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Energy-Efficient Stable Matching for Resource Allocation in Energy Harvesting-Based Device-to-Device Communications

ZHENYU ZHOU[1], (Member, IEEE), CAIXIA GAO[1], CHEN XU[1], (Member, IEEE), TAO CHEN[2], (Member, IEEE), DI ZHANG[3], (Member, IEEE), SHAHID MUMTAZ[4], (Member, IEEE)

[1]State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 102206, China
[2]VTT Technical Research Centre of Finland Ltd, 02150 Espoo, Finland
[3]GITS/GITI, Waseda University, Tokyo 169-8050, Japan
[4]IT-Instituto de Telecomunicações, 3810-193 Aveiro, Portugal

Corresponding author: Chen Xu (chen.xu@ncepu.edu.cn)

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ABSTRACT The explosive growth of mobile date traffic and ubiquitous mobile services cause an high energy consumption in mobile devices with limited energy supplies, which has become a bottleneck for deploying device-to-device (D2D) communication. Simultaneous wireless information and power transfer (SWIPT), which enables mobile devices to harvest energy from the radio frequency signals, has emerged as a promising solution to improve the energy efficiency (EE) performance. In this paper, we address joint power control and spectrum resource allocation problem in SWIPT-based energy-harvesting D2D underlay networks. First, we formulate joint optimization problem as a 2-D matching between D2D pairs and cellular user equipments (CUEs), and propose a preference establishment algorithm based on Dinkelbach method and Lagrange dual decomposition. Second, we propose an energy-efficient stable matching algorithm by exploring the Gale-Shapley algorithm, which is able to maximize the EE performance of D2D pairs and the amount of energy harvested by CUEs simultaneously. Third, we provide in-depth theoretical analysis of the proposed matching algorithm in terms of stability, optimality, and complexity. Simulation results demonstrate that the proposed algorithm can bring significant EE performance gains compared with some heuristic algorithms.

INDEX TERMS Device-to-device communication, energy harvesting, SWIPT, resource allocation, matching theory.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Due to the explosive growth of intelligent terminals and mobile applications, the amount of mobile data traffic and the demand on higher data rate have been increasing dramatically. The conflict between the limited network bandwidth and the growing demands of users poses a significant challenge for cellular networks [1], [2]. Thus, novel technologies need to be investigated for updating current wireless network architecture [3]–[6]. Device-to-Device (D2D) communication, which enables mobile devices to transmit information over local direct links rather than through the base station (BS), has emerged as a key technology for future 5G system. By reusing the spectrum resources allocated to cellular user equipments (CUEs) under the control of the BS, D2D communication can be implemented as an underlay to cellular networks, which can significantly improve network capacity and spectrum efficiency (SE). Furthermore, D2D communication is expected to promote the development of new mobile applications and business models due to the enabled short-range communications.

The growing demand for higher data rate and ubiquitous mobile services have caused a high energy consumption in mobile devices with capacity-constrained batteries, which becomes a bottleneck of the network lifetime. Thus, the operation of D2D communications underlaying cellular networks does pose new challenges for resource allocation management because of the limited spectrum resources and battery capacity. Hence, energy-efficient resource allocation mechanism has become a promising solution to prolong the network lifetime in energy-constrained devices while simultaneously satisfying the stringent SE requirement. Some works have investigated energy-efficient resource allocation schemes to improve energy efficiency (EE) performance for D2D communications [7]–[12]. Authors in [7] and [8] analyzed the tradeoff between SE performance and EE performance theoretically. In [9], the authors developed a resource management scheme to improve EE performance of the system by employing coalition game model. In [10], an interference-aware energy-efficient resource allocation scheme was proposed by employing noncooperative game theory. Authors in [11] developed a resource allocation algorithm to improve the EE performance of users based on game model and matching theory. However, the above works have not incorporated energy harvesting (EH) technology to exploit the energy that can be obtained from ambient environments. With the emergence of EH-based wireless systems, novel resource allocation design schemes are urgently required to harness the full potentials of the harvested energy.

EH technology which enables user equipments (UEs) with limited battery capacity to harvest energy from numerous renewable energy sources including solar, wind, etc., has emerged as an appealing solution to prolong the lifetime of networks [13]–[18]. In [15], the authors proposed an energy-efficient resource management scheme utilizing statistical information of renewable energy, where the average grid power was minimized by adapting on-off states of the BS. Optimal power allocation scheme was developed in [16] by maximizing the sum rate of D2D pairs, where a solar EH model was considered. Authors in [17] studied back-off algorithms for medium access control protocols in D2D communications based on solar EH model, where the EH rate and residual energy were coordinated. And in [18], authors realized the solar EH framework in NS-3 simulator and evaluated the performance of routing protocols in D2D communications.

Due to the dependence on location and weather [19], [20], natural energy resources are not always available to be harvested. Simultaneous wireless information and power transfer (SWIPT), which enables the receivers to recycle the radiated radio frequency (RF) energy from the transmitters to extend their lifetimes and improve the EE, has attracted intensive research interests from both academia and industry [21]–[28]. With SWIPT, the traditional harmful noise and interference can be exploited by D2D communication to offer benefits for EE improvement.

There have been some works investigated D2D communications with SWIPT [29]–[31]. In these works, it is assumed that UEs can harvest energy from RF signals and use the harvested energy for data transmission. However, the mutual preferences and satisfactions of both D2D pairs and CUEs are ignored in most of the previous works. It is commonly assumed that every UE would follow the resource allocation mechanism even though a better performance can be achieved by disrupting it.

The above consideration of SWIPT and UEs' preferences and satisfactions would bring challenges to the system. Firstly, since both the interference and noise can be introduced as beneficial gains with SWIPT, resource allocation mechanisms for mobile devices should be redesigned. Secondly, the modeling of the preferences of UEs is difficult due to the dynamic variety of instantaneous channel states and interference levels. Thirdly, not all UEs would be satisfied with the same resource allocation mechanism owing to the fact that UEs may have diverse or even contradictory preferences.

B. CONTRIBUTIONS

In this paper, we propose an energy-efficient stable matching approach for the joint power control and spectrum resource allocation problem in EH-based D2D communication. The specific characteristics of SWIPT such as power splitting ratio [22], [27], the mutual preferences and satisfactions of UEs, and various practical constraints, including channel reusing, transmission power, and quality of service (QoS), etc., have been taken into consideration. The objective of the joint power control and partner selection problem is to maximize the EE performance of D2D pairs and the amount of energy harvested by CUEs, since every UE only cares about its individual utility and shows little concern to utilities of others. We formulate the original joint optimization problem as a two-dimensional matching between D2D pairs and CUEs, and employ nonlinear fractional programming [32], [33] and matching theory [34]–[36] to solve it. There have been some works on resource allocation optimization by employing matching theory to improve system SE performance [37]–[41] or EE performance [42]–[44], while some works have studied energy-efficient resource allocation schemes for D2D communications [45]–[47]. However, the RF energy that can be harvested form received signal power was ignored. By employing SWIPT, power control and partner selection between D2D pairs and CUEs should be jointly considered in our problem. The main contributions of this paper are summarized as follows:

- We propose an EH-based energy-efficient resource management scheme to solve the joint power control and partner selection problem between D2D pairs and CUEs. Specifically, a resource allocation optimization problem, which considers SWIPT-based EH technology, and preferences of UEs, is formulated as an mixed integer nonlinear programming (MINLP) problem under power, spectrum resource reusing and QoS constraints to optimize EE performance of D2D pairs and maximize the amount of energy harvested by CUEs. The formulation derived utilizes a continuous variable to represent power control strategy (how much transmission power should be assigned to D2D transmitter for the potential D2D-CUE partnership), and a binary variable to represent the partner selection decision (which D2D pair and which CUE can form a D2D-CUE partnership to share the same spectrum resource). To solve the above joint power control and partner selection problem, a *one-to-one matching* model that can match D2D pairs with CUEs based on their mutual preferences is introduced. Thus, the original NP-hard problem can be decomposed into two separate subproblems and solved in a tractable way.

- The establishment of mutual preferences from the perspective of EE for D2D pairs and the perspective of energy for CUEs is the main focus of our work. First, the preference lists of D2D pairs from one side over CUEs from the other side are established based on the maximum achieved EE under the specified D2D-CUE matching, where the power control problem of D2D pairs is solved based on Dinkelbach method. Then, based on the derived power control strategy of D2D pairs, the preference lists of CUEs over D2D pairs are established according to the maximum amount of energy harvested by CUEs. We propose a preference list establishment algorithm for both D2D pairs and CUEs by exploring nonlinear fractional programming and Lagrange dual decomposition [48].
- Based on the established mutual preference lists, we employ the Gale-Shapley (GS) algorithm to solve the formulated energy-efficient one-to-one matching problem. Moreover, the properties of the proposed EH-based energy-efficient matching algorithm including convergence, stability, optimality, and complexity are analyzed theoretically. In the simulation, the proposed algorithm is compared with three heuristic algorithms in terms of the EE performance under different scenarios. Simulation results show that the proposed scheme can achieve significant EE performance gains.

The remainder of this paper is organized as follows. Section II reviews the related works briefly. Section III presents the system model including channel model and power splitting model, and Section IV introduces the formulation of the EH-based joint power control and partner selection problem between D2D pairs and CUEs. Section V describes the EH-based energy-efficient matching algorithm and provides the relevant theoretical analysis. Section VI presents the simulation results and corresponding discussions. Finally, Section VII concludes the paper.

II. RELATED WORKS

Our previous studies mainly solved the peer discovery and resource allocation optimization problem and analyzed the tradeoff between SE and EE theoretically [10], [11], [41]. Moreover, we studied the power control problem in EH-based D2D communications, where UEs can harvest energy form renewable energy sources [49]. In comparison, this paper focuses on the resource allocation problem for SWIPT-based D2D communication, in which both the system model and problem formulation are different from the previous works.

Indeed, the concept of SWIPT was first proposed in [22], where the tradeoff between transmitting information and energy over a single-antenna additive white Gaussian noise (AWGN) channel was studied. Authors in [23] showed that there exists a nontrivial tradeoff between information and power transfer over frequency-selective fading channels. Then, SWIPT has been applied in numerous scenarios, including point-to-point wireless link system [26], orthogonal frequency division multiple access (OFDMA) system [27], multiple-input multiple-output (MIMO) broadcast network [50]–[52], multiple-input single-output (MISO) system [53]–[55], collaborative mobile cloud system [24], and small cell network [56]. For instance, an optimal power control and mode switching method and an optimal transmission scheme were proposed in [26] and [51], [52], respectively, both of which analyzed the tradeoff between information decoding and EH based on the determined rate-energy region. In [53], an optimal transmitting beamforming scheme was obtained to maximize the secrecy rate and the weighted transferred energy. In [54] and [55], the authors studied the design of secure beamforming with confidential messages and external eavesdroppers for MISO systems. Authors in [27] developed an energy-efficient resource allocation algorithm for SWIPT-based OFDMA system to improve the overall EE performance, where discrete and continuous power splitting ratios were considered under power, transmission delay and QoS constraints. In [24], the authors formulated a wireless power transfer enabled collaborative mobile clouds (WeCMC) model, and proposed a resource allocation scheme to minimize the energy consumption. In [56], the authors proposed a power allocation mechanism for BSs in small cells to optimize the achievable throughput and EH rate of UEs by designing power splitting and time switching variables.

In addition, RF signal-oriented EH technology has already been utilized for D2D communications to enhance the system performance. For instance, authors in [57] firstly derived the distribution of relay UEs by considering the impacts of EH parameters, and then developed a joint mode and relay selection scheme for EH-based D2D communications. While in [58], a D2D relay selection scheme was proposed to enhance the network coverage in public safety environment. Three power transfer policies in terms of the power transfer reliability and two receiver selection methods were studied in [59] to enhance the secrecy performance for D2D communications in large-scale cognitive cellular networks. In [60], spectrum access policies including prioritized and random access policies were investigated by employing stochastic geometry tools to evaluate the outage probability of UEs.

Moreover, resource allocation issues for EH-based D2D communications were investigated from different perspectives such as energy consumption, SE performance and EE performance. In [29], the authors considered the uplink spectrum reusing scenario, and proposed both static and dynamic spectrum allocation algorithms to minimize the total energy consumption under the QoS constraints.

In comparison, the authors in [30] considered the downlink spectrum reusing scenario and proposed a joint power and spectrum resource allocation scheme to optimize the system rate for D2D links. Besides, resource allocation problem between D2D pairs and CUEs can be modeled as a two-dimensional matching problem employing matching theory. Some works have investigated resource allocation problems considering mutual preferences for D2D communications. In [45], an energy-efficient resource allocation scheme based on matching theory was proposed for interference-limited and interference-free scenarios to derive a stable matching between D2D transmitters and relays. While in [46], the authors proposed two resource allocation schemes to optimize system EE performance and total individual EE performance, respectively. Matching theory was employed in [61] to solve the resource allocation problem in relay-aided D2D communications.

However, the above mentioned works have not provided an energy-efficient resource allocation scheme for EH-based D2D communication with the consideration of SWIPT and UEs' preferences.

III. SYSTEM MODEL

We study EH-based D2D communications underlaying cellular network, in which a cellular network with one BS and multiple UEs involving traditional CUEs and D2D UEs is considered. Since the BS is powered by the external grid, it makes no sense for the BS to harvest energy from RF signals. Thus, we assume that downlink (DL) resource blocks (RBs) occupied by CUEs can be reused by D2D links to enhance the system SE, and UEs with SWIPT can harvest RF energy to improve the EE performance. For simplicity, one RB is allocated to one CUE and can be reused by at most one D2D pair, which is formed by a pair of D2D transmitter (TX) and receiver (RX) meeting D2D communication requirements. As a result of downlink spectrum reusing, each CUE suffers from the co-channel interference caused by the D2D TX using the same channel, while each D2D RX suffers from the co-channel interference caused by the BS. The illustration of downlink spectrum sharing in EH-based D2D communications underlaying cellular network is shown in Fig. 1. In this paper, we mainly focus on the resource allocation problem based on the finished mode selection and peer selection process for D2D pairs, which includes power control and spectrum resource allocation for D2D pairs. Hence, the resource allocation problem can be formulated as a joint optimization problem of power control and partner selection between D2D pairs and CUEs .

A. CHANNEL MODEL

We assume that there are N D2D pairs, which are denoted by the set $\mathcal{D} = \{1, 2, \cdots, i, \cdots, N\}$. K RBs and the corresponding CUEs are denoted by the set $\mathcal{R}_K = \{R_1, R_2, \cdots, R_k, \cdots, R_K\}$ and $\mathcal{C}_K = \{C_1, C_2, \cdots, C_k, \cdots, C_K\}$, respectively. For the channel model, the Rayleigh fading is used to model the small-scale fading, and

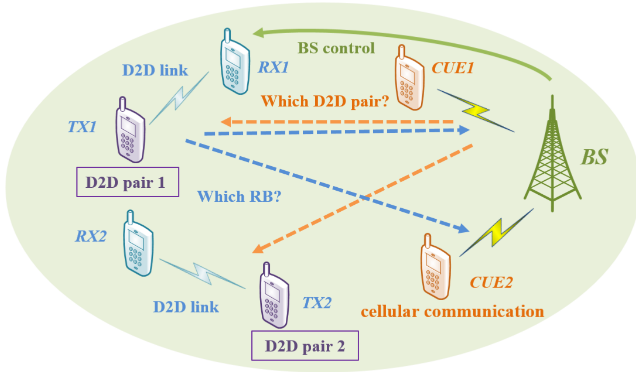

FIGURE 1. System model of EH-based resource allocation in D2D underlay cellular networks.

the free space propagation pathloss is used to model the large-scale fading. The received power of D2D pair $i \in \mathcal{D}$, and the received power of cellular link between the BS and CUE $C_k \in \mathcal{C}_K$, can be expressed as

$$P_{i,r}^D = P_{i,D}h_{i,D}^2 = P_{i,D}d_{i,D}^{-\alpha}h_{0,iD}^2, \tag{1}$$

$$P_{k,r}^C = P_{k,C}h_{k,C}^2 = P_{k,C}d_{k,C}^{-\alpha}h_{0,kC}^2. \tag{2}$$

$P_{i,D}$ and $P_{k,C}$ are the transmission power of D2D link i and cellular link between the BS and CUE C_k, respectively. $h_{i,D}$ and $h_{k,C}$ represent the channel response of the D2D link and the cellular link, respectively. $d_{i,D}$ is the transmission distance between TX and RX of D2D link i, while $d_{k,C}$ denotes the transmission distance between the BS and CUE C_k. α is the pathloss exponent corresponding to the large-scale fading of the transmission channel. $h_{0,iD}$ and $h_{0,kC}$ are the Rayleigh channel coefficients, which obey the complex Gaussian distribution $\mathcal{CN}(0, 1)$.

When D2D pair i reuses the downlink RB $R_k \in \mathcal{R}_K$, D2D RX receives interference from the BS, and the CUE $C_k \in \mathcal{C}_K$ receives interference from D2D TX. Then, the signal to interference plus noise ratio (SINR) of D2D link i on RB R_k and the SINR of CUE C_k are

$$\gamma_{i,k}^D = \frac{P_{i,D}h_{i,D}^2}{P_{k,C}h_{ki}^2 + \sigma_0^2 + \sigma_s^2}, \tag{3}$$

$$\gamma_{k,i}^C = \frac{P_{k,C}h_{k,C}^2}{P_{i,D}h_{ik}^2 + \sigma_0^2 + \sigma_s^2}. \tag{4}$$

h_{ki} and h_{ik} are the channel responses of the interference links between the BS and the RX of D2D link i, between the TX of D2D link i and CUE C_k, respectively. σ_0^2 is the power of the AWGN generated from the antenna, while σ_s^2 is the power of the signal processing noise at the receiver. Then, the channel rate of D2D link i reusing RB R_k and the rate of cellular link between the BS and CUE C_k are obtained by

$$r_{i,k}^D = \log_2\left(1 + \frac{P_{i,D}h_{i,D}^2}{P_{k,C}h_{ki}^2 + \sigma_0^2 + \sigma_s^2}\right), \tag{5}$$

$$r_{k,i}^C = \log_2\left(1 + \frac{P_{k,C}h_{k,C}^2}{P_{i,D}h_{ik}^2 + \sigma_0^2 + \sigma_s^2}\right). \tag{6}$$

B. POWER SPLITTING MODEL

In this paper, we assume that each mobile receiver consists of two units, i.e., traditional signal processing unit and EH unit, which can split the received radio signal into two separate signal streams for information decoding and EH simultaneously. Hence, the receiver can harvest energy from the received desired signals, interference signals and noise. As a result of downlink spectrum reusing, a CUE can scavenge energy from the BS and the D2D TX using the same channel, while a D2D RX can harvest energy from its corresponding D2D TX and the BS. In particular, we adopt a receiver that can split the received signal into two power streams with power splitting ratios δ_I and δ_E, which are utilized for information decoding and EH, respectively, and we have $\delta_I + \delta_E = 1$. The receiver would be a traditional information receiver when $\delta_I = 1, \delta_E = 0$; and an EH receiver when $\delta_I = 0, \delta_E = 1$. Subsequently, the achievable SE of the D2D pair i reusing RB R_k and that of cellular link between the BS and CUE C_k are obtained by

$$U_{ik,SE}^{D} = \log_2\left(1 + \frac{\delta_I P_{i,D} h_{i,D}^2}{\delta_I(P_{k,C} h_{ki}^2 + \sigma_0^2) + \sigma_s^2}\right), \tag{7}$$

$$U_{ki,SE}^{C} = \log_2\left(1 + \frac{\delta_I P_{k,C} h_{k,C}^2}{\delta_I(P_{i,D} h_{ik}^2 + \sigma_0^2) + \sigma_s^2}\right). \tag{8}$$

Meanwhile, the total power consumption of the D2D pair i is given by

$$T_{ik}^{D} = \frac{1}{\eta} P_{i,D} + 2P_{cir} - \delta_E \eta_E (P_{i,D} h_{i,D}^2 + P_{k,C} h_{ki}^2 + \sigma_0^2), \tag{9}$$

and the amount of energy harvested by CUE C_k can be obtained by

$$E_{ki}^{C} = \delta_E \eta_E (P_{k,C} h_{k,C}^2 + P_{i,D} h_{ik}^2 + \sigma_0^2). \tag{10}$$

η is the power amplifier (PA) efficiency, i.e., $0 < \eta < 1$. P_{cir} is the circuit power consumption of any type of UE including values of mixer, frequency synthesizer, etc., while the power consumption of the BS is ignored as it is powered by the external grid. The third term of (9) as well as (10) represent the amount of energy harvested from desired signals, interference signals and noise at RX of D2D pair i and CUE C_k, respectively. η_E is a constant which represents the EH efficiency in converting the received radio signal into electrical energy at any mobile receiver.

IV. PROBLEM FORMULATION

The purpose of this work is to maximize the EE performance of D2D links and the amount of energy harvested at CUEs by designing an efficient resource allocation mechanism. Hence, we need to consider a joint optimization problem of power control and partner selection between D2D pairs and CUEs, both of which can harvest energy from desired signals, interference signals and noise. Furthermore, we formulate the objective function of D2D links as the EE (bits/Hz/J) performance, which is defined as the ratio of SE (bits/Hz/s) to the total power consumption (W). The EE function of the D2D pair i which reuses RB R_k, is obtained by

$$U_{ik,EE}^{D} = \frac{U_{ik,SE}^{D}}{T_{ik}^{D}} = \frac{\log_2\left(1 + \frac{\delta_I P_{i,D} h_{i,D}^2}{\delta_I(P_{k,C} h_{ki}^2 + \sigma_0^2) + \sigma_s^2}\right)}{\frac{1}{\eta} P_{i,D} + 2P_{cir} - \delta_E \eta_E (P_{i,D} h_{i,D}^2 + P_{k,C} h_{ki}^2 + \sigma_0^2)}, \tag{11}$$

and the objective function of CUE C_k is formulated as the total amount of energy harvested from RF signals, i.e., E_{ki}^{C}. To explicitly denote the partner selection strategies between D2D pairs and CUEs, we define that:

Definition 1: The two-dimensional $N \times K$ pairing matrix $\mathbf{X}$ denotes the partner selection strategies between D2D pairs and CUEs, where each element $x_{i,k} \in \{0, 1\}$ is a binary variable to represent the partner selection decision of the D2D-CUE partnership (i, C_k). $x_{i,k} = 1$ denotes that D2D pair i and CUE C_k form a D2D-CUE partnership, i.e., D2D pair i reuses the RB R_k allocated to CUE C_k; $x_{i,k} = 0$, otherwise.

Accordingly, we jointly design the partner selection decision variables $\{x_{i,k}\}$ and the continuous power control strategies $P_{i,D}$ to maximize the EE performance of D2D links and the amount of energy harvested by CUEs. The joint power control and partner selection problem for D2D pair i can be formulated as

$$\begin{aligned} \max_{\{P_{i,D}, x_{i,k}\}_{k=1}^{K}} \quad & x_{i,k} U_{ik,EE}^{D}(P_{i,D}) \\ \text{s.t. } c_{i,1}^{D}: \; & 0 \le P_{i,D} \le P_{max}, \\ c_{i,2}^{D}: \; & U_{ik,SE}^{D} \ge U_{SE,min}^{D}, \quad \forall C_k \in \mathcal{C}_K, \\ c_{i,3}^{D}: \; & x_{i,k} = \{0, 1\}, \quad \forall C_k \in \mathcal{C}_K, \\ c_{i,4}^{D}: \; & \sum_{C_k \in \mathcal{C}_K} x_{i,k} \le 1. \end{aligned} \tag{12}$$

Constraint $c_{i,1}^{D}$ gives the transmission power range of D2D TXs, which ensures the power of D2D TXs should not exceed the maximum power P_{max}. $c_{i,2}^{D}$ guarantees the QoS requirement of D2D links, and $U_{SE,min}^{D}$ denotes the QoS threshold. $c_{i,3}^{D}$ and $c_{i,4}^{D}$ ensure that one D2D pair can reuse at most one RB.

Then, the partner selection problem for CUE C_k is given by

$$\begin{aligned} \max_{\{x_{i,k}\}_{i=1}^{N}} \quad & x_{i,k} E_{ki}^{C} \\ \text{s.t. } c_{k,1}^{C}: \; & U_{ki,SE}^{C} \ge U_{SE,min}^{C}, \quad \forall i \in \mathcal{D}, \\ c_{k,2}^{C}: \; & x_{i,k} = \{0, 1\}, \quad \forall i \in \mathcal{D}, \\ c_{k,3}^{C}: \; & \sum_{i \in \mathcal{D}} x_{i,k} \le 1. \end{aligned} \tag{13}$$

$c_{k,1}^{C}$ gives the QoS requirement of the cellular links, and $U_{SE,min}^{C}$ denotes the QoS threshold. $c_{k,2}^{C}$ and $c_{k,3}^{C}$ guarantee that each RB can be reused by at most one D2D pair.

V. ENERGY-EFFICIENT STABLE MATCHING ALGORITHM FOR EH-BASED D2D COMMUNICATION

In this section, we investigate the proposed EH-based energy-efficient stable matching approach to solve the formulated joint power control and partner selection problem. We firstly introduce some basic concepts of our proposed algorithm. Then, we develop an iterative algorithm to establish mutual preference lists between D2D pairs and CUEs, which are critical for the introduced one-to-one matching model. The mutual preference lists are obtained mainly based on the optimal EE performance of D2D pairs and maximum amount of energy harvested by CUEs, which involves power control process for D2D pairs based on nonlinear fractional programming. Afterwards, we present the proposed EH-based energy-efficient stable matching algorithm, which aims at deriving a stable matching between D2D pairs and CUEs by exploiting GS algorithm. Finally, we provide theoretical analysis of the properties of the proposed matching algorithm, which involves convergence, stability, optimality, and computational complexity.

A. MATCHING CONCEPTS

The formulation combining (12) and (13), which considers the joint power control and partner selection problem and involves both binary and continuous variables for optimization of resource allocation, is an NP-hard MINLP problem. Hence, neither nonlinear fractional programming nor integer programming can be utilized to solve the formulation directly. Moreover, the two approaches may cause an unstable and unsatisfied resource allocation, since UEs' preferences and satisfactions are not taken into consideration. Thus, we formulate a two-dimensional matching problem with N D2D pairs on one side and K CUEs on the other side. And we introduce a one-to-one matching model to form a stable matching between D2D pairs and CUEs based on their mutual preferences, aiming to maximize the EE performance of D2D links and the amount of energy harvested by CUEs under power and QoS constraints. Based on the concepts of matching theory [41], we have the definition as below:

Definition 2: A matching Ψ is a one-to-one correspondence from the set $\mathcal{D} \cup \mathcal{C}_K$ onto itself, which is denoted by $\Psi : \mathcal{D} \cup \mathcal{C}_K \rightarrow \mathcal{D} \cup \mathcal{C}_K$. For $i \in \mathcal{D}$, $\Psi(i) \in \mathcal{C}_K \cup \{i\}$ and for $C_k \in \mathcal{C}_K$, $\Psi(C_k) \in \mathcal{D} \cup \{C_k\}$. $\Psi(i) = C_k$ if and only if $\Psi(C_k) = i$, which means that D2D pair i reuses the RB R_k allocated to CUE C_k.

If $\Psi(i) = i$ or $\Psi(C_k) = C_k$, D2D pair i or CUE C_k stays single. Thus, D2D pair i or CUE C_k can request for forming a matching with its preferred partner according to its preference list and derive the transmission power allocated to the D2D pair for the formed matching. We assume that D2D pairs and CUEs only concern about their own partners rather than matching results of others, which is valid as a result of the individualism and independence of UEs. Furthermore, if there exists a D2D-CUE partnership formed by D2D pair i and CUE C_k that are not matched with each other under matching Ψ but prefer each other to be their partner, i.e., expressed as $C_k >_i \Psi(i)$ and $i >_{C_k} \Psi(C_k)$, Ψ is said to be blocked by the partnership (i, C_k), namely a *blocking pair*. Thus, Ψ is unstable due to the fact that i and C_k would prefer to disrupt the matching to pair with each other. We define that:

Definition 3: A matching Ψ is stable if there exists no D2D-CUE blocking pair.

B. PROCESS OF PREFERENCE ESTABLISHMENT

As individuals on one side need to propose to establish partnership with ones on the other side in a matching model, the mutual preference lists are critical for the matching process. Since the joint power control and partner selection problem is formulated as a two-dimensional one-to-one matching problem with N D2D pairs on one side and K CUEs on the other side, it is necessary to obtain the preference lists of D2D pairs on CUEs as well as that of CUEs on D2D pairs.

1) PREFERENCE ESTABLISHMENT FOR D2D PAIRS

For any D2D pair i, the optimization goal is to maximize its own EE performance by optimizing partner selection decision variable $x_{i,k}$ and power variable $P_{i,D}$. Hence, we formulate the preference value of D2D pair i on CUE C_k as the maximum achievable EE under the matching $\Psi(i) = C_k$. In this case, only the power variable $P_{i,D}$ needs to be optimized, since that the partner selection decision of D2D pair i has been determined. The power control problem for D2D pair i under this matching is formulated as

$$\max_{\{P_{i,D}\}} U^D_{ik,EE} \quad \text{s.t. } c^D_{i,1}, c^D_{i,2}. \tag{14}$$

Thus, the maximum achievable EE of D2D pair i when matching with CUE C_k can be derived by solving (14). However, as a result of the fractional form of $U^D_{ik,EE}$, the formulation in (14) is nonconvex and cannot be solved directly by any existing tractable approach. Therefore, we employ nonlinear fractional programming [32] to transform the nonconvex problem to an equivalent convex problem. We define the optimal value of (14), i.e., the achievable maximum EE of D2D pair i under matching $\Psi(i) = C_k$ as

$$q^{D*}_{ik} = \max_{\{P_{i,D}\}} U^D_{ik,EE}(P_{i,D}) = \frac{U^D_{ik,SE}(P^*_{i,D})}{T^D_{ik}(P^*_{i,D})}, \tag{15}$$

where $P^*_{i,D}$ is the optimal power control strategy of D2D pair i when matching with CUE C_k. According to [32], we can derive the following theorem:

Theorem 1: The optimum q^{D*}_i can be achieved if and only if

$$\max_{\{P_{i,D}\}} U^D_{ik,SE}(P_{i,D}) - q^{D*}_{ik} T^D_{ik}(P_{i,D}) = U^D_{ik,SE}(P^*_{i,D}) - q^{D*}_{ik} T^D_{ik}(P^*_{i,D}) = 0. \tag{16}$$

Theorem 1 indicates that the same optimal EE and power control strategy can be obtained by solving the optimization problem with the objective function in subtractive form, i.e., $U^D_{ik,SE}(P_{i,D}) - q^{D*}_{ik}T^D_{ik}(P_{i,D})$, which is transformed by the original optimization problem with the objective function in fractional form. The equivalent transformed optimization problem is obtained by

$$\max_{\{P_{i,D}\}} \; U^D_{ik,SE}(P_{i,D}) - q^{D*}_{ik}T^D_{ik}(P_{i,D}) \quad \text{s.t. } c^D_{i,1}, c^D_{i,2}. \tag{17}$$

The transformed optimization problem (17) is a convex optimization problem for power variable $P_{i,D}$ ignoring that q^{D*}_{ik} is unknown. Thus, in order to obtain q^{D*}_{ik} and optimal power control strategy $P^*_{i,D}$, (17) is regarded as a multi-objective convex optimization problem and q^{D*}_{ik} is viewed as the negative weight of T^D_{ik}. Then, an iterative algorithm based on Dinkelbach method is developed to find q^{D*}_{ik} and summarized in Algorithm 1. For any matching partnership formed by D2D pair i and CUE C_k, the algorithm would stop when the stopping criteria Δ or the maximum iteration number I is reached, and the corresponding optimal power control strategy for D2D pair i can be derived.

Algorithm 1 Iterative Power Control Algorithm

```
Input: 𝒞_K, 𝒟, ℛ_K, P_max, U^D_{SE,min}.
Output: q^{D*}_{ik}, P^*_{i,D}.
Initialize: q^D_{ik} = q^D_{ik}(0), P̂_{i,D} = P̂_{i,D}(0), I, Δ, t=0.
for i ∈ 𝒟 do
  for C_k ∈ 𝒞_K do
    while t < I do
      Obtain P̂_{i,D} using (21).
      if U^D_{ik,SE}[P̂_{i,D}(t)] − q^D_{ik}(t)T^D_{ik}[P̂_{i,D}(t)] > Δ then
        Update:
        q^D_{ik}(t+1) = U^D_{ik,SE}[P̂_{i,D}(t)]/T^D_{ik}[P̂_{i,D}(t)]
      else
        P^*_{i,D} = P̂_{i,D}(t), q^{D*}_{ik} = U^D_{ik,SE}(P^*_{i,D})/T^D_{ik}(P^*_{i,D})
      end if
      Update: t = t + 1
    end while
  end for
end for
```

The initial value of q^D_{ik} should be set as a small positive number to ensure the convergence of the algorithm. And at the t-th Dinkelbach iteration, the power control strategy $P_{i,D}(t)$ for D2D pair i can be obtained by solving the following problem, where $q^D_{ik}(t)$ is derived from the $(t-1)$-th iteration:

$$\max_{\{P_{i,D}\}} \; U^D_{ik,SE}[P_{i,D}(t)] - q^D_{ik}(t)T^D_{ik}[P_{i,D}(t)] \quad \text{s.t. } c^D_{i,1}, c^D_{i,2}. \tag{18}$$

We employ Lagrange dual decomposition and Karush-Kuhn-Tucker (KKT) conditions to solve the above problem. The Lagrangian corresponding to (18) is given by

$$\begin{aligned}\mathcal{L}^D_{ik,EE}(P_{i,D}, \beta^D_i, \gamma^D_i) = {} & U^D_{ik,SE}[P_{i,D}(t)] - q^D_{ik}(t)T^D_{ik}[P_{i,D}(t)] \\ & - \beta^D_i(t)(P_{i,D}(t) - P_{max}) \\ & + \gamma^D_i(t)(U^D_{ik,SE}[P_{i,D}(t)] - U^D_{SE,min}).\end{aligned} \tag{19}$$

β^D_i and γ^D_i are the Lagrange multipliers associated with constraints $c^D_{i,1}$ and $c^D_{i,2}$, respectively. Then, the equivalent dual problem can be obtained based on Lagrange dual decomposition [48]:

$$\min_{(\beta^D_i, \gamma^D_i \geq 0)} \; \max_{\{P_{i,D}\}} \; \mathcal{L}^D_{ik,EE}(P_{i,D}, \beta^D_i, \gamma^D_i). \tag{20}$$

The optimal $\hat{P}_{i,D}(t)$ corresponding to $q^D_{ik}(t)$ can be obtained by using KKT conditions

$$\hat{P}_{i,D}(t) = \Big[\frac{\eta[1+\gamma^D_i(t)]\log_2 e}{q^D_{ik}(t)(1-\eta\delta_E\eta_E h^2_{i,D}) + \eta\beta^D_i(t)} - \frac{\delta_I(P_{k,C}h^2_{ki} + \sigma^2_0) + \sigma^2_s}{\delta_I h^2_{i,D}}\Big]^+, \tag{21}$$

where $[X]^+ = \max\{0, X\}$. The Lagrange multipliers can be updated based on the gradient method [62]:

$$\begin{aligned}\beta^D_i(t,\omega) = {} & [\beta^D_i(t,\omega-1) + \vartheta_{i,\beta}(t,\omega-1) \\ & \times (\hat{P}_{i,D}(t,\omega-1) - P_{max})]^+,\end{aligned} \tag{22}$$

$$\begin{aligned}\gamma^D_i(t,\omega) = {} & [\gamma^D_i(t,\omega-1) - \vartheta_{i,\gamma}(t,\omega-1) \\ & \times (U^D_{ik,SE}(t,\omega-1) - U^D_{SE,min})]^+.\end{aligned} \tag{23}$$

ω is the index of the iteration of Lagrange multiplier updating and $\vartheta_{i,\beta}, \vartheta_{i,\gamma}$ are step sizes that need to be adopted to guarantee the convergence and optimality of the iterative algorithm. Then, $q^D_{ik}(t+1)$ for the $(t+1)$-th iteration is updated as $q^D_{ik}(t+1) = U^D_{ik,SE}[\hat{P}_{i,D}(t)]/T^D_{ik}[\hat{P}_{i,D}(t)]$ utilizing $\hat{P}_{i,D}(t)$ obtained from (21). In the final iteration, the optimal power control strategy $P^*_{i,D}$ is set as $\hat{P}_{i,D}$, and the achievable maximum EE q^{D*}_{ik} under the matching $\Psi(i) = C_k$ can be derived from (15), i.e., the preference value of D2D pair i on CUE C_k. After sorting the derived preference values of D2D pair i on CUEs in descending order as $\mathcal{E}^D_i = \{e^i_1, e^i_2, \cdots, e^i_K\}$, the corresponding CUE list denoted as $\mathcal{P}^D_i = \{p^i_1, p^i_2, \cdots, p^i_K\}$ is defined as the preference list of D2D pair i on CUEs. Then, we denote $\mathcal{P}^D = \{\mathcal{P}^D_1, \cdots, \mathcal{P}^D_i, \cdots, \mathcal{P}^D_N\}$ as the preference list set of D2D pairs on CUEs.

2) PREFERENCE ESTABLISHMENT FOR CUEs

For any CUE C_k, the optimization goal is to maximize its harvested energy by optimizing partner selection decision variable $x_{i,k}$. Therefore, the preference value of CUE C_k on D2D pair i can be formulated as the maximum amount of energy harvested by C_k under matching $\Psi(C_k) = i$, where the transmission power of D2D pair i has been determined in preference establishment process for D2D pairs. Let $\mathcal{E}^C_k = \{e^k_1, e^k_2, \cdots, e^k_N\}$ denote the achieved maximum amount of energy harvested by CUE C_k matched with each D2D pair in descending order, and $\mathcal{P}_k^C = \{p_1^k, p_2^k, \cdots, p_N^k\}$ denotes the corresponding D2D pair list which is defined as the preference list of CUE C_k on D2D pairs. Then, we denote $\mathcal{P}^C = \{\mathcal{P}_1^C, \cdots, \mathcal{P}_k^C, \cdots, \mathcal{P}_K^C\}$ as the preference list set of CUEs on D2D pairs.

Algorithm 2 Preference List Establishment Algorithm

```
Input: 𝒞_K, 𝒟, P_max, U^D_{SE,min}, U^C_{SE,min}.
Output: 𝒫^D, 𝒫^C.
for i ∈ 𝒟 do
    for C_k ∈ 𝒞_K do
        Calculate the achievable maximum EE q^{D*}_{ik} of D2D
        pair i under matching Ψ(i) = C_k by employing
        Algorithm 1 with the optimization of transmission
        power P_{i,D}, and the maximum energy E^C_{ki} harvested
        at CUE C_k under matching Ψ(C_k) = i.
    end for
end for
for i ∈ 𝒟 do
    Obtain ℰ^D_i by sorting the achieved maximum EE q^{D*}_{ik},
    ∀C_k ∈ 𝒞_K in descending order.
    Establish the preference list 𝒫^D_i of D2D pair i by
    sorting CUEs according to the order of ℰ^D_i.
end for
for C_k ∈ 𝒞_K do
    Obtain ℰ^C_k by sorting the achieved maximum energy
    E^C_{ki}, ∀i ∈ 𝒟 harvested at CUE C_k in descending order.
    Establish the preference list 𝒫^C_k of D2D pair i by
    sorting CUEs according to the order of ℰ^C_k.
end for
```

The detailed preference establishment algorithm for D2D pairs and CUEs is summarized in Algorithm 2, which is the basis of the proposed matching approach. Graphical expressions of preference lists establishment between D2D pairs and CUEs, and a two-dimensional stable matching are shown in Fig. 2.

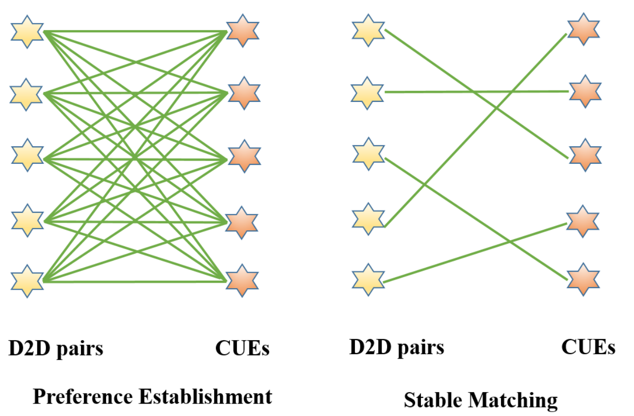

FIGURE 2. Graphical expressions of preference establishment and two-sided stable matching.

C. EH-BASED ENERGY-EFFICIENT STABLE MATCHING ALGORITHM

After obtaining the mutual preference lists $\mathcal{P}^D$ and $\mathcal{P}^C$, we propose an EH-based energy-efficient stable matching algorithm by exploiting GS algorithm to solve the joint power control and partner selection problem between D2D pairs and CUEs, which is summarized in Algorithm 3 and briefly described as follows.

- The proposed matching algorithm proceeds iteratively. In the first iteration, every D2D pair $i \in \mathcal{D}$ would propose to its most preferred CUE based on the established preference list $\mathcal{P}_i^D$. If any CUE $C_k \in \mathcal{C}_K$ receives proposal from only one D2D pair i, the requested CUE C_k would hold the D2D pair i as its candidate. Otherwise, any CUE $C_k \in \mathcal{C}_K$ that has received proposals from more than one D2D pair would choose the most preferred D2D pair based on the preference list $\mathcal{P}_k^C$ and reject other D2D pairs.
- Next, any D2D pair i that has been previously rejected would propose to its new choice $C_{k'} \in \mathcal{C}_K$, which is the most preferred CUE among those who have not rejected it. If CUE $C_{k'}$ has not held any candidate, the selection procedure of D2D pairs is the same as the described before. Otherwise, CUE $C_{k'}$ wold compare the held candidate with all new received proposals and only accept the most preferred D2D pair based on $\mathcal{P}_{k'}^C$. Accordingly, a D2D pair would send no further proposal when it is rejected by all CUEs.

Algorithm 3 EH-Based Energy-Efficient Stable Matching Algorithm

```
Input: 𝒞_K, 𝒟, 𝒫^D, 𝒫^C.
Output: Ψ.
Initialize: Ψ = ∅, Ω = 𝒟.
while Ω ≠ ∅ do
    for i ∈ Ω do
        i proposes to its most preferred CUE among who
        have not rejected it in 𝒫^D_i.
    end for
    for C_k ∈ 𝒞_K do
        if C_k receives a proposal from i, and prefers i to its
        current partner j then
            C_k rejects j and chooses i to be its new candidate,
            i.e., Ψ(C_k) = i.
            Remove i from Ω and add j into Ω.
            Update 𝒫^D_j by removing C_k.
        else
            C_k rejects i and holds j as its candidate continu-
            ally, i.e., Ψ(C_k) = j.
            Update 𝒫^D_i by removing C_k.
        end if
    end for
end while
```

- The matching algorithm would end when every $i \in \mathcal{D}$ has already been matched with a CUE or has been rejected by all CUEs in its preference list $\mathcal{P}_i^D$.

Thus, a stable matching can be derived by proceeding the above steps. Since CUEs can hold the best available candidate at any step rather than matching with it outright, i.e., the best candidate held currently can be rejected in later iterations if a better candidate emerges, the proposed matching algorithm has the nature of *deferred acceptance*.

D. PROPERTIES OF THE EH-BASED ENERGY-EFFICIENT STABLE MATCHING ALGORITHM

In this subsection, we analyze the properties of the proposed EH-based energy-efficient matching algorithm including convergence, stability, optimality, and complexity in details.

1) CONVERGENCE

The achievable maximum EE q_{ik}^{D*} is defined as the preference value of CUE C_k for D2D pair i, while the maximum energy E_{ki}^C harvested at C_k is defined as the preference value of D2D pair i for CUE C_k. At each iteration, D2D pairs that have not been matched would propose to its most preferred CUEs based on preference values. It is noted that there exists competition among D2D pairs when any CUE C_k receives proposals from more than one D2D pair with considering its current candidate. Matching rules in Algorithm 3 indicate that C_k would accept the most preferred one based on $\mathcal{P}_k^C$, and D2D pair i that is rejected by C_k would change its choice according to $\mathcal{P}_i^D$. As D2D pairs would only propose to CUEs in $\mathcal{P}^D$ for once, the request and reject procedure would end when every D2D pair has held a partner or has been rejected by all CUEs. Thus, we conclude the matching algorithm after many finite iterations.

2) STABILITY

Theorem 2: The matching Ψ derived from the proposed Algorithm 3 is stable.

Proof: It is said that the matching Ψ is stable when there exists no blocking pair according to Definition 3. Therefore, we need to prove that the EE performance of any D2D-CUE partnership cannot be improved by disrupting the matching Ψ produced by Algorithm 3, aiming to prove the stability of the proposed EH-based energy-efficient stable matching algorithm. Firstly, we assume that there exists a blocking pair formed by D2D pair $i \in \mathcal{D}$ and CUE $C_k \in \mathcal{C}_K$ under matching Ψ, i.e., $\Psi(i) \neq C_k$, and $C_k >_i \Psi(i)$, $i >_{C_k} \Psi(C_k)$.

In the matching process, each D2D pair would propose to its most preferred CUE in established preference list aiming to maximize its own EE performance. Considering the assumption $C_k >_i \Psi(i)$, D2D pair i must have already proposed to CUE C_k before proposing to $\Psi(i)$ according to the defined rules in Algorithm 3. However, the existence of $\Psi(C_k) \neq i$ in matching result means that CUE C_k prefers $\Psi(C_k)$ than i, i.e., $\Psi(C_k) >_{C_k} i$. Therefore, CUE C_k is not willing to disrupt the current matching to pair with i, i.e., the condition $i >_{C_k} \Psi(C_k)$ cannot hold when $C_k >_i \Psi(i)$, which means that the blocking pair formed by D2D pair i and CUE C_k does not exist. The process to prove that the condition $C_k >_i \Psi(i)$ cannot hold when $i >_{C_k} \Psi(C_k)$ is similar as the previous description with minor revision. It can be seen that the analysis result conflicts with the original assumption. Thus, the matching Ψ derived from Algorithm 3 is stable. ■

3) OPTIMALITY

Theorem 3: For any D2D pair $i \in \mathcal{D}$ under matching $\Psi(i) = C_k$, q_{ik}^D obtained in each iteration by employing Algorithm 1 converges to an unique optimum value q_{ik}^{D*} [32].

Theorem 4: The derived EH-based energy-efficient stable matching is weak Pareto optimal for D2D pairs on CUEs.

Proof: Based on the concept of Pareto improvement given in [41], we give the proof as follows. Firstly, we assume that Pareto improvement for matching Ψ exists, and the improvement for D2D pair i is defined as CUE C_k, i.e., $C_k >_i \Psi(i)$. In one case, CUE C_k has not been matched under matching Ψ, i.e., $\Psi(C_k) = \emptyset$. Obviously, CUE C_k prefers to match with D2D pair i, i.e., $i >_{C_k} \Psi(C_k)$. That is, D2D pair i and CUE C_k would prefer each other to be their partner, and thus they form a blocking pair for matching Ψ. This contradicts the Theorem 2 that matching Ψ derived from the proposed Algorithm 3 is stable. In the other case, CUE C_k has been matched with D2D pair i', i.e., $\Psi(C_k) = i'$, which forbids i to be matched with C_k. Based on the assumption $C_k >_i \Psi(i)$, D2D pair i would propose to CUE C_k. However, i has been rejected by C_k according to the defined matching rules and thus the assumption $C_k >_i \Psi(i)$ cannot hold.

Based on the above analysis, we ensure that no Pareto improvement exists for the derived matching, and Ψ is weak Pareto optimal for D2D pairs. ■

4) COMPLEXITY

The establishment of mutual preference lists, which mainly depends on Algorithm 1, is the basis to derive the stable matching between D2D pairs and CUEs. The computational complexity for D2D pair $i \in \mathcal{D}$ to find the optimal EE q_{ik}^{D*} under matching $\Psi(i) = C_k$ is $\mathcal{O}(I_{loop}I_{dual})$, where I_{loop} and I_{dual} represent the number of iterations required to converge to the optimal EE value and solve dual problem, respectively. Thus, the computational complexity of Algorithm 1 is $\mathcal{O}(NKI_{loop}I_{dual})$ taking N D2D pairs and K CUEs into consideration, since that the preference value for each D2D-CUE partnership needs to be obtained. In Algorithm 2, the computational complexity to obtain the preference lists for N D2D pairs and K CUEs by sorting preference values in descending order is $\mathcal{O}(NK\log(NK))$. And the computational complexity of Algorithm 3 is $\mathcal{O}(NK)$, due to the fact that every D2D pair $i \in \mathcal{D}$ only has one opportunity to propose to CUEs in its established preference list $\mathcal{P}_i^D$.

VI. NUMERICAL RESULTS

In this section, simulation results are analyzed to evaluate the performance of the proposed EH-based energy-efficient

TABLE 1. Simulation parameters.

Simulation Parameter	Value
Cell radius R	200 m
Number of D2D pairs N	$5 \sim 15$
Number of resource blocks and CUEs K	$5 \sim 15$
Max D2D transmission distance d_{max}	20∼70 m
Pathloss exponent α	2
Max transmission power of D2D links P_{max}	23 dBm
Transmission power of the BS to CUEs $P_{k,C}$	26 dBm
Noise power generated from antenna σ_0^2	-114 dBm
Noise power generated from signal processing σ_s^2	-114 dBm
Circuit power consumption P_{cir}	20 dBm
PA efficiency η	0.35
Power splitting ratio δ_I	0.2∼0.8
EH efficiency η_E	0.8
QoS requirement $U^D_{SE,min}$, $U^C_{SE,min}$	0.5 bit/s/Hz

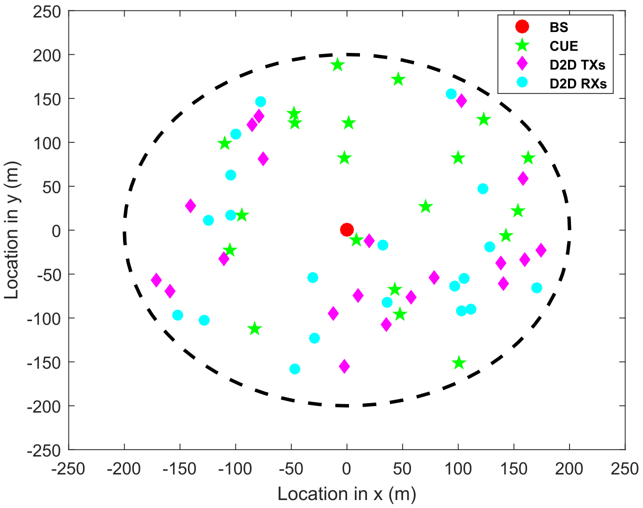

FIGURE 3. A snapshot of user locations for a single cellular network with K CUEs and N D2D pairs including N D2D transmitters and N D2D receivers.

stable matching algorithm. Simulation parameters are summarized in Table 1 [11], [27], [41]. We consider a D2D communication underlay cellular network system, in which N D2D pairs and K CUEs are distributed randomly in the cellular network with the radius of $R = 200$ m. A snapshot of UEs' locations when $N = K = 20$ and $d_{max} = 50$ m is shown in Fig. 3. The distance between D2D TXs and RXs must satisfy the requirements of D2D communication. The proposed matching algorithm is compared with three heuristic algorithms, i.e., EH-based max power with max-SINR matching, EH-based max power with random matching and EH-based random power with random matching algorithms. In particular, the first two algorithms always allocate the maximum transmission power P_{max} to D2D pairs, while the last algorithm allocates the power to D2D pairs randomly in the range $[0, P_{max}]$. Furthermore, D2D pairs and CUEs are matched in a stable way by using the GS algorithm in the first algorithm, and are matched randomly in the second and third algorithms.

Fig. 4 shows the average EE performance of D2D pairs versus the number of Dinkelbach iterations. In the proposed

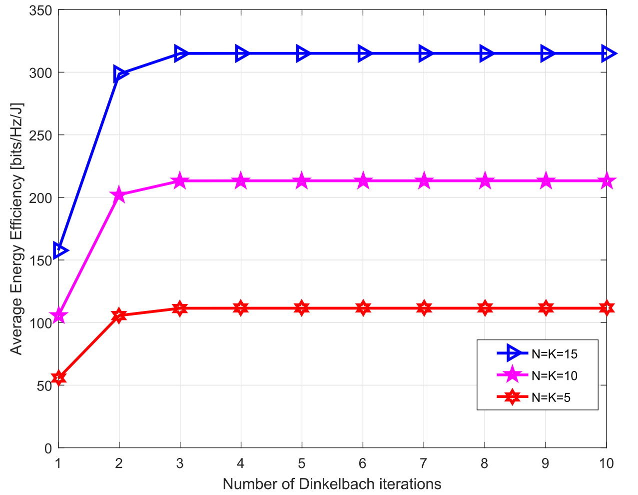

FIGURE 4. Average energy efficiency of D2D pairs vs. number of Dinkelbach iterations ($N = K = 5, 10, 15, d_{max} = 50$ m).

power control algorithm, i.e., Algorithm 1, the initial value of q^D_{ik} is set as a small positive number. With the proceeding of the algorithm, q^D_{ik} gradually converges to an unique optimum value q^{D*}_{ik}. Simulation results demonstrate that it only takes 3∼5 iterations for q^D_{ik} to converge to the unique optimum value q^{D*}_{ik}. It is also noted that varying the numbers of D2D pairs and CUEs has negligible effect on the convergence performance of the proposed power control algorithm.

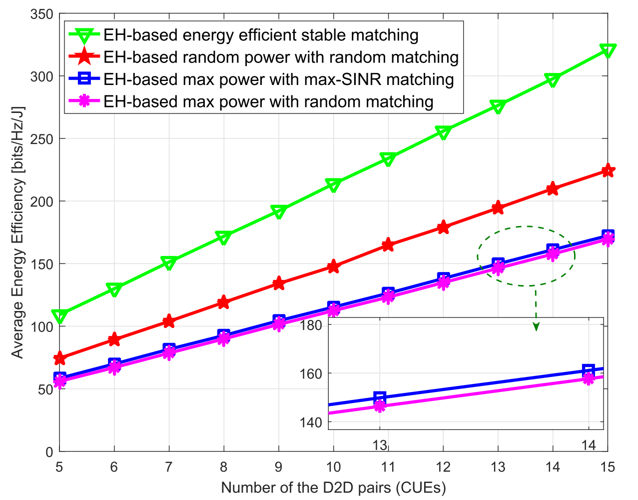

FIGURE 5. Average energy efficiency of D2D pairs vs. number of D2D pairs (CUEs) ($N = K = 5$∼15, $d_{max} = 50$ m, $\delta_I = 0.8$).

Fig. 5 shows the average EE of D2D pairs versus the number of D2D pairs N and CUEs K with $d_{max} = 50$ m and $\delta_I = 0.8$. It is shown that the proposed algorithm achieves significant EE performance gains compared with the other three heuristic algorithms. For instance, the proposed algorithm outperforms the random power with random matching, max-SINR matching, and max power with random matching algorithms by 44.60%, 85.34%, and 90.11%, respectively, when $N = K = 10$. The reason is due to the fact that the heuristic algorithms only focus on the SE performance, and neglect the power consumption issues during the resource allocation process. Specifically, the performance achieved by the random power with random matching algorithm is even better than the max-SINR matching algorithm, which proves that the SE gain obtained by increasing transmission power cannot compensate the corresponding EE loss in an interference-limited network. The max power with random matching algorithm achieves the worst EE performance because the power consumption issue has been completely ignored. Furthermore, it is also clear that the increase of transmission power beyond the point corresponding to the optimal EE would cause severe EE loss and bring little SE improvement. It is also observed that the average EE performance of D2D pairs rises up linearly with the number of D2D pairs and CUEs (RBs) increasing. The reasons are twofolds. Firstly, the increase number of D2D pairs would contribute to a higher EE performance of D2D links. Secondly, as the number of RBs (CUEs) increases, each D2D pair would have a wider selection of CUEs and the corresponding probability to be matched with a more preferred CUE becomes higher. Simulation results also demonstrate that the proposed algorithm has the steepest slope among all of the four algorithms, which indicates that more benefits can be exploited by the proposed algorithm from the diversity of choice than the other three heuristic algorithms.

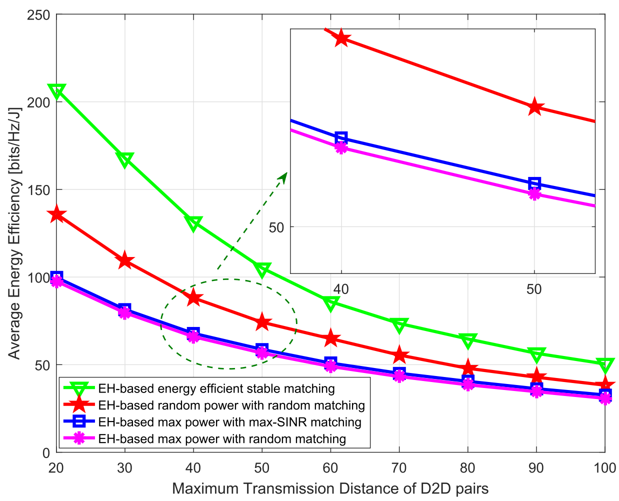

FIGURE 6. Average energy efficiency of D2D pairs vs. maximum transmission distance of D2D pairs ($N = K = 5$, $d_{max} = 20\sim100$ m, $\delta_I = 0.8$).

Fig. 6 shows the average EE of D2D pairs versus the maximum transmission distance d_{max} of D2D pairs with $N = K = 5$ and $\delta_I = 0.8$. The performance of the proposed algorithm is better than the performances of random power with random matching algorithm, max-SINR matching algorithm, and max power with random matching algorithm by 52.36%, 107.57%, and 112.28%, respectively, when $d_{max} = 20$ m. It is obvious that the EE performance decreases with the maximum transmission distance of D2D pairs increasing. The reason is that higher transmission power is required for D2D pairs to satisfy the QoS requirement compared to the scenario that D2D pairs with short distance.

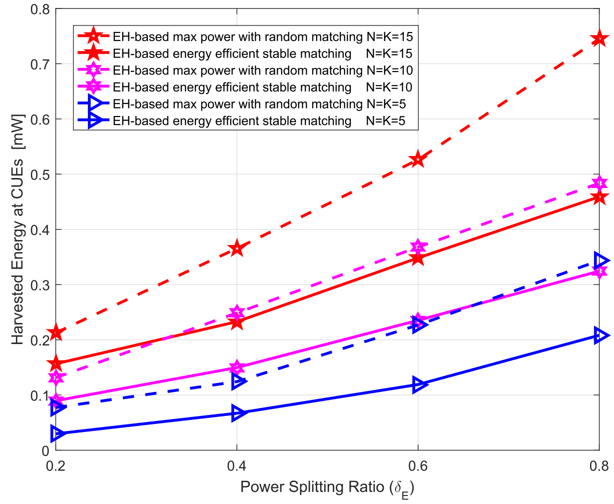

FIGURE 7. Harvested energy at CUEs vs. power splitting ratio δ_E ($d_{max} = 20$ m).

Fig. 7 shows the amount of energy harvested by CUEs versus the power splitting ratio δ_E with $d_{max} = 20$ m. With the power splitting ratio δ_E increasing, less signal power is utilized for information decoding while more signal power would be utilized for EH. Thus, the amount of energy harvested by CUEs increases with the increase of δ_E, which is reflected by the simulation result. Besides, it is shown that the max power with random matching algorithm outperforms the proposed matching algorithm for the same scenario. For instance, the amount of energy harvested at CUEs by employing the proposed algorithm is 66.20% of the amount of energy harvested by employing the max power with random matching algorithm. The reasons are two folds. Firstly, as random matching is not stable, both D2D pairs and CUEs have strong desire to interrupt the random matching to improve individual benefit. Secondly, the proposed algorithm is weak Pareto optimal for D2D pairs rather than for CUEs, since D2D pairs initiate the proposal. Furthermore, we can find that the amount of energy harvested by CUEs would rise up with the amount of CUEs increasing, as more CUEs would contribute to a higher amount of harvested energy.

VII. CONCLUSIONS

In this paper, we studied the resource allocation problem in EH-based D2D communications with downlink spectrum resource reusing. By employing SWIPT, UEs can harvest energy from the received signal power, and thus interference and noise can be introduced as beneficial outcomes. We formulated a joint power control and partner selection problem to optimize EE performance of D2D pairs and the energy harvested by CUEs simultaneously with the consideration of UEs' preferences and satisfactions, which was then transformed to a two-dimensional matching between

D2D pairs and CUEs (RBs). First of all, mutual preferences from the perspective of EE performance for D2D pairs and the perspective of energy for CUEs were established by the proposed preference establishment algorithm, which was developed by exploring nonlinear fractional programming and Lagrange dual decomposition. Then, we proposed an EH-based energy-efficient stable matching algorithm to solve the formulated resource allocation problem under power, spectrum resource reusing and QoS constraints. The properties involving convergence, stability, optimality, and complexity of the proposed matching algorithm were analyzed in details. Finally, the performance of the proposed matching algorithm was compared with three heuristic algorithms. Simulation results demonstrated that the proposed matching algorithm can achieve the best EE performance under all of the considered scenarios. In future works, we will focus on how to jointly optimize power splitting ratio, power control, and partner selection to improve the EE performance in SWIPT-based D2D communications.

REFERENCES

[1] N. Zhang, N. Cheng, A. T. Gamage, K. Zhang, J. W. Mark, and X. Shen, "Cloud assisted HetNets toward 5G wireless networks," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 59–65, Jun. 2015.

[2] Z. Chang, T. Ristaniemi, and Z. Niu, "Radio resource allocation for collaborative OFDMA relay networks with imperfect channel state information," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2824–2835, May 2014.

[3] S. Zhang, N. Zhang, S. Zhou, J. Gong, Z. Niu, and X. Shen, "Energy-aware traffic offloading for green heterogeneous networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1116–1129, May 2016.

[4] S. Zhou, T. Zhao, Z. Niu, and S. Zhou, "Software-defined hyper-cellular architecture for green and elastic wireless access," *IEEE Commun. Mag.*, vol. 54, no. 1, pp. 12–19, Jan. 2016.

[5] S. Xie and Y. Wang, "Construction of tree network with limited delivery latency in homogeneous wireless sensor networks," *Wireless Pers. Commun.*, vol. 78, no. 1, pp. 231–246, 2014.

[6] Z. Chang, S. Zhou, T. Ristaniemi, and Z. Niu, "Collaborative mobile clouds: An energy efficient paradigm for content sharing," *IEEE Wireless Commun.*, to be published.

[7] D. Wu, L. Zhou, Y. Cai, R. Q. Hu, and Y. Qian, "The role of mobility for D2D communications in LTE-advanced networks: Energy vs. bandwidth efficiency," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 66–71, Apr. 2014.

[8] C. Yang, X. Xu, J. Han, and X. Tao, "Energy efficiency-based device-to-device uplink resource allocation with multiple resource reusing," *Electron. Lett.*, vol. 51, no. 3, pp. 293–294, 2015.

[9] D. Wu, J. Wang, R. Q. Hu, Y. Cai, and L. Zhou, "Energy-efficient resource sharing for mobile device-to-device multimedia communications," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2093–2103, Jun. 2014.

[10] Z. Zhou, M. Dong, K. Ota, R. Shi, Z. Liu, and T. Sato, "Game-theoretic approach to energy-efficient resource allocation in device-to-device underlay communications," *IET Commun.*, vol. 9, no. 3, pp. 375–385, Feb. 2015.

[11] Z. Zhou, M. Dong, K. Ota, and C. Xu, "Energy-efficient matching for resource allocation in D2D enabled cellular networks," *IEEE Trans. Veh. Technol.*, to be published.

[12] L. Wei, R. Q. Hu, Y. Cai, and G. Wu, "Energy efficiency and spectrum efficiency of multihop device-to-device communications underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 367–380, Jan. 2016.

[13] S. Zhou, T. Chen, W. Chen, and Z. Niu, "Outage minimization for a fading wireless link with energy harvesting transmitter and receiver," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 3, pp. 496–511, Mar. 2015.

[14] J. Gong, S. Zhou, and Z. Zhou, "Networked MIMO with fractional joint transmission in energy harvesting systems," *IEEE Trans. Commun.*, vol. 64, no. 8, pp. 3323–3336, Aug. 2016.

[15] J. Gong, J. S. Thompson, S. Zhou, and Z. Niu, "Base station sleeping and resource allocation in renewable energy powered cellular networks," *IEEE Trans. Commun.*, vol. 62, no. 11, pp. 3801–3813, Nov. 2014.

[16] U. Saleem, H. K. Qureshi, S. Jangsher, and M. Saleem, "Transmission power management for throughput maximization in harvesting enabled D2D network," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Messina, Italy, Jun. 2016, pp. 1078–1083.

[17] G. P. Wijesiri, S. S. Chowdhury, and F. Y. Li, "Energy harvesting-aware backoff algorithms for distributed device-to-device communication," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, Nanjing, China, Jun. 2016, pp. 1–5.

[18] S. Riaz, H. K. Qureshi, and M. Saleem, "Performance evaluation of routing protocols in energy harvesting D2D network," in *Proc. Int. Conf. Comput., Electron. Elect. Eng. (ICE Cube)*, Quetta, Pakistan, Apr. 2016, pp. 251–255.

[19] L. Jiang *et al.*, "Social-aware energy harvesting device-to-device communications in 5G networks," *IEEE Wireless Commun.*, vol. 23, no. 4, pp. 20–27, Aug. 2016.

[20] Y. Shen, C. Jiang, T. Q. S. Quek, and Y. Ren, "Location-aware device communication design: Exploration and exploitation on energy," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 46–52, Apr. 2016.

[21] V.-D. Nguyen, T. Q. Duong, H. D. Tuan, O.-S. Shin, and H. V. Poor, "Spectral and energy efficiencies in full-duplex wireless information and power transfer," *IEEE Trans. Commun.*, to be published.

[22] L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE Int. Symp. Inf. Theory*, Toronto, ON, Canada, Jul. 2008, pp. 1612–1616.

[23] P. Grover and A. Sahai, "Shannon meets Tesla: Wireless information and power transfer," in *Proc. IEEE Int. Symp. Inf. Theory*, Austin, TX, USA, Jun. 2010, pp. 2363–2367.

[24] Z. Chang *et al.*, "Energy efficient resource allocation for wireless power transfer enabled collaborative mobile clouds," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3438–3450, Dec. 2016.

[25] N. Zhao, F. R. Yu, and V. C. M. Leung, "Wireless energy harvesting in interference alignment networks," *IEEE Commun. Mag*, vol. 53, no. 6, pp. 72–78, Jun. 2015.

[26] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 12, no. 1, pp. 288–300, Jan. 2013.

[27] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems," *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, pp. 6352–6370, Dec. 2013.

[28] N. Zhao, F. R. Yu, and V. C. M. Leung, "Opportunistic communications in interference alignment networks with wireless power transfer," *IEEE Wireless Commun.*, vol. 22, no. 1, pp. 88–95, Feb. 2015.

[29] J. Ding, L. Jiang, and C. He, "Dynamic spectrum allocation for energy harvesting-based underlaying D2D communication," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, Nanjing, China, Jun. 2016, pp. 1–5.

[30] S. Gupta, R. Zhang, and L. Hanzo, "Energy harvesting aided device-to-device communication underlaying the cellular downlink," *IEEE Access*, to be published.

[31] H. H. Yang, J. Lee, and T. Q. S. Quek, "Opportunistic D2D communication in energy harvesting heterogeneous cellular network," in *Proc. IEEE 16th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Stockholm, Sweden, Jun. 2015, pp. 41–45.

[32] W. Dinkelbach, "On nonlinear fractional programming," *Manage. Sci.*, vol. 13, no. 7, pp. 492–498, Mar. 1967.

[33] Y. Zhang, X. Sun, and B. Wang, "Efficient algorithm for k-barrier coverage based on integer linear programming," *China Commun.*, vol. 13, no. 7, pp. 16–23, Jul. 2016.

[34] A. Roth and M. Sotomayor, *Two-Sided Matching: A Study in Game Theoretic Modeling and Analysis*. Cambridge, U.K.: Cambridge Univ. Press, 1992.

[35] Z. Xia, X. Wang, X. Sun, Q. Liu, and N. Xiong, "Steganalysis of LSB matching using differences between nonadjacent pixels," *Multimedia Tools Appl.*, vol. 75, no. 4, pp. 1947–1962, Feb. 2016.

[36] Z. Zhou, Y. Wang, Q. M. J. Wu, C. Yang, and X. Sun, "Effective and efficient global context verification for image copy detection," *IEEE Trans. Inf. Forensics Security*, vol. 12, no. 1, pp. 48–63, Jan. 2017.

[37] X. Feng *et al.*, "Cooperative spectrum sharing in cognitive radio networks: A distributed matching approach," *IEEE Trans. Commun.*, vol. 62, no. 8, pp. 2651–2664, Aug. 2014.

[38] B. Di, S. Bayat, L. Song, and Y. Li, "Radio resource allocation for full-duplex OFDMA networks using matching theory," in *Proc. IEEE INFOCOM*, Toronto, ON, Canada, Apr. 2014, pp. 197–198.
[39] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, "Matching theory for future wireless networks: Fundamentals and applications," *IEEE Commun. Mag*, vol. 53, no. 5, pp. 52–59, May 2015.
[40] S. Zhang, B. Di, L. Song, and Y. Li, "Radio resource allocation for non-orthogonal multiple access (NOMA) relay network using matching game," in *Proc. IEEE ICC*, Tkuala lumpur, Malaysia, May 2016, pp. 1–6.
[41] C. Xu, C. Gao, Z. Zhou, Z. Chang, and Y. Jia, "Social network-based content delivery in device-to-device underlay cellular networks using matching theory," *IEEE Access*, vol. 5, pp. 924–937, Nov. 2016.
[42] M. W. Baidas and M. M. Afghah, "A matching-theoretic approach to energy-efficient partner selection in wireless networks," in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Dubrovnik, Croatia, Aug. 2015, pp. 1260–1265.
[43] Z. Zhou, M. Dong, K. Ota, and Z. Chang, "Energy-efficient context-aware matching for resource allocation in ultra-dense small cells," *IEEE Access*, vol. 3, pp. 1849–1860, Sep. 2015.
[44] Q. Han, B. Yang, C. Chen, and X. Guan, "Matching-based joint uplink and downlink user association for energy-efficient hetnets," in *Proc. 8th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Yangzhou, China, Oct. 2016, pp. 1–6.
[45] L. Xu, C. Jiang, Y. Shen, T. Q. S. Quek, Z. Han, and Y. Ren, "Energy efficient D2D communications: A perspective of mechanism design," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7272–7285, Nov. 2016.
[46] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Energy-efficient resource allocation for D2D communications in cellular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, London, U.K., Jun. 2015, pp. 2251–2256.
[47] B. Ma, H. Shah-Mansouri, and V. W. S. Wong, "A matching approach for power efficient relay selection in full duplex D2D networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Tkuala lumpur, Malaysia, May 2016, pp. 1–6.
[48] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.
[49] Z. Zhou, G. Ma, C. Xu, and Z. Chang, "A game-theoretical approach for green power allocation in energy-harvesting device-to-device communications," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, Nanjing, China, Jun. 2016, pp. 1–5.
[50] C. Song, C. Ling, J. Park, and B. Clerckx, "MIMO broadcasting for simultaneous wireless information and power transfer: Weighted MMSE approaches," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Austin, TX, USA, Dec. 2014, pp. 1151–1156.
[51] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Houston, TX, USA, Dec. 2011, pp. 1–5.
[52] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.
[53] L. Liu, R. Zhang, and K.-C. Chua, "Secrecy wireless information and power transfer with MISO beamforming," *IEEE Trans. Signal Process.*, vol. 62, no. 7, pp. 1850–1863, Apr. 2014.
[54] H. Zhang, Y. Huang, C. Li, and L. Yang, "Secure transmission scheme for SWIPT in MISO broadcast channel with confidential messages and external eavesdroppers," in *Proc. IEEE 82nd Veh. Technol. Conf. (VTC-Fall)*, Boston, MA, USA, Sep. 2015, pp. 1–5.
[55] H. Zhang, Y. Huang, C. Li, and L. Yang, "Secure beamforming design for SWIPT in MISO broadcast channel with confidential messages and external eavesdroppers," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7807–7819, Nov. 2016.
[56] S. Lohani, E. Hossain, and V. K. Bhargava, "On downlink resource allocation for SWIPT in small cells in a two-tier HetNet," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7709–7724, Nov. 2016.
[57] H. H. Yang, J. Lee, and T. Q. S. Quek, "Green device-to-device communication with harvesting energy in cellular networks," in *Proc. 6th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Hefei, China, Oct. 2014, pp. 1–6.
[58] D. Munir, S. T. Shah, W. J. Lee, M. Y. Chung, and S. F. Hasan, "Selection of relay UE with energy harvesting capabilities in public safety environment," in *Proc. IEEE Int. Conf. Inf. Netw. (ICOIN)*, Kota Kinabalu, Malaysia, Jan. 2016, pp. 40–44.
[59] Y. Liu, L. Wang, S. A. R. Zaidi, M. Elkashlan, and T. Q. Duong, "Secure D2D communication in large-scale cognitive cellular networks: A wireless power transfer model," *IEEE Trans. Commun.*, vol. 64, no. 1, pp. 329–342, Jan. 2016.
[60] A. H. Sakr and E. Hossain, "Cognitive and energy harvesting-based D2D communication in cellular networks: Stochastic geometry modeling and analysis," *IEEE Trans. Commun.*, vol. 63, no. 5, pp. 1867–1880, May 2015.
[61] M. Hasan and E. Hossain, "Distributed resource allocation for relay-aided device-to-device communication under channel uncertainties: A stable matching approach," *IEEE Wireless Commun.*, vol. 63, no. 10, pp. 3882–3897, Oct. 2015.
[62] K. T. K. Cheung, S. Yang, and L. Hanzo, "Achieving maximum energy-efficiency in multi-relay OFDMA cellular networks: A fractional programming approach," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 2746–2757, Jul. 2013.

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