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Iterative Energy-Efficient Stable Matching Approach for Context-Aware Resource Allocation in D2D Communications

ZHENYU ZHOU[1], (Member, IEEE), GUIFANG MA[1], MIANXIONG DONG[2], (Member, IEEE), KAORU OTA[2], (Member, IEEE), CHEN XU[1], (Member, IEEE), AND YUNJIAN JIA[3], (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]Department of Information and Electric Engineering, Muroran Institute of Technology, Muroran 050-8585, Japan
[3]College of Communication Engineering, Chongqing University, Chongqing 400044, China

Corresponding author: M. Dong (mx.dong@ieee.org)

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ABSTRACT Energy efficiency (EE) is critical to fully achieve the huge potentials of device-to-device (D2D) communications with limited battery capacity. In this paper, we consider the two-stage EE optimization problem, which consists of a joint spectrum and power allocation problem in the first stage, and a context-aware D2D peer selection problem in the second stage. We provide a general tractable framework for solving the combinatorial problem, which is NP-hard due to the binary and continuous optimization variables. In each stage, user equipments (UEs) from two finite and disjoint sets are matched in a two-sided stable way based on the mutual preferences. First, the preferences of UEs are defined as the maximum achievable EE. An iterative power allocation algorithm is proposed to optimize EE under a specific match, which is developed by exploiting nonlinear fractional programming and Lagrange dual decomposition. Second, we propose an iterative matching algorithm, which first produces a stable match based on the fixed preferences, and then dynamically updates the preferences according to the latest matching results in each iteration. Finally, the properties of the proposed algorithm, including stability, optimality, complexity, and scalability, are analyzed in detail. Numerical results validate the efficiency and superiority of the proposed algorithm under various simulation scenarios.

INDEX TERMS Energy-efficient context-aware resource allocation, many-to-one stable matching, D2D communications, iterative power allocation, mixed integer nonlinear programming.

I. INTRODUCTION

Due to the unprecedented growth in smart devices and mobile Internet applications, the amount of mobile data traffics and the demand for higher data rates are expected to grow dramatically over the next decade [1], [2]. Device-to-device (D2D) communication, which allows localized information exchange among devices without going through the base station (BS), has emerged as an essential technology of the future 5G system to reduce the huge gap between expected data rate and actual communication performance [3]. D2D communications can be implemented as an underlay network to the existing LTE/LTE-A systems through the high-density spatial reuse of the same spectrum resources [4], which represent a novel systematic paradigm shift from conventional long-range, single-tier homogeneous network to short-range, multi-tier heterogeneous cellular network [5].

However, the implementation of D2D communications underlaying cellular networks also gives rise to new problems and challenges due to the following two reasons: first, the co-channel interference caused by spectrum reusing can no longer be neglected for user equipments (UEs) with limited energy supply and signal processing capability; second, due to the fact that limited battery capacity has long been a major bottleneck for smart devices, the ignorance of energy efficiency (EE) in D2D communications may lead to rapid battery depletion and poor user experience. Hence, intelligent energy-efficient resource allocation schemes that are able to carefully manage interference and guarantee quality of service (QoS) requirements are required urgently to fully achieve the aforementioned huge potentials of D2D communications [6].

In this paper, we consider the two-stage EE optimization problem in D2D communications based heterogeneous networks, where uplink spectrum resources allocated to cellular UEs (CUs) are allowed to be reused by multiple D2D transmitters. The formulated two-stage combinatorial problem consists of a joint spectrum and power allocation problem for D2D transmitters and CUs in the first stage, and a context-aware D2D peer selection problem for D2D receivers and D2D transmitters in the second stage. Considering the conflicting objective functions of UEs due to the coupling of the mutual interference terms, noncooperative game theory has been widely used for developing distributed resource allocation algorithms in D2D communications [7]–[9]. However, the Nash equilibrium derived in such game-theoretical models only investigates the unilateral stability per UE, which may not be stable if UEs from two sides could achieve higher utility by deviating from the equilibrium together [10]. In comparison, matching theory based resource allocation provides a distributed self-organizing and self-optimizing solution for the combinatorial problem studied in this work [11]–[13]. It was originally designed to solve the two-sided matching problems such as the stable marriage problem [12], the college admissions problem [11], and the hospital-intern matching problem [13], etc. In particular, matching theory is suitable for solving wireless resource allocation problems due to the following reasons: first, interactions among heterogeneous UEs can be accurately characterized through generally defined preferences; second, the analytical tractability of the solution does not require the objective functions to have special properties such as convexity; last but not least, the matching algorithm can always produce solutions with guaranteed properties such as stability and optimality, etc., and is suitable for online implementation.

The goal of this work is to provide a general tractable framework for solving the NP-hard combinatorial problem with two-sided dynamically varying preferences by employing matching theory. The main contributions of this work are summarized as follows:

- We formulate the energy-efficient context-aware resource allocation problem for D2D communications as a two-stage combinatorial problem. Each stage involves the match of UEs from two finite and disjoint sets according to their mutual preferences. The first-stage match of D2D transmitters with CUs is formulated as a joint partner selection and power allocation problem, in which a binary variable is used to represent the partner selection strategy, and a continuous variable is used to indicate the power allocation strategy. The second-stage match of D2D receivers with D2D transmitters is formulated as a context-aware D2D peer selection problem, which depends on the channel and power allocation strategies in the first stage.
- We provide a general tractable framework for solving the NP-hard combinatorial problem by incorporating a many-to-one matching model, in which the preference of a UE from one side over the UEs from the other side is defined as the maximum achievable EE under the specified match. In the first stage, the EE of each D2D transmitter is maximized by using the proposed iterative power allocation algorithm, which is developed based on nonlinear fractional programming and Lagrange dual decomposition [14], [15]. A major challenge is that the preferences of D2D transmitters are coupled with the matching result through the mutual interference terms. To solve it, we propose an iterative matching algorithm, which firstly produces a stable match by using the Gale-Shapley (GS) algorithm based on the fixed preferences and then dynamically updates the preferences according to the latest matching results in each iteration. Using the channel selection and power allocation strategies obtained in the first stage, the proposed matching algorithm can solve the second-stage context-aware matching problem with little modifications.
- The properties of the proposed matching algorithm such as the stability, optimality, complexity, and scalability, etc., are analyzed theoretically. We compare the proposed algorithm with two heuristic algorithms in terms of EE performance and matching satisfaction under various simulation scenarios. Numerical results show that enormous EE performance gains can be obtained by the proposed algorithm, and the matching satisfaction can be improved dramatically for various satisfaction threshold values.

The remaining parts of this paper are outlined as follows. A brief review of the related works is provided in section II. System model and related assumptions are presented in section III. Section IV provides the formulation of the two-stage combinatorial problem. The proposed energy-efficient context-aware stable matching algorithm and related theoretical analysis are presented in section V. Performance evaluation results are demonstrated and discussed in section VI. In section VII, we conclude the paper and provide possible topics for future research.

II. RELATED WORKS

One major line of resource allocation research for D2D communications is to optimize the spectrum efficiency (SE) defined as bits per second per Hertz (bits/s/Hz). In [16], a reverse iterative combinatorial auction based resource allocation algorithm was proposed to optimize the total system sum rate of the overall cellular network. A game-theoretical approach based spectrum-efficient resource allocation algorithm was proposed in [17], in which each D2D UE chooses a best response strategy to a virtual price signal optimized and issued by the BS. Resource allocation problems with dynamic data arrival models and end-to-end delay constraints were studied in [18]. In addition, spectrum-efficient resource allocation problems have been studied under different application scenarios such as wireless multimedia networks [19], software-defined heterogeneous networks [20], energy-harvesting D2D communications [21], mobile social networks [22], intelligent transportation systems (ITS) [23], cloud radio access networks (C-RAN) [24], relay-aided cooperative networks [25], etc. Comprehensive literature reviews and surveys of spectrum-efficient resource allocation algorithms in D2D communications were provided in [7] and [8].

Although significant improvement in SE can be achieved by the above works, the EE performance is ignored during the resource allocation design. There have been some works investigating energy-efficient resource allocation strategies for D2D underlaying cellular networks. In [6] and [19], the authors considered the D2D-assisted multimedia communication scenario and proposed energy-efficient distributed D2D cluster formation algorithms based on coalition game theory. In [26] and [27], the authors considered the joint spectrum and power allocation optimization and proposed energy-efficient resource allocation algorithm based on auction theory. In [28], genetic algorithm was employed to optimize EE under the scenario with multiple resource pool multiplexing. An energy-efficient interference-aware power allocation algorithm based on noncooperative game theory was proposed firstly in [9], and was extended to the C-RAN based LTE-A networks in [29]. The tradeoff between SE and EE for single-hop and multi-hop D2D communication scenarios was analyzed in [30]–[32].

However, most of the previous works have neglected UEs' individualized preferences and satisfactions, and assumed that any UE is willing to follow the suggested resource allocation decision even though better utility can be achieved by disrupting it. Since UEs from different sides or even the same side may have conflicting preferences, it is impossible for a resource allocation scheme to be satisfied by every UE. The general framework of preference modeling and resource allocation design from an EE perspective has not been well investigated, and several research problems remain to be addressed.

Matching theory has been adopted to address the resource allocation problems with two-sided preferences in heterogeneous cellular networks [10], [33], D2D communications [10], delay tolerant networks with wireless power transfer [34], cognitive radios [35], and etc. In the context of D2D communications, the matching problem between resource blocks and UEs (including small cell UEs, and D2D UEs) in a heterogeneous cellular network was studied in [36]. The same authors then extended their works to the scenario of relay-aided D2D communications considering uncertainties of channel gains by combining matching theory and robust optimization theory [25]. In [37], the authors have incorporated the idea of cheating into the preference establishment process so that certain UEs' preference lists can be falsified. The authors demonstrated that the combined matching and cheating algorithm is able to improve the throughput of D2D UEs without hurting performance of the rest UEs. However, the optimization of EE is ignored in the above matching-based resource allocation algorithms.

Matching-based energy-efficient resource allocation algorithms for D2D communications were proposed in [38] and [39]. In [38], an energy-efficient relay selection algorithm was developed based on the one-to-one stable match for relay-assisted full-duplex D2D communications. In [39], the interactions and interconnections between D2D UEs and CUs were taken into consideration. The authors proposed an energy-efficient resource allocation algorithm for the match of D2D pairs with CUs by employing the one-to-one stable match and noncooperative game theory. It is noted that in [38] and [39], each D2D pair was assumed to be allocated with an orthogonal channel so that the mutual interference among different UEs are avoided, and the overall problem can be directly solved by the standard-form GS algorithm without little modifications. Different from the above works, we consider a more practical scenario where multiple D2D pairs are allowed to reuse the same CU's channel simultaneously as long as the QoS requirement of the CU can be guaranteed. The objective functions of different UEs are coupled with one another through the mutual interference terms. A UE's preference varies dynamically with the matching results and power allocation strategies of other UEs that reuse the same channel, and the change of the UEs' preferences will in turn impact the matching results. In addition, The context-aware D2D peer selection problem is also taken into consideration, which was completely neglected in [38] and [39]. As a result, the formulated many-to-one matching problem can no longer be solved by the methods used in [38] and [39]. The proposed iterative many-to-one stable match can efficiently capture the dynamics of UEs' preferences, and produce a stable and weak Pareto optimal match in each iteration.

III. SYSTEM MODEL

We consider a single multi-tier heterogeneous cellular network which consists of two tiers as shown in Fig. 1. The first tier is the *macro tier* including a macro base station (BS) and CUs, and the second tier is the *underlay tier* that consists of D2D UEs. In order to improve SE, a CU's channel can be reused by multiple D2D transmitters as long as the QoS requirement of the CU is guaranteed. All UEs are initially connected with the BS and are operated as CUs. Each UE is equipped with a data storage that caches the files downloaded from the BS. The BS maintains a file-UE correlation table to keep a record of locations for all known files $\mathcal{F}$ over time, which is shown in Table 1. The f-th row represents the locations of the file f over the set of UEs. For example, if the file f is requested by a UE, the BS can identify which neighboring UEs can be operated in D2D modes to serve the file f by checking the file-UE relationship shown in Table 1. If no such neighbors exist, the UE remains in the cellular mode and is served by the BS.

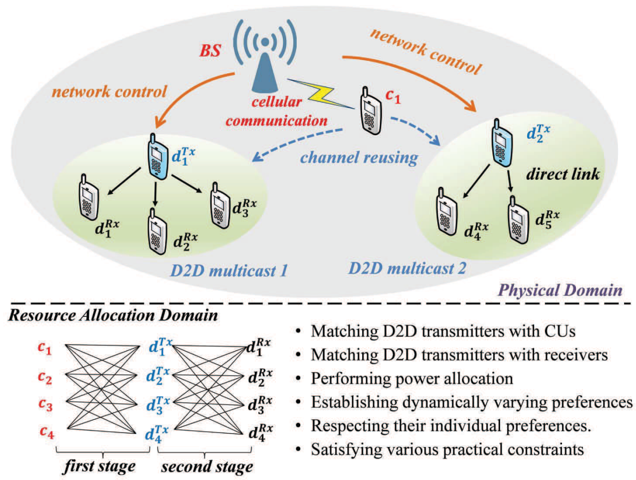

FIGURE 1. Energy-efficient context-aware resource allocation design for D2D communications with mutual preferences.

TABLE 1. The file-UE association table.

	UE_1	UE_2	...	UE_m	...
f=1	N/A	Avail	...	N/A	...
f=2	Avail	N/A	...	N/A	...
...	...	...	...	...	...
$f=\mid\mathcal{F}\mid$	Avail	N/A	...	Avail	...

Block fading model where the channel gain is constant during a slot is adopted [40]. As a file usually contains multiple data packets that span several slots, the resource allocation is performed in a slot-by-slot fashion. At the t-th slot, we assume that there are N_{Rx} potential D2D receivers, i.e., $\mathcal{D}_{Rx}$=$\{d_1^{Rx}, \cdots, d_j^{Rx}, \cdots, d_{N_{Rx}}^{Rx}\}$, and N_{Tx} D2D transmitters, i.e., $\mathcal{D}_{Tx}$=$\{d_1^{Tx}, \cdots, d_i^{Tx}, \cdots, d_{N_{Tx}}^{Tx}\}$. The rest K UEs are operated in the cellular mode, i.e., $\mathcal{C}$ =$\{c_1, \cdots, c_k, \cdots, c_K\}$. Each CU occupies an orthogonal channel (e.g., an orthogonal resource block in LTE), i.e., K active CUs are allocated with a total of K orthogonal channels. We assume that each D2D receiver can only request one file per time and the same file can be requested by multiple receivers simultaneously.

A D2D transmitter and a D2D receiver can form a D2D pair if the following conditions are satisfied: first of all, there are available channels for implementing D2D communications; second, the file requested by the D2D receiver is available in the cache of the D2D transmitter; third, the QoS requirement of the D2D receiver must be satisfied. We adopt uplink spectrum reusing due to the following two reasons: first, uplink spectrum resources are usually under-utilized compared to the downlink in frequency division duplexing (FDD) based cellular systems [6]; second, CUs cannot deal with the co-channel interference caused by D2D UEs efficiently compared to a powerful centralized BS. As a result, the BS will receive co-channel interference from all of the active D2D transmitters, and a D2D receiver will receive co-channel interference from both the CU and other D2D transmitters that operate in the same channel. The channel-reusing partner selection decisions for D2D transmitters and CUs are defined as follows:

Definition 1: Let $\mathbf{X}^d_{N_{Tx}\times K}$ represent the $N_{Tx} \times K$ partner selection matrix of D2D transmitters towards CUs, where the (i, k)-th element $x^d_{i,k} \in \{0, 1\}$ indicates the selection decision of the D2D transmitter d_i^{Tx} towards the CU c_k. If $x^d_{i,k} = 1$, d_i^{Tx} has the intension to form a partnership with c_k, and otherwise, $x^d_{i,k} = 0$.

Definition 2: Let $\mathbf{X}^c_{K\times N_{Tx}}$ represent the $K \times N_{Tx}$ partner selection matrix of CUs towards D2D transmitters, where the (k, i)-th element $x^c_{k,i} \in \{0, 1\}$ indicates the selection decision of the CU c_k towards the D2D transmitter d_i^{Tx}. If $x^c_{k,i} = 1$, c_k has the intension to form a partnership with d_i^{Tx}, and otherwise, $x^c_{k,i} = 0$.

Remark 1: A channel-reusing partnership (d_i^{Tx}, c_k) is formed if and only if both d_i^{Tx} and c_k simultaneously prefer each other to be the channel-reusing partner, i.e., $x^d_{i,k} = x^c_{k,i} = 1$.

Once the N_{Tx} D2D transmitters are allocated with spectrum resources, any D2D receiver $d_j^{Rx} \in \mathcal{D}_{Rx}$ can be served by neighboring D2D transmitters (e.g., $d_i^{Tx} \in \mathcal{D}_{Tx}$) through the D2D mode. Therefore, the D2D peer selection decisions are defined in a similar way as above.

Definition 3: Let $\mathbf{Y}^{Tx}_{N_{Tx}\times N_{Rx}}$ represent the $N_{Tx} \times N_{Rx}$ partner selection matrix of D2D transmitters towards receivers, where the (i, j)-th element $y^{Tx}_{i,j} \in \{0, 1\}$ indicates the selection decision of the D2D transmitter d_i^{Tx} towards the receiver d_j^{Rx}. If $y^{Tx}_{i,j} = 1$, d_i^{Tx} has the intension to form a partnership with d_j^{Rx}, and otherwise, $y^{Tx}_{i,j} = 0$.

Definition 4: Let $\mathbf{Y}^{Rx}_{N_{Rx}\times N_{Tx}}$ represent the $N_{Rx} \times N_{Tx}$ partner selection matrix of receivers towards D2D transmitters, where the (j, i)-th element $y^{Rx}_{j,i} \in \{0, 1\}$ indicates the selection decision of the D2D receiver d_j^{Rx} towards the transmitter d_i^{Tx}. If $y^{Rx}_{j,i} = 1$, d_j^{Rx} has the intension to form a partnership with d_i^{Tx}, and otherwise, $y^{Rx}_{j,i} = 0$.

Remark 2: A D2D pair (d_i^{Tx}, d_j^{Rx}) is formed if and only if both d_i^{Tx} and d_j^{Rx} simultaneously prefer each other, i.e., $y^{Tx}_{i,j} = y^{Rx}_{j,i} = 1$. When a file f is requested by multiple receivers, the D2D transmitter d_i^{Tx} that has the file f is allowed to serve a maximum number of $N^{Tx}_{i,max}$ receivers simultaneously through multicast.

For the channel model, we consider both fast fading due to multipath propagation and slow fading due to shadowing and pathloss. The channel gain between c_k and the BS can be expressed as [41]

$$g^c_{k,B} = \varpi \beta^c_{k,B} \zeta^c_{k,B} d^{-\alpha}_{k,B}, \tag{1}$$

where ϖ is the pathloss constant, $\beta^c_{k,B}$ is the fast-fading gain with exponential distribution, $\zeta^c_{k,B}$ is the slow-fading gain with log-normal distribution, α is the pathloss exponent, and $d_{k,B}$ is the transmission distance. Similarly, we can define the interference channel gain between c_k and d_j^{Rx} as $g^c_{k,j}$, the interference channel gain between d_i^{Tx} and the BS as $g_{i,B}^d$, and the D2D channel gain between d_i^{Tx} and d_j^{Rx} as $g_{i,j}^d$.

IV. PROBLEM FORMULATION

A. THE ENERGY-EFFICIENT CONTEXT-AWARE RESOURCE ALLOCATION PROBLEM

Based on the above analysis, the whole energy-efficient context-aware resource allocation problem is formulated as a two-stage combinatorial problem: the first stage involves the match between D2D transmitters and existing CUs, and the second stage involves the match between D2D transmitters and receivers. The following questions should be addressed:

- How to model the dynamically varying UE preferences from an EE perspective, which are coupled with one another through the mutual interference terms.
- How to design the match to enhance EE performance while avoiding strong interference?
- How to select proper power allocation strategies to optimize EE performance?
- How to satisfy numerous implementation constraints including QoS, channel-reusing, peer selection, and transmission power, etc?
- How to maintain a stable match by avoiding disruptions from other D2D transmitters or CUs that also prefer to form a channel-reusing partnership with the current partner.

B. THE FIRST-STAGE COMBINATORIAL PROBLEM FORMULATION

Let us start from the formulation of the first-stage combinatorial problem. The questions presented in subsection IV-A indicate that the match between D2D transmitters and CUs is actually a *joint partner selection and power allocation problem*. Let p_i^d represent the transmission power of d_i^{Tx}. We define the achievable SE (bits/s/Hz) of any $d_i^{Tx} \in \mathcal{D}_{Tx}$ as

$$U_{i,SE}^{Tx} = \sum_{c_k \in \mathcal{C}} \log_2 \left(1 + \frac{x_{i,k}^d x_{k,i}^c p_i^d g_{i,j'}^d}{N_0 + I_{k,j'}^c + \sum\limits_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j'}^d} \right), \tag{2}$$

where

$$I_{k,j'}^c = x_{i,k}^d x_{k,i}^c p_k^c g_{k,j'}^c, \tag{3}$$
$$I_{l,j'}^d = x_{l,k}^d x_{k,l}^c p_l^d g_{l,j'}^d, \tag{4}$$
$$j' = \operatorname{argmin}_{j' \in \psi_i^{Tx}} g_{i,j'}^d := \{j' \mid \forall j : g_{i,j'}^d \le g_{i,j}^d\}. \tag{5}$$

N_0 is the noise power, p_k^c is the transmission power of c_k, and ψ_i^{Tx} is the set of potential D2D receivers that can be matched with d_i^{Tx}. Denote $d_{j'}^{Rx} \in \psi_i^{Tx}$ as the reference D2D receiver that has the lowest channel gain $g_{i,j'}^d$ between the D2D transmitter d_i^{Tx} and all of its potential D2D receivers ψ_i^{Tx}. In other words, $d_{j'}^{Rx}$ is the mostly affected D2D receiver given the same interference level and transmission power. Thus, $g_{i,j'}^d$ is used to determine $U_{i,SE}^{Tx}$ because satisfying the QoS requirement of $d_{j'}^{Rx}$ will lead to a higher probability that the QoS requirements of other D2D receivers will also be satisfied. $I_{k,j'}^c$ and $\sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j'}^d$ are the interference caused by c_k and other D2D transmitters that reuse c_k's channel, respectively.

We define the SE for any $c_k \in \mathcal{C}$ as

$$U_{k,SE}^c = \log_2 \left(1 + \frac{p_k^c g_{k,B}^c}{N_0 + \sum_{d_i^{Tx} \in D_{Tx}} x_{i,k}^d x_{k,i}^c p_i^d g_{i,B}^d} \right), \tag{6}$$

where $\sum_{d_i^{Tx} \in D_{Tx}} x_{i,k}^d x_{k,i}^c p_i^d g_{i,B}^d$ is the aggregated interference caused by all of the D2D transmitters that reuse c_k's channel simultaneously.

The total power consumption of d_i^{Tx} and c_k are defined as

$$E_i^{Tx} = \sum_{c_k \in \mathcal{C}} \frac{1}{\eta} x_{i,k}^d x_{k,i}^c p_i^d + p_{cir}, \tag{7}$$
$$E_k^c = \frac{1}{\eta} p_k^c + p_{cir}. \tag{8}$$

p_{cir} is the total circuit power consumption, and η is the power amplifier (PA) efficiency, i.e., $0 < \eta < 1$. The power consumption of the BS is not considered because it is powered by external grid power.

We denote the binary partner selection strategy set of any $d_i^{Tx} \in \mathcal{D}_{Tx}$ as $\mathbf{x}_i^{Tx} = \{x_{i,1}^d, \cdots, x_{i,k}^d, \cdots, x_{i,K}^d\}$, and denote the corresponding set of any $c_k \in \mathcal{C}$ as $\mathbf{x}_k^c = \{x_{k,1}^c, \cdots, x_{k,i}^c, \cdots, x_{k,N_{Tx}}^c\}$, respectively. EE (bits/J/Hz) is used as the objective function, which is defined as the ratio of the SE (bits/s/Hz) to the total power consumption (W) [42]. The objective functions of d_i^{Tx} and c_k in terms of EE are defined as

$$U_{i,EE}^{Tx}(\mathbf{x}_i^{Tx}, p_i^d) = \frac{U_{i,SE}^{Tx}(\mathbf{x}_i^{Tx}, p_i^d)}{E_i^{Tx}(\mathbf{x}_i^{Tx}, p_i^d)} = \frac{\sum_{c_k \in \mathcal{C}} \log_2 \left(1 + \frac{x_{i,k}^d x_{k,i}^c p_i^d g_{i,j'}^d}{N_0 + I_{k,j'}^c + \sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j'}^d} \right)}{\sum_{c_k \in \mathcal{C}} \frac{1}{\eta} x_{i,k}^d x_{k,i}^c p_i^d + p_{cir}}, \tag{9}$$

$$U_{k,EE}^c(\mathbf{x}_k^c) = \frac{U_{k,SE}^c(\mathbf{x}_k^c)}{E_k^c} = \frac{\log_2 \left(1 + \frac{p_k^c g_{k,B}^c}{N_0 + \sum_{d_i^{Tx} \in D_{Tx}} x_{i,k}^d x_{k,i}^c p_i^d g_{i,B}^d} \right)}{\frac{1}{\eta} p_k^c + p_{cir}}. \tag{10}$$

Thus, the energy-efficient joint partner selection and power allocation problem for d_i^{Tx} is defined as

$$\begin{aligned} \max_{(\mathbf{x}_i^{Tx}, p_i^d)} \quad & U_{i,EE}^{Tx}(\mathbf{x}_i^{Tx}, p_i^d) \\ \text{s.t.} \quad & C_{i,1}^{Tx} : 0 \le p_i^d \le p_{i,max}^d, \\ & C_{i,2}^{Tx} : U_{i,SE}^{Tx}(\mathbf{x}_i^{Tx}, p_i^d) \ge U_{i,SEmin}^{Tx}, \\ & C_{i,3}^{Tx} : x_{i,k}^d = \{0, 1\}, \forall c_k \in \mathcal{C}, \\ & C_{i,4}^{Tx} : \sum_{c_k \in \mathcal{C}} x_{i,k}^d \le 1. \end{aligned} \tag{11}$$

$C_{i,1}^{Tx}$ is the transmission power constraint that the transmission power p_i^d should not exceed $p_{i,max}^d$. $C_{i,2}^{Tx}$ is the QoS requirement which specifies the minimum SE $U_{i,SEmin}^{Tx}$. $C_{i,3}^{Tx}$ and $C_{i,4}^{Tx}$ are the channel-reusing constraints which make sure that d_i^{Tx} can reuse at most one existing CU's channel.

The combinatorial problem for c_k is defined as

$$\begin{aligned} \max_{(\mathbf{x}_k^c)} \ & U_{k,EE}^c(\mathbf{x}_k^c) \\ \text{s.t. } & C_{k,1}^c : U_{k,SE}^c(\mathbf{x}_k^c) \geq U_{k,SEmin}^c, \\ & C_{k,2}^c : x_{k,i}^c = \{0,1\}, \forall d_i^{Tx} \in \mathcal{D}_{Tx}, \\ & C_{k,3}^c : \sum_{d_i^{Tx} \in \mathcal{D}_{Tx}} x_{k,i}^c \leq N_{k,max}^c. \end{aligned} \tag{12}$$

$C_{k,1}^c$ is the QoS constraint. $C_{k,2}^c$ and $C_{k,3}^c$ are the channel-reusing constraints which make sure that at most $N_{k,max}^c$ D2D transmitters can reuse c_k's channel while $C_{k,1}^c$ must be satisfied simultaneously.

C. THE SECOND-STAGE COMBINATORIAL PROBLEM FORMULATION

In the second stage, the match between D2D transmitters and receivers only involves the D2D peer selection problem since the power allocation strategy has already been decided in the first stage. The binary peer selection strategy set of any $d_i^{Tx} \in \mathcal{D}_{Tx}$ is denoted as $\mathbf{y}_i^{Tx} = \{y_{i,1}^{Tx}, \cdots, y_{i,j}^{Tx}, \cdots, y_{i,N_{Rx}}^{Tx}\}$, and the binary peer selection strategy set of any $d_j^{Rx} \in \mathcal{D}_{Rx}$ is denoted as $\mathbf{y}_j^{Rx} = \{y_{j,1}^{Rx}, \cdots, y_{j,i}^{Rx}, \cdots, y_{j,N_{Tx}}^{Rx}\}$, respectively. Assuming that the channel selection and power allocation strategies obtained in the first stage are $x_{i,k}^d = x_{k,i}^c = 1$, and p_i^{d*}, respectively, the achievable SE of d_i^{Tx} is given by

$$\tilde{U}_{i,SE}^{Tx}\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}} = \sum_{d_j^{Rx} \in \mathcal{D}_{Rx}} \log_2 \left(1 + \frac{s_{i,j}^d y_{i,j}^{Tx} y_{j,i}^{Rx} p_i^{d*} g_{i,j}^d}{N_0 + I_{k,j}^c + \sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j}^d} \right), \tag{13}$$

where $I_{k,j}^c$ and $\sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j}^d$ are the interference caused by CUs and other D2D transmitters to d_j^{Rx}, which can be calculated in a similar way as (3) and (4). $s_{i,j}^d = \{0,1\}$ is the binary indicator for context-aware information, i.e., $s_{i,j}^d = 0$ if the file requested by d_j^{Rx} is not available in the cache of d_i^{Tx}, and otherwise, $s_{i,j}^d = 1$.

The SE for any $d_j^{Rx} \in \mathcal{D}_{Rx}$ is defined as

$$\tilde{U}_{j,SE}^{Rx}\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}} = \sum_{d_i^{Tx} \in \mathcal{D}_{Tx}} \log_2 \left(1 + \frac{s_{i,j}^d y_{i,j}^{Tx} y_{j,i}^{Rx} p_i^{d*} g_{i,j}^d}{N_0 + I_{k,j}^c + \sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j}^d} \right). \tag{14}$$

The objective functions of d_i^{Tx} and d_j^{Rx} in terms of EE are defined as

$$\tilde{U}_{i,EE}^{Tx}(\mathbf{y}_i^{Tx})\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}} = \frac{\tilde{U}_{i,SE}^{Tx}(\mathbf{y}_i^{Tx})}{E_i^{Tx}\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}}} = \frac{\sum_{d_j^{Rx} \in \mathcal{D}_{Rx}} \log_2 \left(1 + \frac{s_{i,j}^d y_{i,j}^{Tx} y_{j,i}^{Rx} p_i^{d*} g_{i,j}^d}{N_0 + I_{k,j}^c + \sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j}^d} \right)}{\frac{1}{\eta} p_i^{d*} + p_{cir}}, \tag{15}$$

$$\tilde{U}_{j,EE}^{Rx}(\mathbf{y}_j^{Rx})\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}} = \frac{\sum_{d_i^{Tx} \in \mathcal{D}_{Tx}} \log_2 \left(1 + \frac{s_{i,j}^d y_{i,j}^{Tx} y_{j,i}^{Rx} p_i^{d*} g_{i,j}^d}{N_0 + I_{k,j}^c + \sum_{d_l^{Tx} \in \mathcal{D}_{Tx} \setminus \{d_i^{Tx}\}} I_{l,j}^d} \right)}{p_{cir}}. \tag{16}$$

The second-stage combinatorial problems for d_i^{Tx} and d_j^{Rx} are formulated as

$$\begin{aligned} \max_{(\mathbf{y}_i^{Tx})} \ & \tilde{U}_{i,EE}^{Tx}(\mathbf{y}_i^{Tx})\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}} \\ \text{s.t. } & \tilde{C}_{i,1}^{Tx} : y_{i,j}^{Tx} = \{0,1\}, \forall d_j^{Rx} \in \mathcal{D}_{Rx}, \\ & \tilde{C}_{i,2}^{Tx} : \sum_{d_j^{Rx} \in \mathcal{D}_{Rx}} y_{i,j}^{Tx} \leq N_{i,max}^{Tx}, \end{aligned} \tag{17}$$

$$\begin{aligned} \max_{(\mathbf{y}_j^{Rx})} \ & \tilde{U}_{j,EE}^{Rx}(\mathbf{y}_j^{Rx})\Big|_{x_{i,k}^d = x_{k,i}^c = 1, p_i^{d*}} \\ \text{s.t. } & \tilde{C}_{j,1}^{Rx} : \tilde{U}_{j,SE}^{Rx} \geq \tilde{U}_{j,SEmin}^{Rx}, \\ & \tilde{C}_{j,2}^{Rx} : y_{j,i}^{Rx} = \{0,1\}, \forall d_i^{Tx} \in \mathcal{D}_{Tx}, \\ & \tilde{C}_{j,3}^{Tx} : \sum_{d_i^{Tx} \in \mathcal{D}_{Tx}} y_{j,i}^{Rx} \leq 1. \end{aligned} \tag{18}$$

$\tilde{C}_{i,1}^{Tx}$, $\tilde{C}_{i,2}^{Tx}$, $\tilde{C}_{j,2}^{Rx}$ and $\tilde{C}_{j,3}^{Rx}$ specify the D2D peer selection constraints that only a maximum number of $N_{i,max}^{Tx}$ D2D receivers can be served by d_i^{Tx} simultaneously, while d_j^{Rx} can be served by at most one D2D transmitter. $\tilde{C}_{j,1}^{Rx}$ is the QoS requirement.

D. THE MANY-TO-ONE MATCHING PROBLEM FORMULATION

To solve the NP-hard two-stage combinatorial problem defined in (11), (12), (17), and (18) with both binary and continuous optimization variables, we employ an many-to-one matching approach that has taken UEs' preferences into consideration to obtain an stable and low-complexity match-based resource allocation algorithm. It is noted that although (17) and (18) only involve a binary optimization variable, standard integer programming cannot be applied here because the stability of the matching result is not guaranteed.

The first-stage and second-stage many-to-one matching problems are formulated as follows:

- The formulated matching problem for the first stage is denoted as $(\mathcal{C}, \mathcal{D}_{Tx}, \mathcal{P}_c, \mathcal{P}_{Tx}, \mu)$. $\mathcal{P}_c$ and $\mathcal{P}_{Tx}$ represent

the set of preferences for CUs and D2D transmitters, respectively. μ is a many-to-one mapping from $\mathcal{D}_{Tx} \cup \mathcal{C}$ onto itself under mutual preferences $\mathcal{P}_{Tx}$ and $\mathcal{P}_c$ [12]. In other words, for any $c_k \in \mathcal{C}$ and $d_i^{Tx} \in \mathcal{D}_{Tx}$, we must have $\mu(c_k) \in \mathcal{D}_{Tx} \cup \{c_k\}$ and $\mu(d_i^{Tx}) \in \mathcal{C} \cup \{d_i^{Tx}\}$. $d_i^{Tx} \in \mu(c_k)$ if and only if $\mu(d_i^{Tx}) = c_k$, i.e., $x_{i,k}^d = x_{k,i}^c = 1$.
- The formulated matching problem for the second stage is denoted as $(\mathcal{D}_{Tx}, \mathcal{D}_{Rx}, \tilde{\mathcal{P}}_{Tx}, \tilde{\mathcal{P}}_{Dx}, \tilde{\mu})$. $\tilde{\mathcal{P}}_{Tx}$ and $\tilde{\mathcal{P}}_{Rx}$ represent the set of preferences for D2D transmitters and receivers, respectively. $\tilde{\mu}$ is defined in a similar way as μ, which is a many-to-one mapping from $\mathcal{D}_{Tx} \cup \mathcal{D}_{Rx}$ onto itself under mutual preferences $\tilde{\mathcal{P}}_{Tx}$ and $\tilde{\mathcal{P}}_{Rx}$.

Remark 3: The match of a UE onto itself should be interpreted case by case according to the type of UE. First, the interpretation of $\mu(c_k) = c_k$ implies that c_k's channel is left unused by any D2D transmitter under μ. Second, $\mu(d_i^{Tx}) = d_i^{Tx}$ indicates that there is no available spectrum resource for d_i^{Tx} to implement D2D communications. The reason is that either d_i^{Tx} is less preferred by CUs than other D2D transmitters, or the QoS requirement of d_i^{Tx} is set too high to be satisfied. Third, $\tilde{\mu}(d_i^{Tx}) = d_i^{Tx}$ represents that d_i^{Tx} is less preferred by D2D receivers than other D2D transmitters. Finally, $\tilde{\mu}(d_j^{Rx}) = d_j^{Rx}$ indicates that either there exists no such D2D transmitter that can satisfy the QoS requirement of d_j^{Rx}, or d_j^{Rx} is less preferred by D2D transmitters than other D2D receivers.

Remark 4: In any many-to-one match, we assume that UEs are selfish and reasonable, which only care about their own matching results and show no interest towards other UEs.

V. THE ENERGY-EFFICIENT CONTEXT-AWARE STABLE MATCHING ALGORITHM FOR D2D COMMUNICATIONS

In this section, the proposed energy-efficient context-aware stable matching algorithm is introduced as follows. First, starting from the first-stage many-to-one matching problem, we introduce how to establish preference list, and propose an iterative power allocation algorithm by combining nonlinear fractional programming and Lagrange dual decomposition. Then we propose an iterative matching algorithm to derive a many-to-one stable match between D2D transmitters and CUs with dynamically varying preferences. Second, using the channel selection and power allocation strategies obtained in the first stage, the second-stage many-to-one matching problem can also be solved by the proposed algorithm with little modifications. Finally, we analyze the matching stability, optimality, scalability, and complexity in details.

A. SOLUTION OF THE FIRST-STAGE MANY-TO-ONE MATCHING PROBLEM BETWEEN D2D TRANSMITTERS AND CUS

1) THE NONLINEAR FRACTIONAL PROGRAMMING BASED ITERATIVE POWER ALLOCATION ALGORITHM

In the first-stage many-to-one matching problem, each $d_i^{Tx} \in \mathcal{D}_{Tx}$ and $c_k \in \mathcal{C}$ needs to specify its preference over the opposite set, i.e., $P(d_i^{Tx})$ and $P(c_k)$ respectively. We use the EE as the criteria to establish $P(d_i^{Tx})$ and $P(c_k)$. For example, the preference of d_i^{Tx} over c_k is calculated as the maximum achievable EE of d_i^{Tx} through the optimization of p_i^d under the match $\mu(d_i^{Tx}) = c_k$ ($x_{i,k}^d = x_{k,i}^c = 1$) and known co-channel interference. In this way, the preference of d_i^{Tx} over any CU in the set $\mathcal{C}$ can be calculated by solving a power allocation problem, and the obtained maximum EE values are sorted in descending order to establish $P(d_i^{Tx})$. The power allocation problem for d_i^{Tx} under the match μ is formulated as

$$\max_{p_i^d} \; U_{i,EE}^{Tx}(p_i^d)\Big|_{\mu(d_i^{Tx})=c_k} \quad \text{s.t. } C_{i,1}^{Tx}, C_{i,2}^{Tx}. \tag{19}$$

Algorithm 1 The Iterative Power Allocation Algorithm for the First-Stage Many-to-One Matching Problem

Input: $g_i^d, I_{k,j'}^c, \sum_{d_l^{Tx} \in \mathcal{W}_k^c \setminus \{d_i^{Tx}\}} I_{l,j'}^d, U_{i,SEmin}^{Tx}$.
Output: p_i^{d*}.
Initialize: $q_i^{Tx}, N_{d,max}, \Delta_d, \hat{p}_i^d$.
while $n_d < N_{d,max}$ **do**
  calculate $\hat{p}_i^d(n)$ as (26)
  if $U_{i,SE}^{Tx}[\hat{p}_i^d(n_d)] - q_i^{Tx}(n_d) E_i^{Tx}[\hat{p}_i^d(n_d)] > \Delta_d$ **then**
    Update: $q_i^{Tx}(n_d+1) = U_{i,SE}^{Tx}[\hat{p}_i^d(n_d)] / E_i^{Tx}[\hat{p}_i^d(n_d)]$
  else
    $p_i^{d*} = \hat{p}_i^d(n_d)$, and $q_i^{Tx*} = U_{i,SE}^{Tx}[p_i^{d*}] / E_i^{Tx}[p_i^{d*}]$
  end if
  Update the iteration index: $n_d \leftarrow n_d + 1$
end while

To solve the nonconvex problem defined above with the fractional-form objective function, we exploit nonlinear fractional programming (Dinkelbach's algorithm) [14] to transform (19) into an equivalent convex one, and propose an iterative power allocation problem as shown in Algorithm 1. Define the iteration index as n_d, the algorithm stops if either the specified iteration constraint $N_{d,max}$ is reached, or the achieved power allocation strategy has already converged to p_i^{d*}. Define the maximum EE of d_i^{Tx} as

$$q_i^{Tx*} := \max_{p_i^d} U_{i,EE}^{Tx}(p_i^d)\Big|_{\mu(d_i^{Tx})=c_k} = \frac{U_{i,SE}^{Tx}(p_i^{d*})}{E_i^{Tx}(p_i^{d*})}, \tag{20}$$

where p_i^{d*} is the optimum power allocation strategy of d_i^{Tx}. The optimality condition is given by

Theorem 1: q_i^{Tx*} is achieved if and only if [14]

$$\max_{p_i^d} U_{i,SE}^{Tx}(p_i^d) - q_i^{Tx*} E_i^{Tx}(p_i^d) = U_{i,SE}^{Tx}(p_i^{d*}) - q_i^{Tx*} E_i^{Tx}(p_i^{d*}) = 0. \tag{21}$$

Theorem 1 reveals that given the condition $\max_{p_i^d} U_{i,EE}^{Tx}(p_i^d)\Big|_{\mu(d_i^{Tx})=c_k} = q_i^{Tx*}$, we could obtain the same

p_i^{d*} by solving the convex problem $\max_{p_i^d} U_{i,SE}^{Tx}(p_i^d) - q_i^{Tx*} E_i^{Tx}(p_i^d)$ rather than solving the original nonconvex problem $\max_{p_i^d} U_{i,EE}^{Tx}(p_i^d)\Big|_{\mu(d_i^{Tx})=c_k}$. The equivalent convex optimization problem of (19) is written as

$$\max_{p_i^d} \; U_{i,SE}^{Tx}(p_i^d) - q_i^{Tx*} E_i^{Tx}(p_i^d)$$
$$\text{s.t. } C_{i,1}^{Tx}, C_{i,2}^{Tx}. \tag{22}$$

Although (22) is convex, it cannot be solved directly because q_i^{Tx*} is still unknown. Therefore, q_i^{Tx*} must be obtained iteratively. To start, we initialize q_i^{Tx} as a small positive number, e.g., 10^{-4}. At the n_d-th iteration, the optimal $\hat{p}_i^d(n_d)$ is obtained by solving the following problem with $q_i^{Tx}(n_d)$ obtained from the $(n_d - 1)$-th iteration:

$$\max_{p_i^d} \; U_{i,SE}^{Tx}[p_i^d(n_d)] - q_i^{Tx}(n_d) E_i^{Tx}[p_i^d(n_d)]$$
$$\text{s.t. } C_{i,1}^{Tx}, C_{i,2}^{Tx}. \tag{23}$$

The augmented Lagrangian of (23) is given by

$$\mathcal{L}_{i,EE}^{Tx}(p_i^d, \delta_i^d, \theta_i^d) = U_{i,SE}^{Tx}[p_i^d(n_d)] - q_i^{Tx}(n_d) E_i^{Tx}[p_i^d(n_d)] + \theta_i^d \left(U_{i,SE}^{Tx}[p_i^d(n_d)] - U_{i,SEmin}^{Tx} \right) - \delta_i^d [p_i^d(n_d) - p_{i,max}^d], \tag{24}$$

where δ_i^d and θ_i^d are the Lagrange multipliers associated with the constraints $C_{i,1}^{Tx}$ and $C_{i,2}^{Tx}$, respectively. According to [43], (24) is decomposed as

$$\min_{(\delta_i^d, \theta_i^d \geq 0)} \; \max_{(p_i^d)} \; \mathcal{L}_{i,EE}^{Tx}(p_i^d, \delta_i^d, \theta_i^d), \tag{25}$$

which combines an inner subproblem to maximize the Lagrangian and an outer subproblem to minimize the duality gap. The optimal value $\hat{p}_i^d(n_d)$ can be obtained by using the Karush-Kuhn-Tucker (KKT) conditions as

$$\hat{p}_i^d(n_d) = \left[\frac{\eta[1+\theta_i^d]\log_2 e}{q_i^{Tx}(n_d) + \eta\delta_i^d} - \frac{N_0 + I_{k,j'}^c + \sum_{d_l^{Tx} \in \mathcal{W}_k^c \setminus \{d_i^{Tx}\}} I_{l,j'}^d}{g_i^d} \right]^+, \tag{26}$$

where $[x]^+ = \max\{0, x\}$, and $\mathcal{W}_k^c$ represents the set of D2D transmitters that are matched with c_k, which is obtained in Algorithm 3.

In the outer loop, δ_i^d and θ_i^d are updated as [44]

$$\delta_i^d(n_l+1) = \left[\delta_i^d(n_l) + \epsilon_{i,\delta}^d(n_l) \left(\hat{p}_i^d(n_d, n_l) - p_{i,max}^d \right) \right]^+, \tag{27}$$

$$\theta_i^d(n_l+1) = \left[\theta_i^d(n_l) - \epsilon_{i,\theta}^d(n_l) \left(U_{i,SE}^{Tx}(n_d, n_l) - U_{i,SEmin}^{Tx} \right) \right]^+, \tag{28}$$

where n_l is the index of updating iteration, $\epsilon_{i,\delta}^d$ and $\epsilon_{i,\theta}^d$ are the step sizes, which require careful design to guarantee convergence and optimality.

Then, $q_i^{Tx}(n_d + 1)$ of the next iteration is updated as $q_i^{Tx}(n_d+1) = U_{i,SE}^{Tx}[\hat{p}_i^d(n_d)]/E_i^{Tx}[\hat{p}_i^d(n_d)]$. When the iteration loop terminates, setting the optimum strategy as $p_i^{d*} = \hat{p}_i^d$, q_i^{Tx*} is calculated as $q_i^{Tx*} = U_{i,SE}^{Tx}[p_i^{d*}]/E_i^{Tx}[p_i^{d*}]$.

Algorithm 2 The Preference Establishment Algorithm for the First-Stage Many-to-One Matching Problem

1: **Input:** $\mathcal{C}, \mathcal{D}_{Tx}, \mu, p_i^{d*}, \forall d_i^{Tx} \in \mathcal{D}_{Tx}$
2: **Output:** $\mathcal{P}_{Tx}, \mathcal{P}_c$.
3: **for** $d_i^{Tx} \in \mathcal{D}_{Tx}$ **do**
4: Calculate $q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_k}$ for any $c_k \in \mathcal{C}$ by using (20).
5: Establish $P(d_i^{Tx})$ by sorting each $c_k \in \mathcal{C}$ in descending order based on $q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_k}$.
6: **end for**
7: **for** $c_k \in \mathcal{C}$ **do**
8: Calculate $U_{k,EE}^c\Big|_{\mu(c_k)=d_i^{Tx}}$ for any $d_i^{Tx} \in \mathcal{D}_{Tx}$ using (10).
9: Establish $P(c_k)$ by sorting each $d_i^{Tx} \in \mathcal{D}_{Tx}$ in descending order based on $U_{k,EE}^c\Big|_{\mu(c_k)=d_i^{Tx}}$.
10: **end for**

2) THE PREFERENCE ESTABLISHMENT ALGORITHM

The proposed preference establishment algorithm is summarized in Algorithm 2. The preference of any $d_i^{Tx} \in \mathcal{D}_{Tx}$ over any $c_k \in \mathcal{C}$ is denoted as $q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_k}$, and is calculated by using (20). When comparing the preferences, we introduce a binary preference relation "$\succ$" that is complete, reflexive, and transitive [12]. For example, we use $c_k \succ_{d_i^{Tx}} c_{k'}$ to represent d_i^{Tx} prefers c_k to $c_{k'}$, which is given by

$$c_k \succ_{d_i^{Tx}} c_{k'} := q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_k} > q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_{k'}}, \tag{29}$$

If c_k is preferred by d_i^{Tx} at least as well as $c_{k'}$, we use the notation $c_k \succeq_{d_i^{Tx}} c_{k'}$, which is given by

$$c_k \succeq_{d_i^{Tx}} c_{k'} := q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_k} \geq q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_{k'}}, \tag{30}$$

The preference list $P(d_i^{Tx})$ of any $d_i^{Tx} \in \mathcal{D}_{Tx}$ is obtained by sorting all of CUs in a descending order according to the criteria of $q_i^{Tx*}\Big|_{\mu(d_i^{Tx})=c_k}$, $\forall c_k \in \mathcal{C}$, while the preference list $P(c_k)$ of any $c_k \in \mathcal{C}$ is obtained by sorting D2D transmitters according to $U_{k,EE}^c\Big|_{\mu(c_k)=d_i^{Tx}}$, $\forall d_i^{Tx} \in \mathcal{D}_{Tx}$. It is noted that the maximum achievable EE for both d_i^{Tx} and c_k actually depends on the co-channel interference caused by other channel-reusing D2D transmitters, i.e., $\sum_{d_l^{Tx} \in \mathcal{W}_k^c \setminus \{d_i^{Tx}\}} I_{l,j'}^d$ and $\sum_{d_l^{Tx} \in \mathcal{W}_k^c \setminus \{d_i^{Tx}\}} p_l^d g_{l,B}^d$. Therefore, when performing the match of D2D transmitters and CUs based on the established preference lists, the produced matching result will

Algorithm 3 The First-Stage Energy-Efficient Stable Matching Algorithm

Input: $\mathcal{C}, \mathcal{D}_{Tx}, \mathcal{P}_c, \mathcal{P}_{Tx}$.
Output: μ.
Initialization:
Each $d_i^{Tx} \in \mathcal{D}_{Tx}$ is randomly matched with a CU, and is allocated with a random transmission power.
Every $d_i^{Tx} \in \mathcal{D}_{Tx}$ and $c_k \in \mathcal{C}$ build its preference list by using Algorithm 2.
Set $\mu = \phi$, $n_m = 1$.
The Fist-Stage Matching Iteration:
while [$\mathbf{x}_i^{Tx}(n_m) \neq \mathbf{x}_i^{Tx}(n_m - 1), \forall d_i^{Tx} \in \mathcal{D}_{Tx}$, & $\mathbf{x}_k^c(n_m) \neq \mathbf{x}_k^c(n_m - 1), \forall c_k \in \mathcal{C}$] and $n_m < N_{m,max}$ **do**
  Initialize: $\Phi_{Tx} = \mathcal{D}_{Tx}$
  while $\Phi_{Tx} \neq \phi$ **do**
    for $d_i^{Tx} \in \Phi_{Tx}$ **do**
      Assuming the index of the most-preferred CU from $P(d_i^{Tx})$ is k', d_i^{Tx} sends a request by setting $x_{i,k'}^{Tx} = 1$, calculates p_i^{d*} using Algorithm 1.
    end for
    for $c_k \in \mathcal{C}$ **do**
      if c_k receives a request from d_i^{Tx} **then**
        Place d_i^{Tx} on c_k's waiting list $\mathcal{W}_k^c$, i.e., $x_{k,i}^c = 1$, remove d_i^{Tx} from Φ_{Tx}, and remove c_k from $P(d_i^{Tx})$.
        while $U_{k,SE}^c > U_{k,SEmin}^c$ and $|\ \mathcal{W}_k^c\ | > N_{k,max}^c$ **do**
          Assuming the index of the least-preferred D2D transmitter in $\mathcal{W}_k^c$ as i', reject $d_{i'}^{Tx}$ by setting $x_{k,i'}^c = x_{i',k}^{Tx} = 0$, add $d_{i'}^{Tx}$ into Φ_{Tx}, and remove c_k from its preference list.
        end while
      end if
    end for
  end while
  Set: $\mu(d_i^{Tx}) = c_k$ if $d_i^{Tx} \in \mathcal{W}_k^c$. $\mu(c_k) = \mathcal{W}_k^c$.
  Update:
  Update $\mathbf{x}_i^{Tx}(n_m), \forall d_i^{Tx} \in \mathcal{D}_{Tx}$, and $\mathbf{x}_k^c(n_m^1), \forall c_k \in \mathcal{C}$.
  Every $d_i^{Tx} \in \mathcal{D}_{Tx}$ and $c_k \in \mathcal{C}$ update its preference list by using Algorithm 2 based on μ and $p_i^{d*}(n_m)$.
  $n_m \leftarrow n_m + 1$
end while

change the aggregated interference levels and the preference lists should be updated correspondingly. However, the change of UEs' preferences will in turn affect the matching results, which cannot be solved by using the method proposed in [38] and [39].

3) THE ITERATIVE ENERGY-EFFICIENT MATCHING ALGORITHM FOR THE FIRST-STAGE MATCHING PROBLEM

In the previous subsection, we have introduced how to establish the preference list for each $d_i^{Tx} \in \mathcal{D}_{Tx}$ and $c_k \in \mathcal{C}$. We propose an energy-efficient iterative many-to-one stable matching approach summarized in Algorithm 3. When implementing Algorithm 3, Algorithm 1 and Algorithm 2 are executed repeatedly to perform energy-efficient power allocation, and to establish and update preference lists. The GS algorithm with deferred acceptance property has been modified to adapt to the dynamically varying preferences [11], in which the acceptance of a partner request is deferred until no better request appears. In particular, Algorithm 3 can proceed as follows:

- In the initial stage, randomly select a partner selection and power allocation strategy, establish the preference lists by using Algorithm 2, and perform the many-to-one match according to the following steps.
- In the first step, each $d_i^{Tx} \in \mathcal{D}_{Tx}$ sends a channel-reusing request to its top CU of $P(d_i^{Tx})$ with transmission power p_i^{d*}, which is obtained by using Algorithm 1. Each $c_k \in \mathcal{C}$ places all of the D2D transmitters from which it has received requests on its waiting list $\mathcal{W}_k^c$. All of the D2D transmitters in $\mathcal{W}_k^c$ are kept as candidates if $U_{k,SE}^c \leq U_{k,SEmin}^c$ and $|\ \mathcal{W}_k^c\ | \leq N_{k,max}^c$. Otherwise, the least preferred D2D transmitters in $\mathcal{W}_k^c$ are rejected until the constraints, i.e., $U_{k,SE}^c \geq U_{k,SEmin}^c$ and $|\ \mathcal{W}_k^c\ | \leq N_{k,max}^c$, are satisfied.
- In any middle step, any $d_i^{Tx} \in \mathcal{D}_{Tx}$ that was rejected in the previous iteration by any CU sends a channel-reusing request to its most-preferred CU that has not yet rejected it before.
- Each $c_k \in \mathcal{C}$ compares all of the D2D transmitters from which it has received requests including the candidates that were kept from previous iterations, and rejects the least preferred D2D transmitters to satisfy the constraints $U_{k,SE}^c \leq U_{k,SEmin}^c$ and $|\ \mathcal{W}_k^c\ | \leq N_{k,max}^c$.
- In the final step, each $c_k \in \mathcal{C}$ is matched with the D2D transmitters on its waiting list $\mathcal{W}_k^c$.
- Update preference lists using Algorithm 2 based on the obtained partner selection and power allocation strategies, and perform the match again with the newly updated preference lists.

Due to the fact that none D2D transmitter is allowed to send a request twice to the same CU, the matching process in each iteration of Algorithm 3 always terminates in finite steps. Algorithm 3 terminates when either the matches produced in two consecutive iterations are the same, or the maximum specified number of iterations is reached.

B. SOLUTION OF THE SECOND-STAGE MANY-TO-ONE MATCHING PROBLEM BETWEEN D2D TRANSMITTERS AND RECEIVERS

1) PREFERENCE ESTABLISHMENT FOR D2D TRANSMITTERS AND RECEIVERS

The proposed preference establishment algorithm for the second stage is summarized in Algorithm 4. For any $d_i^{Tx} \in \mathcal{D}_{Tx}$, assuming that $\mu(d_i^{Tx}) = c_k$ and the optimum power

Algorithm 4 The Preference Establishment Algorithm for the Second-Stage Many-To-One Matching Problem

Input: $\mathcal{D}_{Rx}$, $\mathcal{D}_{Tx}$, μ, p_i^{d*}, $\forall d_i^{Tx} \in \mathcal{D}_{Tx}$.
Output: $\tilde{\mathcal{P}}_{Tx}$, $\tilde{\mathcal{P}}_{Rx}$.
for $d_j^{Rx} \in \mathcal{D}_{Rx}$ **do**
  Calculate its preference over any $d_i^{Tx} \in \mathcal{D}_{Tx}$ as (16).
  Establish $\tilde{P}(d_j^{Rx})$ by sorting each $d_i^{Tx} \in \mathcal{D}_{Tx}$ in descending order based on $\tilde{U}_{j,EE}^{Rx}\Big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_j^{Rx})=d_i^{Tx}}$.
end for
for $d_i^{Tx} \in \mathcal{D}_{Tx}$ **do**
  Calculate its preference over any $d_j^{Rx} \in \mathcal{D}_{Rx}$ as (15).
  Establish $\tilde{P}(d_i^{Tx})$ by sorting each $d_j^{Rx} \in \mathcal{D}_{Rx}$ in descending order based on $\tilde{U}_{i,EE}^{Tx}\Big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_i^{Tx})=d_j^{Rx}}$.
end for

allocation strategy is p_i^{d*}, its preference over any $d_j^{Rx} \in \mathcal{D}_{Rx}$ is calculated as (15). The preference list $\tilde{P}(d_i^{Tx})$ is obtained by sorting all of D2D receivers in a descending order according to the criteria of $\tilde{U}_{i,EE}^{Tx}\Big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_i^{Tx})=d_j^{Rx}}$, $\forall d_j^{Rx} \in \mathcal{D}_{Rx}$. In a similar way, the preference of any $d_j^{Rx} \in \mathcal{D}_{Rx}$ over any $d_i^{Tx} \in \mathcal{D}_{Tx}$ is calculated as (16). The preference list $\tilde{P}(d_j^{Rx})$ is obtained by sorting all of D2D transmitters in a descending order according to the criteria of $\tilde{U}_{j,EE}^{Rx}\Big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_j^{Rx})=d_i^{Tx}}$, $\forall d_i^{Tx} \in \mathcal{D}_{Tx}$.

It is noted that $\tilde{U}_{i,EE}^{Tx}\Big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_i^{Tx})=d_j^{Rx}}$ and $\tilde{U}_{j,EE}^{Rx}\Big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_j^{Rx})=d_i^{Tx}}$ actually have the same nominator, which depends on the channel-reusing partner selection and power allocation strategies obtained in the first-stage matching process. Although the nominators of $\tilde{U}_{i,EE}^{Tx}\big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_i^{Tx})=d_j^{Rx}}$ and $\tilde{U}_{j,EE}^{Rx}\big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_j^{Rx})=d_i^{Tx}}$ are the same, it is not guaranteed that d_j^{Rx} can always be matched with d_i^{Tx} in the second-stage match unless both d_j^{Rx} and d_i^{Tx} prefer each other to other candidates.

Remark 5: The difference between the preference establishment of the second-stage match and that of the first-stage match is that both $\tilde{P}(d_i^{Tx})$ and $\tilde{P}(d_j^{Rx})$, $\forall d_i^{Tx} \in \mathcal{D}_{Tx}$, $\forall d_j^{Rx} \in \mathcal{D}_{Rx}$, do not depend on the match $\tilde{\mu}$.

2) THE ENERGY-EFFICIENT STABLE MATCHING ALGORITHM FOR THE SECOND-STAGE MATCHING PROBLEM

In this subsection, the proposed energy-efficient stable matching algorithm for the second stage is summarized in Algorithm 5, which is developed by modifying the Algorithm 3 to match D2D transmitters and receivers with

Algorithm 5 The Second-Stage Energy-Efficient Stable Matching Algorithm

Input: $\mathcal{D}_{Tx}$, $\mathcal{D}_{Rx}$, μ, p_i^{d*},$\forall d_i^{Tx} \in \mathcal{D}_{Tx}$
Output: $\tilde{\mu}$.
Each $d_j^{Rx} \in \mathcal{D}_{Rx}$ and $d_i^{Tx} \in \mathcal{D}_{Tx}$ build its preference list by using Algorithm 4.
Set $\tilde{\mu} = \phi$ and initialize $N_{i,max}^{Tx}$.
Initialize: $\Phi_{Rx} = \mathcal{D}_{Rx}$
while $\Phi_{Rx} \neq \phi$ **do**
  for $d_j^{Rx} \in \Phi_{Rx}$ **do**
    Assuming the index of the most-preferred d_i^{Tx} from $\tilde{P}(d_j^{Rx})$ is $i^{'}$, d_j^{Rx} sends a request by setting $y_{j,i^{'}}^{Rx} = 1$.
  end for
  for $d_i^{Tx} \in \mathcal{D}_{Tx}$ **do**
    if d_i^{Tx} receives a request from d_j^{Rx} **then**
      Place d_j^{Rx} on d_i^{Tx}'s waiting list $\mathcal{W}_i^{Tx}$, i.e., $y_{i,j}^{Tx} = 1$, remove d_j^{Rx} from Φ_{Rx}, and remove d_i^{Tx} from $\tilde{P}(d_j^{Rx})$.
      while $|\mathcal{W}_i^{Tx}| > N_{i,max}^{Tx}$ **do**
        Assuming the index of the least-preferred D2D receiver in $\mathcal{W}_i^{Tx}$ as $j^{"}$, reject $d_{j^{"}}^{Rx}$ by setting $y_{i,j^{"}}^{Tx} = y_{j^{"},i}^{Rx} = 0$, add $d_{j^{"}}^{Rx}$ into Φ_{Rx}, and remove d_i^{Tx} from its preference list.
      end while
    end if
  end for
end while
Set: $\tilde{\mu}(d_j^{Rx}) = d_i^{Tx}$ if $d_j^{Rx} \in \mathcal{W}_i^{Tx}$. $\tilde{\mu}(d_i^{Tx}) = \mathcal{W}_i^{Tx}$.

fixed preferences. In particular, Algorithm 5 can proceed as follows:

- Establish the preference lists $\tilde{\mathcal{P}}_{Tx}$ and $\tilde{\mathcal{P}}_{Rx}$ using Algorithm 4.
- In the first step, each $d_j^{Rx} \in \mathcal{D}_{Rx}$ sends a request to its top D2D transmitter of $\tilde{P}(d_j^{Rx})$. Each $d_i^{Tx} \in \mathcal{D}_{Tx}$ places all of the D2D receivers from which it has received requests on its waiting list $\mathcal{W}_i^{Tx}$. All of the D2D receivers in $\mathcal{W}_i^{Tx}$ are kept if $|\mathcal{W}_i^{Tx}| \leq N_{i,max}^{Tx}$. Otherwise, the least preferred D2D receivers in $\mathcal{W}_i^{Tx}$ are rejected until $|\mathcal{W}_i^{Tx}| \leq N_{i,max}^{Tx}$.
- In any middle step, any $d_j^{Rx} \in \mathcal{D}_{Rx}$ that was rejected at the previous iteration by any D2D transmitter sends a request to its most-preferred D2D transmitter that has not yet rejected it before.
- Each $d_i^{Tx} \in \mathcal{D}_{Tx}$ compares all of the D2D receivers from which it has received requests including the candidates that were kept from previous iterations, and rejects the least preferred D2D receivers to satisfy the requirement $|\mathcal{W}_i^{Tx}| \leq N_{i,max}^{Tx}$.
- In the final step, each $d_i^{Tx} \in \mathcal{D}_{Tx}$ is matched with the D2D receivers on its waiting list $\mathcal{W}_i^{Tx}$.

C. PROPERTIES OF THE ENERGY-EFFICIENT CONTEXT-AWARE STABLE MATCHING ALGORITHM

In this subsection, the properties of the proposed energy-efficient context-aware stable matching algorithm is analyzed in details.

1) CONVERGENCE AND STABILITY

Theorem 2: In Algorithm 1, q_i^{Tx} of any $d_i^{Tx} \in \mathcal{D}_{Tx}$ obtained in each iteration must be larger or at least equal to the one obtained in the previous iteration, i.e., $q_i^{Tx}(n_d+1) \geq q_i^{Tx}(n_d)$, and converges to the optimum EE q_i^{Tx*}.

Proof: Please see the Appendix A.

Theorem 3: Both Algorithm 3 and Algorithm 5 generate a two-sided stable match in finite iterations.

Proof: Please see the Appendix B.

2) OPTIMALITY

Theorem 4: The energy-efficient many-to-one match μ and $\tilde{\mu}$ are weak Pareto optimal to D2D transmitters and D2D receivers, respectively.

Proof: Please see Appendix C.

3) COMPLEXITY

In the first-stage many-to-one matching problem, the computational complexity of Algorithm 1 for any $d_i^{Tx} \in \mathcal{D}_{Tx}$ is $\mathcal{O}(N_i^{loop} N_i^{dual})$. N_i^{loop} is the required Dinkelbach iterations for q_i^{Tx} to converge to q_i^{Tx*}, and N_i^{dual} is the required Lagrange multiplier updating iterations for $\hat{p}_i^d$ to converge to p_i^{d*}. In Algorithm 2, the computational complexity for sorting the preferences of each D2D transmitter is $\mathcal{O}\big(K\log(K)\big)$, and the complexity for sorting the preferences of each CU is $\mathcal{O}\big(N_{Tx}\log(N_{Tx})\big)$. In Algorithm 3, the match of each iteration has a complexity of $\mathcal{O}(N_{Tx}K)$ under the rule that $d_i^{Tx} \in \mathcal{D}_{Tx}$ can only send at most one request to any $c_k \in \mathcal{C}$ [13]. Since the maximum number of allowed matching iterations is specified as $N_{m,max}$, the complexity of the Algorithm 3 is linear with N_{Tx} and K. In the second-stage many-to-one matching problem, the computational complexity of Algorithm 4 is similar to that of Algorithm 2, which is $\mathcal{O}\big(N_{Rx}\log(N_{Rx})\big)$ for any D2D transmitter, and $\mathcal{O}\big(N_{Tx}\log(N_{Tx})\big)$ for any D2D receiver. The computational complexity of Algorithm 5 is $\mathcal{O}(N_{Tx}N_{Rx})$.

4) SCALABILITY

Scalability issues arise as a problem when the acquisition of the CSI for a large number of links becomes infeasible due to the increasing communication overheads and transmission delays. For example, if the channel gain between d_i^{Tx} and d_j^{Rx} is unknown, it is impossible to calculate $\tilde{U}_{i,EE}^{Tx}\big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_i^{Tx})=d_j^{Rx}}$ and $\tilde{U}_{j,EE}^{Rx}\big|_{\mu(d_i^{Tx})=c_k, p_i^{d*}, \tilde{\mu}(d_j^{Rx})=d_i^{Tx}}$. As a result, the preference lists $\tilde{P}(d_i^{Tx})$ and $\tilde{P}(d_j^{Rx})$ become incomplete and inconsistent. In this case, the match has to proceed with *incomplete and inconsistent preference lists*. One solution is to make the preference lists look like consistent and complete by deleting d_i^{Tx} and d_j^{Rx} from $\tilde{P}(d_j^{Rx})$ and $\tilde{P}(d_i^{Tx})$, respectively. With the modified preference lists, both Algorithm 3 and Algorithm 5 can proceed in the same fashion and obtain a new match in polynomial time.

When the number of UEs becomes large enough, a *preference tie* occurs if more than one potential matching partners are equally preferred by a UE. To adapt the matching algorithm to the preference tie, tie-breaking rules have to be incorporated into the Algorithm 3 and Algorithm 5 to force that UE to choose among the equally preferred partners according to a new criteria other than the maximum EE. The new criteria can be flexibly designed to optimize miscellaneous performance metrics such as SE, reliability, security, fairness, and coverage, etc.

TABLE 2. Simulation parameters.

Simulation Parameter	Value
Cell radius	300 m
Max D2D transmission distance d_{max}^d	30 m
Pathloss exponent α	4
Pathloss constant ϖ	10^{-2}
Shadowing $\zeta_{k,B}^c$ (standard deviation of a log-normal distribution)	8 dB
Multi-path fading $\beta_{k,B}^c$ (the mean of an exponential distribution)	1
Max Tx power $p_{i,max}^d$	23 dBm
CU's TX power (uniform distribution) p_k^c	$0 \sim 23$ dBm
Constant circuit power p_{cir}	20 dBm
Noise power N_0	-114 dBm
Number of D2D transmitters N_{Tx}	$20 \sim 50$
Number of cellular UEs K	$1 \sim 20$
Number of D2D receivers N_{Rx}	$50 \sim 100$
PA efficiency η	35%
QoS requirement $U_{k,SEmin}^c$, $U_{i,SEmin}^{Tx}$, $\tilde{U}_{j,SEmin}^{Rx}$ (uniform distribution)	$0.5 \sim 1$ bit/s/Hz
The quota of D2D transmitter $N_{i,max}^{Tx}$	3, 6
The quota of CU $N_{k,max}^c$	3, 6

VI. NUMERICAL RESULTS

In this section, we evaluate the proposed energy-efficient context-aware stable matching algorithm, labeled as "the proposed algorithm", through simulations under various scenarios. The simulation parameters are shown in Table 2 [9], [16], [41]. In each round of the simulation, K CUs, N_{Tx} D2D transmitters, and N_{Rx} D2D receivers are randomly placed in a cellular network with a cell radius of 300 m. A snapshot of UEs' locations with $K = 10$, $N_{Tx} = 20$, and $N_{Rx} = 100$ is shown in Fig. 2. The small blue dotted circle with a radius of $d_{max}^d = 30$ m around the D2D transmitter represents the D2D communication enabling region for this particular D2D transmitter, i.e., only those D2D receivers that are inside this region can potentially receive data from this D2D transmitter. We assume that each $d_j^{Rx} \in \mathcal{D}_{Rx}$ requests one file per time out of a set of 10 files, which are randomly cached by the D2D receivers. QoS requirements in terms of minimum

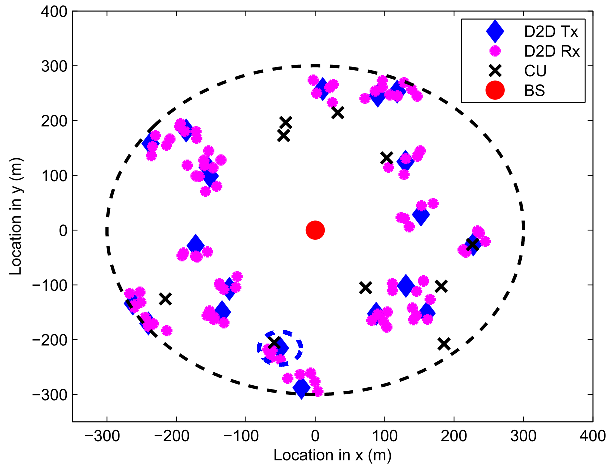

FIGURE 2. **A snapshot of UEs' locations for a single cellular network with K CUs, N_{Tx} D2D transmitters, and N_{Rx} D2D receivers ($K = 10$, $N_{Tx} = 20$, $N_{Rx} = 100$, $d^d_{max} = 30$ m, and the cell radius is 300 m).**

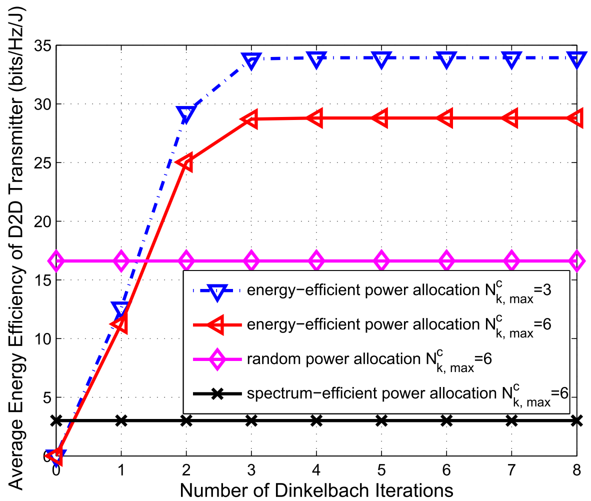

FIGURE 3. **Average EE performance of D2D transmitters in the fist-stage match versus the number of Dinkelbach iterations ($d^d_{max} = 30$ m, $K = 10$, $N_{Tx} = 20$, $N^c_{k,max} = 3, 6$).**

SE are randomly chosen from the range [0.5, 1] bit/s/Hz based on a uniform distribution. We compare the proposed algorithm with two heuristic algorithms. The first one is the spectrum-efficient power allocation algorithm [9], [40], [45]. The second one is the random power allocation algorithm, in which the transmission power are chosen randomly from the range $[0, p^d_{i,max}]$ for any $d^{Tx}_i \in \mathcal{D}_{Tx}$. Despite the difference of the power allocation strategies, random match is adopted for the random power allocation algorithm, while maximum SINR-based UE association is adopted for the spectrum-efficient power allocation algorithm.

Fig. 3 shows the convergence of the proposed iterative power allocation algorithm (Algorithm 1) versus the Dinkelbach iteration index n_d. We only consider the power allocation problem and compare the average EE performances of D2D transmitters achieved by the three algorithms in the first stage. For the purpose of fair comparison, the performances are evaluated under the same match, which is generated randomly in each time of the simulation. The initial value of q^{Tx}_i for any $d^{Tx}_i \in \mathcal{D}_{Tx}$ is set as a small positive value such as 10^{-4}. It is shown that the proposed algorithm only requires $4 \sim 5$ iterations to converge to an equilibrium. Under the same matching algorithm, the average EE achieved by the proposed algorithm with $N^c_{k,max} = 6$ outperforms the random power allocation algorithm and the spectrum-efficient power allocation algorithm by 73% and 850%, respectively. The random power allocation algorithm performs even better than the spectrum-efficient power allocation algorithm. When the transmission power is increased beyond the point for the most energy-efficient transmission, significant EE performance loss is incurred while the SE performance is only slightly improved. Furthermore, the performance becomes worse when $N^c_{k,max}$ is increased form 3 to 6. The reason is that as more and more D2D transmitters are allowed to reuse the same CU's channel simultaneously, the EE performance is degraded by the increasing aggregated interference levels.

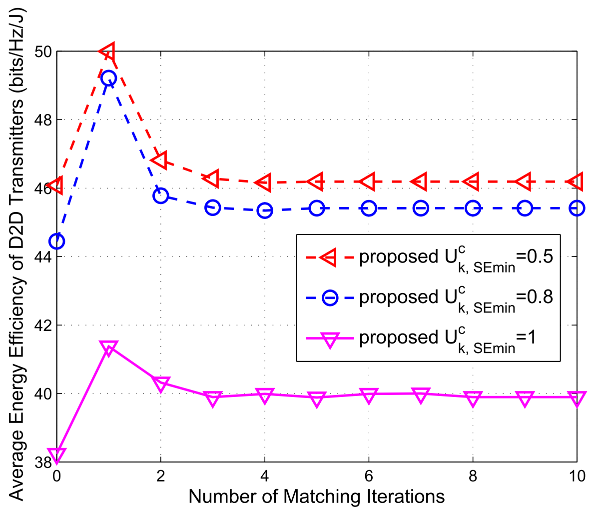

FIGURE 4. **Average EE performance of D2D transmitters in the fist-stage match versus the number of match iterations ($d^d_{max} = 30$ m, $K = 10$, $N_{Tx} = 20$, $U^c_{k,SEmin} = 0.5, 0.8$, and 1 bit/Hz/J).**

Fig. 4 shows the convergence of the proposed iterative many-to-one matching algorithm (Algorithm 3) versus the matching iteration index n_m. When the QoS requirement of CU is low, e.g., $U^c_{k,minSE} = 0.5$ and 0.8 bits/Hz/J, the proposed algorithm is able to converge within only $4 \sim 5$ iterations. When the QoS requirement of CU is high, e.g., $U^c_{k,minSE} = 1$ bits/Hz/J, it requires additional $4 \sim 5$ iterations for the proposed algorithm to converge. The reason is that the coupling between the preferences and the matching result becomes closer as more D2D transmitters prefer to be matched with the same CU. When $U^c_{k,minSE}$ is decreased from 0.8 to 0.5 bits/Hz/J, the average performance of D2D transmitters is improved by 13.49% because the probability for any $d^{Tx}_i \in \mathcal{D}_{Tx}$ to be matched with the top-ranked CUs in $P(d^{Tx}_i)$ becomes much larger. However, the improvement is only 1.71% when $U^c_{k,minSE}$ is decreased from

1 to 0.8 bits/Hz/J. Compared to the average EE performance shown in Fig. 3, it is clear that the combination of the energy-efficient iterative matching and the iterative power allocation algorithm can achieve significant EE performance gains compared to the random matching algorithm. We also observe that the performance firstly becomes good and then degrades after the first iteration. The reason is that CUs and D2D transmitters are randomly matched in the beginning, and a huge performance gain can be achieved by the proposed algorithm in the first iteration. However, after the first iteration, the performance degrades due to the competition among D2D transmitters to be matched with preferred CUs.

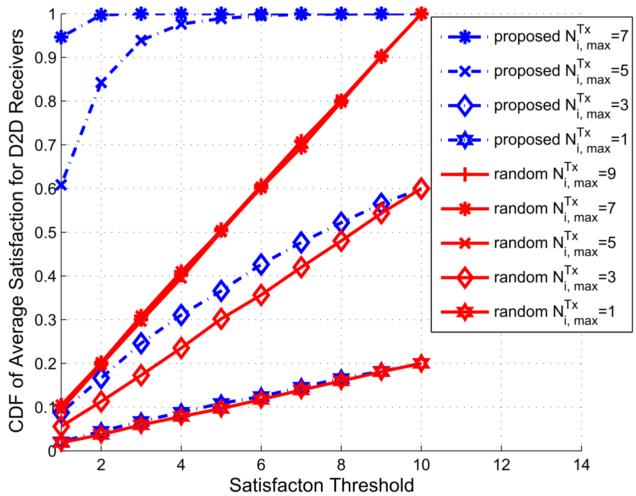

FIGURE 5. CDF of D2D receivers' average satisfaction versus satisfaction threshold (N_{Tx} = 10, N_{Rx} = 50, $N^{Tx}_{i,max} = 1 \sim 9$).

Fig. 5 shows the cumulative distribution functions (CDFs) of average satisfaction for D2D receivers. We assume that there exist $N_{Tx} = 10$ D2D transmitters and $N_{Rx} = 50$ D2D receivers. Using the Monte-Carlo approach, the second-stage match is repeated for a total of 10^3 times and the satisfaction of each D2D receiver regarding to the threshold is statistically counted and averaged to calculate the CDF. For example, assuming d_j^{Rx}'s satisfaction threshold as d_i^{Tx}, d_j^{Rx} is said to be satisfied with $\tilde{\mu}(d_j^{Rx})$ if $\tilde{\mu}(d_j^{Rx}) \succeq_{d_j^{Rx}} d_i^{Tx}$. Otherwise, d_j^{Rx} is unsatisfied with $\tilde{\mu}(d_j^{Rx})$ if $d_i^{Tx} \succ_{d_j^{Rx}} \tilde{\mu}(d_j^{Rx})$. The CDF is denoted as $Pr\{\tilde{\mu}(d_j^{Rx}) \succeq_{d_j^{Rx}} d_i^{Tx}\}$, which represents the probability that d_j^{Rx} is matched with a D2D transmitter that ranks higher or at least equal to d_i^{Tx}.

In the case of $N^{Tx}_{i,max} = 1$ and $N^{Tx}_{i,max} = 3$, the proposed matching algorithm achieves only slightly better performance than the random match. The reason is that only a fraction of D2D receivers can be matched to D2D transmitters and the achievable satisfaction gain is severely limited by the small quota value. However, in the case of $N^{Tx}_{i,max} = 5$ and $N^{Tx}_{i,max} = 7$, the proposed matching algorithm can achieve significant satisfaction gains compared to the random match. For example, when $N^{Tx}_{i,max} = 5$, the probability of being matched to the first choice for D2D receivers is 60.8%, while the corresponding probability achieved by the random match is only 9.4%. When $N^{Tx}_{i,max}$ is increased from 5 to 7, the probability achieved by the proposed match increases dramatically to 94.6%, while the corresponding probability achieved by the random match is still very low, i.e., 10.4%. Furthermore, the performance of the random match is saturated and no further improvement can be achieved even if $N^{Tx}_{i,max}$ is increased from 7 to 9.

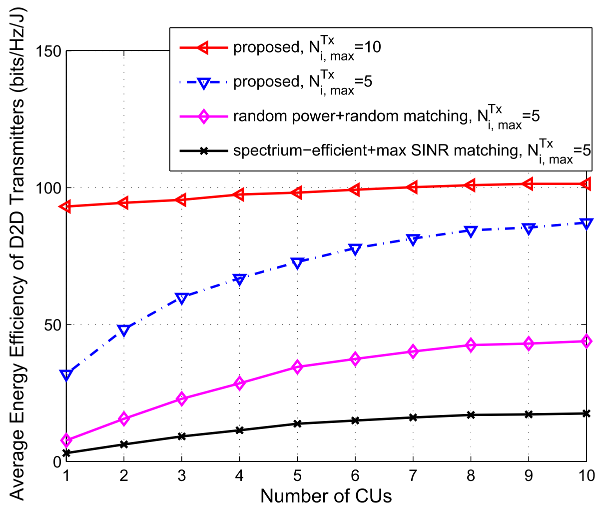

FIGURE 6. Average EE of D2D transmitters in the second stage versus numbers of active CUs (d^d_{max} = 30 m, $K = 1 \sim 10$, $N_{Tx} = 5$, $N_{Rx} = 50$, $N^{Tx}_{i,max} = 5, 10$).

Fig. 6 shows the average EE performance of D2D transmitters in the second stage versus the number of CUs with $N_{Tx} = 10$ D2D transmitters, and $N_{Rx} = 50$ D2D receivers. When $N^{Tx}_{i,max} = 5$ and $K = 10$, the proposed algorithm outperforms the random power allocation algorithm with random match, and the spectrum-efficient algorithm with maximum SINR match by 230%, and 396%, respectively. As $N^{Tx}_{i,max}$ is increased from 5 to 10, the EE performance gain achieved by the proposed algorithm is increased by 16.2%, which is because the aggregated interference level decreases as less D2D transmitters are allocated with the same channel. The spectrum-efficient algorithm with maximum SINR match achieves worse performance compared to the random power allocation algorithm with random match. This proves again that the SE performance gain achieved by increasing transmission power in an interference-limited environment is not able to compensate the corresponding EE loss. It is also clear that the average EE performances of all three algorithms decrease with K because the total number of available orthogonal channels becomes less. Simulation results demonstrate that the proposed algorithm can outperform the two heuristic algorithms under all of the possible simulation scenarios by increasing K from 1 to 10.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, an energy-efficient iterative matching algorithm was proposed for the context-aware resource allocation problem in device-to-device (D2D) communications. The formulated two-stage combinatorial problem involved the match of user equipments (UEs) from two finite and disjoint sets with both binary and continuous optimization variables, which was nonconvex and computationally intractable. To provide a general framework for solving the NP-hard combinatorial problem, we incorporated the many-to-one matching model with two-sided UE preferences, which were modeled from an energy efficiency (EE) perspective. We proposed an energy-efficient iterative matching algorithm to handle the dynamically varying preferences caused by the coupling of the mutual interference terms. In each iteration, the first-stage joint partner and power allocation problem was decoupled into two separate subproblems. Under a specific match, the EE of each D2D transmitter was firstly maximized by using the proposed iterative power allocation algorithm, which was developed based on nonlinear fractional programming. After the establishment of preference lists, the match proceeded in a similar fashion as the Gale-Shapley (GS) algorithm. The UEs' preferences were then updated by using the latest obtained matching results and aggregated interference levels in the end of each iteration. We formulated the second-stage combinatorial problem as a D2D peer selection problem with context information, was also solved by using the proposed matching algorithm with little modifications. The UEs' preferences were fixed, which only depends on the channel selection and power allocation strategies obtained in the first stage. We also provided an in-depth theoretical analysis of the properties of the proposed algorithm including the stability, optimality, complexity, and scalability. Extensive simulations were conducted to compare the proposed algorithm with two heuristic ones under different application scenarios and the efficiency and superiority of the proposed algorithm were validated by the numerical results. Potential future works include the modeling of UE preference from a big-data perspective, and the joint optimization of energy-efficient context-aware resource allocation and distributed content caching, etc.

APPENDIX A
PROOF OF THEOREM 2

Assuming $q_i^{Tx}(n_d) \neq q_i^{Tx*}$, $q_i^{Tx}(n_d+1)$ is obtained by $q_i^{Tx}(n_d+1) = U_{i,SE}^{Tx}[\hat{p}_i^d(n_d)]/E_i^{Tx}[\hat{p}_i^d(n_d)]$. (23) in the n_d-th iteration can be rewritten as

$$\begin{aligned}
&\max_{p_i^d} U_{i,SE}^{Tx}[p_i^d(n_d)] - q_i^{Tx}(n_d)E_i^{Tx}[p_i^d(n_d)] \\
&\quad = U_{i,SE}^{Tx}[\hat{p}_i^d(n_d)] - q_i^{Tx}(n_d)E_i^{Tx}[\hat{p}_i^d(n_d)] \\
&\quad = q_i^{Tx}(n_d+1)E_i^{Tx}[\hat{p}_i^d(n_d)] - q_i^{Tx}(n_d)E_i^{Tx}[\hat{p}_i^d(n_d)] \\
&\quad = E_i^{Tx}[\hat{p}_i^d(n_d)][q_i^{Tx}(n_d+1) - q_i^{Tx}(n_d)] \overset{(a)}{\geq} 0. \\
&\overset{(b)}{\Longrightarrow} q_i^{Tx}(n_d+1) \geq q_i^{Tx}(n_d)
\end{aligned} \tag{31}$$

By using ***Theorem 1***, (a) can be derived as

$$\begin{aligned}
&\max_{p_i^d} U_{i,SE}^{Tx}[p_i^d(n_d)] - q_i^{Tx}(n_d)E_i^{Tx}[p_i^d(n_d)] \\
&\quad \geq U_{i,SE}^{Tx}[\tilde{p}_i^d(n_d)] - q_i^{Tx}(n_d)E_i^{Tx}[\tilde{p}_i^d(n_d)] = 0,
\end{aligned} \tag{32}$$

where $\tilde{p}_i^d(n_d)$ is defined as $q_i^{Tx}(n_d) = U_{i,SE}^{Tx}[\tilde{p}_i^d(n_d)]/E_i^{Tx}[\tilde{p}_i^d(n_d)]$.

Since $E_i^{Tx}[\hat{p}_i^d(n_d)][q_i^{Tx}(n_d+1) - q_i^{Tx}(n_d)] \geq 0$ and $E_i^{Tx}[\hat{p}_i^d(n_d)] > 0$, we must have $q_i^{Tx}(n_d+1) - q_i^{Tx}(n_d) \geq 0$. Therefore, q_i^{Tx} obtained in each iteration must be larger or at least equal to the one obtained in the previous iteration, and eventually converges to q_i^{Tx*} in finite iterations.

APPENDIX B
PROOF OF THEOREM 3

First, we prove that the match μ obtained in Algorithm 3 is stable. In any iteration of the Algorithm 3, for any $d_i^{Tx} \in \mathcal{D}_{Tx}$ and any $c_k \in \mathcal{C}$ that are not matched with each other, i.e., $\mu(d_i^{Tx}) \neq c_k$, μ is said to be unstable if d_i^{Tx} and c_k form a blocking pair, i.e., $d_i^{Tx} \succ_{c_k} \mu(c_k)$, $c_k \succ_{d_i^{Tx}} \mu(d_i^{Tx})$. In the following, we prove that the two necessary conditions $d_i^{Tx} \succ_{c_k} \mu(c_k)$ and $c_k \succ_{d_i^{Tx}} \mu(d_i^{Tx})$ cannot hold simultaneously.

Assuming $c_k \succ_{d_i^{Tx}} \mu(d_i^{Tx})$, d_i^{Tx} must have already sent a channel-reusing request to c_k according to the matching rules. However, the matching result $\mu(d_i^{Tx}) \neq c_k$ illustrates that c_k prefers $\mu(c_k)$ to d_i^{Tx}, i.e., $\mu(c_k) \succ_{c_k} d_i^{Tx}$. Although d_i^{Tx} prefers to be matched with c_k rather than $\mu(d_i^{Tx})$, c_k still prefers to be matched with $\mu(c_k)$ rather than d_i^{Tx}. That is, the condition $d_i^{Tx} \succ_{c_k} \mu(c_k)$ does not hold when $c_k \succ_{d_i^{Tx}} \mu(d_i^{Tx})$. In a similar way, we can prove that the condition $c_k \succ_{d_i^{Tx}} \mu(d_i^{Tx})$ does not hold neither if $d_i^{Tx} \succ_{c_k} \mu(c_k)$. Therefore, d_i^{Tx} and c_k cannot form a blocking pair, and the match μ obtained in each iteration of the Algorithm 3 is stable.

Second, we can prove that the match $\tilde{\mu}$ is also stable by showing that any $d_j^{Rx} \in \mathcal{D}_{Rx}$ and $d_i^{Tx} \in \mathcal{D}_{Tx}$ do not form a blocking pair when $\mu(d_j^{Rx}) \neq d_i^{Tx}$. Since the Algorithm 5 terminates in one iteration, $\tilde{\mu}$ must be a two-sided stable match.

APPENDIX C
PROOF OF THEOREM 4

Proof: Let us start from the proof for μ. In any iteration of the Algorithm 3, for any D2D transmitter $d_i^{Tx} \in \mathcal{D}_{Tx}$, we assume that there exists a better match μ' which satisfies that $\mu'(d_i^{Tx}) \succ_{d_i^{Tx}} \mu(d_i^{Tx})$. That is, every $d_i^{Tx} \in \mathcal{D}_{Tx}$ prefers this new match μ' to the original match μ because it can be matched to a better CU under μ'. In other words, every $d_i^{Tx} \in \mathcal{D}_{Tx}$ can be matched to some CU under μ' which has rejected its request under μ. For example, assuming $\mu'(d_i^{Tx}) = c_k$, then we must have $\mu(c_k) \succ_{c_k} d_i^{Tx}$ so as to satisfy $\mu'(d_i^{Tx}) \succ_{d_i^{Tx}} \mu(d_i^{Tx})$. However, considering the final step of the match, any CU that receives a request in the final step is not able to issue a rejection and will be left unmatched at μ' since every $d_i^{Tx} \in \mathcal{D}_{Tx}$ prefers $\mu'(d_i^{Tx})$ to $\mu(d_i^{Tx})$. This contradicts with the assumption that μ is a stable. Thus, μ is weak Pareto optimal for D2D transmitters. A similar proof can be derived by following the above analysis to show that $\tilde{\mu}$ is weak Pareto optimal for D2D receivers.

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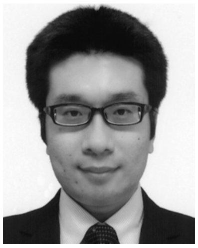
ZHENYU ZHOU (M'11) received the M.E. and Ph.D. degrees from Waseda University, Tokyo, Japan, in 2008 and 2011, respectively. From 2012 to 2013, he was the Chief Researcher with the Department of Technology, KDDI, Tokyo. Since 2013, he has been an Associate Professor with the School of Electrical and Electronic Engineering, North China Electric Power University, China. He has also been a Visiting Scholar with the Tsinghua-Hitachi Joint Laboratory on Environment-Harmonious ICT, University of Tsinghua, Beijing, since 2014. He served as the Workshop Co-Chair for the IEEE ISADS 2015, the Session Chair for the IEEE Globecom 2014, and a TPC Member for the IEEE Globecom 2015, ACM Mobimedia 2015, the IEEE Africon 2015, and so on. He received the Young Researcher Encouragement Award from the IEEE Vehicular Technology Society in 2009. His research interests include green communications and smart grid. He is a member of IEICE and CSEE.

GUIFANG MA is currently pursuing the M.S. degree with North China Electric Power University, China. Her research interests include resource allocation, interference management, and energy management in D2D communications.

MIANXIONG DONG received the B.S., M.S., and Ph.D. degrees from The University of Aizu, Japan, all in computer science and engineering. He was a Researcher with the National Institute of Information and Communications Technology, Japan. He was a JSPS Research Fellow with the School of Computer Science and Engineering, The University of Aizu, Japan, and was a Visiting Scholar with the BBCR group, University of Waterloo, Canada, supported by JSPS Excellent Young Researcher Overseas Visit Program from 2010 to 2011. He is currently an Associate Professor with the Department of Information and Electronic Engineering, Muroran Institute of Technology, Japan. He was selected as a Foreigner Research Fellow (a total of three recipients all over Japan) by the NEC C&C Foundation in 2011. His research interests include wireless networks, cloud computing, and cyber-physical Systems. His research results have been published in 140 research papers in international journals, conferences, and books. He received best paper awards from the IEEE HPCC 2008, the IEEE ICESS 2008, ICA3PP 2014, GPC 2015, and the IEEE DASC 2015. He serves as an Editor for the IEEE Communications Surveys and Tutorials, the IEEE Network, the IEEE Wireless Communications Letters, the IEEE Cloud Computing, the IEEE Access, and *Cyber-Physical Systems* (Taylor & Francis), a Leading Guest Editor for *ACM Transactions on Multimedia Computing*, *Communications and Applications* (TOMM), the IEEE Transactions on Emerging Topics in Computing, the IEEE Transactions on Computational Social Systems, *Peer-to-Peer Networking and Applications* (Springer), and *Sensors*, and a Guest Editor for the IEEE Access, *Peer-to-Peer Networking and Applications* (Springer), *IEICE Transactions on Information and Systems*, and *International Journal of Distributed Sensor Networks*. He served as the Program Chair of the IEEE SmartCity 2015 and has been serving as the Symposium Chair of the IEEE GLOBECOM 2016, 2017. He is a Research Scientist with the A3 Foresight Program (2011-2016) funded by Japan Society for the Promotion of Sciences, the NSFC of China, and the NRF of Korea.

KAORU OTA was born in Aizuwakamatsu, Japan. She received the B.S. degree in computer science and engineering from The University of Aizu, Japan, in 2006, the M.S. degree in computer science from Oklahoma State University, USA, in 2008, and the Ph.D. degree in computer science and engineering from The University of Aizu, in 2012. She is currently an Assistant Professor with the Department of Information and Electronic Engineering, Muroran Institute of Technology, Japan. From 2010 to 2011, she was a Visiting Scholar with the University of Waterloo, Canada. Also, she was a Japan Society of the Promotion of Science (JSPS) Research Fellow with the Kato-Nishiyama Laboratory, Graduate School of Information Sciences, Tohoku University, Japan, from 2012 to 2013. Her research interests include wireless networks, cloud computing, and cyber-physical Systems. Her research results have been published in 110 research papers in international journals, conferences, and books. She received best paper awards from ICA3PP 2014, GPC 2015, and the IEEE DASC 2015. She serves as an Editor for *Peer-to-Peer Networking and Applications* (Springer), *Ad Hoc and Sensor Wireless Networks*, and the *International Journal of Embedded Systems* (Inderscience), a Leading Guest Editor for *ACM Transactions on Multimedia Computing*, *Communications and Applications* (TOMM), and a Guest Editor for the IEEE Wireless Communications, *IEICE Transactions on Information and Systems*. She is currently a Research Scientist with the A3 Foresight Program (2011-2016) funded by the Japan Society for the Promotion of Sciences (JSPS), the NSFC of China, and the NRF of Korea.

CHEN XU (S'12–M'15) received the B.S. degree from the Beijing University of Posts and Telecommunications in 2010, and the Ph.D. degree from Peking University in 2015. She is currently a Lecturer with the School of Electrical and Electronic Engineering, North China Electric Power University, China. Her research interests mainly include wireless resource allocation and management, game theory, optimization theory, heterogeneous networks, and smart grid communication. She received the best paper award in the International Conference on Wireless Communications and Signal Processing (2012), and she is the Winner of the IEEE Leonard G. Abraham Prize 2016.



YUNJIAN JIA received the B.S. degree from Nankai University, China, in 1999, and the M.E. and Ph.D. degrees in engineering from Osaka University, Japan, in 2003 and 2006, respectively. From 2006 to 2012, he was with the Central Research Laboratory, Hitachi, Ltd., where he engaged in research and development on wireless networks, and also contributed to LTE/LTE-Advanced standardization in 3GPP. He is currently a Professor with the College of Communication Engineering, Chongqing University, Chongqing, China. He has authored more than 60 published papers, and 30 granted patents. His research interests include radio access technologies, mobile networks, and IoT. He has won several prizes from industry and academia, including the IEEE Vehicular Technology Society Young Researcher Encouragement Award, the IEICE Paper Award, the Yokosuka Research Park R&D Committee YRP Award, and the Top 50 Young Inventors of Hitachi. Moreover, he was a recipient of the Research Fellowship Award from the International Communication Foundation in 2004, and Telecommunications Advancement Foundation Japan in 2005.