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Combined Centralized and Distributed Resource Allocation for Green D2D Communications

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Abstract—When integrating device-to-device (D2D) communications with densely deployed cellular networks, both energy efficiency (EE) and quality of service (QoS) will be severely degraded by strong intracell and intercell interference. To optimize EE while guaranteeing QoS provisioning, a three-stage energy-efficient resource allocation algorithm is proposed, which combines centralized interference mitigation and distributed power allocation algorithms by exploiting multi-cell cooperations, noncooperative game, nonlinear fractional programming, and Lagrange dual decomposition. Simulation results have demonstrated that the proposed algorithm achieves a nearly zero infeasibility ratio, and improves EE performance significantly for both cellular and D2D user equipments (UEs) compared to the previous distributed scheme.

I. INTRODUCTION

Device-to-device (D2D) communication that enables ubiquitous information acquisition and exchange among devices over a direct link [1], is a key enabler to facilitate future 5G mobile systems [2]. However, the integration of D2D communications with dense cellular networks poses new challenges in resource allocation design. With continuously shrinking cell size, user equipments (UEs) near the edge of a cell suffer from not only the intracell interference but also the intercell interference [3]. To meet quality of service (QoS) requirements, UEs have to continuously increase transmission power, which in turn increases aggregate interference levels of the overall network. As a result, UEs can quickly run out of battery if without careful energy optimization and interference management design.

A few works have addressed the energy-efficient resource allocation problem. Centralized resource allocation algorithms in device-to-multi-device (D2MD) and D2D-cluster scenarios were studied in [4] and [5], respectively. Auction based resource allocation and D2D cooperative relay selection algorithms were proposed in [6], [7]. A two-stage resource allocation algorithm that employs fractional frequency reuse (FFR) was proposed in [8]. A noncooperative game based iterative power allocation algorithm was proposed in [9]. A joint mode selection and resource scheduling optimization algorithm that is based on coalition game was proposed in [10]. The tradeoff between energy-efficiency (EE) and spectral efficiency (SE) was studied in [11].

However, most of the previous works focus on either centralized or distributed approaches, and have not taken advantage of both of them. In addition, they lack the detailed

modeling of complex interference scenarios encountered when deploying D2D communications in dense cellular networks, in particular the intercell interference among D2D pairs, cellular UEs (CUs), and base stations (BSs) located in different cells.

To optimize EE while guaranteeing QoS provisioning, we propose a three-stage energy-efficient resource allocation algorithm. The proposed algorithm has a hybrid structure, which includes centralized interference mitigation schemes in the first and second stages, and a distributed power allocation scheme in the third stage. In the first stage, strong interference caused by CUs is canceled by exploiting multi-cell cooperation based interference reconstruction and cancellation techniques. In the second stage, interference caused by D2D pairs is suppressed by adaptively regulating the maximum transmission power cap on each channel based on interference threshold. Finally, the available power resources are scheduled by each UE in an energy-efficient way by solving a distributed power allocation problem. We adopt a game-theoretic approach to model the distributed power problem as a non-cooperative game, and derive an iterative algorithm based on nonlinear fractional programming [12] and Lagrange dual decomposition [13]. Implementation issues and algorithmic complexity are discussed and analyzed. Simulation results also show that the proposed algorithm outperforms the conventional distributed scheme significantly, in particular when the QoS requirement is high.

The structure of this paper is organized as follows: Section II introduces the system model. Section III introduces the problem formulation. The proposed algorithm is introduced in Section IV. Section V introduces simulation parameters, results and analyses. Section VI draws relevant conclusions.

II. SYSTEM MODEL

We consider uplink spectrum sharing in D2D communications underlying cellular networks. Fig. 1 shows an example of the complex interference environment of two cells. There are two CUs (UE₁ and UE₂), and two D2D pairs (UE₃ and UE₄, and UE₅ and UE₆ respectively). Since each CU is allocated with an orthogonal link (e.g., an orthogonal resource block in LTE), i.e., there is no intracell interference among CUs in the same cell, but there is intercell interference among CUs located in adjacent cells. Block fading model where the channel gain is constant during a slot is adopted [14]. At the same time, D2D pairs are allowed to reuse multiple channels allocated to

CUs in order to improve SE. As a result, the base station (BS) BS₁ suffers from the intercell interference caused by the CU in the adjacent cell (UE₂) as shown in Fig. 1(a), the intracell interference caused by the D2D transmitter in the same cell (UE₃) as shown in Fig. 1(b), and the intercell interference caused by the D2D transmitter in the adjacent cell (UE₅) as shown in Fig. 1(c). D2D receivers (UE₄ and UE₆) suffer from the interference caused by CUs (UE₁ and UE₂) as shown in Fig. 1(b), (c), and D2D transmitters that reuse the same channel (UE₅ and UE₃ respectively) as shown in Fig. 1(d).

For a more general case, we consider a total of M ($M \geq 2$) adjacent cells. In the m -th cell ($m \in \mathcal{M}, \mathcal{M} = \{1, 2, \dots, M\}$), let $\mathcal{D}_m = \{d_{1_m}, \dots, d_{N_m}\}$ and $\mathcal{C}_m = \{c_1, \dots, c_{K_m}\}$ denote the sets of D2D pairs and CUs, respectively. Let $\mathcal{K}_m = \{1, \dots, K_m\}$ denote the set of orthogonal channels. K_m CUs occupy a total of K_m orthogonal channels. The SE (defined as bits/s/Hz) of the i -th D2D pair in the m -th cell d_{i_m} on the k -th channel ($k \in \mathcal{K}_m$) is given by

$$U_{i_m, SE}^d = \sum_{k \in \mathcal{K}_m} \log_2 \left(1 + \frac{p_{i_m}^k g_{i_m}^k}{I_{i_m, 1}^d + I_{i_m, 2}^d + I_{i_m, 1}^c + I_{i_m, 2}^c + N_0} \right), \quad (1)$$

where

$$I_{i_m, 1}^d = \sum_{d_{j_m} \in \mathcal{D}_m \setminus \{d_{i_m}\}} p_{j_m}^k g_{j_m, i_m}^k, \quad (2)$$

$$I_{i_m, 2}^d = \sum_{m' \in \mathcal{M} \setminus \{m\}} \sum_{d_{i_{m'}} \in \mathcal{D}_{m'}} p_{i_{m'}}^k g_{i_{m'}, i_m}^k, \quad (3)$$

$$I_{i_m, 1}^c = p_{k_m}^c g_{k_m, i_m}^c, \quad (4)$$

$$I_{i_m, 2}^c = \sum_{m' \in \mathcal{M} \setminus \{m\}} p_{k_{m'}}^c g_{k_{m'}, i_m}^c. \quad (5)$$

$I_{i_m, 1}^d$ and $I_{i_m, 2}^d$ denote the intracell interference and intercell interference caused by D2D pairs to d_{i_m} , respectively. $I_{i_m, 1}^c$ and $I_{i_m, 2}^c$ denote the intracell interference and intercell interference caused by CUs to d_{i_m} , respectively. $p_{i_m}^k$, $p_{j_m}^k$, and $p_{k_m}^c$ are the transmission power of D2D pair d_{i_m} , d_{j_m} , and CU c_{k_m} on the k -th channel, respectively. $p_{i_{m'}}^k$ and $p_{k_{m'}}^c$ are the transmission power of D2D pair $d_{i_{m'}}$ and CU $c_{k_{m'}}$ in the m' -th cell ($m' \in \mathcal{M} \setminus \{m\}$). $g_{i_m}^k$ is the desired D2D signal channel gain. g_{j_m, i_m}^k denotes the intracell interference channel gain between the transmitter of d_{j_m} and the receiver of d_{i_m} , and g_{k_m, i_m}^c denotes the intracell interference channel gain between c_{k_m} and the receiver of d_{i_m} . Similarly, $g_{i_{m'}, i_m}^k$ and $g_{k_{m'}, i_m}^c$ are the intercell interference channel gains for the D2D interferer $d_{i_{m'}}$ and the cellular interferer $c_{k_{m'}}$ in the m' -th cell, respectively. N_0 is the noise power.

The SE of the CU c_{k_m} is given by

$$U_{k_m, SE}^c = \log_2 \left(1 + \frac{p_{k_m}^c g_{k_m}^c}{I_{k_m, 1}^d + I_{k_m, 2}^d + I_{k_m, 2}^c + N_0} \right), \quad (6)$$

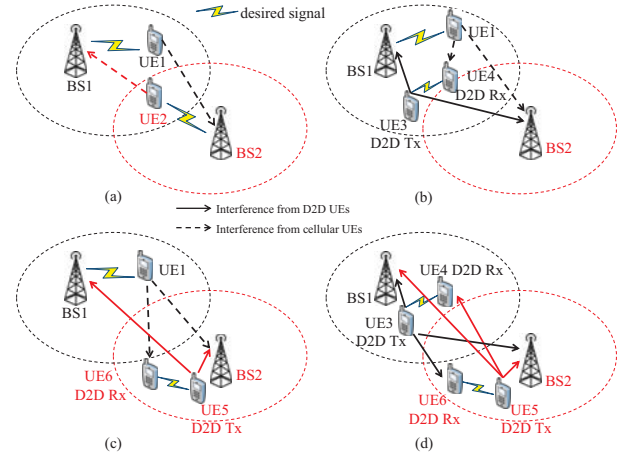


Fig. 1. The complex interference environment of two cells: (a) intercell interference among CUs; (b) intracell interference among CUs and D2D pairs; (c) intercell interference among CUs and D2D pairs; (d) intercell interference among D2D pairs.

where

$$I_{k_m, 1}^d = \sum_{d_{i_m} \in \mathcal{D}_m} p_{i_m}^k g_{i_m, k_m}^c, \quad (7)$$

$$I_{k_m, 2}^d = \sum_{m' \in \mathcal{M} \setminus \{m\}} \sum_{d_{i_{m'}} \in \mathcal{D}_{m'}} p_{i_{m'}}^k g_{j_{m'}, k_m}^c, \quad (8)$$

$$I_{k_m, 2}^c = \sum_{m' \in \mathcal{M} \setminus \{m\}} p_{k_{m'}}^c g_{k_{m'}, k_m}^c. \quad (9)$$

$I_{k_m, 1}^d$ and $I_{k_m, 2}^d$ denote the intracell interference and intercell interference caused by D2D pairs to c_{k_m} , respectively. $I_{i_m, 2}^c$ denote the intercell interference caused by CUs to c_{k_m} , respectively. $g_{i_m}^c$ is the desired cellular signal channel gain. g_{i_m, k_m}^c is the intracell interference channel gains for the D2D interferer d_{i_m} . $g_{j_{m'}, k_m}^c$ and $g_{k_{m'}, k_m}^c$ are the intercell interference gains for the D2D interferer $d_{i_{m'}}$ and the cellular interferer $c_{k_{m'}}$, respectively.

The total power consumptions are given by

$$p_{i_m, t}^d = \sum_{k \in \mathcal{K}_m} \frac{1}{\eta} p_{i_m}^k + 2p_{cir}, \quad (10)$$

$$p_{k_m, t}^c = \frac{1}{\eta} p_{k_m}^c + p_{cir}, \quad (11)$$

where $p_{i_m, t}^d$ is the total power consumption of d_{i_m} , which is composed of the transmission power over all of the K_m channels, i.e., $\sum_{k \in \mathcal{K}_m} \frac{1}{\eta} p_{i_m}^k$, 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 is denoted as p_{cir} . η is the power amplifier (PA) efficiency, i.e., $0 < \eta < 1$. $p_{k_m, t}^c$ is the total power consumption of c_{k_m} , which is composed of the transmission power ($1/\eta$) $p_{k_m}^c$ and the circuit power only at the transmitter side. The power consumption of the BS is not taken into consideration since BS is usually powered by external grid power.

III. PROBLEM FORMULATION

Since each UE is only interested in optimizing its individual EE, the distributed power allocation problem can be modeled as a noncooperative game \mathcal{G} . The game \mathcal{G} can be described as the triplet $\mathcal{G} = [\{\mathcal{S}\}, \{\mathcal{A}\}, \{\mathcal{U}\}]$, wherein $\mathcal{S} = \{\mathcal{C}_m, \mathcal{D}_m, \forall m \in \mathcal{M}\}$ is the set of active UEs participating in the game, $\mathcal{A} = \{\mathbf{p}_{i_m}^d, \mathbf{p}_{k_m}^c, d_{i_m} \in \mathcal{D}_m, c_{k_m} \in \mathcal{C}_m, m \in \mathcal{M}\}$ is the set of possible actions (strategies) that UEs can take, where $\mathbf{p}_{i_m}^d = \{p_{i_m}^1, \dots, p_{i_m}^{K_m}\}$, and $\mathbf{p}_{k_m}^c = \{p_{k_m}^c\}$, and $\mathcal{U} = \{U_{i_m,EE}^d, U_{k_m,EE}^c, d_{i_m} \in \mathcal{D}_m, c_{k_m} \in \mathcal{C}_m, m \in \mathcal{M}\}$ is the set of UEs' utilities which are based on EE. $p_{i_m,max}^d$ and $p_{k_m,max}^c$ are the maximum transmission power constraints.

The EE of the d_{i_m} (including both the D2D transmitter and receiver) is defined as

$$U_{i_m,EE}^d(\mathbf{p}_{i_m}^d) = \frac{U_{i_m,SE}^d(\mathbf{p}_{i_m}^d)}{p_{i_m,t}^d(\mathbf{p}_{i_m}^d)}. \quad (12)$$

The corresponding EE optimization problem is formulated as

$$\begin{aligned} \max_{(\mathbf{p}_{i_m}^d)} \quad & U_{i_m,EE}^d(\mathbf{p}_{i_m}^d) \\ \text{s.t.} \quad & C_1 : 0 \leq \sum_{k \in \mathcal{K}_m} p_{i_m}^k \leq p_{i_m,max}^d. \end{aligned} \quad (13)$$

C_1 is the maximum transmission power constraint, i.e., the total transmission power allocated over all of the K_m channels should be no greater than $p_{i_m,max}^d$. Since D2D pairs communicate in a cognitive way, we have not imposed any QoS requirement for D2D pairs.

Similarly, the EE of c_{k_m} , i.e., $U_{k_m,EE}^c$, is defined as

$$U_{k_m,EE}^c(\mathbf{p}_{k_m}^c) = \frac{U_{k_m,SE}^c(\mathbf{p}_{k_m}^c)}{p_{k_m,t}^c(\mathbf{p}_{k_m}^c)}. \quad (14)$$

The corresponding EE maximization problem is formulated as

$$\begin{aligned} \max_{(\mathbf{p}_{k_m}^c)} \quad & U_{k_m,EE}^c(\mathbf{p}_{k_m}^c) \\ \text{s.t.} \quad & C_2, C_3. \end{aligned} \quad (15)$$

$$C_2 : U_{k_m,SE}^c(\mathbf{p}_{k_m}^c) \geq U_{k_m,SEmin}^c, \quad (16)$$

$$C_3 : 0 \leq p_{k_m}^c \leq p_{k_m,max}^c. \quad (17)$$

The constraint C_2 specifies the QoS requirement in terms of minimum SE.

There are two challenges when solving the above optimization problems. Firstly, the problems are non-convex due to the fractional form, which are computationally intractable and NP-hard. Although we can use the bisection method [13] for iteratively finding the optimum strategy by proving that (13) and (15) are quasi-concave [15], it is still impossible to derive a closed-form solution. Secondly, the CU's transmission rate defined in (6) depends on both intercell and intracell interference. If the combined interference is strong, the QoS constraint C_2 cannot be guaranteed unless interference mitigation is employed. We adopt infeasibility ratio to measure the probability that the QoS constraint C_2 cannot be satisfied, i.e., $Pr\{\max_{(\mathbf{p}_{k_m}^c)} U_{k_m,SE}^c(p_{k_m}^c) < U_{k_m,SEmin}^c\}$, which is a key performance measurement for D2D communications [16].

IV. THE ENERGY-EFFICIENT HYBRID RESOURCE ALLOCATION ALGORITHM

In this section, we introduce the proposed energy-efficient resource allocation algorithm that combines centralized and distributed approaches. Firstly, we introduce how to transform non-convex problems into a sequence of parameterized convex problems. Then, we introduce the proposed centralized interference mitigation scheme which can efficiently reduce infeasibility ratio. Finally, we introduce the distributed power allocation scheme.

A. Objective Function Transformation

Define $q_{i_m}^{d*}$ as the maximum EE of d_{i_m} , which is given by

$$q_{i_m}^{d*} = \max_{(\mathbf{p}_{i_m}^d)} U_{i_m,EE}^d(\mathbf{p}_{i_m}^d) = \frac{U_{i_m,SE}^d(\mathbf{p}_{i_m}^{d*})}{p_{i_m,t}^d(\mathbf{p}_{i_m}^{d*})}, \quad (18)$$

where $\mathbf{p}_{i_m}^{d*}$ is the optimum strategy. The following theorem can be easily proved [12]:

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

$$\begin{aligned} \max_{(\mathbf{p}_{i_m}^d)} \cdot U_{i_m,SE}^d(\mathbf{p}_{i_m}^d) - q_{i_m}^{d*} p_{i_m,t}^d(\mathbf{p}_{i_m}^d) \\ = U_{i_m,SE}^d(\mathbf{p}_{i_m}^{d*}) - q_{i_m}^{d*} p_{i_m,t}^d(\mathbf{p}_{i_m}^{d*}) = 0. \end{aligned} \quad (19)$$

Theorem 1 shows that the transformed problem with an objective function in subtractive form is equivalent to the non-convex problem with an objective function in fractional form. Then, the original problem (13) can be rewritten as

$$\max_{(\mathbf{p}_{i_m}^d)} U_{i_m,SE}^d(\mathbf{p}_{i_m}^d) - q_{i_m}^{d*} p_{i_m,t}^d(\mathbf{p}_{i_m}^d), \text{s.t. } C_1. \quad (20)$$

The new problem can be viewed as a weighted sum of SE and power consumption, where the parameter $q_{i_m}^{d*}$ acts as the *price* (negative weight) of the power consumption. Similarly, the original problem (15) can be rewritten as

$$\max_{(\mathbf{p}_{k_m}^c)} \cdot U_{k_m,SE}^c(\mathbf{p}_{k_m}^c) - q_{k_m}^{c*} p_{k_m,t}^c(\mathbf{p}_{k_m}^c), \text{s.t. } C_2, C_3. \quad (21)$$

It can be easily seen that both (20) and (21) are convex. However, the specific values of $q_{i_m}^{d*}$ and $q_{k_m}^{c*}$ are still unknown, and (21) may even be infeasible if C_2 cannot be guaranteed. In the next subsection, we introduce how to reduce the infeasibility ratio.

B. Centralized Interference Mitigation Algorithms

We propose a multi-cell cooperation based interference mitigation algorithm to reduce the infeasibility ratio.

In the first stage, the interference caused by CUs is canceled by interference regeneration based techniques such as network interference cancellation engine (NICE) [17]. We target CUs firstly because the transmission power of CUs is usually much higher than D2D pairs due to longer transmission distances between CUs and BSs. In particular, CUs near the cell edge may cause significant interference. NICE opportunistically performs interference cancellation by exchanging decoded interferers' data within cooperating BSs. NICE is invoked only if the intercell interference exceeds a

certain threshold. To start, the suffering BS firstly performs channel estimation to identify dominant interferers, and requests decoded data associated with those dominant interferers from cooperative BSs. Due to limited backhaul capacity, an interfering signal is likely to be selected for cancellation only if its signal strength is large enough. Secondly, the interfering signal is reconstructed and then subtracted from the overall received signal vectors. This results in a new post-cancellation of the received signal vector with reduced interference level. The detailed mathematical equations can be found in [17].

In the second stage, both the intracell interference and intercell interference caused by D2D pairs are suppressed by adaptively regulating the maximum transmission power cap on each channel based on interference threshold. Then, D2D pairs are forced to transmit at a power level that is lower than this cap, which should not cause too much interference to CUs using the same channel. The constraint C_1 is replaced by the following K_m constraints:

$$C_{i_m,1} \sim C_{i_m,K_m} : 0 \leq p_{i_m}^k \leq p_{i_m,max}^k, \forall k \in \mathcal{K}_m. \quad (22)$$

In addition, the power cap $p_{i_m,max}^k$ should also satisfy

$$C_{i_m,K_m+1} : \sum_{k \in \mathcal{K}_m} p_{i_m,max}^k \leq p_{i_m,max}^d. \quad (23)$$

The interference threshold for c_{k_m} is calculated based on the QoS constraint specified in C_2 , which is given by

$$I_{k_m,1}^d + I_{k_m,2}^d \leq \frac{p_{k_m}^c g_{k_m}^c}{2^{U_{k_m,SEmin}^c} - 1} - N_0 = I_{k_m,th}^c. \quad (24)$$

C_2 can be rewritten as

$$C_{k_m,1} : \sum_{d_{i_m} \in \mathcal{D}_m} p_{i_m,max}^k g_{i_m,k_m} + \sum_{m' \in \mathcal{M} \setminus \{m\}} \sum_{d_{j_{m'}} \in \mathcal{D}_{m'}} p_{j_{m'},max}^k g_{j_{m'},k_m} \leq I_{k_m,th}^c. \quad (25)$$

Define $\mathbf{p}_{max}^d = \{p_{i_m,max}^k, \forall m \in \mathcal{M}, \forall k \in \mathcal{K}_m, \forall d_{i_m} \in \mathcal{D}_m\}$, which can be obtained by solving the following problem

$$\begin{aligned} & \max_{\mathbf{P}_{max}^d} \prod_{m \in \mathcal{M}} \prod_{d_{i_m} \in \mathcal{D}_m} \prod_{k \in \mathcal{K}_m} \left(\frac{p_{i_m,max}^k}{w_{i_m}^k} \right) \\ & \text{s.t. } C_{i_m,K_m+1}, C_{k_m,1}, \forall m \in \mathcal{M}, \forall k \in \mathcal{K}_m, \forall d_{i_m} \in \mathcal{D}_m. \end{aligned} \quad (26)$$

$w_{i_m}^k$ is the weight of $p_{i_m,max}^k$. If $w_{i_m}^k = 1, \forall m \in \mathcal{M}, \forall k \in \mathcal{K}_m, \forall d_{i_m} \in \mathcal{D}_m$, then the BS allocates resources based on the instantaneous interfering channel gains. D2D pairs that would cause stronger interference are allocated with less resources. Alternatively, $w_{i_m}^k$ can be designed to take fairness into consideration such as the proportional fair scheduling [14].

C. The Distributed Power Allocation Algorithm

In this subsection, we introduce the iterative power allocation algorithm based on the Dinkelbach method [12]. The initial values of $q_{i_m}^d$ or $q_{k_m}^c$ can be set as a small positive number near to zero, e.g., 10^{-4} . At each iteration, the transformed convex problems specified in (20) and (21) are solved by replacing $q_{i_m}^{d*}$ and $q_{k_m}^{c*}$ with $q_{i_m}^d$ and $q_{k_m}^c$ respectively. It is noted that if the D2D interference mitigation algorithm is used,

the constraint C_1 should be replaced by $C_{i_m,1} \sim C_{i_m,K_m}$. The impacts of using tighter power constraints for D2D pairs are explored in detail in simulation results.

Since the transformed problem is convex, Karush-Kuhn-Tucker (KKT) conditions and Lagrange dual decomposition are used to find the optimum strategy [13]. Taking (20) as an example, the associated Lagrangian with the constraint C_1 is given by

$$\begin{aligned} \mathcal{L}_{EE}(\mathbf{p}_{i_m}^d, \alpha_{i_m}) &= U_{i_m,SE}^d(\mathbf{p}_{i_m}^d) \\ &- q_{i_m}^d p_{i_m,t}^d(\mathbf{p}_{i_m}^d) - \alpha_{i_m} \left(\sum_{k \in \mathcal{K}_m} p_{i_m}^k - p_{i_m,max}^d \right), \end{aligned} \quad (27)$$

where α_{i_m} is the Lagrange multiplier. The optimal value $\hat{p}_{i_m}^k$ corresponding to $q_{i_m}^d$ is given by

$$\hat{p}_{i_m}^k = \left[\frac{\eta \log_2 e}{q_{i_m}^d + \eta \alpha_{i_m}} - \frac{I_{i_m,1}^d + I_{i_m,2}^d + I_{i_m,1}^c + I_{i_m,2}^c + N_0}{g_{i_m}^k} \right]^+, \quad (28)$$

where $[x]^+ = \max\{0, x\}$. Equation (28) indicates a water-filling algorithm, where the water level is determined by the cost of allocating power, i.e., α_{i_m} , as well as the current cost of total power consumption given by $q_{i_m}^d$. The Lagrange multipliers can be updated by using the gradient method [15] as

$$\begin{aligned} & \alpha_{i_m}(\tau + 1) \\ &= \left[\alpha_{i_m}(\tau) + \mu_{i_m,\alpha}(\tau) \left(\sum_{k \in \mathcal{K}_m} \hat{p}_{i_m}^k(\tau) - p_{i_m,max}^d \right) \right]^+, \end{aligned} \quad (29)$$

where τ is the iteration index, $\mu_{i_m,\alpha}$ is the positive step size. We have adopted a constant step size to strike a balance between optimality and convergence speed. If instead of C_1 , constraints $C_{i_m,1} \sim C_{i_m,K_m}$ are employed, the optimal value $\hat{p}_{i_m}^k$ is similar to (28) by replacing α_{i_m} with $\beta_{i_m}^k$, which is the Lagrange multiplier associated with $C_{i_m,k}$. $\beta_{i_m}^k$ is updated as

$$\beta_{i_m}^k(\tau + 1) = [\beta_{i_m}^k(\tau) + \mu_{i_m,\beta}^k(\tau) (\hat{p}_{i_m}^k(\tau) - p_{i_m,max}^k)]^+ \quad (30)$$

Then, $q_{i_m}^d$ is updated for the next iteration as

$$q_{i_m}^d = \frac{U_{i_m,SE}^d(\hat{\mathbf{p}}_{i_m}^d)}{p_{i_m,t}^d(\hat{\mathbf{p}}_{i_m}^d)}. \quad (31)$$

The iteration process will continue until $U_{i_m,SE}^d(\hat{\mathbf{p}}_{i_m}^d) - q_{i_m}^d p_{i_m,t}^d(\hat{\mathbf{p}}_{i_m}^d) \leq \Delta$, or the maximum iteration number is reached. Δ is the maximum tolerance. Then we set $\mathbf{p}_{i_m}^{d*} = \hat{\mathbf{p}}_{i_m}^d$, and calculate $q_{i_m}^{d*}$ as (18). The optimization problem (21) can be solved in a similar way, which is omitted here due to space limitation.

D. Implementation Issues and Complexity Analysis

When implementing the algorithm, channel estimation is particularly important since the efficiency of both interference mitigation and power allocation depends on channel estimation accuracy. In the case of interference mitigation, a BS needs to be aware of the reference symbols assigned by cooperative

BSs, and orthogonal or near orthogonal reference symbols can be used to improve estimation accuracy. In this paper, we assume that precise channel estimates are available. The impacts of channel estimation errors will be discussed in future works. In the distributed power allocation algorithm, each D2D pair only needs to estimate the received interference rather than know the specific transmission power strategies of interferers. The reason is that sufficient information of strategies are contained in the form of interference. CUs also need to have the knowledge of interference, which can be estimated firstly by powerful BSs and then fed back to CUs for EE optimization.

The interference cancellation algorithm in the first stage is, in essence, a *multi-cell successive interference cancellation* (MC-SIC) technique with a low computation complexity that is of the same order as conventional SIC receivers. The optimization problem (26) of the second stage is a geometric programming problem, and can be transformed to a convex problem by a change of variables and a transformation of the objective and constraint functions. It involves solving a convex problem with $\sum_{m \in \mathcal{M}} N_m K_m$ optimization parameters, and $\sum_{m \in \mathcal{M}} (N_m + K_m)$ linear inequality constraints, which can be solved in polynomial time [13]. If D2D pairs in the same cell or clusters are allocated with the same resource, e.g., $p_{i_m, \max}^k = p_{j_m, \max}^k, \forall m \in \mathcal{M}, \forall d_{i_m}, d_{j_m} \in \mathcal{D}_m$, the number of optimization parameters and inequality constraints are further reduced to $\sum_{m \in \mathcal{M}} K_m$ and $\sum_{m \in \mathcal{M}} (K_m + 1)$ respectively.

The iterative algorithm of the third stage produces an increasing sequence of $q_{i_m}^d$ and $q_{k_m}^c$ values, which converges to the optimum value $q_{i_m}^{d*}$ and $q_{k_m}^{c*}$ at a super-linear convergence rate [15], respectively. Taking (20) as an example, the complexity is dominated by the calculations given by (28), which leads to a total complexity $\mathcal{O}(K_m I_{i_m}^{loop} I_{i_m}^{dual})$, where $I_{i_m}^{loop}$ and $I_{i_m}^{dual}$ are the numbers of iterations required for reaching convergence and solving the dual problem respectively.

V. SIMULATION RESULTS

In this section, the proposed algorithm, labeled as “hybrid scheme”, is compared with the works of [9], [11] without centralized interference cancellation and mitigation, which are labeled as “conventional scheme”. The values of simulation parameters are based on [9], [18], [19], and are summarized as follows. The cell radius is 1000 m, and the intercell distance is 1800 m. The maximum D2D transmission distance is 50 m. The maximum transmission power of CUs is the same as D2D pairs, i.e., $p_{k_m, \max}^c = p_{i_m, \max}^d = 200$ mW (23 dBm). The constant circuit power p_{cir} is 100 mW (20 dBm), and the thermal noise power N_0 is 10^{-7} W. We consider a total of $M = 6$ cells. 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 $h_{i,j} \sim \mathcal{CN}(0, 1)$. The numbers of CUs and D2D pairs in each cell are $K_m = N_m = 10, \forall m \in \mathcal{M}$. The PA efficiency η is 35%. The simulation results are averaged through a total number of 500 simulations. The locations of CUs and D2D pairs are generated randomly in each simulation.

Fig. 2 shows the infeasibility ratio corresponding to various QoS requirements. The minimum QoS requirement of CUs

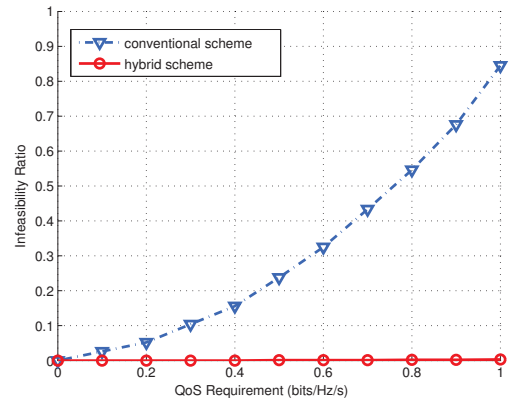


Fig. 2. Infeasibility ratio versus QoS requirements ($N_m = K_m = 10$, $m = 1, \dots, 6$, $U_{k_m, SE_{min}}^c = 0 \sim 1$ bits/s/Hz, 500 simulations).

$U_{k_m, SE_{min}}^c$ is increased from 0 to 1 bits/s/Hz with a step of 0.1, and the corresponding infeasibility ratio is obtained through simulations. We observe that as the QoS requirement increases, the infeasibility ratio of the conventional algorithm increases dramatically, which shows that it is barely possible to achieve higher QoS performance due to severe co-channel interference. In comparison, the proposed algorithm that employs centralized interference mitigation schemes achieves a nearly zero infeasibility ratio.

Fig. 3 and Fig. 4 show the EE performances of CUs and D2D pairs corresponding to the number of game iterations, respectively. We assume that both cellular and D2D pairs are forced to stop transmission and wait for resource rescheduling if the QoS requirement cannot be satisfied due to interference. In this way, we take infeasible scenarios into considerations and avoid using only good channel conditions of feasible scenarios for unfair comparison. From Fig. 3 and Fig. 4, simulation results show that the hybrid scheme improves the EE performance of CUs by 14% and 71% and improves the EE performance of D2D pairs by 8.29% and 65% for $U_{k_m, SE_{min}}^c = 0.2$ and $U_{k_m, SE_{min}}^c = 0.7$, respectively. The improvement is increasing as the QoS requirement increases since the infeasibility ratio is much higher in higher QoS requirement scenario. An amazing fact is that D2D pairs also benefits from the proposed scheme, due to reduced aggregate interference levels and improved infeasibility ratio. We also observe that the improvement for D2D pairs is less than that of CUs since CUs has a higher priority.

VI. CONCLUSION

In this paper, we proposed a hybrid resource allocation scheme which takes advantage of both the centralized interference mitigation algorithms and distributed power allocation algorithm. Simulation results show that the proposed scheme achieves a nearly zero infeasibility ratio, and improves the EE performance by 71% for CUs and 65% for D2D pairs when $U_{k_m, SE_{min}}^c = 0.7$ bits/s/Hz. Future works will analyze the impact of channel estimation errors.

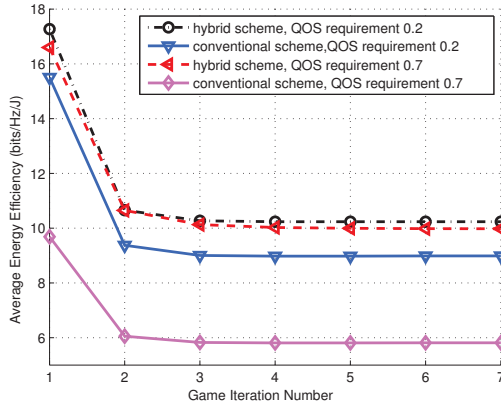


Fig. 3. Average energy efficiency of CUs versus the number of game iterations ($N_m = K_m = 10$, $m = 1, \dots, 6$, $U_{k_m, SE_{min}}^c = 0.2, 0.7$ bits/s/Hz, 500 simulations).

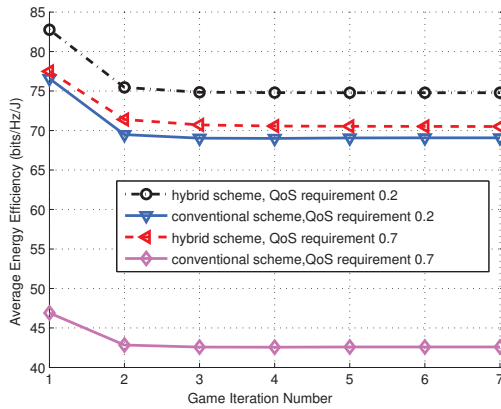


Fig. 4. Average energy efficiency of D2D pairs versus the number of game iterations ($N_m = K_m = 10$, $m = 1, \dots, 6$, $U_{k_m, SE_{min}}^c = 0.2, 0.7$ bits/s/Hz, 500 simulations).

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