_j}h_{s_i,r_j}}{N_0+P_{r_j,d_i}h_{LI}}\right), \log_2\left(1+\frac{P_{r_j,d_i}h_{r_j,d_i}}{N_0+P_{s_i,r_j}h_{s_i,d_i}}\right)\right) \geq C_{l_i}^{\min}, \quad \forall\ l_i=(s_i,d_i)\in\mathcal{L}, \quad (7b)$$

$$\sum_{r_j\in\mathcal{R}} x_{s_i,r_j} \leq 1, \qquad \forall\ s_i\in\mathcal{S}, \qquad (7c)$$

$$\sum_{s_i\in\mathcal{S}} x_{s_i,r_j} \leq N_{r_j}, \qquad \forall\ r_j\in\mathcal{R}, \qquad (7d)$$

$$0 \leq P_{s_i,r_j} \leq P_s^{\max}, \qquad \forall\ s_i\in\mathcal{S}, r_j\in\mathcal{R}, \qquad (7e)$$

$$0 \leq P_{r_j,d_i} \leq P_r^{\max}, \qquad \forall\ r_j\in\mathcal{R}, d_i\in\mathcal{D}, \qquad (7f)$$

$$x_{s_i,r_j} \in \{0,1\}, \qquad \forall\ s_i\in\mathcal{S}, r_j\in\mathcal{R}. \qquad (7g)$$

Problem (7) is a non-convex combinatorial optimization problem. Constraint (7b) guarantees that the minimum date rate requirement is satisfied for each D2D user pair. Constraint (7c) indicates that each user pair can be assisted by at most one relay. Constraint (7d) ensures that the number of D2D user pairs assisted by relay $r_j$ is less than or equal to the number of subchannels that $r_j$ can use. Constraint (7e) indicates the physical constraint for the transmission power of mobile devices, while constraint (7f) guarantees that the transmission power of each relay is not greater than the maximum transmission power allowed by the Federal Communications Commission (FCC).

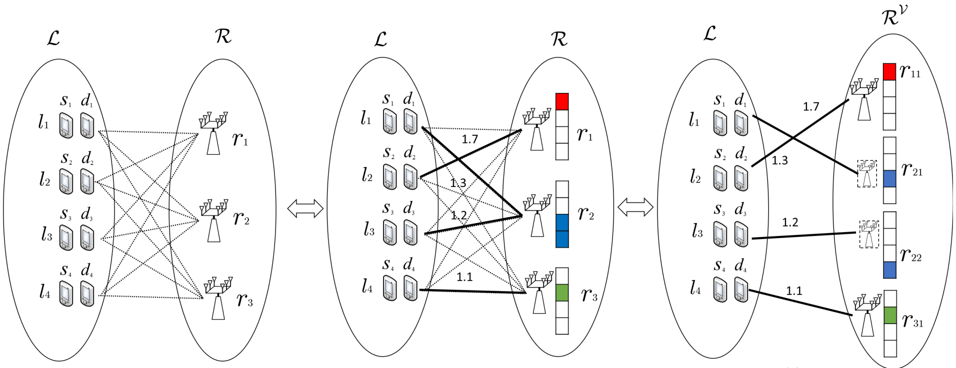
## III. POWER-EFFICIENT RELAY SELECTION USING MATCHING THEORY

Problem (7) is difficult to be solved directly using standard optimization techniques due to the binary variables $\boldsymbol{X}$ and continuous variables $\boldsymbol{P}_s$ and $\boldsymbol{P}_r$. The optimization methods for this type of mixed integer programming problems, such as branch-and-bound and Benders decomposition methods, incur high computational complexity. In this section, we transform the combinatorial optimization problem (7) into a canonical matching problem [13]. We first show that problem (7) can be transformed into a *many-to-one* matching problem [14]. We further utilize the characteristic of our system and transform the many-to-one matching problem into a one-to-one matching problem by introducing virtual relays. We then propose an optimal power-efficient relay selection algorithm.

### A. Bipartite Graph Construction

Matching theory is a mathematical framework, which describes the formation of mutually beneficial relationships. It provides tractable solutions for combinatorial problems of matching the players, which are denoted by vertices in disjoint sets [13]. In this paper, we regard vertex sets as the set of D2D user pairs $\mathcal{L}$ and the set of relays $\mathcal{R}$. We consider all possible relay selections as different *matchings*. The goal is to find the best matching (i.e., relay selection) between the D2D user pairs and the relays, which results in the minimum total power consumption as given in the objective function of problem (7). To achieve this goal, we construct a *bipartite graph*, which consists two disjoint *vertex* sets, *edges*, and corresponding *weights*. As shown in Fig. 2(a), the vertex sets are $\mathcal{L}$ and $\mathcal{R}$. The edges, which are shown by the dotted lines, connect two vertices in the disjoint sets. A matching is represented by a set of distinct edges. We use tuple $(l_i, r_j)$ to denote the edge which connects D2D user pair $l_i$ with relay $r_j$. For instance, as shown in Fig. 2(b), the graph with four solid edges $(l_1,r_2), (l_2,r_1), (l_3,r_2)$, and $(l_4,r_3)$ corresponds to a matching example. Each edge has a weight which represents the minimum power consumption when the corresponding D2D user pair and relay are matched. For a given matching, the summation of the weights for all edges is equal to the total power consumption, which is the same as the objective function of problem (7).

In the following, we consider the matching rules in the graph so that the optimal matching is guaranteed to be within the feasible region of problem (7). By considering constraint (7c), at most one edge can be connected with each D2D user pair. Meanwhile, we allow at most $N_{r_j}$ edges to be connected with relay $r_j \in \mathcal{R}$ to satisfy constraint (7d). Constraints (7c) and (7d) indicate that the equivalent matching problem is a many-to-one matching. We further consider constraints (7b), (7e), and (7f), which are related to the transmission power variables. We first assume that D2D user pair $l_i$ is assisted by relay $r_j$.



(a) (b) (c)

Fig. 2. (a) A bipartite graph with four D2D user pairs and three relays. (b) A matching example with four edges $(l_1, r_2)$, $(l_2, r_1)$, $(l_3, r_2)$, and $(l_4, r_3)$. (c) The one-to-one matching with virtual relays in dashed frames.

Note that each D2D user pair can be assisted by at most one relay. Then, constraint (7b) becomes

$$B \min\left(\log_2\left(1+\frac{P_{s_i,r_j}h_{s_i,r_j}}{N_0+P_{r_j,d_i}h_{LI}}\right),\right.$$
$$\left.\log_2\left(1+\frac{P_{r_j,d_i}h_{r_j,d_i}}{N_0+P_{s_i,r_j}h_{s_i,d_i}}\right)\right) \geq C_{l_i}^{\min}, \tag{8}$$

which is equivalent to

$$\frac{P_{s_i,r_j}h_{s_i,r_j}}{N_0+P_{r_j,d_i}h_{LI}} \geq 2^{(C_{l_i}^{\min}/B)}-1, \tag{9a}$$
$$\frac{P_{r_j,d_i}h_{r_j,d_i}}{N_0+P_{s_i,r_j}h_{s_i,d_i}} \geq 2^{(C_{l_i}^{\min}/B)}-1. \tag{9b}$$

Therefore, when we consider that relay $r_j$ is selected to assist user pair $l_i$, we can determine the minimum transmission power of source $s_i$ in user pair $l_i$ by solving the following problem.

$$\underset{P_{s_i,r_j},P_{r_j,d_i}}{\text{minimize}} \quad P_{s_i,r_j} \tag{10a}$$
$$\text{subject to} \quad 0 \leq P_{s_i,r_j} \leq P_s^{\max}, \tag{10b}$$
$$0 \leq P_{r_j,d_i} \leq P_r^{\max}, \tag{10c}$$
$$\text{constraints} \quad \text{(9a) and (9b)}.$$

Note that constraints (9a) and (9b) are affine constraints. Therefore, problem (10) is a linear programming problem which can be solved in polynomial time using standard optimization techniques. The solution of problem (10) is denoted by $P^*_{s_i,r_j}$ and $P^*_{r_j,d_i}$. Problem (10) is formulated to obtain the weight of each edge, when we assume that the user pair is assisted by a particular relay. This problem, however, cannot achieve the optimal relay selection. The weight of edge $(l_i, r_j)$ is set to $P^*_{s_i,r_j}$, which always satisfies constraints (7b), (7e), and (7f). If problem (10) is infeasible, it means that the minimum data rate requirement $C_{l_i}^{\min}$ cannot be satisfied when source device $s_i$ selects relay $r_j$. In other words, source device $s_i$ will not use relay $r_j$ and edge $(l_i, r_j)$ will not be selected in the matching. In order to exclude such infeasible edge, we set its weight to infinity so that the edge will not be considered when minimizing the sum of the weights. Therefore, all possible matchings will be in the feasible region of problem (7) and satisfy all of its constraints.

Formally, we construct bipartite graph $\mathcal{G} = (\mathcal{L}, \mathcal{R}, \mathcal{E}, \boldsymbol{W})$, where D2D user pair set $\mathcal{L}$ and relay set $\mathcal{R}$ are the sets of vertices, $\mathcal{E}$ is the set of edges, and $\boldsymbol{W} = (w_{l_i,r_j})_{l_i\in\mathcal{L}, r_j\in\mathcal{R}}$ is the weighting matrix for the edges. Each edge has a weight, which represents the minimum power consumption of the matched vertices (i.e., $w_{l_i,r_j} = P^*_{s_i,r_j}$). Therefore, obtaining the optimal relay selection is equivalent to find the matching $\mathcal{F}^* \in \mathcal{E}$ such that the sum weight of all edges is minimized.

$$\underset{\mathcal{F}^*\in\mathcal{E}}{\text{minimize}} \sum_{(l_i,r_j)\in\mathcal{F}^*} w_{l_i,r_j}. \tag{11a}$$

Up to now, we have transformed the combinatorial relay selection problem into a many-to-one matching problem with bipartite graph $\mathcal{G}$. However, it is still difficult, if not impossible, to obtain the optimal solution for this many-to-one matching problem in an efficient manner. Note that in our system, although each relay can serve multiple D2D user pairs, eventually, each pair is allocated a non-overlapping subchannel in the OFDMA system. By utilizing this feature, we can further transform the many-to-one matching problem into a one-to-one weighted bipartite matching problem that can be solved optimally in polynomial time [14]. Since each relay $r_j$ has $N_{r_j}$ subchannels, we replace $r_j$ with $N_{r_j}$ virtual relays, which are located at the same point. Each virtual relay is assigned a non-overlapping subchannel, as shown in Fig. 2(c). We use $r_{jk}$ to represent the virtual relay that operates on the $k^{\text{th}}$ subchannel of relay $r_j$. Then, we denote the set of virtual relays as $\mathcal{R}^v = \{r_{11}, \cdots, r_{1N_{r_1}}, \cdots r_{|\mathcal{R}|1}, \cdots, r_{|\mathcal{R}|N_{r_{|\mathcal{R}|}}}\}$, which represents the new vertex set. For ease of exposition, we denote $r_j^v$ as the $j^{\text{th}}$ virtual relay in set $\mathcal{R}^v$. We denote the new set of edges as $\mathcal{E}^v$ and the new weighting matrix as $\boldsymbol{W}^v = (w^v_{l_i,r_j^v})_{l_i\in\mathcal{L}, r_j^v\in\mathcal{R}^v}$. Now, we transform the many-to-one matching problem into a one-to-one matching problem denoted by graph $\mathcal{G}^v = (\mathcal{L}, \mathcal{R}^v, \mathcal{E}^v, \boldsymbol{W}^v)$. The goal is to find the one-to-one matching $\mathcal{F}^{v*} \in \mathcal{E}^v$ such that $\sum_{(l_i,r_j^v)\in\mathcal{F}^{v*}} w^v_{l_i,r_j^v}$ is minimized.

**Algorithm 1:** Power-efficient Relay Selection for Relay-assisted D2D Networks (PRS-D2D)

```
1  input $\mathcal{L}$, $\mathcal{S}$, $\mathcal{D}$, $\mathcal{R}^v$, $C_{l_i}^{\min}, \forall l_i \in \mathcal{L}$, $N_{r_j}, \forall r_j \in \mathcal{R}$, $P_s^{\max}$, $P_r^{\max}$
2  for $l_i \in \mathcal{L}$ do
3      for $r_j^v \in \mathcal{R}^v$ do
4          Solve problem (10) to obtain $P_{s_i,r_j^v}^{v*}$ and $P_{r_j^v,d_i}^{v*}$
5          $w_{l_i,r_j^v}^v := P_{s_i,r_j^v}^{v*}$
6          if problem (10) is infeasible then
7              $w_{l_i,r_j^v}^v := +\infty$
8          end
9      end
10     if $\min(\{P_{s_i,r_j^v}^{v*}, \forall r_j^v \in \mathcal{R}^v\}) > P_s^{\max}$ then
11         Return infeasible
12     end
13 end
14 $\boldsymbol{W}^v := (w_{l_i,r_j^v}^v)_{l_i \in \mathcal{L}, r_j^v \in \mathcal{R}^v}$
15 $\boldsymbol{P}_r^{v*} := (P_{r_j^v,d_i}^{v*})_{r_j^v \in \mathcal{R}^v, d_i \in \mathcal{D}}$
16 $\boldsymbol{X}^{v*} :=$ Hungarian($\boldsymbol{W}^v$)
17 $\boldsymbol{P}_s^{v*} := \boldsymbol{X}^{v*} \odot \boldsymbol{W}^v$
18 $\boldsymbol{P}_r^{v*} := \boldsymbol{X}^{v*} \odot \boldsymbol{P}_r^{v*}$
19 output: Virtual relay selection decision $\boldsymbol{X}^{v*}$, transmission
   power matrices $\boldsymbol{P}_s^{v*}$ and $\boldsymbol{P}_r^{v*}$.
```

### B. Power-efficient Relay Selection Algorithm

In this subsection, we propose PRS-D2D to obtain the optimal relay selection based on the Hungarian method [15]. As shown in Algorithm 1, we first compute the weight of all edges in the graph (Lines 2 to 13). By solving problem (10), we determine the weight of each edge (Lines 4 and 5). If problem (10) is infeasible, we set the corresponding weight to infinity (Lines 6 to 8). By doing so, we exclude those relays which would result in infeasible power consumption for the corresponding D2D user pair. If the transmission power of a D2D user pair is always infeasible regardless of which relay it uses (Line 10), this user pair should communicate using cellular base station and operate under the resource allocation rules for regular cellular users. If the problem is feasible, then the Hungarian method [15] is used to obtain the optimal relay selection matrix $\boldsymbol{X}^{v*}$ (Line 16). Let $\boldsymbol{P}_s^{v*}$ and $\boldsymbol{P}_r^{v*}$ denote the optimal transmission power matrices for source devices and relays, respectively. These matrices are obtained in Lines 17 and 18, where $\odot$ represents entrywise product of two matrices.

Note that the computational complexity of the Hungarian method is proved to be $O(|\mathcal{L}|^3)$ [14]. The complexity of computing the weights of all edges in the graph is $O(|\mathcal{L}||\mathcal{R}^v|)$, since we need to solve problem (10) for $|\mathcal{L}||\mathcal{R}^v|$ edges. Note that problem (10) only has two variables. Therefore, the overall complexity of our proposed algorithm is $O(|\mathcal{L}|^3 + |\mathcal{L}||\mathcal{R}^v|)$, which is polynomial. This shows the practicality of the algorithm.

## IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of PRS-D2D and compare our proposed algorithm with a recently proposed relay selection algorithm, which is called GECC [9]. GECC iteratively assigns a relay to each user pair such that it results in the minimum transmission power among all user pairs.

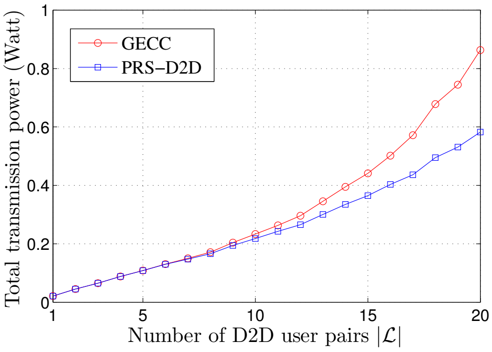


Fig. 3. Total transmission power versus number of D2D user pairs $|\mathcal{L}|$ with $|\mathcal{R}| = 5$.

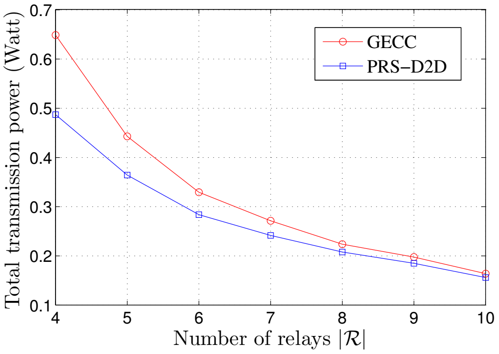


Fig. 4. Total transmission power versus number of relays $|\mathcal{R}|$ with $|\mathcal{L}| = 15$.

We consider the D2D devices and relays are randomly located in a 1 km × 1 km region. The average distance between the source and destination devices of each D2D user pair is 400 m. Each relay can use four subchannels (i.e., $N_{r_j} = 4, \forall r_j \in \mathcal{R}$). The bandwidth of each subchannel $B = 1$ MHz, and the noise power spectrum density is $-174$ dBm/Hz. Other simulation parameters are as follows: $P_s^{\max} = 2$ Watt, $P_r^{\max} = 10$ Watt [16], $C_{l_i}^{\min} = 8$ Mbps, $\forall l_i \in \mathcal{L}$, $M^t = M^r = 10$ dB, $m^t = m^r = -5$ dB, $\Theta_{\text{HPBW}}^t = \Theta_{\text{HPBW}}^r = 15^o$, $\alpha = 2$, $\sigma = 1.5$, and $h_{LI} = -70$ dB [5], [11]. We use Monte Carlo simulations and calculate the average value of the total transmission power over different network settings.

In Fig. 3, we compare the total transmission power of PRS-D2D and GECC for different number of D2D user pairs. As shown in this figure, PRS-D2D substantially outperforms GECC when the number of D2D user pairs is greater than 10. This is because PRS-D2D achieves the optimal solution, while GECC selects relays based on a heuristic greedy approach. GECC provides a near-optimal solution when the number of D2D user pairs is small. However, when the number of D2D user pairs is 20, PRS-D2D results in 32% less transmission power than GECC.

In Fig. 4, we compare the total transmission power versus different number of relays when the number of D2D user pairs is 15. It is shown that the total transmission power

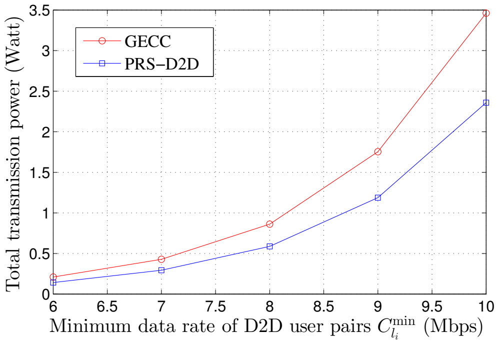


Fig. 5. Total transmission power versus minimum data rate requirement $C_{l_i}^{\min}, \forall l_i \in \mathcal{L}$ with $|\mathcal{R}| = 5$ and $|\mathcal{L}| = 20$.

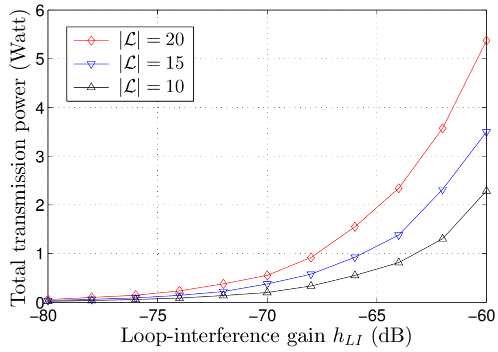


Fig. 6. Total transmission power versus loop-interference gain $h_{LI}$ with $|\mathcal{R}| = 5$.

is decreasing for both algorithms as the number of relays increases. This is because the D2D user pairs have more opportunity to select a relay which is closer. As shown in the figure, PRS-D2D always outperforms GECC. When the number of relays is 4, PRS-D2D saves 25% power compared with GECC.

In Fig. 5, we compare the total transmission power versus different minimum data rate requirements of D2D user pairs. It is shown that a higher transmission power is consumed when the required data rate increases. Mobile devices consume 31% less transmission power for $C_{l_i}^{\min} = 10$ Mbps when PRS-D2D is used in comparison with GECC.

We now evaluate the impact of self interference on the performance of PRS-D2D. In Fig. 6, the total transmission power of mobile devices is shown for different values of $h_{LI}$. The total transmission power increases as the loop-interference gain increases. When $h_{LI} = -60$ dB, the average transmission power for 10 and 20 D2D user pairs are $2.3/10 = 0.23$ Watt and $5.4/20 = 0.27$ Watt, respectively. This indicates that the average power consumption increases as the number of D2D user pairs becomes larger.

## V. CONCLUSION

In this paper, we studied the power-efficient relay selection problem in full duplex relay-assisted D2D networks using a matching approach. We first formulated the relay selection problem as a combinatorial optimization problem to minimize the power consumption of the transmitting devices. We then transformed the non-convex combinatorial optimization problem into a many-to-one matching problem. By introducing the concept of virtual relays, we further transformed the problem into a one-to-one weighted matching problem, which can be solved optimally in polynomial time. Moreover, we proposed PRS-D2D algorithm based on the Hungarian method to obtain the optimal relay selection. Simulation results show that the proposed algorithm substantially outperforms an existing algorithm in terms of total power consumption. For future work, we will consider that subchannels can be reused among D2D user pairs and study the relay selection problem in highly dense networks.

## REFERENCES

[1] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: Challenges, solutions, and future directions," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 86–92, May 2014.

[2] X. Chen, B. Proulx, X. Gong, and J. Zhang, "Exploiting social ties for cooperative D2D communications: A mobile social networking case," *IEEE/ACM Trans. on Networking*, vol. 23, no. 5, pp. 1471–1484, Oct. 2015.

[3] L. Jimenez Rodriguez, N. Tran, and T. Le-Ngoc, "Optimal power allocation and capacity of full-duplex AF relaying under residual self-interference," *IEEE Wireless Commun. Letters*, vol. 3, no. 2, pp. 233–236, Apr. 2014.

[4] J.-S. Han, J.-S. Baek, S. Jeon, and J.-S. Seo, "Cooperative networks with amplify-and-forward multiple-full-duplex relays," *IEEE Trans. on Wireless Commun.*, vol. 13, no. 4, pp. 2137–2149, Apr. 2014.

[5] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. on Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sept. 2011.

[6] 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. on Wireless Commun.*, vol. 13, no. 4, pp. 2322–2338, Apr. 2014.

[7] G. Zhang, K. Yang, P. Liu, and J. Wei, "Power allocation for full-duplex relaying-based D2D communication underlaying cellular networks," *IEEE Trans. on Vehicular Technology*, vol. 64, no. 10, pp. 4911–4916, Oct. 2015.

[8] M. Hasan and E. Hossain, "Distributed resource allocation for relay-aided device-to-device communication under channel uncertainties: A stable matching approach," *IEEE Trans. on Commun.*, vol. 63, no. 10, pp. 3882–3897, Oct. 2015.

[9] P. Li, S. Guo, Z. Cheng, and A. Vasilakos, "Joint relay assignment and channel allocation for energy-efficient cooperative communications," in *Proc. of IEEE WCNC*, Shanghai, China, Apr. 2013.

[10] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. Wong, J. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, May 2013.

[11] T. S. Rappaport, F. Gutierrez, E. Ben-Dor, J. N. Murdock, Y. Qiao, and J. Tamir, "Broadband millimeter-wave propagation measurements and models using adaptive-beam antennas for outdoor urban cellular communications," *IEEE Trans. on Antennas and Propagation*, vol. 61, no. 4, pp. 1850–1859, Apr. 2013.

[12] T. Bai and R. W. Heath, "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Trans. on Wireless Commun.*, vol. 14, no. 2, pp. 1100–1114, Feb. 2015.

[13] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, "Matching theory for future wireless networks: Fundamentals and applications," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 52–59, May 2015.

[14] D. B. West, *Introduction to Graph Theory*. Prentice Hall, 2001.

[15] H. W. Kuhn, "The Hungarian method for the assignment problem," *Naval Research Logistics Quarterly*, vol. 2, no. 1-2, pp. 83–97, 1955.

[16] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 106–113, Feb. 2014.