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Energy Efficient Relay Matching With Bottleneck Effect Elimination Power Adjusting for Full-Duplex Relay Assisted D2D Networks Using mmWave Technology

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ABSTRACT In the fifth-generation (5G) of the wireless communication systems, the millimeter wave (mmWave)-based device-to-device (D2D) communication is a promising technique to boost the end-to-end capacity. However, the well-known blockage and high path loss problems of the mmWave severely restrict the reachability of the D2D communication. Therefore, the relaying transmission scheme becomes a necessary component to complete the puzzle of the technologies for 5G. In this paper, we aim to boost the energy efficiency (EE) of the full-duplex relay-aided mmWave D2D communications. To achieve this goal, the nonlinear fractional programming-based iterative power allocation algorithm is first developed to optimize the EE. Then, on top of it, the bottle-neck effect elimination power (BEEP) adjusting method is proposed to further reduce the transmission power while maintaining the end-to-end capacity. By combining these techniques with the properly designed matching algorithm, we propose the EE relaying with the BEEP (BEEPER) algorithm. Via the simulation results, the superior performance of the BEEPER algorithm is verified.

INDEX TERMS D2D, energy efficiency, full duplex relay, matching, mmWave.

I. INTRODUCTION

The well-known device-to-device (D2D) communications has been recognized as one of the important technologies for the fifth-generation (5G) of the wireless communication systems [1]. Via the D2D communications, the performance of traffic offloading, energy consumption, packet deliver delay and end-to-end capacity can be significantly improved. These benefits can further be exaggerated by using the millimeter wave (mmWave) transmission scheme, since it can provide larger bandwidth and possess highly directional propagation characteristic [2]. Nevertheless, the directionality and blockage problems of the mmWave seriously restrict the reachability of the D2D communications. Fortunately, via relaying, the problem of limited reachability can be alleviated. Therefore, how to design a relay system for the mmWave-based D2D communications to further boost the system performance becomes a critical issue.

In the literature, several schemes have been proposed to boost the transmission rate for the mmWave-based D2D communications. For example, in [3], a relay selection scheme for the piconet controller was designed by dividing the long-hop path into several short-hop transmissions. Consequently, higher data rate can be achieved by the well-arranged non-interfering concurrent transmissions. In [4]–[6], the joint relay selection and scheduling algorithms were proposed to serve multiple transmission requests using the minimum time slots. In [7], two relaying protocols were developed for the mmWave-based wireless personal area networks. Specifically, one is to minimize the number of relays under the connectivity, bandwidth and robustness constraints, while the other one aims to maximize the achievable rates using a fixed number of relays subject to the robustness constraint. In [8], based an optimized time-splitting for the half-duplex relaying, a relay priority region (RPG) was firstly defined to judge the existence of the candidate relays. When the RPG exists, properly selecting relays among the RPGs can further optimize the end-to-end capacity for the indoor 60 GHz network.

In [9], the criterion for selecting a relay in the 60 GHz network is based on the distance between the source and relay (d_{sr_i}), and that between the relay and destination (d_{r_id}). In principle, the relay with minimum imparity of distance (i.e. $\varepsilon_i = |d_{sr_i} - d_{r_id}|$) is the one which contributes to the maximum end-to-end capacity. In [10], with consideration of the blockage effect, two relay selection schemes were proposed by analyzing the end-to-end signal-to-noise ratio (SNR) distribution. On the one hand, the best relay is selected so that the end-to-end SNR can be optimized; on the other hand, the best relay can also be adopted so that the transmission path is affected by the least blockages. The former one contributes to maximum capacity, while the latter one maximally extends the coverage areas. In [11], the coverage probability of relay-assisted mmWave networks was analyzed. Considering various distributions of base station (BS), user equipments (UEs), blockages, and relays (RNs), the SNR distributions for low and ultra-high dense networks were derived. Based on the analytical results, the superior performance of the relay-assisted mmWave networks was verified. In [12], the relay-assisted mmWave networks was also applied to carry out the transmissions of the uncompressed high-definition (HD) video stream. To solve the mixed integer nonlinear programming (MINLP) problem of the relay selection, a heuristic algorithm was proposed to select an optimal relay which contributes to the maximum sum quality of all HD applications. However, the direct transmission path rather than the relay path should be used if the sum quality of the relay path is below the predefined threshold.

In addition to the SNR, coverage, transmission rate and end-to-end capacity, the energy efficiency (EE) is also one of the critical factors in the mmWave-based D2D communications. In [13], the challenges of raising the EE for the mmWave full-duplex relaying systems have been well discussed. Among the suggested solutions to these challenges, properly adapting the transmission power is one important strategy to improve the EE and cut the carbon footprint. In [14], the EE of relaying in the mmWave-based system was firstly analyzed by considering the outage zone in the metropolitan environment. In order to reach beyond the outage zone by using the minimum transmission power, the Hungarian algorithm was applied to design an efficient relay strategy. Similarly, in [15], the Hungarian algorithm was also been applied to minimize the energy consumption for the D2D communications using full-duplex relay. To this end, the minimum transmission power to satisfy the capacity constrain was used to construct the weighting matrix such that the matching problem between the each D2D pair and relay can be effectively solved.

Motivated by [13], we wonder whether more energy can be saved when boosting the EE by properly adjusting the transmission power and matching the D2D pairs up with relays rather than using the minimum power to satisfy the capacity constrain, as what has been done in [15]. To this end, the nonlinear fractional programming (NFP) based iterative power allocation (IPA) algorithm is firstly applied to optimize the EE of the mmWave full duplex relay-assisted D2D network. Secondly, on top of the NFP-based IPA algorithm, the bottle-neck effect elimination power (BEEP) adjusting method is proposed to further reduce the transmission power while maintaining the same end-to-end capacity (i.e. the spectrum efficiency in other words). Equivalently, one can say that the proposed BEEP method can further raise the energy efficiency by using least transmission power. Jointing the NFP-based IPA algorithm and BEEP scheme together with the properly designed matching algorithm, we develop the EE relaying scheme and it is named the BEEPER algorithm. Compared with the conventional counterpart in [15], the proposed BEEPER algorithm can reduce the power consumption by 45.9% and 61.6% for the relay and D2D pairs, respectively, which is equivalent to the 32.3% enhancement of EE. To make the discussions more complete, two matching algorithms (i.e. the Gale-Shapley and Hungarian algorithms) are taken into account. The simulation results show that the Hungarian algorithm can be beneficial to the D2D, while the Gale-Shapley algorithm favors the relay in terms of the power consumption.

To sum up, the contributions of this paper can be listed as follows.

1 We approach the full-duplex relay selection for the mmWave-based D2D communications from the aspect of the EE rather than the minimization of the transmission power under the constraint of the minimal capacity requirement in [15].
2 We propose the BEEPER algorithm to optimize the EE by three steps:
   a) Apply the NFP method to transform the non-convex optimization problem of EE into its convex form; and then, design a Game theoretical IPA algorithm to maximize the EE for all possible matches between the relays and D2D pairs.
   b) Bipartitely prioritize each relay and D2D pair based on the EE; and then, utilize the matching algorithm to select the better matches between the relays and D2D pairs.
   c) Use the proposed BEEP scheme to further reduce the transmission power and boost the EE without sacrificing the end-to-end capacity.
3 The simulation results verify the advantages of the proposed scheme to remarkably save the transmission power and enhance the EE at the acceptable and worthy cost of the mildly degraded fairness.

The rest of this paper is organized as follows. The system model as well as the assumptions is introduced in Section II. Section III proposes the BEEPER algorithm, including the NFP-based IPA algorithm, matching algorithm and BEEP scheme. At last, the numerical results and concluding remarks, including some suggestions for future works, are given in Sections IV and V, respectively.

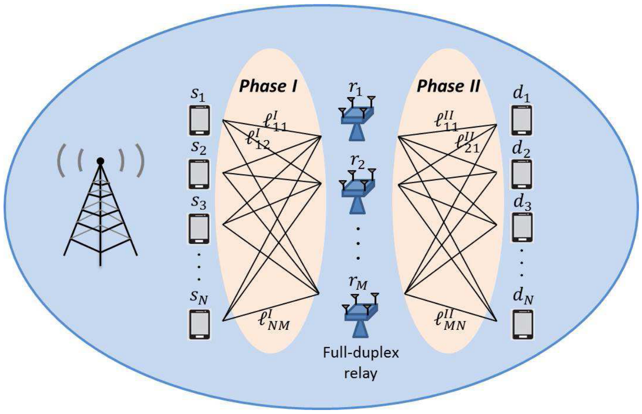

FIGURE 1. Relay-assisted mm-wave D2D network.

II. SYSTEM MODEL

In this paper, we consider an mmWave cellular network with full duplex relay-assisted D2D communications. As shown in Fig. 1, the N D2D pairs and M relays are uniformly distributed over the coverage areas of the single base-station (BS). To facilitate the following presentation, denote $\mathcal{R} = \{r_j\}$, $\forall j = 1, \cdots, M$ and $\mathcal{P} = \{\mathfrak{p}_i\}$, $\forall i = 1, \cdots, N$ the sets of relays and the D2D pairs. Literally, each D2D pair consists of a source and destination. Thus, the i-th pair can be expressed as $\mathfrak{p}_i = (s_i, d_i)$, where s_i and d_i represent the i-th source and destination. Moreover, the sets of the source and destination can be written as $\mathcal{S} = \{s_i\}$ and $\mathcal{D} = \{d_i\}$ for $i = 1, \cdots, N$, respectively. For simplicity, we further indicate the transmission link during Phase I, i.e. the link from s_i to r_j, as $\ell^I_{i,j}$; also, the Phase II's transmission link from r_j to d_i is denoted by $\ell^{II}_{j,i}$.

Similar to [15], we assume that the j-th relay r_j owns H_j pair of transmitting and receiving antennas. Each antenna pair possesses one orthogonal frequency division multiple access (OFDMA) subchannels and implements the decode-and-forward relaying protocol. Then, each D2D pair can select one pair of transmitting and receiving antennas to transmit over a subchannel. Also, with the aid of BS, all the relays and D2D pairs can steer the antenna beams to develop the transmission paths.

Considering the mmWave of 38 GHz, the corresponding path loss can be modeled by

$$PL(d) = PL(d_0) + 10\alpha log(d) + \mathcal{X}_\sigma, \tag{1}$$

where α and $PL(d_0)$ denote the path loss exponent and free-space path loss at the reference distance d_0 m, respectively; $\mathcal{X}_\sigma$ represents the shadowing effect with zero-mean and standard deviation (std.) of σ in the dB domain [15], [16]. Moreover, referring to [15] and [17], the transmitting antenna gain $G^t(\theta^t)$ can be written as

$$G^t(\theta^t) = \begin{cases} M^t, & 0^o \le \theta^t \le \theta^t_{HP} \\ m^t, & \theta^t_{HP} < \theta^t \le 180^o \end{cases} \tag{2}$$

whereas that at the receiving end can be expressed as

$$G^r(\theta^r) = \begin{cases} M^r, & 0^o \le \theta^r \le \theta^r_{HP} \\ m^r, & \theta^r_{HP} < \theta^r \le 180^o \end{cases} \tag{3}$$

where θ^t and θ^r represent the angles of departure and arrival; θ^t_{HP} and θ^r_{HP} are the half power beamwidth at the transmitting and receiving ends, respectively. Note that M^t and m^t are the transmitting antenna gain for the main-lobe and side-lobe, while M^r and m^r are those at the receiving ends. 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 signal from transmitter i to receiver j and $\theta^r_{j,i}$ is the angle of arrival signal in receiver j transmitted from i. Accordingly, the joint channel gain between the i-th and j-th devices now be expressed as

$$h_{i,j} = G_{i,j} \times 10^{-PL(d_{i,j})/10}, \tag{4}$$

where $d_{i,j}$ is the distance between the i-th and j-th devices.

Now, the signal to interference plus noise ratio (SINR) of the Phase I link $\ell^I_{i,j}$ can be defined as

$$SINR_{s_i,r_j} = \frac{P_{s_i,r_j} h_{s_i,r_j}}{WN_0 + P_{r_j,d_i} h_{LI}}, \tag{5}$$

where P_{s_i,r_j} denotes the transmission power for the link $\ell^I_{i,j}$, while P_{r_j,d_i} is that for the link $\ell^{II}_{j,i}$; W and N_0 are the subchannel bandwidth and power spectrum density of the additive white Gaussian noise (AWGN), respectively; h_{s_i,r_j} denotes the channel gain of the link $\ell^I_{i,j}$, while h_{LI} is the channel gain to model the effect of residual self-interference (SI) [1] for the full-duplex relaying scheme. Observing (5), It is apparently to find that the benefit of the doubled transmission rate by using the full-duplex relaying highly depends on the ability of cancelling the strong SI. Therefore, here, it is assumed that some SI cancellation techniques can be applied such that the benefit of using the full-duplex relaying can be attained. Similarly, the SNR of the Phase II link $\ell^{II}_{j,i}$ can be written as

$$SNR_{r_j,d_i} = \frac{P_{r_j,d_i} h_{r_j,d_i}}{P_{s_i,r_j} h_{s_i,d_i} + WN_0}, \tag{6}$$

where the definitions of P_{r_j,d_i} and h_{r_j,d_i} are analogous to those in (5). Note that h_{s_i,d_i} represents the channel gain of the direct link for the i-th D2D pair $\mathfrak{p}_i = (s_i, d_i)$. Thus, the term $P_{s_i,r_j} h_{s_i,d_i}$ stands for co-channel interference. Based on (5) and (6), the EE of the links $\ell^I_{i,j}$ and $\ell^{II}_{j,i}$ can be defined as

$$\begin{aligned} E_{s_i}(P_{s_i,r_j}) &= \frac{U_{s_i}(P_{s_i,r_j})}{T_{s_i}(P_{s_i,r_j})} \\ &= \frac{\log_2\left(1 + \frac{P_{s_i,r_j} h_{s_i,r_j}}{WN_0 + P_{r_j,d_i} h_{LI}}\right)}{\frac{1}{\eta} P_{s_i,r_j} + 2P_{cir}}, \end{aligned} \tag{7}$$

[1] Note that the channel gain of SI and its impact after using some SI cancellation techniques can be estimated and/or analyzed. Some interesting readers can find various related works from the literature, e.g. [13], [18]–[21].

and

$$E_{r_j}(P_{r_j,d_i}) = \frac{U_{r_j}(P_{r_j,d_i})}{T_{r_j}(P_{r_j,d_i})} = \frac{\log_2\left(1+\frac{P_{r_j,d_i}h_{r_j,d_i}}{P_{s_i,r_j}h_{s_i,d_i}+WN_0}\right)}{\frac{1}{\eta}P_{r_j,d_i}+2P_{cir}}, \quad (8)$$

respectively, where U_{s_i} and T_{s_i} denote the spectrum efficiency (SE) and the total power consumptions of the link $\ell^I_{i,j}$, and the same definition can also apply to U_{r_j} and T_{r_j}; P_{cir} is the total circuit power and η is the power amplifier (PA) efficiency. Moreover, the end-to-end EE can be defined as

$$E_{\mathfrak{p}_i}(P_{s_i,r_j}, P_{r_j,d_i}) = \frac{\min\left[U_{s_i}(P_{s_i,r_j}), U_{r_j}(P_{r_j,d_i})\right]}{T_{s_i}(P_{s_i,r_j}) + T_{r_j}(P_{r_j,d_i})}. \quad (9)$$

Note that the end-to-end capacity for the $\mathfrak{p}_i = (s_i, d_i)$ is

$$\min\Big[\underbrace{W \times U_{s_i}(P_{s_i,r_j})}_{C_{\ell^I_{i,j}}}, \underbrace{W \times U_{r_j}(P_{r_j,d_i})}_{C_{\ell^{II}_{j,i}}}\Big]. \quad (10)$$

III. BEEPER ALGORITHM

In this paper, the objective is to maximize the overall end-to-end EE. Thus, we formulate the optimization as follows.

$$\max_{\mathbf{X},\mathbf{P_s},\mathbf{P_r}} \sum_{\mathfrak{p}_i\in\mathcal{P}}\sum_{r_j\in\mathcal{R}} x_{\mathfrak{p}_i,r_j}E_{\mathfrak{p}_i}(P_{s_i,r_j}, P_{r_j,d_i}) \quad (11a)$$

$$\text{s.t.} \sum_{r_j\in\mathcal{R}} x_{\mathfrak{p}_i,r_j} \le 1, \qquad \forall \mathfrak{p}_i \in \mathcal{P} \quad (11b)$$

$$\sum_{\mathfrak{p}_i\in\mathcal{P}} x_{\mathfrak{p}_i,r_j} \le H_j, \qquad \forall\, r_j \in \mathcal{R} \quad (11c)$$

$$x_{\mathfrak{p}_i,r_j} \in \{0,1\}, \qquad \forall\, \mathfrak{p}_i \in \mathcal{P},\ r_j \in \mathcal{R} \quad (11d)$$

$$0 \le P_{s_i,r_j} \le P_s^{max}, \qquad \forall\, s_i \in \mathcal{S},\ r_j \in \mathcal{R} \quad (11e)$$

$$0 \le P_{r_j,d_i} \le P_r^{max}, \qquad \forall\, r_j \in \mathcal{R},\ d_i \in \mathcal{D} \quad (11f)$$

$$U_{s_i}(P_{s_i,r_j}) \ge U_s^{min} \quad (11g)$$

$$U_{r_j}(P_{r_j,d_i}) \ge U_r^{min} \quad (11h)$$

where the element at the ℓ_i-th row and the r_j-th column of the matching matrix $\mathbf{X}$ is defined as $x_{\mathfrak{p}_i,r_j}$. And, $x_{\mathfrak{p}_i,r_j} = 1$ if the i-th D2D pair and the j-th relay are matched, otherwise $x_{\mathfrak{p}_i,r_j} = 0$. For simplicity, the matching matrix can be expressed as $\mathbf{X} = (x_{\mathfrak{p}_i,r_j})_{\mathfrak{p}_i\in\mathcal{P},r_j\in\mathcal{R}}$. By analogy, the power matrix $\mathbf{P_s} = (P_{s_i,r_j})_{s_i\in\mathcal{S},r_j\in\mathcal{R}}$ and $\mathbf{P_r} = (P_{r_j,d_i})_{r_j\in\mathcal{R},d_i\in\mathcal{D}}$ can be defined. Also, $U^{min}_{s_i}$ and $U^{min}_{r_j}$ denote the minimal required SE for the Phase I's and II's transmissions. P^{max}_s and P^{max}_r stand for the maximum transmission power for the source and relay, respectively. To be clear, the constraint (11b) indicates that each D2D pair can be assisted by at most one relay; and similarly, (11c) means that each relay r_j can assist at most H_j D2D pairs.

Observing the optimization problem, one can find that it is indeed an MINLP problem. Note that the matching matrix $\mathbf{X}$ consists of the binary-valued variables, while the power matrixes $\mathbf{P_s}$ and $\mathbf{P_r}$ are composed of the continuous-valued variables. To tackle the MINLP problem, we decompose it into two subproblems. Firstly, the NFP-based IPA algorithm is applied to optimized the EE for all the possible associations between the D2D pairs and relays. Based the resulted EE, the matching matrix $\mathbf{X}$ is solved by the matching theory. At last, we propose the BEEP scheme to further boost the EE. To be brief, the proposed EE relaying with BEEP algorithm (abbreviated by BEEPER) can be carried out by three steps:

1 Apply the NFP method to solve the nonconvex problem of EE; and then the IPA algorithm is utilized to maximize the EE for all possible associations between the relays and D2D pairs.

2 Establish preference lists for each relay and D2D pair according to the EE obtained in Step 1; and then apply the ***bipartite*** matching algorithm to develop the links between the relays and D2D pairs.

3 Apply the proposed BEEP scheme to further reduce the transmission power and boost the EE.

A. NFP-BASED IPA ALGORITHM

Observing the definitions of the SINR and EE (as listed in (5), (6), (7) and (8), respectively) it is not difficult to find that the interests of the relay and D2D pair are conflicted with each other. Rising the transmission power unilaterally on one side can cause degradation on the other side. Therefore, in the considered distributed network, the power allocation process to boost the EE for two sides can be modelled by a non-cooperative Game. That is to say each D2D pair and relay can selfishly optimize its EE by iteratively adjusting the transmission power on its own. Moreover, owing to the two-hop transmission scenario, the power allocation problem can be decomposed into two subproblems (i.e. two phases) as

$$\max_{P_{s_i,r_j}} E_{s_i}(P_{s_i,r_j}) \quad \text{s.t. (11e), (11g)} \quad (12)$$

and

$$\max_{P_{r_j,d_i}} E_{r_j}(P_{r_j,d_i}) \quad \text{s.t. (11f), (11h),} \quad (13)$$

respectively. However, owing to the fractional form of the EE (as defined in (7) and (8), respectively), the subproblems of (12) and (13) becomes nonconvex. Applying the NFP method as follows can transform it into the convex counterpart [22].

Define the optimal EE as

$$q^*_{s_i} = \max_{P_{s_i,r_j}} E_{s_i}(P_{s_i,r_j}) = \frac{U_{s_i}(P^*_{s_i,r_j})}{T_{s_i}(P^*_{s_i,r_j})}, \quad (14)$$

where $P^*_{s_i,r_j}$ is the optimal power allocation for the s_i, and its optimality can be verified by Theorem 1.

Theorem 1: $q^*_{s_i}$ is achieved if and only if

$$\max_{P_{s_i,r_j}} U_{s_i}(P_{s_i,r_j}) - q^*_{s_i}T_{s_i}(P_{s_i,r_j}) = U_{s_i}(P^*_{s_i,r_j}) - q^*_{s_i}T_{s_i}(P^*_{s_i,r_j}) = 0. \quad \square \quad (15)$$

Accordingly, the nonconvex (12) and (13) can be transformed into

$$\max_{P_{s_i,r_j}} \; U_{s_i}(P_{s_i,r_j}) - q^*_{s_i} T_{s_i}(P_{s_i,r_j}) \quad \text{s.t. (11e), (11g)} \tag{16}$$

and

$$\max_{P_{r_j,d_i}} \; U_{r_j}(P_{r_j,d_i}) - q^*_{r_j} T_{r_j}(P_{r_j,d_i}) \quad \text{s.t. (11f), (11h),} \tag{17}$$

respectively. And then the optimal transmission power of P_{s_i,r_j} and P_{r_j,d_i} can be obtained by using the Lagrange dual decomposition and Karush-Kuhn-Tucker (KKT) conditions, as the $\hat{P}_{s_i,r_j}$ of (A.3) and $\hat{P}_{r_j,d_i}$ of (A.6), respectively. At last, based on the above descriptions, Algorithm 1 summarizes the procedures of the IPA algorithm; therein, the $\hat{P}_{s_i,r_j}(n)$ and $\hat{P}_{r_j,d_i}(n)$ denote the transmission power at the n-th iteration. By analogy, the $q_{s_i}(n)$ and $q_{r_j}(n)$ stands for the optimal EE defined by the results obtained at the $n-1$-th iteration (as listed at Lines 14 and 22, respectively). Note that the power adjust iteration terminates when (i) it reaches the maximum number of iterations i.e. N_{max}, as Line 6 of Algorithm 1 or (ii) (16) and (17) approximate zeros, as listed in Lines 9 and 17 of Algorithm 1, where ε_s and ε_r are the predefined thresholds.

B. EE RELAY MATCHING

Recall that the relays and D2D pairs are prioritized by EE obtained in Step 1, i.e. $q^*_{r_j}$ and $q^*_{s_i}$, respectively. Based on the priority lists, the Gale-Shapley algorithm and the Hungarian algorithm are applied to solve the bipartite *one-to-one* matching problem [23], [24]. It should be noticed that the relay $r_j \; \forall j \in \mathcal{R}$ owns H_j subchannels. Also, using these algorithms, each subchannel is regarded as a player. Therefore, the relay r_j with H_j subchannels should be extensively regarded as H_j *virtual relays*. For clarity, these virtual relays are denoted by r^v_{jk} for $k = 1, \cdots, H_j$, which leads to $q^*_{r^v_{j1}} = q^*_{r^v_{j2}} = \cdots = q^*_{r^v_{jH_j}} = q^*_{r_j}$. Moreover, we can have $\mathcal{R}^v = \{r^v_{11}, \cdots, r^v_{1H_1}, \cdots, r^v_{M1}, \cdots, r^v_{MH_M}\}$ as well. To ease the presentation, the j-th element of $\mathcal{R}^v$ is denoted by r^v_j and the corresponding EE becomes $q^*_{r^v_j}$. The Algorithm 2 summarizes the EE relay matching algorithm, where $|\mathcal{Y}|$ measure the volume of the set $\mathcal{Y}$. Note that when the Hungarian algorithm is applied, only the unilateral priority is taken into account, i.e. only the Phase I's EE $q^*_{s_i}$ is used to prioritize the D2D pairs.

C. BEEP SCHEME

Owing to the well-known bottle-neck effect, the end-to-end capacity of an arbitrary D2D pair is restrained by the phase with lower capacity, as illustrated in (10). In other words, the phase with higher capacity can possibly cause some extra power consumption to sustain the non-necessary higher capacity. That is to say reducing the transmission power for the phase with higher capacity can definitely save power

Algorithm 1 Iterative Power Allocation Algorithm for Obtaining $q^*_{s_i}$ and $q^*_{r_j}$

1: **Input**: $\mathcal{P}$, $\mathcal{R}$, $\hat{P}_{r_j,d_i}$, $\hat{P}_{s_i,r_j}$, P_{cir}, η, h_{s_i,r_j}, h_{r_j,d_i}, h_{LI}, P^{max}_s, P^{max}_r, U^{min}_s, U^{min}_r
2: **Output**: $q^*_{s_i}$, $q^*_{r_j}$, $P^*_{s_i,r_j}$, $P^*_{r_j,d_i}$.
3: **Initialize**: q_{s_i}, q_{r_j}, N_{max}, ε_s, ε_r, $\hat{P}_{s_i,r_j}$, $\hat{P}_{r_j,d_i}$.
4: *for* $\mathfrak{p}_i \in \mathcal{P}$
5:   *for* $r_j \in \mathcal{R}$
6:     *while* $n < N_{max}$ *do*
7:       $\varsigma_1 = 0$; $\varsigma_2 = 0$
8:       obtain $\hat{P}_{s_i,r_j}(n)$ using (A.3)
9:       *if* $\left|U_{s_i}[\hat{P}_{s_i,r_j}(n)] - q_{s_i}(n)T_{s_i}[\hat{P}_{s_i,r_j}(n)]\right| < \varepsilon_s$
10:         $P^*_{s_i,r_j} = \hat{P}_{s_i,r_j}(n)$
11:         $q^*_{s_i} = U_{s_i}(P^*_{s_i,r_j})/T_{s_i}(P^*_{s_i,r_j})$
12:         $\varsigma_1 = 1$
13:       *else*
14:         $q_{s_i}(n+1) = U_{s_i}[\hat{P}_{s_i,r_j}(n)]/T_{s_i}[\hat{P}_{s_i,r_j}(n)]$
15:       *end if*
16:       obtain $\hat{P}_{r_j,d_i}(n)$ using (A.6).
17:       *if* $\left|U_{r_j}[\hat{P}_{r_j,d_i}(n)] - q_{r_j}(n)T_{r_j}[\hat{P}_{r_j,d_i}(n)]\right| < \varepsilon_r$
18:         $P^*_{r_j,d_i} = \hat{P}_{r_j,d_i}(n)$
19:         $q^*_{r_j} = U_{r_j}(P^*_{r_j,d_i})/T_{r_j}(P^*_{r_j,d_i})$
20:         $\varsigma_2 = 1$
21:       *else*
22:         $q_{r_j}(n+1) = U_{r_j}[\hat{P}_{r_j,d_i}(n)]/T_{r_j}[\hat{P}_{r_j,d_i}(n)]$
23:       *end if*
24:       *if* $\varsigma_1 = 1$ & $\varsigma_2 = 1$
25:         break
26:       *else*
27:         Update the iteration index: $n \to n+1$.
28:       *end if*
29:     *end while*
30:   *end*
31: *end*

Algorithm 2 Optimal EE Relay Matching Algorithm

Input: $\mathcal{P}$, $\mathcal{R}^v$, $q^*_{s_i}$, $q^*_{r^v_j}$
Output: $\mathbf{X}$
for $i = 1$ to $|\mathcal{P}|$ *do*
  sort the virtual relays for each D2D pair according to $q^*_{s_i}$ in decreasing order
end for
for $j = 1$ to $|\mathcal{R}^v|$ *do*
  sort the D2D pairs for each virtual relay according to $q^*_{r^v_j}$ in decreasing order.
end for
Apply the Gale-Shapley (or Hungarian) algorithm to find the matrix $\mathbf{X}$.

without incurring any loss of the end-to-end capacity. Therefore, when $C_{\ell^I_{i,j}} > C_{\ell^{II}_{j,i}}$, the Phase I's transmission power

TABLE 1. Simulation parameters.

Simulation Parameters	Values
Number of D2D pairs (N)	$2-20$
Number of relays (M)	5
Cell radius	300 m
Distance between the two ends of a D2D pair	$(50, 200]$ m [16]
Maximum Tx power P_s^{max}, P_r^{max}	100 mW
Circuit power P_{cir}	50 mW
Minimum spectrum efficiency U_s^{min}, U_r^{min}	1 bit/s/Hz
PA efficiency η	35%
Subchannel bandwidth W	100 MHz
Subchannel numbers of relay H_j	4
Path loss exponent α	2, 2.5 [16]
Std. of the Log-normal shadowing σ	6.56, 10 dB [16]
Average power of the residual SI h_{LI}	-100 dB [13], [18]–[21]
Power spectrum density of the AWGN N_0	-174 dBm/Hz
Antenna half power beamwidth θ_{HP}^t, θ_{HP}^r	15°
Antenna gain for main-lobe M^t, M^r	10 dB
Antenna gain for side-lobe m^t, m^r	-5 dB

$\tilde{P}_{s_i,r_j}$ can just be adjusted to maintain $C_{\ell_{i,j}^I} = C_{\ell_{j,i}^{II}}$, which results in

$$\tilde{P}_{s_i,r_j} = \frac{1}{h_{s_i,r_j}} \left(2^{C_{\ell_{j,i}^{II}}/W} - 1\right)\left(P^*_{r_j,d_i} h_{LI} + WN_0\right). \tag{18}$$

Similarly, for the case with $C_{\ell_{i,j}^I} < C_{\ell_{j,i}^{II}}$, we can have

$$\tilde{P}_{r_j,d_i} = \frac{1}{h_{r_j,d_i}} \left(2^{C_{\ell_{i,j}^{I}}/W} - 1\right)\left(P^*_{s_i,r_j} h_{s_i,d_i} + WN_0\right). \tag{19}$$

IV. SIMULATION RESULTS

In this section, we compare the performance of the proposed BEEPER algorithm with the conventional power efficient relay selection (PRS) scheme in [15] using the performance metrics of the end-to-end EE, average transmission power of D2D pairs, average transmission power of relays and the well-known Jain's fairness index, which is defined as

$$\mathcal{J}(x_1, x_2, \cdots, x_n) = \frac{\left(\sum_{i=1}^n x_i\right)^2}{n \cdot \sum_{i=1}^n x_i^2}. \tag{20}$$

Also, to investigate the effectiveness of the BEEP scheme, the algorithm without it (i.e. the solely NFP-based IPA scheme with the EE relay matching algorithm) is added into the performance comparisons. To facilitate the discussions, it is denoted by ER in the following figures. Moreover, for a fair comparison, the assumption of the equal sum capacity is made. To be specific, by properly adjusting the constraint of the end-to-end capacity in the PRS scheme, the same sum rate as achieved by the BEEPER algorithm can be obtained. To make the discussions more complete, the two most well-known matching algorithms are considered, i.e. the Hungarian and Gale-Shapley algorithms; and two sets of the environmental parameters are taken into account as well. In the smooth environment, the path loss exponent α and std. of the log-normal shadowing σ are 2 and 6.56 dB; whereas they becomes 2.5 and 10 dB in the harsh environment. In addition, the same power of residual SI is assumed for each relay. The rest of the simulation parameters are listed in Table 1.

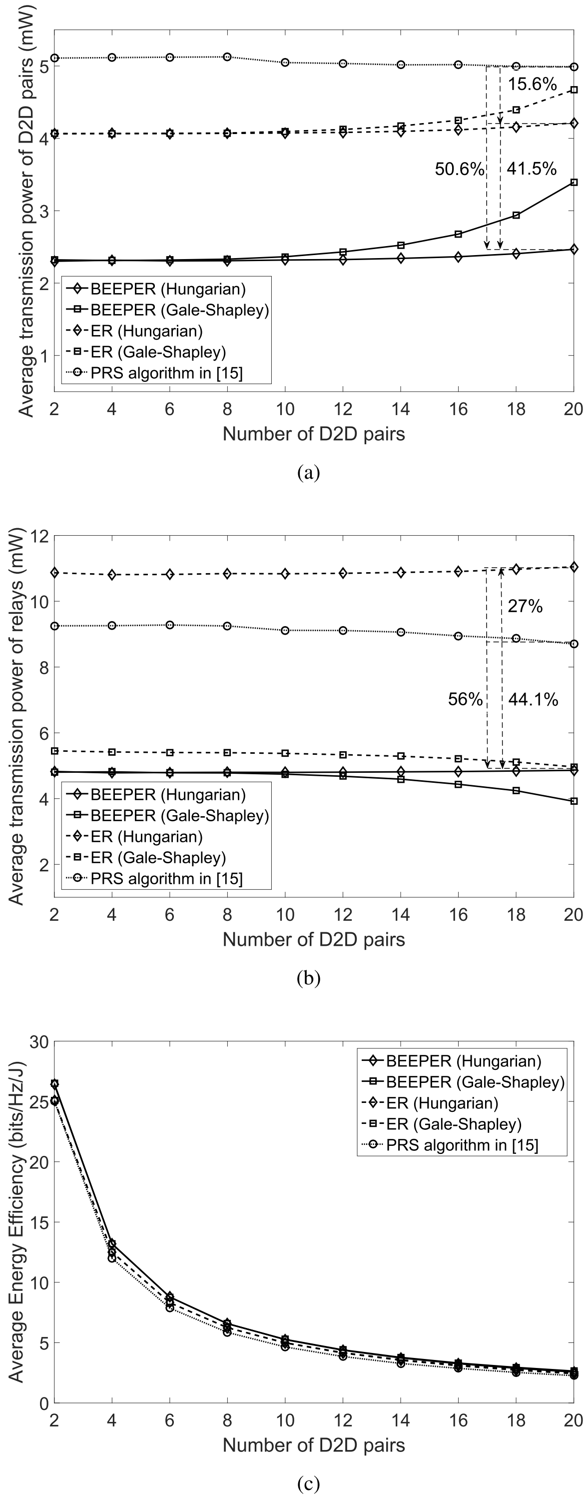

FIGURE 2. Performance of the (a) Average transmission power of D2D pairs, (b) Average transmission power of relays, and (c) Average energy efficiency with respective to the number of D2D pairs for the proposed BEEPER and conventional PRS schemes in the smooth environment, where the number of relays is $|\mathcal{R}| = 5$.

A. SMOOTH ENVIRONMENT WITH $\alpha = 2$ AND $\sigma = 6.56$ dB

Fig. 2 shows the (a) average transmission power of D2D pairs, (b) average transmission power of relays, and

TABLE 2. Improvement of EE, as demonstrated in Fig. 2(c) for the various proposed schemes, compared with the conventional PRS scheme in the smooth environment.

No. of D2D pairs	4	12	20
BEEPER (Hungarian)	10.1%	13.6%	13.1%
BEEPER (Gale-Shapley)	9.9%	14.2%	16.7%
ER (Hungarian)	4.3%	7.4%	7.0%
ER (Gale-Shapley)	4.2%	8.3%	10.6%

(c) average energy efficient with respective to the number of D2D pairs for the proposed BEEPER and conventional PRS schemes in the smooth environment, where the number of relays is $|\mathcal{R}| = 5$. Note that the PRS scheme in [15] applied the Hungarian algorithm to solve the matching problem. Therefore, the following performance comparisons are conducted based on the assumption of using the Hungarian matching algorithm. Apparently, it can be found that the proposed BEEPER algorithm can significantly outperform the conventional PRS counterpart. For example, using the Hungarian matching algorithm with 20 D2D pairs, the D2D's and relay's average transmission power can be reduced by 50.6% and 44.1%, respectively. And consequently, the EE (as listed in Table 2) can be raised by 13.1%, while it can be 16.7% for the case of using the Gale-Shapley matching scheme. Note that owing to the circuit power, the EE can not explicitly reflect the saved power consumption.

Observing the performance curves of the BEEPER and ER scheme, one can find that the BEEP along can contribute remarkable performance improvements. As shown in Fig. 2(a), among the mentioned 50.6% improvement, more than a half of the increment is incurred by the BEEP method. Moreover, as shown in Fig. 2(b), using the BEEP method can largely reduce the relay's transmission power by 56%. It should be noticed that in the Hungarian algorithm, the Phase I's EE is used to prioritize the D2D pairs for matching with the relays, while the Gale Shapley algorithm takes the bipartite priorities into account. In other words, the Hungarian algorithm favors the D2D pairs rather than the relays, which explains the relay's higher transmission power for the ER(Hungarian) scheme. This phenomenon can also be observed when the comparisons are made between the BEEPER(Hungarian) and BEEPER(Gale-Shapley) schemes. However, the performance differences become significant only when the number of D2D pairs is large. Furthermore, the BEEP method can contribute to the additional 6.1% enhancement in EE.

B. HARSH ENVIRONMENT WITH $\alpha = 2.5$ AND $\sigma = 10$ dB

Fig. 3 shows the (a) average transmission power of D2D pairs, (b) average transmission power of relays, and (c) average energy efficient with respective to the number of D2D pairs for the proposed BEEPER and conventional PRS schemes in the harsh environment, where the number of relays is $|\mathcal{R}| = 5$. It is obviously to find the similar performance trends as those observed from Fig. 2. However, compared with the cases in the smooth environment, the effectiveness of the BEEP method becomes relatively smaller in terms of the D2D's and relay's transmission power; whereas the larger improvement in the aspect of the EE can be observed. Most importantly, more significant performance enhancement

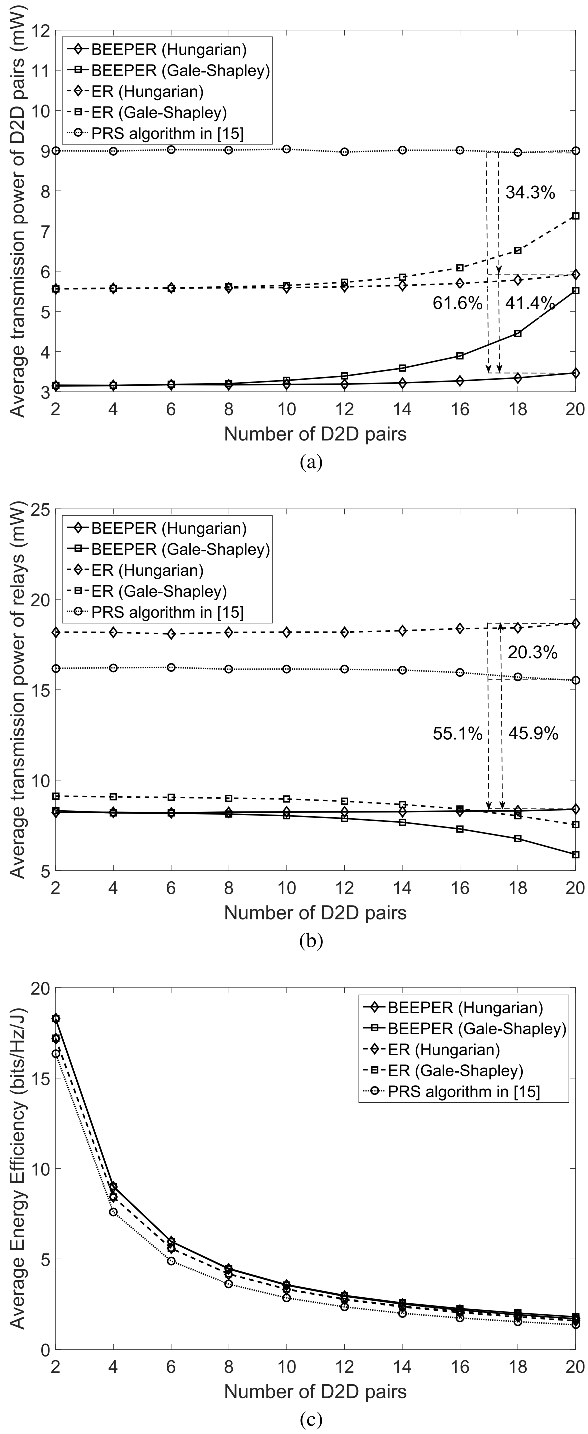

FIGURE 3. Performance of the (a) Average transmission power of D2D pairs, (b) Average transmission power of relays, and (c) Average energy efficiency with respective to the number of D2D pairs for the proposed BEEPER and conventional PRS schemes in the harsh environment, where the number of relays is $|\mathcal{R}| = 5$.

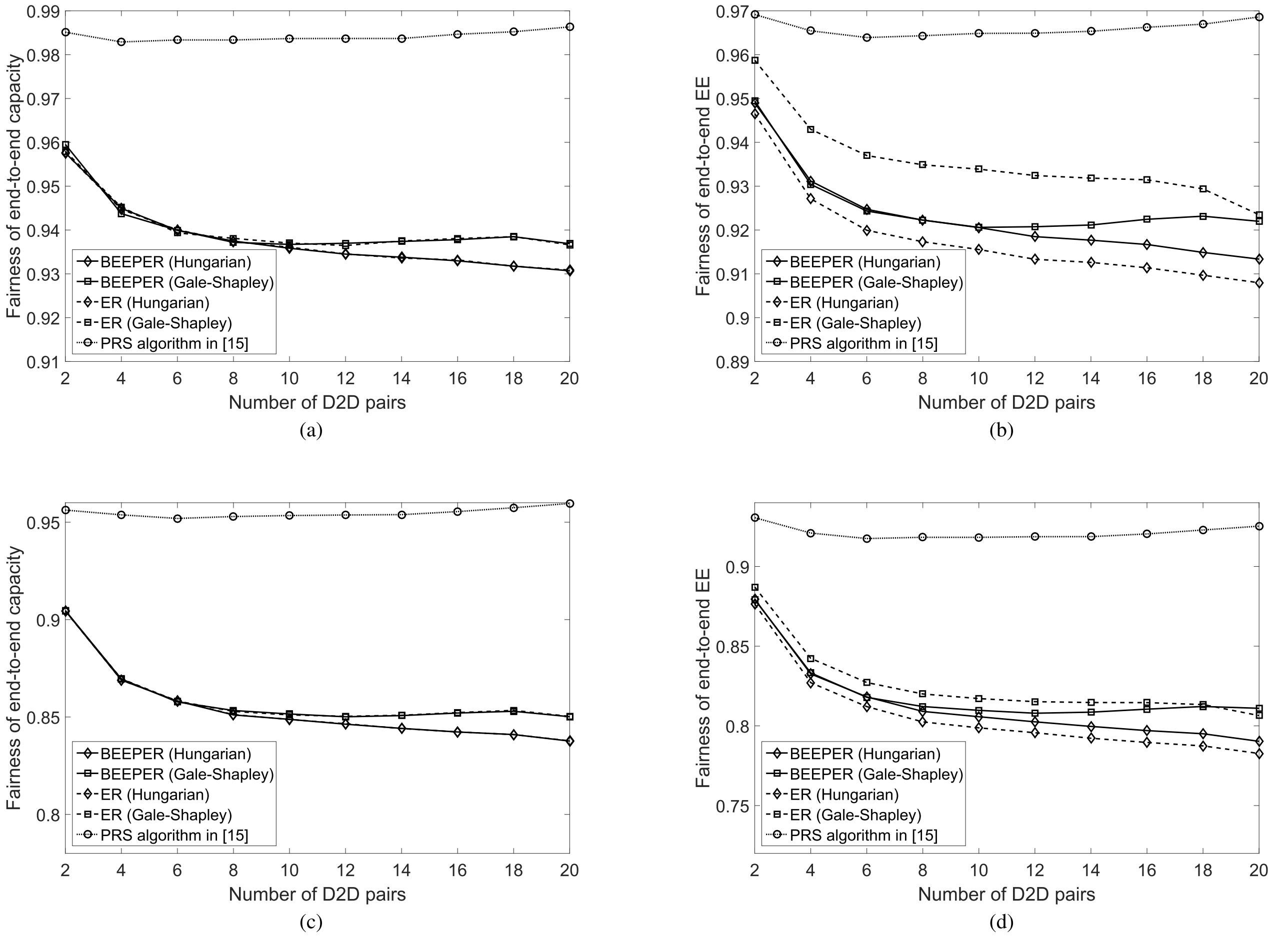

FIGURE 4. The Jain's fairness index of the end-to-end capacity and EE with respective to the number of D2D pairs in the smooth and harsh environments, where the number of relays is $|\mathcal{R}| = 5$. (a) End-to-end capacity (smooth environment). (b) End-to-end EE (smooth environment). (c) End-to-end capacity (harsh environment). (d) End-to-end EE (harsh environment).

TABLE 3. Improvement of EE, as demonstrated in Fig. 2(c) for the various proposed schemes, compared with the conventional PRS scheme in the harsh environment.

No. of D2D pairs	4	12	20
BEEPER (Hungarian)	18.5%	25.2%	24.8%
BEEPER (Gale-Shapley)	18.8%	26.9%	32.3%
ER (Hungarian)	11.0%	17.1%	16.4%
ER (Gale-Shapley)	11.3%	18.6%	23.2%

can be obtained by using the proposed BEEPER algorithm. For example, the aforementioned 50.6%, 44.1% and 13.1% improvements become 61.6%, 45.9% and 24.8%, respectively. Note that as listed in Table 3, 32.3% enhancement of EE can be obtained when the Gale-Shapley matching algorithm is applied. Also, in the harsh environment with a larger σ, using a proper transmission power to sustain its comparable end-to-end capacity is more reasonable to attain the minimum capacity requirement using a much larger transmission power.

C. THE JAIN'S FAIRNESS INDEX

Fig. 4 shows the well-known Jain's fairness index of the end-to-end capacity and EE with respective to the number of D2D pairs in the smooth and harsh environments, where the number of relays is $|\mathcal{R}| = 5$. As shown in the figures, the fairness index of the proposed scheme is slightly less than the conventional PRS scheme in the smooth environment; whereas, the performance gap grows in the harsh environment. Despite of this fact, it can still be maintained at the well-performed level. For example, with 10 D2D pairs in the smooth environment, the fairness index for proposed BEEPER scheme can be 0.94 and 0.92 in terms of the end-to-end capacity and EE, respectively. However, they become 0.85 and 0.81 for the cases in the harsh environment. In contrast to the largely reduced power consumption, this minor sacrifice is acceptable and worthful.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we have developed the BEEPER algorithm to boost the EE for the full duplex relay-assisted D2D network using mmWave technology. In the BEEPER algorithm, the NFP method is firstly applied to solve the nonconvex EE problem; and then the IPA algorithm is utilized to maximize the EE for all possible associations between the relays and D2D pairs. Then, based on the preference lists made according to the EE, the Gale-Shapely and Hungarian matching algorithms are used to pair the relays and D2D pairs. On the top of the pairing results, the BEEP scheme is applied to further reduce the power consumption while maintaining the same end-to-end capacity. In one of our considered cases, the proposed BEEPER algorithm can reduce the power consumption for the relay and D2D pairs by 45.9% and 61.6%, respectively. Moreover, the EE can be raised by 32.3% as well. Some suggestions for the future works include: (1) spectrum reuse scheme for the considered full duplex relay-aided mmWave D2D communications; (2) extension of the two-hop relaying scheme to the multi-hop relaying scenario; (3) optimal routing path and scheduling algorithms for the concurrent transmissions in the multi-hop relaying scenario.

APPENDIX

In this Appendix, we solve the optimization problems of (16) and (17) to attain the $\hat{P}_{s_i,r_j}$ and $\hat{P}_{r_j,d_i}$, respectively. Firstly, the augmented Lagrangian for the optimization problem of (16) at the n-th iteration can be defined as

$$\begin{aligned} L_{s_i}(P_{s_i,r_j}, \delta_{s_i}, \theta_{s_i}) &= U_{s_i}\big(P_{s_i,r_j}(n)\big) - q_{s_i}(n)T_{s_i}\big(P_{s_i,r_j}(n)\big) \\ &\quad - \delta_{s_i}(n)\big(P_{s_i,r_j}(n) - P_s^{\max}\big) \\ &\quad + \theta_{s_i}(n)\Big[U_{s_i}\big(P_{s_i,r_j}(n)\big) - U_s^{min}\Big], \end{aligned} \tag{A.1}$$

where $\delta_{s_i}(n)$ and $\theta_{s_i}(n)$ are the Lagrange multipliers for the constraints (11e) and (11g). By exploiting Lagrange dual decomposition, (A.3) can be decomposed into the following min max problem [25]

$$\min_{(\delta_{s_i},\theta_{s_i}\geq 0)} \max_{(P_{s_i,r_j})} L_{s_i}(P_{s_i,r_j}, \delta_{s_i}, \theta_{s_i}). \tag{A.2}$$

Then, using Karush-Kuhn-Tucker (KKT) conditions renders the optimal solution of $\hat{P}_{s_i,r_j}(n)$ corresponding to $q_{s_i}(n)$ as

$$\hat{P}_{s_i,r_j}(n) = \left[\frac{\eta[1+\theta_{s_i}(n)]\log_2 e}{q_{s_i}(n)+\eta\delta_{s_i}(n)} - \frac{\hat{P}_{r_j,d_i}(n)h_{LI} + WN_0}{h_{s_i,r_j}}\right]^+, \tag{A.3}$$

where $[x]^+ = \max\{0, x\}$. In addition, through the gradient method [26], the Lagrange multipliers can be updated as

$$\delta_{s_i}(n,\tau+1) = [\delta_{s_i}(n,\tau) + \epsilon_{s_i,\delta}(n,\tau)(\hat{P}_{s_i,r_j}(n,\tau) - P_s^{max})]^+ \tag{A.4}$$

and

$$\theta_{s_i}(n,\tau+1) = [\theta_{s_i}(n,\tau) - \epsilon_{s_i,\theta}(n,\tau)(U_{s_i}(n,\tau) - U_s^{min})]^+, \tag{A.5}$$

where τ denotes the iteration of the updating procedure for the Lagrange multipliers; $\epsilon_{s_i,\delta}$ and $\epsilon_{s_i,\theta}$ are the step sizes. Following the same procedure of obtaining $\hat{P}_{s_i,r_j}$, we can have $\hat{P}_{r_j,d_i}(n)$ corresponding to $q_{r_j}(n)$ as

$$\hat{P}_{r_j,d_i}(n) = \left[\frac{\eta[1+\xi_{r_j}(n)]\log_2 e}{q_{r_j}(n)+\eta\rho_{r_j}(n)} - \frac{P^*_{s_i,r_j}h_{s_i,d_i} + WN_0}{h_{r_j,d_i}}\right]^+, \tag{A.6}$$

where $\xi_{r_j}(n)$ and $\rho_{r_j}(n)$ are the Lagrange multipliers for the constraints (11f) and (11h). Similarly, $\xi_{r_j}(n)$ and $\rho_{r_j}(n)$ can be updated as those listed in (A.4) and (A.5), respectively.

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