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# Maximizing throughput gain via resource allocation in D2D communications

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**Abstract**

By reusing the cellular resources, device-to-device (D2D) communication is becoming a very promising technology that greatly enhances the spectrum utilization. To harvest the benefits that D2D communications can offer, efficient resource allocation strategy is required to guarantee the demands of quality of service (QoS) for both cellular and D2D users. This paper proposes a resource allocation scheme to alleviate the performance deterioration of the D2D communications with spectrum reuse. To maximize the overall throughput gain, the proposed scheme is designed to reduce the rate loss of cellular users and improve the rate of D2D users simultaneously in a two-step manner. Specifically, it first calculates the reuse gain for a single D2D pair and a single cellular user. Next, a maximum weight bipartite matching is further proposed to select the reuse pair to maximize the overall network throughput gain. Numerical results demonstrate that the proposed resource allocation scheme can significantly improve the network throughput performance with average user rate guaranteed.

**Keywords:** D2D communications, Resource allocation, Optimization, Throughput gain, Rate loss

## 1 Introduction

The device-to-device (D2D) communication is widely recognized as one of the key technology of the evolving 5G architecture due to the enhanced cellular spectrum utilization [1]. In the D2D scenario, the terminals can communicate directly with one another without the base station (BS) [2]. Therefore, the end-to-end latency can be decreased; also, the area spectral efficiency can be improved simultaneously. Therefore, the network is able to accommodate more users [3, 4].

It is worth noting that D2D communications rely on the reuse of cellular spectrum resources; thus, the performance of the cellular system will be subject to the interference incurred as a consequence. This key problem has drawn much attention from both the academic and industrial fields. In references, methods in [4–7] suggest to mitigate the interference that cellular users suffer by either limiting the D2D user's transmit power or choosing the D2D users only in the interference limited area. However, the two approaches mentioned above cannot fully enhance the performance of D2D communications.

On the other hand, the motivation of works in [8–11] is to increase the network throughput. In [8], a single D2D pair is allowed to reuse a single cellular user's resource to maximize the throughput, and also, a closed expression of the optimal power allocation is given. In [9], the overall network throughput is maximized via reusing cellular users' resources by multiple D2D pairs where the optimization problem is solved in three steps, i.e., access control, power allocation, and channel allocation. Moreover, the literatures in [10, 11] still consider the resource allocation with the goal of maximizing the throughput while taking the throughput gain as the access control criterion. Unfortunately, none of the above studies take into account the performance loss of cellular users incurred by the spectrum reuse. In [12], the authors propose a power management scheme for an adjacent femtocell network and formulate a non-convex optimization problem in order to maximize the capacity under the power constraints. The joint uplink subchannel and power allocation in cognitive small cells using cooperative Nash bargaining game theory is investigated in [13], where the cross-tier interference mitigation, minimum outage probability requirement, imperfect CSI, and fairness are considered. In [14], the authors propose an iterative gradient user association and power allocation approach with attention

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to load balance constraints, energy harvesting by base stations, user quality of service requirements, energy efficiency, and cross-tier interference limits. More recently, [15] analyzes the characteristics of optimal joint power control and D2D matching strategy, based on which an energy-efficient iterative algorithm for D2D communications is proposed.

For the future evolution of cellular networks, it is significant to maintain the quality of service (QoS) of both cellular and D2D users. To this end, this paper proposes a resource allocation algorithm that maximizes the throughput gain while reducing the rate loss of cellular users and increasing the rate of D2D users at the same time. It is demonstrated that the resource allocation in this study can be modeled as a mixed integer nonlinear programming (MINLP) optimization problem. To find a tractable solution, the original MINLP problem is decomposed into two subproblems, where the optimal solutions are able to be obtained in a two-step manner without reducing the feasible domain. Specifically, the first subproblem is to obtain the maximum reuse gain when a single D2D user shares a single cellular user's resource and determine whether it is eligible for spectrum reuse. Moreover, the second subproblem determines the best pairing between D2D and cellular users and finally maximizes the overall network throughput.

The rest of the paper is organized as follows. The system model and optimization problem description are given in Section 2. Then, in Section 3, the optimal resource allocation algorithm is investigated in detail. Numerical results are presented in Section 4 to demonstrate the performance of the proposed scheme. Finally, Section 5 concludes this paper.

## 2 System model and problem formulation

### 2.1 Introduction of system model

In the time-division duplexing (TDD) system, D2D users are enabled to access time-frequency resources of the cellular networks. As a result, both D2D and cellular users are subject to the interference from each other. As shown in Fig. 1, the receiver of the D2D pair D1 is interfered by the cellular user C1, also the BS is interfered by the transmitter of the D2D pair D1. Assuming that there are $N$ available orthogonal frequency resource blocks (RB) in one cell, the BS allocates resources to $N$ cellular users with the traditional algorithm. Here, we assume that the number of cellular users is fixed, the case of varying numbers can refer to [16]. Let $C = \{1, 2, \ldots, N\}$ and $D = \{1, 2, \ldots, M\}$ denote the sets of cellular and D2D users, respectively. Furthermore, only one or zero D2D user is allowed to share the same RB with the cellular user $n$. At last, it is assumed that the BS has the knowledge of the channel state information (CSI), which is kept constant during the coherence time and changes independently in different coherence intervals. Furthermore, the proposed algorithm is based on a generic model in device-to-device and cellular hybrid network, which could be applicable in content sharing, gaming, connectivity extension, traffic offloading, disaster relief, etc.

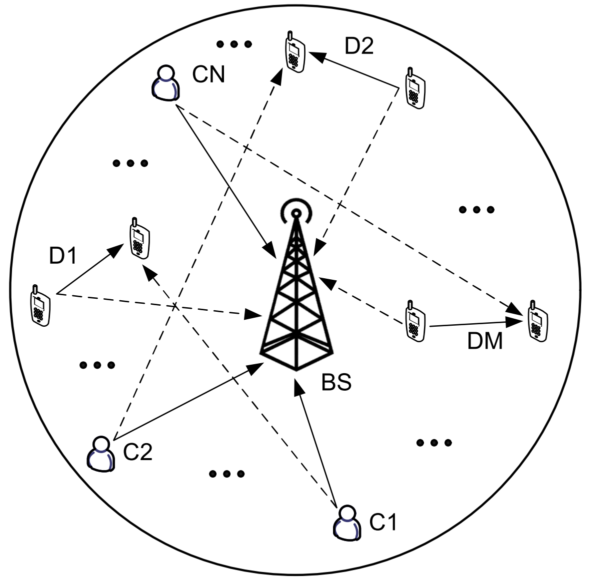

**Fig. 1** The illustration of interference between D2D and cellular users

The path loss model in [5] is employed in this paper. Specifically, the path gain between the terminals $i$ and $j$ ($j = 1$ represents the BS) can be modeled as:

$$g_{i,j} = K\beta_{i,j}\eta_{i,j}d_{i,j}^{-\alpha} \tag{1}$$

where $K$ is a system-related constant, $\beta_{i,j}$ represents the multipath gain of the link between terminals $i$ and $j$, which follows the exponential distribution, $\eta_{i,j}$ denotes the shadow gain of the link, following the logarithm distribution, $d_{i,j}$ indicates the distance of the link, and $\alpha$ indicates the path-loss factor. In order to distinguish different links in the system model, we adopt the following rules: $D_{m,m}$ indicates the D2D link $m$ and the corresponding path gain is $g_{D_{m,m}}$, $C_{n,B}$ indicates the link between cellular user $n$ and BS and the path gain is represented as $g_{C_{n,B}}$, $D_{m,B}$ denotes the link between the transmitter of D2D pair $m$ to BS and the path gain is $g_{D_{m,B}}$, and $C_{n,m}$ represents the link between the cellular user $n$ to the receiver of the D2D pair $m$, whereas the path gain is expressed as $g_{C_{n,m}}$.

### 2.2 Problem formulation

Our study aims to maximize the throughput gain while reducing the rate loss of cellular users. First, it is necessary to measure the rate loss of cellular users, which can be expressed as the difference between the rate of cellular users with or without the interference caused by D2D users under the same transmit power constraint. Thus, the rate loss can be formulated as follows:

$$R_{\text{loss}} = \log_2\left(1+\xi_n^{\text{no}}\right) - \log_2\left(1+\xi_n\right) \tag{2}$$

where $R_{\text{loss}}$ is the rate loss and $\xi_n$ and $\xi_n^{\text{no}}$ indicate the signal to interference plus noise ratio (SINR) in the case of sharing resources with D2D users or not, respectively. The expressions of $\xi_n$ and $\xi_n^{\text{no}}$ are

$$\begin{aligned} \xi_n &= \frac{P_n g_{C_{n,B}}}{\sigma^2 + P_m g_{D_{m,B}}}, \quad \forall n \in C \\ \xi_n^{\text{no}} &= \frac{P_n g_{C_{n,B}}}{\sigma^2}, \qquad\quad \forall n \in C \end{aligned} \tag{3}$$

where $P_n$ and $P_m$ indicate the transmission power of the cellular user and D2D user, separately, and $\sigma^2$ denotes the variance of the additive white Gaussian noise (AWGN).

On the other hand, this study is proposed to minimize the rate loss of the cellular user while ensuring the rate gain of the D2D user. Specifically, when the same time-frequency resource is shared between a single D2D pair and a cellular user, the optimization problem can be described as:

$$\begin{aligned} &\max_{P_n,P_m} \log_2\left(1+\xi_m\right) \\ &\min_{P_n,P_m} \log_2\left(1+\xi_n^{\text{no}}\right) - \log_2\left(1+\xi_n\right) \end{aligned} \tag{4}$$

where $\xi_m$ is the SINR obtained after D2D users access the cellular resources, i.e., $\xi_m = P_m g_{Dm,m} / \left(\sigma^2 + P_n g_{C_{n,m}}\right)$.

Equation (4) is a multi-objective optimization problem, where the non-inferior solution can be solved by the weighted evaluation function method [17]. We use the linear weighting method to construct the evaluation function, which can be written as follows:

$$\begin{aligned} \max_{P_n,P_m} \; & \lambda_1\left(\log_2\left(1+\xi_m\right)\right) \\ & + \lambda_2\left(\log_2\left(1+\xi_n^{\text{no}}\right) - \log_2\left(1+\xi_n\right)\right) \end{aligned} \tag{5}$$

The target function should be converted to the maximum problem without any bias. Let $\lambda_1 = 1$ and $\lambda_2 = -1$, so that the evaluation function is obtained. The purpose of this function is to maximize the system throughput gain. A suboptimal solution could be given to the original optimization problem, thus maximizing the system throughput gain can take into account the performance gain of the D2D user and at the same time the performance loss of the cellular user.

Considering that there are multiple D2D links and cellular links in the cell, the optimization problem is described as:

$$\begin{aligned} \max_{x_{m,n},P_n,P_m} \; & \sum_{m\in D_m}\sum_{n\in C_n}\Big\{\log_2\left(1+\xi_n\right) + x_{m,n}\log_2\left(1+\xi_m\right) \\ & - \log_2\left(1+\xi_n^{\text{no}}\right)\Big\} \\ s.t. \quad & \xi_n = \frac{P_n g_{C_{n,B}}}{\sigma^2 + P_m g_{D_{m,B}}} \ge \xi_{n,\min}; \\ & \xi_m = \frac{P_m g_{D_{m,m}}}{\sigma^2 + P_n g_{C_{n,m}}} \ge \xi_{m,\min}; \\ & \sum_m x_{m,n} \le 1,\; x_{m,n} \in \{0,1\}; \\ & \sum_n x_{m,n} \le 1,\; x_{m,n} \in \{0,1\}; \qquad \forall n \in C;\; \forall m \in D_A \\ & 0 \le P_n \le P_{n,\max}; \\ & 0 \le P_m \le P_{m,\max}; \qquad\qquad \forall n \in C;\; \forall m \in D_A \end{aligned} \tag{6}$$

where $D_A$ ($D_A \in D$) represents the subset of D2D users that can access the cellular network, $\xi_{n,\min}$ and $\xi_{m,\min}$ are the minimum SINR requirements for cellular users and D2D users, respectively, and $\xi_m$ represents the SINR of D2D user with interference caused by the cellular user. According to the expressions of $\xi_n$ and $\xi_n^{\text{no}}$, it can be found that when $\xi_n \ge \xi_{n,\min}$, it is straightforward to derive that $\xi_n^{\text{no}} \ge \xi_{n,\min}$, thus the constraint of $\xi_n^{\text{no}} \ge \xi_{n,\min}$ is not required. $x_{m,n}$ is the identifier of the resource reuse, i.e., when the D2D user $m$ reuses the resource of cellular user $n$, then $x_{m,n} = 1$; otherwise, $x_{m,n} = 0$. Since the optimization problem contains the integer variable $x_{m,n}$ and the objective function is nonlinear, it can be considered as a mixed integer nonlinear programming problem which is difficult to directly obtain the optimal solution. Alternatively, this optimization procedure can be decomposed into two subproblems without changing the feasible domain of the original problem. After that, the corresponding optimal solutions to subproblems are obtained separately. The next section will present the detailed description of solving the optimization problem.

## 3 Resource allocation for throughput gain maximization

Two subproblems are obtained from the original mixed integer nonlinear programming problem to facilitate the optimization procedure. The first subproblem is to solve the maximum reuse gain of a single D2D user when reusing a single cellular user's resource and determine whether it is eligible to share the spectrum. The second subproblem determines the best pairings that maximize the overall network throughput gain, when multiple D2D users reuse multiple cellular users' resources.

### 3.1 Joint access control and power allocation based on multiplexing gain

In order to maximize the overall network throughput gain, it is necessary to determine the subset of D2D users that can access the cellular network. First, we need to establish the optimal objective function for maximizing the throughput gain with constraints of QoS and transmit power. Then, by solving the objective function, the optimal power allocation and maximum throughput gain can be obtained. Finally, we can obtain the subset of D2D users $D_A$ by judging whether the maximum throughput gain is greater than zero.

From the analysis of the Section 2, it can be found that Eq. (6) becomes the optimization problem of maximizing the throughput gain when $\lambda_1 = 1$ and $\lambda_2 = -1$. Accordingly, the expression is

$$\begin{aligned} \left(P_n^*, P_m^*\right) = \underset{P_n,P_m}{\arg\max} & \left\{\log_2\left(1+\xi_n\right)+\log_2\left(1+\xi_m\right)\right. \\ & \left. -\log_2\left(1+\xi_n^{\text{no}}\right)\right\} \\ s.t. \quad & \xi_n = \frac{P_n g_{C_{n,B}}}{\sigma^2 + P_m g_{D_{m,B}}} \geq \xi_{n,\min}; \\ & \xi_m = \frac{P_m g_{D_{m,m}}}{\sigma^2 + P_n g_{C_{n,m}}} \geq \xi_{m,\min}; \\ & 0 \leq P_n \leq P_{n,\max}; \\ & 0 \leq P_m \leq P_{m,\max} \end{aligned} \tag{7}$$

where $\xi_n^{\text{no}} = P_n g_{C_{n,B}} / \sigma^2$.

Obviously, Eq. (7) is a nonlinear programming problem. When the equal sign of QoS constraint is established, it can be converted to a function of $P_n$ and $P_m$ separately, i.e.,

$$\begin{aligned} l_c: \ P_n &= \frac{g_{D_{m,B}}\xi_{n,\min}}{g_{C_{n,B}}} P_m + \frac{\xi_{n,\min}\sigma^2}{g_{C_{n,B}}} \\ l_d: \ P_n &= \frac{g_{D_{m,m}}}{g_{C_{n,m}}\xi_{m,\min}} P_m - \frac{\sigma^2}{g_{C_{n,m}}} \end{aligned} \tag{8}$$

where $l_c$ represents the QoS constraint of cellular user $n$ and the power allocation which is larger than $l_c$ can satisfy cellular user $n$'s QoS. Whereas $l_d$ represents the QoS constraint of D2D user $m$, the power allocation which is smaller than $l_d$ can satisfy D2D user $m$'s QoS. In addition, the power allocation should follow the maximum and minimum power constraint of cellular users and D2D users. Thus, the area enclosed by straight lines $l_c$ and $l_d$ and power constraints is the feasible solution range of power allocation, which is the represented by $\Gamma$ and shown as the shadow area in Fig. 2. In order to solve the nonlinear programming problem of Eq. (7), we need to apply the following conclusion:

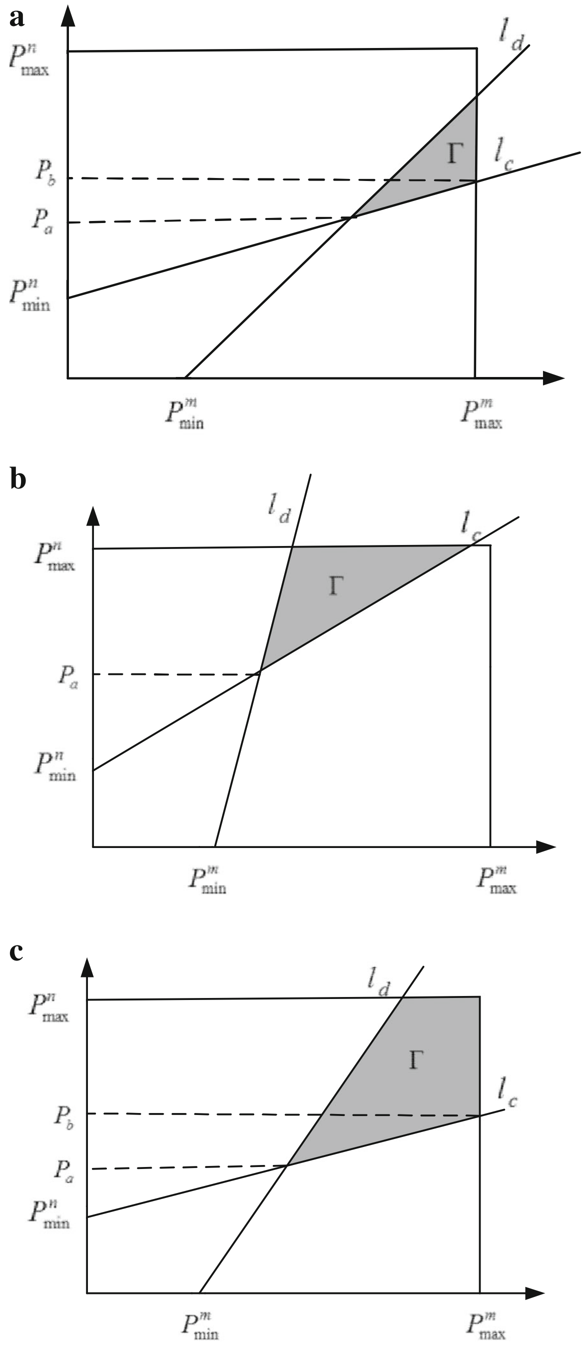

**Fig. 2** The admissible area according to power and QoS constraints. **a** The scope of solution 1. **b** The scope of solution 2. **c** The scope of solution 3

**Theorem 1** *The power distribution exists at the lower boundary of the feasible solution domain, i.e., a straight line* $P_n g_{C_{n,B}} = \xi_{n,\min}\left(\sigma^2 + P_m g_{D_{m,B}}\right)$.

*Proof* First, the following relationship can be obtained with straightforward mathematical manipulations:

$$\begin{aligned} f\left(P_n, P_m\right) &= g\left(P_n, P_m\right) + h\left(P_n, P_m\right) \\ g\left(P_n, P_m\right) &= \log_2\left(1+\xi_m\right) \\ h\left(P_n, P_m\right) &= \log_2\left(1+\xi_n\right) - \log_2\left(1+\xi_n^{\text{no}}\right) \end{aligned} \tag{9}$$

Evidently, $g\left(P_n, P_m\right)$ is a monotonically decreasing function of $P_n$, and it can be proved that $h\left(P_n, P_m\right)$ is a monotonically increasing function with respect to $P_n$. Consequently, we can get $\xi_n < \xi_n^{\text{no}}$ for any $P_m \neq 0$. Furthermore, let us define

$$\begin{aligned} h\left(\kappa P_n, P_m\right) - h\left(P_n, P_m\right) = \log_2\left(\frac{1+\kappa\xi_n}{1+\kappa\xi_n^{\text{no}}}\right) \\ - \log_2\left(\frac{1+\xi_n}{1+\xi_n^{\text{no}}}\right) \end{aligned} \tag{10}$$

For any $\kappa > 1$, we can have the following:

$$\left(\frac{1+\kappa\xi_n}{1+\kappa\xi_n^{\text{no}}}\right) < \left(\frac{1+\xi_n}{1+\xi_n^{\text{no}}}\right) \tag{11}$$

Also, it comes to

$$\begin{aligned} h\left(\kappa P_n, P_m\right) &< h\left(P_n, P_m\right) \\ g\left(\kappa P_n, P_m\right) &< g\left(P_n, P_m\right) \end{aligned} \tag{12}$$

Finally, we arrive at the conclusion $f\left(kP_n, P_m\right) < f\left(P_n, P_m\right)$. Thus, for any $P_m \in \Gamma, f\left(P_n, P_m\right)$ is a monotonically decreasing function with respect to $P_n$; thus, the optimal solution corresponds to the lower boundary of constraint domain $\Gamma$, i.e., $P_n g_{C_{n,B}} = \xi_{n,\min}\sigma^2 + P_m g_{Dm,B}$. Therefore, the power distribution exists at the lower boundary of the feasible solution domain, and the theorem is proved. ☐

When applying Theorem 1 to the original optimization problem, the feasible solution range can be reduced to the lower boundary. As a result, the original optimization problem can be transformed into the following equation:

$$P_m = \frac{P_n g_{C_{n,B}} - \xi_{n,\min}\sigma^2}{\xi_{n,\min} g_{D_{m,B}}} \tag{13}$$

It is necessary to point out that a constant after conversion of $\log_2\left(1+\xi_{m,\min}\right)$, which does not affect the solution to the problem, can be safely removed in Eq. (13).

Consequently, the original optimization problem is converted to

$$\begin{aligned} P_n^* = \max_{P_n} \Bigg( \log_2 \left( 1 + \frac{\left(P_n g_{C_{n,B}} - \xi_{n,\min}\sigma^2\right) g_{D_{m,m}}}{\left(\sigma^2 + P_n g_{C_{n,m}}\right) \xi_{n,\min} g_{D_{m,B}}} \right) \\ - \log_2 \left( 1 + \frac{P_n g_{C_{n,B}}}{\sigma^2} \right) \Bigg) \end{aligned} \tag{14}$$

Let us define

$$Q\left(P_n\right) = \left( 1 + \frac{\left(P_n g_{C_{n,B}} - \xi_{n,\min}\sigma^2\right) g_{D_{m,m}}}{\left(\sigma^2 + P_n g_{C_{n,m}}\right) \xi_{n,\min} g_{D_{m,B}}} \right) \Bigg/ \left( 1 + \frac{P_n g_{C_{n,B}}}{\sigma^2} \right) \tag{15}$$

Thus, we have the partial derivative as

$$\frac{\partial Q}{\partial P_n} = \frac{-ACP_n^2 - 2BCP_n + AE - DB}{F} \tag{16}$$

where

$$\begin{aligned} A &= \sigma^2\left(\xi_{n,\min} g_{C_{n,m}} g_{D_{m,B}} + g_{D_{m,m}} g_{C_{n,B}}\right) \\ B &= \sigma^2\sigma^2\xi_{n,\min}\left(g_{D_{m,B}} - g_{D_{m,m}}\right) \\ C &= \xi_{n,\min} g_{C_{n,m}} g_{D_{m,B}} \\ D &= \sigma^2\xi_{n,\min} g_{D_{m,B}}\left(g_{C_{n,m}} + g_{C_{n,B}}\right) \\ E &= \sigma^2\sigma^2\xi_{n,\min} g_{D_{m,B}} \\ F &= \left(CP_n^2 + DP_n + E\right)^2 \end{aligned}$$

Let us further define $-ACP_n^2 - 2BCP_n + AE - DB = 0$, then the extreme point of $Q\left(P_n\right)$ can be calculated by

$$P_n^{\Delta} = \frac{2BC \pm \sqrt{(2BC)^2 + 4AC\,(AE - DB)}}{-2AC} \tag{17}$$

One of the poles is negative and another is positive; thus, in the range $P_n \in (0, P_{n,\max}]$, the positive solution $P_n^{\Delta}$ could be its extreme points. Due to the fact that $4AC(AE - DB) \ll (2BC)^2$, then the extreme value of the solution can be simplified as:

$$\begin{aligned} P_n^{\Delta} &= \frac{2BC + \sqrt{(2BC)^2 + 4AC\,(AE - DB)}}{-2AC} \\ &\approx \frac{-2\sigma^2\xi_{n,\min}\left(g_{D_{m,B}} - P_{m,\max} g_{D_{m,m}}\right)}{\xi_{n,\min} g_{C_{n,m}} g_{D_{m,B}} + g_{D_{m,m}} g_{C_{n,B}}} \end{aligned} \tag{18}$$

If there is an extreme value in the feasible solution range, the maximum value is the extreme value. If there is no extreme value in the feasible solution range, the maximum value is the boundary. Therefore, the solution to the optimal power distribution is:

$$P_n^* = \begin{cases} P_n^{\Delta}, & P_a \le P_n^{\Delta} \le P_b \\ P_a, & P_n^{\Delta} \le P_a \\ P_b, & P_b \le P_n^{\Delta} \end{cases}; \qquad P_m^* = \frac{P_n^* g_{C_{n,B}} - \xi_{n,\min}\sigma^2}{\xi_{n,\min} g_{D_{m,B}}} \tag{19}$$

where $P_a = \frac{\sigma^2\left(\xi_{n,\min} g_{D_{m,m}} + \xi_{n,\min}\xi_{m,\min} g_{D_{m,B}}\right)}{g_{C_{n,B}} g_{D_{m,m}} - \xi_{n,\min}\xi_{m,\min} g_{D_{m,B}} g_{C_{n,m}}}$ is obtained by using (8), $P_n^{\Delta}$ is the extremum obtained by (19), and $P_b$ is the intersection solution of the feasible solution boundary, which is different from the change of the feasible solution range. Interesting remarks can be obtained as follows.

1. When the feasible solution domain is shown as in the case of Fig. 2a, c, the range of $P_n$ is from $P_a$ to $P_b$, where $P_b = \xi_{n,\min}\left(\sigma^2 + g_{D_{m,B}}\right)/g_{C_{n,B}}$
2. When the feasible solution domain is shown as in the case of Fig. 2b, the range of $P_n$ is from $P_a$ to $P_{n,\max}$

The optimal power distribution pair $\left(P_n^*, P_m^*\right)$ can be obtained by Eq. (19). It is necessary to confirm whether the multiplexed pair can bring the throughput gain. Hence, $\left(P_n^*, P_m^*\right)$ will be substituted into Eq. (21) to obtain $R_{n,m}^{\text{Gain}}$, which can be defined as

$$R_{n,m}^{\text{Gain}} = \log_2\left(1+\xi_n\right) + \log_2\left(1+\xi_m\right) - \log_2\left(1+\xi_n^{\text{no}}\right) \tag{20}$$

If $R_{n,m}^{\text{Gain}}$ is greater than zero, it comes to the conclusion that D2D user $m$ is actually qualified to reuse the resource of cellular user $n$.

**Algorithm 1** The maximize throughput gain (MTG) resource allocation algorithm

```
Parameter initialization;
$C = \{C_1, C_2, \ldots, C_N\}$, $D = \{D_1, D_2, \ldots, D_N\}$;
$C'_M$: reuse candidate sets for D2D user $m$;
for all $n \in C$, $m \in D$ do
    Calculate $\left(P_n^*, P_m^*\right)$ and $R_{n,m}^{\text{Gain}}\left(P_n^*, P_m^*\right)$;
    if $R_{n,m}^{\text{Gain}}\left(P_n^*, P_m^*\right) \geq 0$ then
        $n \in C'_m$;
    end if
end for
get $X = \left\{x_{m,n} = 1\right\}$ form Kuhn-Munkres algorithm.
```

### 3.2 Multiple D2D users multiplex multiple cellular users' resources

After the D2D user set $D_A$ and the maximum reuse gain of the reused pair are obtained, it is next required to determine the best pairing which could maximize the overall network throughput gain when multiple D2D users reuse multiple cellular users' resources. The problem can be modeled as the weighted matching of the weighted bipartite graphs in graph theory, which is represented as follows:

$$\begin{aligned} \max_{x_{m,n}} \quad & \sum_{n \in C'_m, m \in D'} x_{n,m} R_{n,m}^{\text{Gain}} \\ s.t. \quad & \sum_{m} x_{m,n} \leq 1,\ x_{m,n} \in \{0,1\},\ \forall m \in D_A \\ & \sum_{n} x_{m,n} \leq 1,\ x_{m,n} \in \{0,1\},\ \forall n \in C \end{aligned} \tag{21}$$

where $D'$ represents the set of accessible D2D users and $C'_m$ denotes the set of cellular users of which the resources that D2D users $m$ can reuse. Figure 3 shows the bipartite graph optimal matching problem of Eq. (21) with $D_A = \{1, 2, \ldots, M_1\}$, where $M_1$ is the maximum number of D2D pairs allowed to access the cellular spectrum. When the D2D user $m$ reuses the resource of the cellular user $n$, it establishes a connection and takes $R_{n,m}^{\text{Gain}}$ as a weight.

The solution to the above problem can be solved by the Kuhn-Munkres algorithm in [18], and the details is beyond the scope of this paper. The pseudo-code of the maximizing throughput gain via resource allocation is summarized in Algorithm 1.

## 4 Simulation results and discussion

In order to verify the performance of our scheme, the resource allocation algorithm based on maximized system throughput proposed in [5] is used as the benchmark. The throughput gain in [5] is defined as the maximum throughput increase after the introduction of D2D, shown as follows:

$$R_{n,m}^{\text{Gain}} = R_{n,m}^{\max} - R_n^{\max} \tag{22}$$

The throughput gain in this paper is defined as the gain obtained by the power distribution according to the maximum throughput gain:

$$R_{n,m}^{\text{Gain}} = R_{n,m}^{\text{max,gain}} \tag{23}$$

In order to compare with fairness, the rate gain in the reference [5] is modified. The formula is as follows:

$$R_{n,m}^{\text{Gain}} = R_{n,m}^{\max} - R_n^{\text{no}} \tag{24}$$

where $R_n^{\text{no}}$ is the rate of cellular user without interference under the same transmit power constraint.

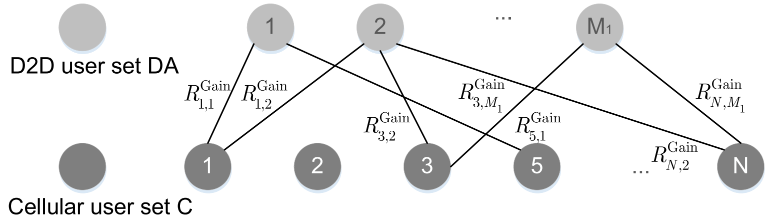

**Fig. 3** Weighted bipartite graph for D2D users and cellular users

**Table 1** Simulation parameters

| Parameters | Value |
|---|---|
| Cell radio/m | 500 |
| Uplink bandwidth/MHz | 20 |
| RBs | 100 |
| The maximum CU TX power/dBm | 24 |
| The maximum D2D TX power /dBm | 24 |
| D2D user SINR/dB | $U$ [0, 25] |
| Cellular user SINR/dB | $U$ [0, 25] |
| Number of cellular users | 100 |
| Number of D2D users | 10, 20, . . . , 100% of CUE |
| Multi-path fading $\lambda$ /dB | 1 |
| Shadowing $\mu = 0$ /dB | 8 |
| Pathloss exponent $\alpha$ | 4 |
| Noise power spectrum density/(dBm/Hz) | − 174 |

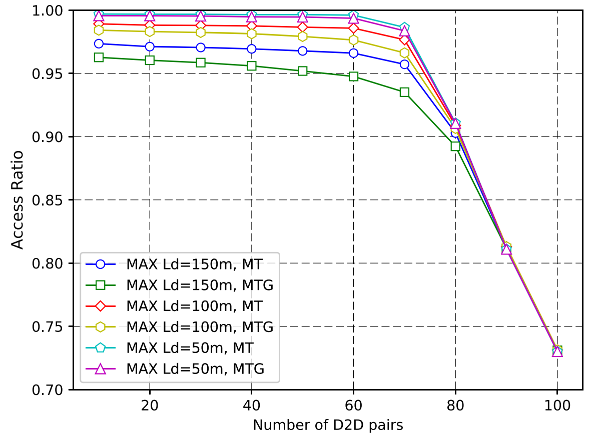

**Fig. 5** The relationship between the total rate loss of cellular users and the number of D2D pairs

The simulation parameters are listed in Table 1. Specifically, the multipath fading follows the exponential distribution, and shadow fading follows a log-normal distribution.

Figure 4 shows the relationship between the system throughput gain and the number of D2D pairs for a cell multiplexing with the D2D users. MT denotes the maximum throughput algorithm in [5]. It can be observed that the throughput gain increases when the number of D2D users increases. As the maximum transmission distance of D2D users increases, the throughput gain reduces consequently. However, the gain of the proposed algorithm is significantly higher than that of the MT scheme, since the purpose of optimization taken in this paper is to maximize the throughput gain.

Figure 5 demonstrates the access rate, which is defined as the ratio of the actual number of access D2D users to the total number of D2D users. The access rates of the two algorithms decrease as the D2D user increases and decreases with the maximum transmission distance of the D2D user. In this paper, the access rate based on the multiplexing gain access control is slightly lower than the MT algorithm. The reason behind is that the access control is based on the throughput gain, and to ensure the access quality, D2D users who can not bring the gain are not permitted to access the cellular spectrum.

The total rate loss of cellular users is shown in Fig. 6. The rate loss of both the proposed algorithm and MT is independent of the distance of D2D users and the number of D2D pairs. The total rate loss of cellular users of the proposed allocation is much lower than that of the MT algorithm, which reduces the cost of resource sharing for cellular users.

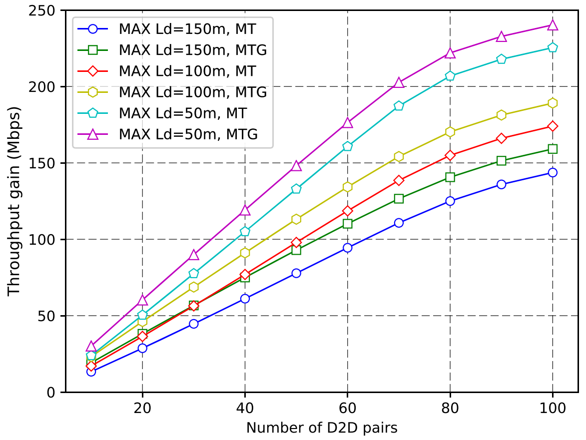

**Fig. 4** The relationship between the access rate and the number of D2D pairs

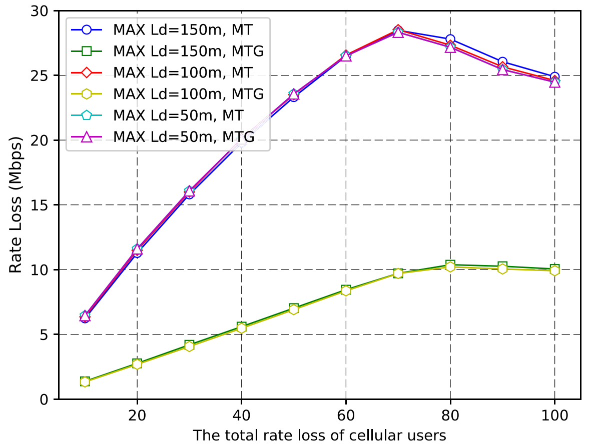

**Fig. 6** The relationship between the system throughput gain and the number of D2D pairs

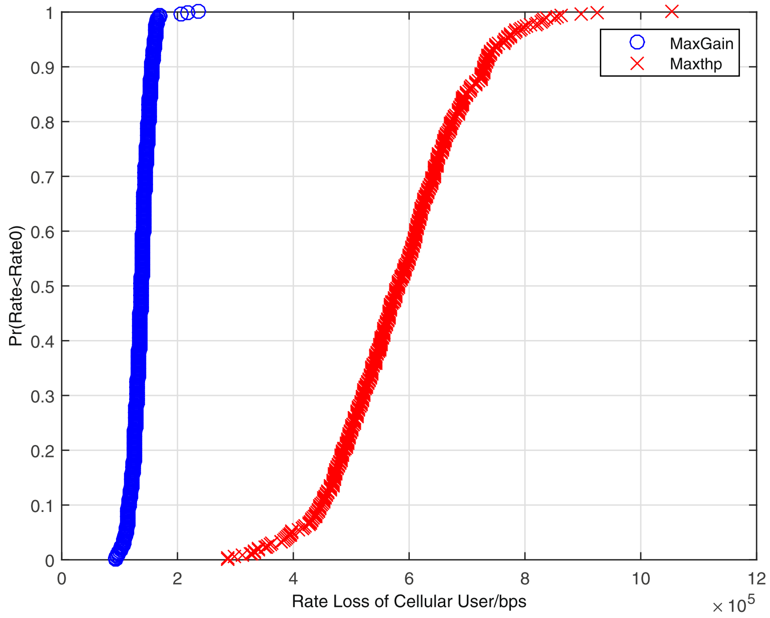

**Fig. 7** The CDF of cell user's rate loss

Figure 7 shows the cumulative distribution function (CDF) of average rate loss of cellular users. It is observed from this figure that the rate loss of cellular users using this method is much lower than that of MT algorithm and the loss range is more concentrated. Therefore, one can come to the conclusion that the proposed algorithm reduces not only the rate loss, but also the cost of spectrum sharing between the cellular and D2D users.

## 5 Conclusions

Aiming at reducing the performance loss caused by the reuse of cellular resources by D2D users, the concept of reuse cost is proposed to measure the rate loss of cellular users. The multi-objective optimization problem of maximizing the gain of D2D users and minimizing the loss of cellular users is established and transformed into single-objective optimization problem by constructing evaluation function. To solve the optimization problem, the original mixed integer nonlinear programming is divided into two sub-problems, and the optimal solution of the sub-problems is given. The simulation results show that the proposed algorithm can maximize the throughput gain and reduce the rate of loss of cellular users while ensuring the QoS requirements of D2D users and cellular users.

In this study, we assume the perfect CSI while the channel estimation can never be error-free in practice [19]. Therefore, the effect of imperfect CSI on the resource allocation scheme in D2D communication is worth studying further.

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**Availability of data and materials**
All data are fully available without restriction.

**Authors' contributions**
YW, XL, and XH contributed to the main idea, designed and implemented the algorithms, and drafted the manuscript. QY and WX designed and carried out the simulation and analyzed the results. All authors read and approved the final manuscript.

**Competing interests**
The authors declare that they have no competing interests.

## Publisher's Note

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