Joint Mode Selection and Resource Allocation in Underlaying D2D Communication

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Abstract. Device-to-device (D2D) communication as an underlay to cellular networks is a promising technology to improve network capacity and user experience. However, it depends on elegant resource management between cellular users and D2D pairs. In this work, we study the problem of D2D communication underlaying cellular networks sharing uplink resources, which focuses on maximizing the sum rate of D2D pairs while guaranteeing the quality of existing cellular users. A three-step scheme is proposed. We first conduct mode selection to decide whether a D2D pair can share links with a cellular user. And then, we match a cellular user with each D2D pair based on the principle of fairness and try to maximize the sum rate of D2D pairs. Finally, a joint power control strategy is developed and a closed-form of solution is provided. The superiority of the proposed scheme is demonstrated in the numerical results.

Keywords: D2D communication · Mode selection · Resource allocation Non-convexity · Joint optimization

1 Introduction

With the explosive growth of information and the increasing demand of user experience, device-to-device (D2D) technique, as an effective method to relieve the traffic load of cellular networks and improve local service flexibility, has attracted much attention in recent years [1]. By enabling two users in proximity to communicate directly without being relayed by a base station (BS), D2D communication can bring four types of benefits, that is, proximity gain, reuse gain, hop gain and paring gain, which may achieve higher rate, lower power consumption and more efficient resource utilization [2]. Thus, introducing D2D communications into cellular networks is worth consideration.

However, enabling D2D communication in a cellular network poses some inevitable challenges [3, 4]. It will generate interference between D2D pairs and cellular users due to the sharing of links and furthermore it may decrease the QoS (Quality of Service) of

This work is supported by the National Natural Science Foundation of China (No. 61671474, No. 61371122).

K. Long et al. (Eds.): 5GWN 2017, LNICST 211, pp. 206–219, 2018.
https://doi.org/10.1007/978-3-319-72823-0_20

both users. As such, an elegant resource management to coordinate with the interference is in urgent demand [5, 6]. Resource management includes mode selection and resource allocation, which refers to the allocation of link and power. D2D communication underlaying cellular networks can either exploit cellular mode, in which the communication will be relayed by the BS, or communicate directly sharing links with primary cellular users, referred to as reuse mode, which can further improve the spectral efficiency [7]. Link allocation should be jointly considered with mode selection, that is, a D2D pair with reuse mode chooses which cellular user to share its link. Power control includes power allocation among D2D pairs, as well as cellular users, which will ultimately achieve optimal network performance with limited power resource.

There are some existing works that study resource management for D2D communication underlaying cellular networks. In particular, an interference limited area (ILA) is suggested in [8], where a D2D pair cannot be admitted to reuse the links of cellular users to decrease their quality of communication. To further mitigate the interference from D2D transmission to cellular communication, a distance-based resource allocation scheme is developed in [9], based on the outrage probability analysis while restricting the maximum transmit power of D2D pairs. [10] provides an optimal resource sharing strategy based on convex optimization, to maximize the rate of one D2D pair which can share the link resources of all the cellular users in the cell. However, there is only one D2D pair considered. In [11], a heuristic algorithm is proposed to match D2D pairs and cellular users, which chooses the cellular users with higher channel gain to share with D2D pairs with lower interference gain, while in that case, coordination between both of the users is not considered. [12] jointly considers three respects of resource management, which exploits maximum weight bipartite matching based scheme to choose cellular partners for D2D pairs to maximize the network throughput.

Motivated by the above literature, we investigate D2D communication underlaying a multi-user cellular network sharing uplink resources. We aim to design a resource management scheme which jointly considers mode selection, link allocation and power control to maximize the sum rate of D2D pairs, and meanwhile, to guarantee the QoS of both cellular users and D2D pairs. The contributions are summarized as follows:

(i) We consider multiple D2D pairs and multiple cellular users in a cell, rather than only one D2D pair. And we model a joint mode selection and resource allocation optimization problem, where the QoS requirements of both cellular users and D2D pairs are simultaneously considered. Moreover, we constrain the total power budget of D2D pairs.

(ii) We formulate the uplink resource sharing problem into a non-convex optimization problem, and then, we divide it into three serial subproblems and obtain the closed-form of the solution. Firstly, we decide an interference limited area (ILA) for each potential D2D pair and then conduct mode selection based on a minimum distance metric. Then, we allocate the links of cellular users based on a principle of fairness to maximize the sum rate of D2D pairs, which will achieve the tradeoff between the efficiency and the fairness of the network [13]. Moreover, we use Lagrangian Algorithm to simultaneously allocate the power for both cellular users and D2D pairs.

The remainder of the paper is organized as follows. In Sect. 2, we describe the network model and formulate the optimization problem. The joint mode selection and resource allocation algorithm is illustrated in Sect. 3. Section 4 presents the numerical results to demonstrate the performance of the proposed scheme. Finally, Sect. 5 concludes the paper.

2 Problem Formulation

We consider a single cell, where there exist one BS, L cellular users and M D2D pairs, and the later compose the sets $\mathcal{C} = \{1, \ldots, L\}$ and $\mathcal{D} = \{1, \ldots, M\}$, respectively, as shown in Fig. 1. We assume that each cellular user occupies a frequency band normalized to be one, and then, the transmission links are orthogonal. In order to improve spectrum efficiency, we exploit the underlaying D2D communication sharing uplink resources with reuse mode. As such, the mutual interference among D2D pairs and cellular users may become more serious. To facilitate manipulation, we assume that the link of each cellular user is reused by at most one D2D pair. However, for those lacking in a proper cellular partner, the D2D pairs conduct cellular mode to communicate through the BS.

Considering the resource sharing between cellular users and D2D pairs, the SINR of cellular user i and D2D pair j sharing the link of user i are given respectively by

$$\xi_i^c = \frac{p_i h_i^c}{\sigma_N^2 + q_j g_{j,i}^d} \tag{1}$$

$$\xi_j^d = \frac{q_j h_j^d}{\sigma_N^2 + p_i g_{i,j}^c} \tag{2}$$

where σ_N^2 represents Gaussian noise variance on each channel of cellular user i and D2D pair j. h_i^c is denoted as the channel gain from cellular user i to the BS. Similarly, denote $g_{i,j}^c$, h_j^d, and $g_{j,i}^d$ as the channel gain between cellular user i and the receiver of D2D pair j, between the transmitter to the receiver of D2D pair j and between the transmitter of D2D pair j to the BS on frequency i, respectively. Let p_i and q_j represent the transmit power of cellular user i and D2D pair j, respectively.

Thus, their rate can be expressed as

$$R_i^c(p_i, q_j) = log_2(1 + \xi_i^c) \tag{3}$$

$$R_j^d(p_i, q_j) = log_2(1 + \xi_j^d) \tag{4}$$

Our goal is to maximize the total rate of D2D pairs, and also satisfy the requirements of cellular users and D2D pairs, in terms of their individual rate and power limit, and the total power budget for all D2D pairs sharing the links. The joint mode selection and resource allocation optimization problem in D2D communication underlaying cellular system is formulated as

$$\text{maximize} \quad \sum_{j=1}^{N} R_j^d(p_i, q_j) \tag{5}$$

$$\text{subject to} \quad R_i^c(p_i, q_j) \geq \rho_i \,, \forall i \in \mathcal{C} \tag{5a}$$

$$R_j^d(p_i, q_j) \geq \gamma_j \,, \forall j \in \mathcal{S} \tag{5b}$$

$$0 \leq p_i \leq P_i \,, \forall i \in \mathcal{C} \tag{5c}$$

$$0 \leq q_j \leq Q_j \,, \forall j \in \mathcal{S} \tag{5d}$$

$$\sum_{j=1}^{N} q_j \leq Q \tag{5e}$$

where $\mathcal{S}(\mathcal{S} \subseteq \mathcal{D}, \mathcal{S}\{1, \ldots, N\})$ denotes the set of D2D pairs. ρ_i and γ_j represent the rate threshold of cellular user i and potential D2D pair j, respectively, and hence, (5a) and (5b) ensure that both cellular users and potential D2D pairs reach their minimum QoS requirements in terms of rate. (5c) and (5d) guarantee that the transmit power of cellular users and potential D2D pairs are within the maximize limit P_i and Q_j, respectively. (5e) represents Q is the total power budget of the D2D pairs on all links.

Since it is a nonconvex problem, it is difficult to find the solution of (5). To facilitate manipulation, we will transform it into a convex one and provide a fully analytical characterization of the optimized solution to (5). We divide the optimization problem into three subproblems since the matching process of D2D pairs and cellular users belongs to the problem based on discrete space, while the power allocation problem belongs to continuous space.

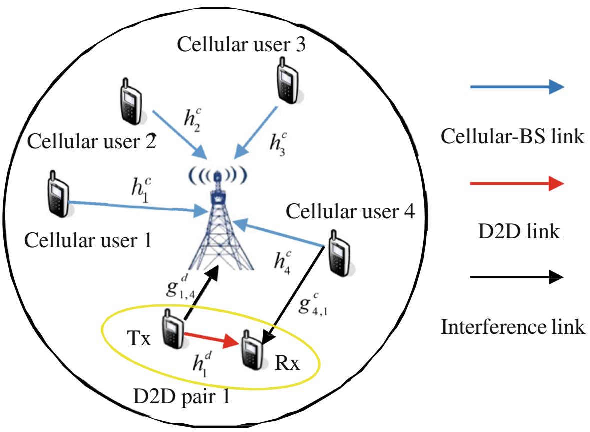

Fig. 1. System model of D2D communication underlaying cellular networks.

3 Joint Mode Selection and Resource Allocation Algorithm

In this section, to solve the joint mode selection and resource allocation optimization problem in underlaying D2D communication, we divide the joint optimization problem into three subproblems, referred as mode selection, link allocation and power control. Then, we propose an optimization algorithm and analyze the properties of the scheme.

3.1 Distance-Oriented Admission Control of D2D Pairs

Before introducing D2D pairs into the cellular network, we first consider which mode to choose for them. That is, we need to determine whether a potential D2D pair can reuse the links of existing cellular users. If a potential D2D pair is admitted, it selects reuse mode, and furthermore, we need to decide a reuse cellular partner for it. If not, its communication will be relayed by the BS with cellular mode.

For each potential D2D pair, if it is admitted to reuse a cellular user's link, the constraints in (5a), (5b), (5c), (5d) must be primarily satisfied. As such, we obtain a set of reuse candidates for potential D2D pair j and denote them as $\mathcal{R}_j$ and then potential D2D pair j is admitted if $\mathcal{R}_j = \emptyset$. Since the channel condition and the mutual interference mainly depend on distance, we will divide an ILA for each potential D2D pair based on the distance between two kinds of users, outside of where the cellular candidates in $\mathcal{R}_j$ are distributed.

It can be verified that it is a linear programming problem, and hence, there will be a feasible area for potential D2D pair j, as the shadow part shown in Fig. 2. The line l_c and l_d represent constraints (5a) and (5b) with equality, respectively. Let $p_{i,\min}$ and $q_{j,\min}$ denote the minimum power of cellular user i and D2D pair j, respectively, which indicate there is no link sharing and no interference between them.

To guarantee that there will be a feasible root of the linear programming problem, point T,$(p_{i,T}, q_{j,T})$, as shown in Fig. 2, must be within the square area, that is, they satisfy constraints (5c) and (5d). And then, there may be feasible power for both cellular user i and potential D2D pair j in the shadow area. Computing the intersection of l_c and l_d in the first place, and point T, $(p_{i,T}, q_{j,T})$ can be expressed as

$$\begin{cases} p_{i,T} = \frac{(2^{\rho_i}-1)\sigma_N^2[h_j^d + (2^{\gamma_j}-1)g_{j,i}^d]}{h_i^c h_j^d - (2^{\rho_i}-1)(2^{\gamma_j}-1)g_{i,j}^c g_{j,i}^d} \\ q_{i,T} = \frac{(2^{\gamma_j}-1)\sigma_N^2[h_i^c + (2^{\rho_i}-1)g_{i,j}^c]}{h_i^c h_j^d - (2^{\rho_i}-1)(2^{\gamma_j}-1)g_{i,j}^c g_{j,i}^d} \end{cases} \tag{6}$$

where $p_{i,T}$ and $q_{i,T}$ represent the transmit power of cellular user i and potential D2D pair j to meet constraints (5a) and (5b) with equality, respectively. If point T is within the square area, any point in the shadow area can manage a feasible power pair for cellular user i and potential D2D pair j. However, if not, potential D2D pair j cannot reuse the link of cellular user i. As such, the admissible condition is,

$$\begin{cases} 0 < p_{i,T} \le P_i \\ 0 < q_{j,T} \le Q_j \end{cases} \tag{7}$$

Accordingly, combining with the distance based path loss model, $h_{i,j} = Kd_{i,j}^{-\alpha}$, we can impose a distance control between cellular users and potential D2D pairs to decide $\mathcal{R}_j$. Denote $L_{i,j}$ as the distance between cellular user i and the receiver of potential D2D pair j. We have the following proposition that characterizes the admission control of a potential D2D pair.

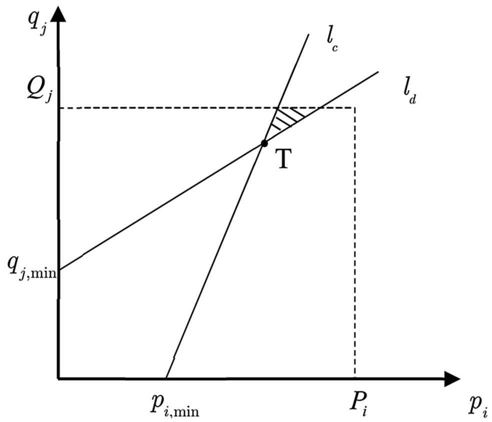

Fig. 2. Admission control of D2D pair j.

Proposition 1. *Potential D2D pair j can be admitted to reuse the link of cellular user i, if and only if* $L_{i,j} \geq L_{i,j}^{\min}$, *where* $L_{i,j}^{\min}$ *is the minimum distance limit between cellular user i and the receiver of potential D2D pair j, and it is given by, (i)* $\left\{\frac{KP_i(2^{\rho_i}-1)(2^{\gamma_j}-1)g_{j,i}^d}{P_i h_i^c h_j^d-(2^{\rho_i}-1)\sigma_N^2[h_j^d+(2^{\gamma_j}-1)g_{j,i}^d]}\right\}^{\frac{1}{\alpha}}$, *if* $\log_2(1+\frac{P_i h_i^c}{Q_i g_{j,i}^d+\sigma_N^2}) \leq \rho_i$. *(ii)* $[\frac{K(2^{\rho_i}-1)(2^{\gamma_j}-1)(Q_j g_{j,i}^d+\sigma_N^2)}{Q_j h_i^c h_j^d-(2^{\gamma_j}-1)\sigma_N^2 h_i^c}]^{\frac{1}{\alpha}}$, *if* $\log_2(1+\frac{P_i h_i^c}{Q_j g_{j,i}^d+\sigma_N^2}) \leq \rho_i$.

Proof. According to constraint (7), we can simplify it into the following

$$g_{i,j}^c \leq \begin{cases} \frac{P_i h_i^c h_j^d-(2^{\rho_i}-1)\sigma_N^2[h_j^d+(2^{\gamma_j}-1)g_{j,i}^d]}{P_i(2^{\rho_i}-1)(2^{\gamma_j}-1)g_{j,i}^d} = g_c \\ \frac{Q_j h_i^c h_j^d-(2^{\gamma_j}-1)\sigma_N^2 h_i^c}{(2^{\rho_i}-1)(2^{\gamma_j}-1)(Q_j g_{j,i}^d+\sigma_N^2)} = g_d \end{cases} \tag{8}$$

To move a step forward, it can be transformed into

$$g_{i,j}^c \leq \begin{cases} g_c, & \log_2(1+\frac{P_i h_i^c}{Q_i g_{j,i}^d+\sigma_N^2}) \leq \rho_i \\ g_d, & \log_2(1+\frac{P_i h_i^c}{Q_j g_{j,i}^d+\sigma_N^2}) > \rho_i \end{cases} \tag{9}$$

Finally, we can get the distance limit $L_{i,j}^{\min}$ according to path loss model.

Thus, we set an ILA for each potential D2D pair, and a potential D2D pair can only match with the cellular users outside of its ILA, since the mutual interference between them cannot be too serious to decrease their QoS, or the D2D pair must be far enough from the potential cellular partner. If there is no cellular user outside of a potential D2D pair's ILA, it can only select cellular mode, instead.

3.2 Link Allocation for D2D Pairs

Algorithm: Link Allocation Algorithm

$\mathcal{S}$: List of D2D pairs
$\mathcal{R}_j$: List of reuse cellular candidates of D2D pair j
$\mathcal{M}$: List of D2D pairs with $|\mathcal{R}_j|$ in increasing order
for all $j \in \mathcal{S}$ do
    find $|\mathcal{R}_j| = 1$
end for
if there is more than one D2D pair that satisfies
  $|\mathcal{R}_j| = 1$ and the $i \in \mathcal{R}_j$ is the same **then**
  find $j^* = \arg\max_{i \in \mathcal{R}_{j^*}} R^d_{j^*}(p_i, q_{j^*})$ and D2D pair
  j^* reuse the link of cellular user i
  delete i from other D2D pairs' $\mathcal{R}_j$ and upgrade
  $|\mathcal{R}_j|$ and $\mathcal{M}$
end if
for all $j \in \mathcal{S} \setminus \{j^*\}$
    choose cellular users in $\mathcal{R}_j$ for D2D pair j in
    the order of $\mathcal{M}$
end for
find $\max \sum_{j \in \mathcal{S}} R^d_i(p_i, q_j)$

Here, we investigate how to choose a cellular user in $\mathcal{R}_j$ for D2D pairs with reuse mode to maximize the rate of all these D2D pairs while guaranteeing that each of them can access a cellular candidate to share its link.

Without loss of generality, we assume that each cellular user and D2D pair has the same transmit power respectively, which ensures that every D2D pair has the same chance to reuse links and the same chance for cellular users to be reused. According to the previous subsection, we have determined $\mathcal{R}_j$ for each D2D pair and $\mathcal{S}$ by finding D2D pair j when it satisfies $\mathcal{R}_j = \varnothing$.

There are three steps in the link allocation algorithm. We firstly calculate $\left|\mathcal{R}_j\right|$, which denotes the number of $\mathcal{R}_j$, and obtain $\mathcal{M}$, which contains the D2D pairs with $\left|\mathcal{R}_j\right|$ in increasing order. According to this, we can try to allocate cellular users with priority to those with less candidates and ensure each D2D pair will find a partner. Then, considering that different D2D pairs may have only one cellular candidate, if there is more than one D2D pair that can only share the link of cellular user i, we allocate link i to D2D pair j^* which can achieve the maximum rate, as shown in line 4 to 13. Finally, we match the remaining D2D pairs with cellular candidates in the order of $\mathcal{M}$, as line 14 to 17 indicate. And we will find a union of D2D-cellular pairs which can maximiz $\sum_{j\in\mathcal{S}} R_i^d(p_i, q_j)$. Therefore, we can guarantee a kind of fairness for D2D pairs, and also achieve the maximum benefit in that case.

3.3 Optimal Power Control for Cellular Users and D2D Pairs

In previous subsections, we have matched D2D pair with appropriate cellular users. Hence, we denote the cellular user and its link which is reused by D2D pair j as index j as well. We rewrite problem (5) as,

$$\text{maximize} \quad \sum_{j=1}^{N} R_j^d(p_j, q_j) \tag{10}$$

$$\text{subject to} \quad R_j^c(p_j, q_j) \geq \rho_j, \forall j \in \mathcal{C} \tag{10a}$$

$$R_j^d(p_j, q_j) \geq \gamma_j, \forall j \in \mathcal{S} \tag{10b}$$

$$0 \leq p_j \leq P_j, \forall j \in \mathcal{C} \tag{10c}$$

$$0 \leq q_j \leq Q_j, \forall j \in \mathcal{S} \tag{10d}$$

$$\sum_{j=1}^{N} q_j \leq Q \tag{10e}$$

Then, we denote $\alpha_j = h_j^c/\sigma_N^2$, $\beta_j = h_j^d/\sigma_N^2$, $\gamma_j = g_j^d/\sigma_N^2$, and $\theta_j = g_j^c/\sigma_N^2$ as the normalized channel gains. And the rate of D2D-cellular pair j is expressed as,

$$R_j^c(p_j, q_j) = log_2(1 + \frac{p_j\alpha_j}{1 + q_j\gamma_j}) \tag{11}$$

$$R_j^d(p_j, q_j) = log_2(1 + \frac{q_j\beta_j}{1 + p_j\theta_j}) \tag{12}$$

Now, we will propose an optimal power control strategy for all these paired users to solve the problem in (10).

Proposition 2. *Denote* (p_j^*, q_j^*) *as the optimal power allocation for problem (10)*, and $k_j = 2^{\rho_j} - 1$. *Then, for all* $j = 1, \ldots, N$, *we define* $A_j = k_j\gamma_j\theta_j(\alpha_j\beta_j + k_j\gamma_j\theta_j)$, $B_j = (\alpha_j + k_j\theta_j)(2k_j\gamma_j\theta_j + \alpha_j\beta_j)$, $C_j = (\alpha_j + k_j\theta_j)(\frac{\alpha_j + k_j\theta_j - \alpha_j\beta_j}{\lambda})$ *and renew* $Q_j = \min\left\{Q_j, \frac{\alpha_j P_j - k_j}{k_j\gamma_j}\right\}$. *We can get the optimal solution as, (i) if* $\sum_{j=1}^{N} Q_j \le Q$, *then,* $q_j^* = Q_j$, $p_j^* = \frac{k_j(1+\gamma_j Q_j)}{\alpha_j}$. *(ii) if* $\sum_{j=1}^{N} Q_j > Q$, *then,* $q_j^* = \left[\frac{\sqrt{B_j^2 - 4A_jC_j(\lambda)} - B_j}{2A_j}\right]_0^{Q_j}$, $p_j^* = \frac{k_j(1+\gamma_j q_j^*)}{\alpha_j}$, *where* $[\cdot]_0^{Q_j}$ *indicates the projection onto the interval* $[0, \mathrm{Q}_j]$.

Proof. The rate of D2D pair j defined in (12) is monotonically decreasing by increasing p_j, when q_j is fixed. Moreover, to satisfy the constraint in (10a), we can get $p_j \ge \frac{k_j(1+\gamma_j q_j)}{\alpha_j}$, and hence, the optimal p_j^* is obtained when $p_j^* = p_{j,\min} = \frac{k_j(1+\gamma_j q_j)}{\alpha_j}$. Then, we substitute it into (12) and it can be further expressed as

$$R_j^d(p_j^*, q_j) = \log_2(1 + \frac{\alpha_j\beta_j q_j}{\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j}) \tag{13}$$

Now, we investigate how to decide q_j in (13) to maximize the sum rate of D2D pairs.

Denote $h(q_j) = \frac{\alpha_j\beta_j q_j}{\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j}$, we can easily confirm that

$$h'(q_j) = \frac{\alpha_j\beta_j(\alpha_j + k_j\theta_j)}{(\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j)^2} \ge 0 \tag{14}$$

$$h''(q_j) = -\frac{2k_j\alpha_j\beta_j\gamma_j\theta_j(\alpha_j + k_j\theta_j)}{(\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j)^3} \le 0 \tag{15}$$

It is obviously that $h(q_j)$ is a concave function and increases by increasing q_j, which contributes to that $R_j^d(p_j^*, q_j)$ is also a concave function and increases with the increasing of q_j. Now, we have transformed the problem in (5) which is nonconvex into a convex one indicated in (10).

In order to maximize $R_j^d(p_j^*, q_j)$ in (13), it is essential to determine the feasible region of q_j. The power constraint in (10c) is equal to $q_j \le \frac{\alpha_j P_j - k_j)}{k_j\gamma_j}$, therefore, we renew the power limit as $Q_j = \min\left\{Q_j, \frac{\alpha_j P_j - k_j}{k_j\gamma_j}\right\}$. To solve the problem in (10), we consider two different situations, *(i)* if $\sum_{j=1}^{N} Q_j \le Q$, we can take $q_j^* = Q_j$ to maximize $R_j^d(p_j^*, q_j^*)$. And accordingly, $p_j^* = \frac{k_j(1+\gamma_j Q_j^*)}{\alpha_j}$. *(ii)* if $\sum_{j=1}^{N} Q_j > Q$ we use Lagrangian Algorithm to solve the problem: $l(\mathrm{q},\lambda) = \ln 2 \sum_{j=1}^{N} \log_2(1 + \frac{\alpha_j \beta_j q_j}{\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j}) + \lambda(Q - \sum_{j=1}^{N} q_j)$ with $\lambda \geq 0$. Then, we will illustrate how to find the optimal solution with the constraint $\sum_{j=1}^{N} q_j^* = Q$.

The first partial derivative of $l(\mathrm{q},\lambda)$ with respect to λ is given as,

$$\frac{\partial l(\mathrm{q},\lambda)}{\partial q_j} = \frac{\alpha_j \beta_j (\alpha_j + k_j\theta_j)}{(\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j)^2 + \alpha_j\beta_j q_j(\alpha_j + k_j\theta_j + k_j\gamma_j\theta_j q_j)} - \lambda \tag{16}$$

The solution of problem (10) is equal to that $\frac{\partial l(\mathrm{q},\lambda)}{\partial q_j} = 0$ and it is obvious that there will be a feasible solution only when λ is positive. Therefore, we can get a quadratic equation expressed as $A_j q_j^{*2} + B_j q_j^* + C_j(\lambda) = 0$, with $A_j, B_j, C_j(\lambda)$ defined in proposition 2, and the projection of the positive solution for the equation is onto $[0, \mathrm{Q}_j]$.

By now, we are able to investigate how to get a proper λ to determine q_j^*, which is difficult with direct computing. We can primarily confirm an interval $[0, \lambda_{\max}]$, where $\lambda_{\max} = \max_{j \in \mathcal{S}} \left\{ \frac{\alpha_j \beta_j}{\alpha_j + k_j\theta_j} \right\}$, according to $C_j(\lambda) \leq 0$, which ensures $B_j^2 - 4A_jC_j(\lambda)$ in proposition 2 positive. Moreover, given the condition that q_j^* is monotonically decreasing as λ increases, and that we can absolutely find a positive root in the feasible region, bisection method is exploited to obtain the optimal λ^*. Thus, we can finally determine an optimal λ^* to get the power allocation strategy as (p_j^*, q_j^*).

4 Numerical Results

The simulation setup is as follows: Consider a hexagonal cell with a radius of 250 m, where the BS is centered, and some cellular users and potential D2D pairs are randomly where the BS is centered, and some cellular users and potential D2D pairs are randomly distributed. Each potential D2D transmitter is 50 m away from its receiver. The power spectral density of additive white Gaussian noise is 10^{-8} W/Hz, and the QoS threshold of cellular users is $\rho_i = \gamma_j = 1\,\mathrm{bit/s}$. It is verified in [10] that the maximum SNR of cellular user i is $\alpha_i P_i$, and without loss of generality, we set P_i for each cellular user so that they can reach the same maximum SNR.

Figure 3 shows the sum rate of D2D pairs at different total D2D SNR, which is denoted by Q/σ_N^2 [10], comparing the performance with different amount of cellular users. As the number of cellular users increases, the rate of D2D pairs derived by our proposed scheme also increases, however, the speed of the increasing is slower gradually. When there are only 8 or 16 cellular users for the 4 D2D pairs we set in the cell, the sum rate of the D2D pairs increases obviously. However, when the amount of cellular users is up to 32 and above, the performance tends to approach. Note that, for a fixed amount of D2D pairs, if there exists only a small number of cellular candidates, there is a larger space for them to improve the performance, and their rate will increase dramatically with the increasing of cellular users. While if they have well enough cellular candidates to choose, they can achieve a fairly high rate as a whole and the effect of increasing cellular users is less obvious.

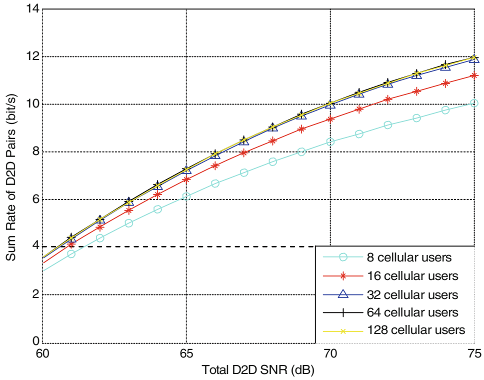

Fig. 3. The sum rate of D2D pairs versus total D2D SNR with different amount of cellular users.

As Fig. 4 indicates, the sum rate of D2D pairs is almost linearly increased by increasing the power limit of each D2D pair. And at a fixed power limit, the D2D pairs with more cellular users to reuse perform better. Actually, with D2D power limit increasing, D2D pairs will choose different cellular users to reuse and they are more likely to obtain higher rate.

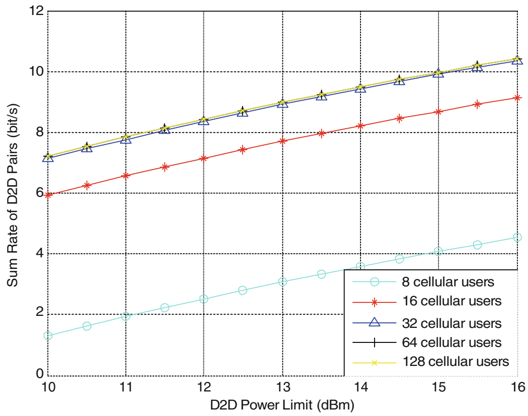

Fig. 4. The sum rate of D2D pairs versus D2D power limit with different amount of cellular users.

To comparison, we compare the proposed scheme to two other algorithms,

(i) Global search: it doesn't divide an ILA for D2D pairs or consider fairness when D2D pairs choose cellular candidates to share. Since the global search only deals with link allocation, we incorporate the proposed power control strategy into it.
(ii) Suboptimal power control [10]: it is based on waterfilling algorithm, in which the cellular users simply use their maximum power.

We consider a cell with 16 cellular users and 4 potential D2D pairs. Figure 5 indicates that the proposed scheme can obtain higher D2D rate than suboptimal power control strategy, while lower than global search. After ILA division in the first step, our proposed scheme performs better than global search in pairing, in terms of computational complexity. And the suboptimal power control only optimizes the power of D2D pairs with a fixed cellular users' power. As shown in Fig. 6, with the increasing of total D2D SNR, the average energy efficiency of cellular users is monotonically decreasing. Since D2D pairs use a higher power and then cause more severe interference to their shared cellular users, cellular users have to increase their transmit power to reach the rate threshold. The proposed scheme can perform better than two other algorithms with regard to energy efficiency of cellular users. As the simulation result indicates, D2D pairs tend to choose cellular users which are far away from them and the BS which cause less interference in global search, and in that case, cellular users will use a higher transmit power. Moreover, in the suboptimal power control scheme, cellular users simply use their fixed maximum power. Then, by jointly optimizing the power of D2D-cellular pair while satisfying the total SNR constraint, our scheme achieves better performance.

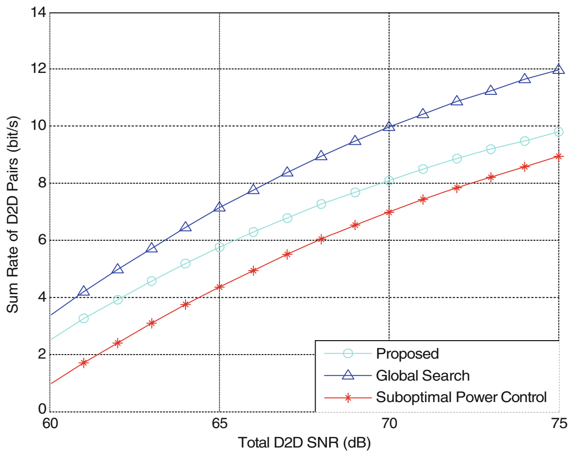

Fig. 5. The sum rate of D2D pairs versus total D2D SNR.

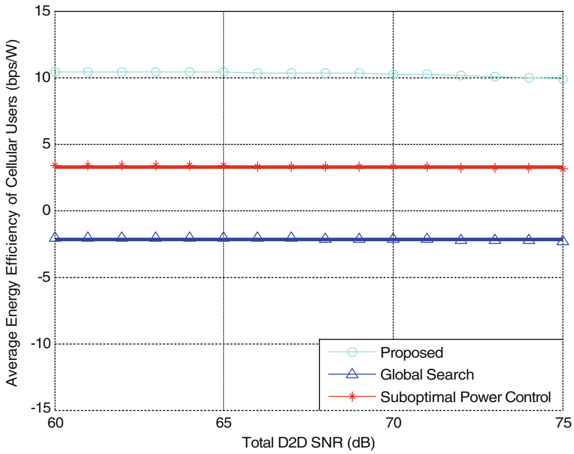

Fig. 6. Average energy efficiency of cellular users versus total D2D SNR.

5 Conclusion

In this paper, we investigated D2D communication as an underlay sharing uplink resources in cellular networks and proposed a joint mode selection and resource allocation scheme which jointly considers mode selection, link allocation and power control. In particular, we maximized the sum rate of D2D pairs with guaranteed QoS requirements of existing cellular users, as well as D2D pairs. Moreover, we set a fairness principle to ensure that each D2D pair shares links with a cellular user. Simulation results demonstrated that the proposed scheme brings substantial performance improvements.

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