Distributed Interference-Aware Energy-Efficient Resource Allocation for Device-to-Device Communications Underlaying Cellular Networks

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Abstract—The introduction of device-to-device (D2D) into cellular networks poses many new challenges in the resource allocation design due to the co-channel interference caused by spectrum reuse and limited battery life of user equipments (UEs). In this paper, we propose a distributed interference-aware energy-efficient resource allocation algorithm to maximize each UE's energy efficiency (EE) subject to its specific quality of service (QoS) and maximum transmission power constraints. We model the resource allocation problem as a noncooperative game, in which each player is self-interested and wants to maximize its own EE. The formulated EE maximization problem is a nonconvex problem and is transformed into a convex optimization problem by exploiting the properties of the nonlinear fractional programming. An iterative optimization algorithm is proposed and verified through computer simulations.

I. INTRODUCTION

Device-to-device (D2D) communications underlaying cellular networks bring numerous benefits including the proximity gain, the reuse gain, and the hop gain [1], increase the total throughput of the overall cellular network, [3], and can fit perfectly for future ubiquitous radio network [2]. However, the introduction of D2D communications into cellular networks poses many new challenges in the resource allocation design due to the co-channel interference caused by spectrum reuse and limited battery life of user equipments (UEs). Most of the previous studies mainly focus on how to maximize the spectral efficiency (SE) and ignore the energy consumption of UEs (see [4]-[7] and references therein). Only a limited amount of works have considered the energy efficiency (EE) optimization problem. In practical implementation, UEs are typically handheld devices with limited battery life and can quickly run out of battery if the energy consumption is ignored in the system design. Therefore, in this paper, we focus on how to optimize the EE through resource allocation in an interference-limited environment.

For the EE optimization problem, distributed resource allocation algorithms which are based on either the reverse iterative combinatorial auction (ICA) game or the bisection method were proposed in [8] and [9] respectively. However, the authors have not considered the QoS provisioning constraints and have not derived a close-form solution. Centralized resource allocation algorithms for optimizing the EE in the device-tomultidevice (D2MD) or D2D-cluster scenarios were proposed in [10] and [11] respectively. One major disadvantage of the centralized algorithms is that the computational complexity and signaling overhead increase significantly with the number of UEs. Besides, since the optimization process is carried out in the BS, the optimal solution needs to be delivered to the UEs within the channel coherence time. Instead of maximizing EE, an auction-based resource allocation algorithm was proposed to maximize the battery lifetime in [12], but cellular UEs were not taken into consideration. A coalition game based resource sharing algorithm was proposed in [13] to jointly optimize the model selection and resource scheduling. The authors assumed that independent D2D UEs and cellular UEs can communicate with one another and act together as one entity to improve their EE in the game.

In this paper, we propose a distributed interference-aware energy-efficient resource allocation algorithm to maximize each UE's EE subject to the QoS provisioning and transmission power constraints. We model the resource allocation problem as a noncooperative game. Compared to the cooperative game model used in [13], the noncooperative model has the advantage of a lower overhead for information exchange between UEs. Both of the D2D UEs and cellular UEs are taken into consideration. The EE utility function of each player is defined as the SE divided by the total power consumption, which includes both transmission and circuit power. The formulated EE maximization problem is a non-convex problem and is transformed into a convex optimization problem by using the nonlinear fractional programming developed in [14]. A Nash equilibrium is proved to exist in the noncooperative game. An iterative optimization algorithm is proposed to find the Nash equilibrium and is verified through computer simulations. EE and SE tradeoffs of the proposed algorithm are studied in [15]

The structure of this paper is organized as follows: Section II introduces the system model of the D2D communication un-

derlaying cellular networks. Section III introduces the centralized resource allocation scenario and provides some insights by considering several special cases. Section IV introduces the distributed iterative optimization algorithm for maximizing each UE's EE. Section V introduces the simulation parameters, results and analyses. Section VI gives the conclusion.

II. SYSTEM MODEL

In this paper, we consider the uplink scenario of a single cellular network, which is composed of the base station, the D2D UEs, and the cellular UEs. Fig. 1 shows the system model of the D2D communications with uplink resource sharing. There are two cellular UEs (UE₁ and UE₂), and two D2D pairs (UE₃ and UE₄, and UE₅ and UE₆ respectively). A pair of D2D transmitter and receiver form a D2D link, and a cellular UE and the BS form a cellular link. The UEs in a D2D pair are close enough to enable D2D communication. Each cellular UE is allocated with an orthogonal link (e.g., an orthogonal resource block in LTE), i.e., there is no co-channel interference between cellular UEs. At the same time, the two D2D pairs reuse the same channels allocated to cellular UEs in order to improve the spectrum efficiency. As a result, the BS suffers from the interference caused by the D2D transmitters (UE₃ and UE₅), and the D2D receiver (UE₄ and UE₆) suffers from the interference caused by cellular UEs (UE₁ and UE₂) and the other D2D transmitters that reuse the same channel (UE_5 or UE₃ respectively).

The set of UEs is denoted as $S = \{N, \mathcal{K}\}$, where N and \mathcal{K} denote the sets of D2D UEs and cellular UEs respectively. The total number of D2D links and cellular links are denoted as N and K respectively. The signal to interference plus noise ratio (SINR) of the *i*-th D2D pair ($i \in N$) in the *k*-th ($k \in \mathcal{K}$) channel is given by

$$\gamma_i^k = \frac{p_i^k g_i^k}{p_c^k g_{c,i}^k + \sum_{j=1, j \neq i}^N p_j^k g_{j,i}^k + N_0},$$
(1)

where p_i^k , p_c^k , and p_j^k are the transmission power of the *i*th D2D transmitter, the *k*-th cellular UE, and the *j*-th D2D transmitter in the *k*-th channel respectively. g_i^k is the channel gain of the *i*-th D2D pair, $g_{c,i}^k$ is the interference channel gain between the *k*-th cellular UE and the *i*-th D2D receiver, and $g_{j,i}^k$ is the interference channel gain between the *j*-th D2D transmitter and the *i*-th D2D receiver. N_0 is the nosier power. $p_c^k g_{c,i}^k$ and $\sum_{j=1, j\neq i}^N p_j^k g_{j,i}^k$ denote the interference from the cellular UE and the other D2D pairs that reuse the *k*-th channel respectively.

The received SINR of the k-th cellular UE at the BS is given by

$$\gamma_{c}^{k} = \frac{p_{c}^{k} g_{c}^{k}}{\sum_{i=1}^{N} p_{i}^{k} g_{i,c}^{k} + N_{0}},$$
(2)

where g_c^k is the channel gain between the *k*-th cellular UE and the BS, $g_{i,c}^k$ is the interference channel gain between the *i*-th D2D transmitter and the BS in the *k*-th channel. $\sum_{i=1}^{N} p_i^k g_{i,c}^k$

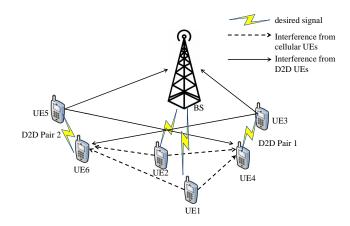


Fig. 1. System model of D2D communications with uplink channel reuse.

denote the interference from all of the D2D pairs to the BS in the k-th channel.

The achievable rates of the i-th D2D pair and the k-th cellular UE are given by

$$r_{i}^{d} = \sum_{k=1}^{K} \log_{2} \left(1 + \gamma_{i}^{k} \right), \tag{3}$$

$$r_k^c = \log_2\left(1 + \gamma_c^k\right).\tag{4}$$

The total power consumption of the *i*-th D2D pair and the k-th cellular UE are given by

$$p_{i,total}^{d} = \sum_{k=1}^{K} \frac{1}{\eta} p_{i}^{k} + 2p_{cir},$$
(5)

$$p_{k,total}^{c} = \frac{1}{\eta} p_{c}^{k} + p_{cir},\tag{6}$$

where $p_{i,total}^d$ is the total power consumption of the *i*-th D2D pair, which is composed of the transmission power over all of the *K* channels, i.e., $\sum_{k=1}^{K} \frac{1}{\eta} p_i^k$, and the circuit power of both the D2D transmitter and receiver, i.e., $2p_{cir}$. The circuit power of any UE is assumed as the same and denoted as p_{cir} . η is the Power Amplifier (PA) efficiency, i.e., $0 < \eta < 1$. $p_{k,total}^c$ is the total power consumption of the *k*-th cellular UE, which is composed of the transmission power $\frac{1}{\eta}p_c^k$ and the circuit power only at the transmitter side. The power consumption of the BS is not taken into consideration.

III. CENTRALIZED INTERFERENCE-AWARE ENERGY-EFFICIENT RESOURCE ALLOCATION

The EE introduced in [16] is defined as the SE divided by the total power consumed, i.e., bit/Hz/J. In this section, we study the centralized energy-efficient resource allocation method, which is employed at the BS. The EE of the overall network is a function of the power allocation strategies, which is given by

$$U_{EE}(\mathcal{P}_{d}, \mathcal{P}_{c}) = \sum_{i=1}^{N} \frac{r_{i}^{d}}{p_{i,total}^{d}} + \sum_{k=1}^{K} \frac{r_{k}^{c}}{p_{k,total}^{c}},$$
(7)

where \mathcal{P}_d and \mathcal{P}_c are the sets of power allocation strategies for the D2D UEs and cellular UEs respectively, i.e., $\mathcal{P}_d = \{p_i^k \mid 0 \le \sum_{k=1}^{K} p_i^k \le p_{i,max}^d, i \in \mathcal{N}, k \in \mathcal{K}\}, \mathcal{P}_c = \{p_k^c \mid 0 \le p_c^k \le p_{k,max}^c, k \in \mathcal{K}\}, p_{i,max}^d$ and $p_{k,max}^c$ are the maximum transmission power of the *i*-th D2D transmitter and the *k*-th cellular UE respectively. This definition of (7) is not based on the ratio of sum network throughput to sum network power consumption as in [8], [13] because transmission power and achievable rates can not be shared among UEs [17]. Taking (1), (2), (3), (4), (5), and (6) into (7), the EE of the overall network is rewritten as

$$U_{EE}(\mathcal{P}_{d},\mathcal{P}_{c}) = \sum_{i=1}^{N} \frac{\sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k} g_{c}^{k}}{p_{c}^{k} g_{c,i}^{k} + \sum_{j=1, j \neq i}^{N} p_{j}^{k} g_{j,i}^{k} + N_{0}}\right)}{\sum_{k=1}^{K} \frac{1}{\eta} p_{i}^{k} + 2p_{cir}} + \sum_{k=1}^{K} \frac{\log_{2} \left(1 + \frac{p_{c}^{k} g_{c}^{k}}{\sum_{i=1}^{N} p_{i}^{k} g_{i,c}^{k} + N_{0}}\right)}{\frac{1}{\eta} p_{c}^{k} + p_{cir}}.$$
(8)

The U_{EE} defined in (8) is not a concave function for p_i^k, p_c^k $(p_i^k \in \mathcal{P}_d, p_c^k \in \mathcal{P}_c)$, and it is intractable to find the global maximum EE of the overall network. However, we can get some insights about energy-efficient power allocation design by considering some special cases.

A. The Circuit Power Dominated Case

The circuit power dominated case represents that $p_{cir} >> p_i^k, p_c^k, \forall i \in \mathcal{N}, \forall k \in \mathcal{K}$. The circuit power dominated case arises when the transmitter is close to the receiver and little transmission power is needed to satisfy the QoS requirement. The U_{EE} defined in (8) is rewritten as

$$U_{EE}(\mathcal{P}_{d}, \mathcal{P}_{c}) \approx \frac{1}{2p_{cir}} \left[\sum_{i=1}^{N} \sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k} g_{i}^{k}}{p_{c}^{k} g_{c,i}^{k} + \sum_{j=1, j \neq i}^{N} p_{j}^{k} g_{j,i}^{k} + N_{0}} \right) + \sum_{k=1}^{K} 2 \log_{2} \left(1 + \frac{p_{c}^{k} g_{c}^{k}}{\sum_{i=1}^{N} p_{i}^{k} g_{i,c}^{k} + N_{0}} \right) \right].$$
(9)

The EE maximization problem in the circuit power dominated case is equivalent to the conventional sum rate maximization problem, which has been discussed in [4]–[7].

B. The Transmission Power Dominated Case

The transmission power dominated case represents that $p_i^k, p_c^k >> p_{cir}, \forall i \in N, \forall k \in \mathcal{K}$. This case arises in long-range communication and interference-limited scenarios where large transmission power is required to compensate for the degradation of the received SINR. The U_{EE} defined in (8) can be rewritten as

$$U_{EE}(\mathcal{P}_{d},\mathcal{P}_{c}) \approx \sum_{i=1}^{N} \frac{\sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k} g_{i}^{k}}{p_{c}^{k} g_{c,i}^{k} + \sum_{j=1, j \neq i}^{j} p_{j}^{k} g_{j,i}^{k} + N_{0}}\right)}{\sum_{k=1}^{K} \frac{\log_{2} \left(1 + \frac{p_{c}^{k} g_{c}^{k}}{\sum_{i=1}^{N} p_{i}^{k} g_{i,c}^{k} + N_{0}}\right)}{\frac{1}{\eta} p_{c}^{k}}.$$
 (10)

Since U_{EE} is strictly decreasing with p_i^k, p_c^k (it can be proved that $\frac{\partial U_{EE}}{p_i^k} < 0$ and $\frac{\partial U_{EE}}{p_c^k} < 0$, $\forall i, k$), the optimal strategy is to use as little power as possible subject to the QoS constraint.

C. Noise Dominated Case

The noise dominated case represents that $N_0 >> p_c^k g_{c,i}^k + \sum_{j=1, j\neq i}^N p_j^k g_{j,i}^k$, $N_0 >> \sum_{i=1}^N p_i^k g_{i,c}^k$, $\forall i \in \mathcal{N}, \forall k \in \mathcal{K}$. The U_{EE} defined in (8) can be rewritten as

$$U_{EE}(\mathcal{P}_{d},\mathcal{P}_{c}) \approx \sum_{i=1}^{N} \frac{\sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k} g_{i}^{k}}{N_{0}}\right)}{\sum_{k=1}^{K} \frac{1}{\eta} p_{i}^{k} + 2p_{cir}} + \sum_{k=1}^{K} \frac{\log_{2} \left(1 + \frac{p_{c}^{k} g_{c}^{k}}{N_{0}}\right)}{\frac{1}{\eta} p_{c}^{k} + p_{cir}}$$
(11)

Thus, the EE maximization problem in the noise dominated case is decomposed into independent N + K subproblems, in which each UE tries to maximize its own EE without considering the other UEs' strategies.

D. Interference Dominated Case

In the interference dominated case, the interference is much stronger than the noise, i.e., $p_c^k g_{c,i}^k + \sum_{j=1, j\neq i}^N p_j^k g_{j,i}^k >> N_0$, $\sum_{i=1}^N p_i^k g_{i,c}^k >> N_0$, $\forall i \in \mathcal{N}, \forall k \in \mathcal{K}$. The U_{EE} defined in (8) can be rewritten as

$$U_{EE}(\mathcal{P}_{d}, \mathcal{P}_{c}) \approx \sum_{i=1}^{N} \frac{\sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k} g_{i}^{k}}{p_{c}^{k} g_{ci}^{k} + \sum_{j=1, j \neq i}^{N} p_{j}^{k} g_{ji}^{k}} \right)}{\sum_{k=1}^{K} \frac{1}{\eta} p_{i}^{k} + 2p_{cir}} + \sum_{k=1}^{K} \frac{\log_{2} \left(1 + \frac{p_{i}^{k} g_{i}^{k}}{\sum_{i=1}^{N} p_{i}^{k} g_{ic}^{k}} \right)}{\frac{1}{\eta} p_{c}^{k} + p_{cir}}.$$
(12)

The EE in the interference dominated case is maximized by only allowing the UE (either the cellular UE or the D2D UE) with the highest channel gain to transmit since that $\log_2\left(1 + \frac{p_i^k g_j^k}{p_c^k g_{c,i}^k + \sum_{j=1, j \neq i}^N p_j^k g_{j,i}^k}\right) \to \infty$ as $p_c^k \to 0$, $p_j^k \to 0$.

E. Cellular UE Dominated Case

The cellular UE dominated case arises in scenarios where a cellular UE is far from the BS but close to the D2D pair, and the transmission power of cellular UEs is much stronger than the transmission power of the D2D transmitter, i.e., $p_c^k >> p_i^k$, $\forall i \in \mathcal{N}, \forall k \in \mathcal{K}$. The U_{EE} defined in (8) can be rewritten as

$$U_{EE}(\mathcal{P}_d, \mathcal{P}_c) \approx \sum_{k=1}^{K} \frac{\log_2\left(1 + \frac{p_c^k q_c^k}{N_0}\right)}{\frac{1}{\eta} p_c^k + p_{cir}}.$$
(13)

The D2D UEs are forced to stop transmission due to the severe interference caused by cellular UEs, which solely occupy all of the available channels. The optimum solution can be obtained by using the bisection method [18].

F. D2D UEs Dominated Case

In the D2D UEs dominated case, we have $p_i^k >> p_c^k$, $\forall i \in \mathcal{N}, \forall k \in \mathcal{K}$. The U_{EE} defined in (8) can be rewritten as

$$U_{EE}(\mathcal{P}_{d},\mathcal{P}_{c}) \approx \sum_{i=1}^{N} \frac{\sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k} g_{i}^{k}}{\sum_{j=1, j \neq i}^{N} p_{j}^{k} g_{j,j}^{k} + N_{0}} \right)}{\sum_{k=1}^{K} \frac{1}{\eta} p_{i}^{k} + 2p_{cir}}.$$
 (14)

The cellular UEs are forced to stop transmission due to the severe interference caused by D2D UEs, which solely occupy all of the available channels. The optimum solution can be obtained by using the bisection method [18].

IV. DISTRIBUTED INTERFERENCE-AWARE ENERGY-EFFICIENT RESOURCE ALLOCATION

A. Problem Formulation

In the centralized resource allocation, the BS requires the complete network knowledge and the computational complexity and signaling overhead increase significantly with the number of UEs. Therefore, in this section, we focus on the more practical distributed resource allocation problem, which is modeled as a noncooperative game.

In the noncooperative game, each UE is self-interested and wants to maximize its own EE. The strategy set of the *i*-th D2D transmitter is denoted as $\mathbf{p}_i^d = \{p_i^k \mid 0 \leq \sum_{k=1}^{K} p_i^k \leq p_{i,max}^d, k \in \mathcal{K}\}, \forall i \in \mathcal{N}$. The strategy set of the *k*-th cellular UE is denoted as $\mathbf{p}_c^c = \{p_c^k \mid 0 \leq p_c^k \leq p_{k,max}^c\}, \forall k \in \mathcal{K}$. The strategy set of the other D2D transmitters in $\mathcal{N}\setminus\{i\}$ is denoted as $\mathbf{p}_{-i}^d = \{p_j^k \mid 0 \leq \sum_{k=1}^{K} p_j^k \leq p_{j,max}^d, k \in \mathcal{K}, j \in \mathcal{N}, j \neq i\}, \forall i \in \mathcal{N}$. The strategy set of the other cellular UEs in $\mathcal{K}\setminus\{k\}$ is denoted as $\mathbf{p}_{-k}^c = \{p_c^m \mid 0 \leq p_c^m \leq p_{m,max}^c, m \in \mathcal{K}, m \neq k\}, \forall k \in \mathcal{K}$.

For the *i*-th D2D pair, its EE U_i^d depends not only on \mathbf{p}_i^d , but also on the strategies taken by other UEs in $S \setminus \{i\}$, i.e., $\mathbf{p}_{-i}^d, \mathbf{p}_k^c, \mathbf{p}_{-k}^c, U_i^d$ is defined as

$$U_{i}^{d}(\mathbf{p}_{i}^{d}, \mathbf{p}_{-i}^{d}, \mathbf{p}_{k}^{c}, \mathbf{p}_{-k}^{c}) = \frac{r_{i}^{d}}{p_{i,total}^{d}} = \frac{\sum_{k=1}^{K} \log_{2} \left(1 + \frac{p_{i}^{k}g_{i}^{k}}{p_{c}^{k}g_{c,i}^{k} + \sum_{j=1, j \neq i}^{N} p_{j}^{k}g_{j,i}^{k} + N_{0}}\right)}{\sum_{k=1}^{K} \frac{1}{\eta}p_{i}^{k} + 2p_{cir}}.$$
 (15)

Therefore, the EE maximization problem of the *i*-th D2D pair is formulated as

max.
$$U_i^d(\mathbf{p}_i^d, \mathbf{p}_{-i}^d, \mathbf{p}_k^c, \mathbf{p}_{-k}^c)$$

s.t. $C1, C2.$ (16)

$$C1: r_i^d \ge R_{i,min}^d, \tag{17}$$

$$C2: 0 \le \sum_{k=1}^{K} p_i^k \le p_{i,max}^d.$$
(18)

Similarly, the EE of the k-th cellular UE U_k^c is defined as

$$U_{k}^{c}(\mathbf{p}_{i}^{d}, \mathbf{p}_{-i}^{d}, \mathbf{p}_{k}^{c}, \mathbf{p}_{-k}^{c}) = \frac{r_{k}^{c}}{p_{k,total}^{c}} = \frac{\log_{2}\left(1 + \frac{p_{k}^{c}g_{c}^{k}}{\sum_{i=1}^{N} p_{i}^{k}g_{i,c}^{k} + N_{0}}\right)}{\frac{1}{\eta}p_{c}^{k} + p_{cir}}.$$
(19)

The corresponding EE maximization problem is formulated as

max.
$$U_k^c(\mathbf{p}_i^d, \mathbf{p}_{-i}^d, \mathbf{p}_k^c, \mathbf{p}_{-k}^c)$$

s.t. C3, C4. (20)

$$C3: r_k^c \ge R_{k,\min}^c, \tag{21}$$

$$C4: 0 \le p_c^k \le p_{k\,max}^c. \tag{22}$$

The constraint C1 and C3 specify the QoS requirements in terms of minimum transmission rate. C2 and C4 are the non-negative constraints on the power allocation variables.

B. The Objective Function Transformation

The objective functions in (16) and (20) are non-convex due to the fractional form. In order to derive a closed-form solution, we transformed the fractional objective function to a convex optimization function by using the nonlinear fractional programming developed in [14]. We define the maximum EE of the *i*-th D2D pair as q_i^{d*} , which is given by

$$q_i^{d*} = \max .U_i^d(\mathbf{p}_i^d, \mathbf{p}_{-i}^d, \mathbf{p}_k^c, \mathbf{p}_{-k}^c) = \frac{r_i^d(\mathbf{p}_i^{d*})}{p_{i,total}^d(\mathbf{p}_i^{d*})}.$$
 (23)

where \mathbf{p}_i^{d*} is the best response of the *i*-th D2D transmitter given the other UEs' strategies $\mathbf{p}_{-i}^d, \mathbf{p}_k^c, \mathbf{p}_{-k}^c$. The following theorem can be proved:

Theorem 1: The maximum EE q_i^{d*} is achieved if and only if

$$\max \, . \, r_i^d(\mathbf{p}_i^d) - q_i^{d*} p_{i,total}^d(\mathbf{p}_i^d) = r_i^d(\mathbf{p}_i^{d*}) - q_i^{d*} p_{i,total}^d(\mathbf{p}_i^{d*}) = 0$$
(24)

Proof: The proof of Theorem 1 is similar to the proof of the Theorem (page 494 in [14]).

Similarly, for the maximum EE of the *k*-th cellular UE q_k^{c*} , we will have similar theorem as **Theorem 1**:

Theorem 2: The maximum EE q_k^{c*} is achieved if and only if

max.
$$r_k^c(\mathbf{p}_k^c) - q_k^{c*} p_{k,total}^c(\mathbf{p}_k^c) = r_k^c(\mathbf{p}_k^{c*}) - q_k^{c*} p_{k,total}^c(\mathbf{p}_k^{c*}) = 0$$
(25)

 \mathbf{p}_k^{c*} is the best response of the *k*-th cellular UE given the other UEs' strategies $\mathbf{p}_i^d, \mathbf{p}_{-k}^d, \mathbf{p}_{-k}^c$.

C. The Iterative Optimization Algorithm

The proposed algorithm is summarized in Algorithm 1. *n* is the iteration index, L_{max} is the maximum number of iterations, and Δ is the maximum tolerance. At each iteration, for any given q_i^d or q_k^c , the resource allocation strategy for the D2D UE or the cellular UE can be obtained by solving the following transformed optimization problems respectively:

max.
$$r_i^d(\mathbf{p}_i^d) - q_i^d p_{i,total}^d(\mathbf{p}_i^d)$$

s.t. C1, C2. (26)

$$\max \cdot r_k^c(\mathbf{p}_k^c) - q_k^c p_{k,total}^c(\mathbf{p}_k^c)$$

s.t. C3, C4. (27)

Algorithm 1 Iterative Resource Allocation Algorithm

1: $q_i^d \leftarrow 0, q_k^c \leftarrow 0, L_{max} \leftarrow 10, n \leftarrow 1, \Delta \leftarrow 10^{-3}$ 2: for n = 1 to L_{max} do if D2D link then 3: solve (26) for a given q_i^d and obtain the set of 4: strategies \mathbf{p}_{i}^{d} **if** $r_{i}^{d}(\mathbf{p}_{i}^{d}) - q_{i}^{d}p_{i,total}^{d}(\mathbf{p}_{i}^{d}) \leq \Delta$, then 5: $\mathbf{p}_i^{d*} = \mathbf{p}_i^d$, and $q_i^{d*} = \frac{r_i^d(\mathbf{p}_i^{d*})}{p_{i,total}^d(\mathbf{p}_i^{d*})}$ 6: break 7. else 8: $q_i^d = \frac{r_i^d(\mathbf{p}_i^d)}{p_{i \text{ total}}^d(\mathbf{p}_i^d)}$, and n = n+19: 10: else 11: solve (27) for a given q_k^c and obtain the set of 12: strategies p if $r_k^c(\mathbf{p}_k^c) - q_k^c p_{k,total}^c(\mathbf{p}_k^c) \le \Delta$, then 13: $\mathbf{p}_k^{c*} = \mathbf{p}_c$, and $q_k^{c*} = \frac{r_k^c(\mathbf{p}_k^{c*})}{p_k^c total(\mathbf{p}_k^{c*})}$ 14: 15: break else 16: $q_k^c = \frac{r_k^c(\mathbf{p}_k^c)}{p_{k,total}^c(\mathbf{p}_k^c)}$, and n = n + 117: 18: end if 19: 20: end for

Taking the D2D UEs as an example, the Lagrangian associated with the problem (26) is given by

$$\mathcal{L}_{EE}(\mathbf{p}_{i}^{d}, \alpha_{i}, \beta_{i}) = r_{i}^{d}(\mathbf{p}_{i}^{d}) - q_{i}^{d} p_{i,total}^{d}(\mathbf{p}_{i}^{d}) + \alpha_{i} \left(r_{i}^{d} - R_{i,min}^{d} \right) - \beta_{i} \left(\sum_{k=1}^{K} p_{i}^{k} - p_{i,max}^{d} \right),$$
(28)

where α_i , β_i are the Lagrange multipliers associated with the constraints C1 and C2 respectively. The constraint $p_i^k \ge 0$ is absorbed into the Karush-Kuhn-Tucker (KKT) condition when solving the equivalent Lagrange dual problem:

$$\min_{\substack{(\alpha_i \ge 0, \beta_i \ge 0)}} \max_{\substack{(\mathbf{p}_i^d)}} \mathcal{L}_{EE}(\mathbf{p}_i^d, \alpha_i, \beta_i)$$
(29)

It is noted that the objective function in (26) is a concave function of \mathbf{p}_i^d , and the primal and dual optimal points forms an saddle-point of the Lagrangian. The dual problem in (29) can be decomposed into two subproblems: the maximization problem solves the power allocation problem to find the best strategy and the minimization problem solves the master dual problem to find the corresponding Lagrange multiplier. For any given q_i^d , the solution is given by

$$p_i^k = \left[\frac{\eta(1+\alpha_i)\log_2 e}{q_i^d + \eta\beta_i} - \frac{p_c^k g_{c,i}^k + \sum_{j=1,j\neq i}^N p_j^k g_{j,i}^k + N_0}{g_i^k}\right]^+, \quad (30)$$

TABLE I Simulation Parameters.

Parameter	Value
Cell radius	500 m
Maximum D2D transmission distance	25 m
Maximum transmission power $p_{i,max}^d, p_{k,max}^c$	200 mW (23 dBm)
Constant circuit power p_{cir}	10 mW (10 dBm)
Thermal noise power N_0	10^{-7} W
Number of D2D pairs N	5
Number of cellular UEs K	3
PA efficiency η	35%
QoS of cellular UEs $R_{k,min}^c$	0.1 bit/s/Hz
QoS of D2D UEs $R_{i,min}^d$	0.5 bit/s/Hz

where $[x]^+ = \max\{0, x\}$. Equation (30) indicates a waterfilling algorithm for transmission power allocation, and the interference from the other UEs decreases the water level. For solving the minimization problem, the Lagrange multipliers can be updated by using the gradient method [19], [20] as

$$\alpha_i(\tau+1) = \left[\alpha_i(\tau) - \mu_{i,\alpha}(\tau) \left(r_i^d(\tau) - R_{i,min}^d\right)\right]^+, \qquad (31)$$

$$\beta_i(\tau+1) = \left[\beta_i(\tau) + \mu_{i,\beta}(\tau) \left(\sum_{k=1}^n p_i^k(\tau) - p_{i,max}^d\right)\right] \quad , \qquad (32)$$

where τ is the iteration index, $\mu_{i,\alpha}, \mu_{i,\beta}$ are the positive step sizes. Similarly, the optimum solution of p^c is given by

$$p_{c}^{k} = \left[\frac{\eta(1-\delta_{k})\log_{2}e}{q_{k}^{c}+\eta\theta_{k}} - \frac{\sum_{i=1}^{N}p_{i}^{k}g_{i,c}^{k}+N_{0}}{g_{c}^{k}}\right]^{+},$$
(33)

where δ_k , θ_k are the Lagrange multipliers associated with the constraints C3 and C4 respectively.

A Nash equilibrium is a set of power allocation strategies that none UE (neither D2D UE nor cellular UE) can unilaterally improve its EE by choosing a different power allocation strategy, i.e., $\forall i \in N, \forall k \in \mathcal{K}$,

$$U_{i}^{d}(\mathbf{p}_{i}^{d*}, \mathbf{p}_{-i}^{d*}, \mathbf{p}_{k}^{c*}, \mathbf{p}_{-k}^{c*}) \geq U_{i}^{d}(\mathbf{p}_{i}^{d}, \mathbf{p}_{-i}^{d}, \mathbf{p}_{k}^{c}, \mathbf{p}_{-k}^{c}),$$
(34)

$$U_{k}^{c}(\mathbf{p}_{i}^{d*}, \mathbf{p}_{-i}^{d*}, \mathbf{p}_{k}^{c*}, \mathbf{p}_{-k}^{c*}) \geq U_{k}^{c}(\mathbf{p}_{i}^{d}, \mathbf{p}_{-i}^{d}, \mathbf{p}_{k}^{c}, \mathbf{p}_{-k}^{c}).$$
(35)

Theorem 3: A Nash equilibrium exists in the noncooperaive game. Furthermore, the strategy set $\{\mathbf{p}_i^{d*}, \mathbf{p}_k^{c*} \mid i \in \mathcal{N}, k \in \mathcal{K}\}$ obtained by using Algorithm 1 is the Nash equilibrium.

Proof: The proof of Theorem 3 is given in [21].

V. SIMULATION RESULTS

In this section, the proposed algorithm is verified through computer simulations. The values of simulation parameters are inspired by [5], [7], [8], and are summarized in Table I. We compare the proposed EE maximization algorithm (labeled as "energy-efficient") with the SE maximization algorithm (labeled as "spectral-efficient") and the random power allocation algorithm (labeled as "random"), whose details are given in [22]. The results are averaged through a total number of 1000 simulations and normalized by the maximum EE value of D2D links. For each simulation, the locations of the cellular UEs and D2D UEs are generated randomly within a cell with a

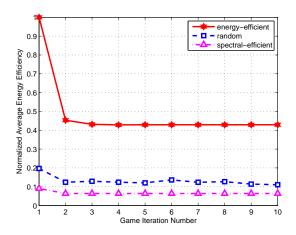


Fig. 2. The normalized average energy efficiency of D2D links corresponding to the number of game iterations.

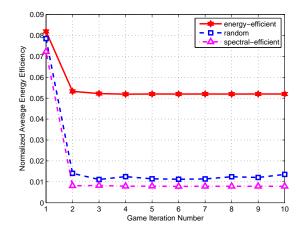


Fig. 3. The normalized average energy efficiency of cellular links corresponding to the number of game iterations.

radius of 500 m. The maximum distance between any two D2D UEs that form a D2D pair is 25 m. The channel gain between the transmitter *i* and the receiver *j* is calculated as $d_{i,j}^{-2} |h_{i,j}|^2$, where $d_{i,j}$ is the distance between the transmitter *i* and the receiver *j*, $h_{i,j}$ is the complex Gaussian channel coefficient that satisfies $h_{i,j} \sim CN(0, 1)$.

Fig. 2 shows the normalized average EE of D2D links corresponding to the number of game iterations. It is clear that the proposed energy-efficient algorithm significantly outperforms the conventional spectral-efficient algorithm and the random algorithm in terms of EE. The spectral-efficient algorithm has the worst EE performance among the three because power consumption is completely ignored in the optimization process.

Fig. 3 shows the normalized average EE of cellular links corresponding to the number of game iterations. The simulation results demonstrate that the proposed algorithm achieves the best performance again. Comparing Fig. 3 with Fig. 2, we find that the D2D links can achieve a much better EE than the cellular links due to the proximity gain and the channel reuse gain. The proposed EE algorithm and the conventional SE algorithm converges to the equilibrium within $3 \sim 4$ game iterations, while the random algorithm fluctuates around the equilibrium since that the transmission power strategy is randomly selected. In the beginning of the game, we assume that channels are only used by cellular links. Hence, the EE of cellular links is highest in the first iteration due to the lack of interference. Then, D2D UEs enter into the game, and decides its optimum transmission power. The EE of D2D links is also highest in the first iteration since that the interference from cellular UEs and other D2D links is lowest in the first iteration.

VI. CONCLUSION

In this paper, a distributed interference-aware energyefficient resource allocation algorithm was proposed for D2D communications with uplink channel reuse. The close-form optimal solution was derived and was proved to be a Nash equilibrium. Simulation results verified that the proposed algorithm significantly outperforms conventional algorithms in terms of energy efficiency.

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