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Research Article

A Novel Access Control and Energy-Saving Resource Allocation Scheme for D2D Communication in 5G Networks

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This paper investigates access link control and resource allocation for the device-to-device (D2D) communication in the fifth generation (5G) cellular networks. The optimization objective of this problem is to maximize the number of admitted D2D links and minimize the total power consumption of D2D links under the condition of meeting the minimum transmission rate requirements of D2D links and common cellular links. This problem is a two-stage nondeterministic polynomial (NP) problem, the solving process of which is very complex. So, we transform it into a one-stage optimization problem. According to the monotonicity of objective function and constraint conditions, a monotone optimization problem is established, which is solved by reverse polyblock approximation algorithm. In order to reduce the complexity of this algorithm, a solution algorithm based on iterative convex optimization is proposed. Simulation results show that both algorithms can maximize the number of admitted D2D links and minimize the total power consumption of D2D links. The proposed two algorithms are better than the energy efficiency optimization algorithm.

1. Introduction

As one of the key technologies for the fifth generation wireless communication networks, D2D communication technology has attracted wide attention in academia and industry [1]. Cellular user equipment in close proximity can communicate with each other directly, which can improve spectral efficiency, reduce transmission delay, and offload traffic from the base station (BS) [2]. The implementation of D2D communication can be divided into two categories [3]. One is out-of-band D2D communication, which occurs on an unauthorized frequency band, such as bluetooth and WiFi Direct. The other is in-band D2D communication. For in-band D2D communication, D2D users adopt the authorized frequency band and benefit from reasonable resource planning and interference management. Based on whether or not D2D users share resources with cellular users, in-band D2D communication is divided into underlay mode and overlay mode. Overlay D2D communication means that sharing the same frequency bands with cellular users is prohibited [4]. Although overlay D2D communication is simple, it cannot make full use of the advantages of D2D communication to improve spectrum efficiency [5]. Underlay cellular D2D communication can improve the efficiency of local business, but may be subject to interference from cellular and D2D users [6]. Appropriate resource allocation can avoid serious interference, which keep interference below a reasonable level. Thus, resource allocation is one of the most critical issues for underlay D2D cellular networks [6, 7].

A kind of D2D resource allocation scheme based on energy efficiency was proposed by Xu et al. [8], which aimed to maximize the energy efficiency of D2D links while ensuring the minimum throughput of cellular users. In this scheme, D2D links reused the uplink resources of cellular

users and multiple D2D links could reuse all cellular users' resources at the same time. It decomposed the original nonconvex optimization problem into two subproblems, and iterative algorithm was used to solve the problem, but it did not consider access control of D2D links. The method of graph theory was introduced into D2D resource allocation [9], which took cellular link, D2D link, and spectrum channel as vertices in the graph. The superedge in the graph corresponded to each channel allocation scheme. Based on this, the cyclic iteration algorithm and branch and bound method were designed to optimize the maximum weight rate of the system. However, in this scheme, each cellular user and each D2D user could occupy one channel at most, thus limiting the spectrum utilization. Yang et al. [10] studied the resource allocation and power control of D2D and cellular users in a single cellular D2D network. Multiple pairs of D2D users could share the same resources with cellular users, the goal of which was to maximize the total rate of D2D users under the condition that cellular users' rate requirements were met. Zhu et al. [11] proposed a channel allocation and power control algorithm for multiple D2D users and cellular users so as to make good use of uplink resources in cellular systems while ensuring the communication quality of common cellular users. Ban and Jung [12] proposed a centralized link access control algorithm to ensure maximum transmission rate for overlay D2D cellular users. However, D2D users occupied special spectrum resources and the spectrum utilization rate was not high, but this scheme was not suitable for underlay D2D communication. Qian et al. [13] proposed a joint channel selection and power control algorithm based on convex optimization to maximize the total rate of D2D users, without considering the access control problem of D2D users. A kind of interference-aware resource optimization for D2D communications in 5G networks was put forward by Hao et al. [14], but it did not take access control into account. The NP-hard joint resource allocation problem was formulated as a one-to-one matching problem, which also did not consider access control problem of D2D links [15]. A signal to interference plus noise ratio (SINR) aware mode selection, scheduling, and resource allocation scheme for D2D communications was put forward by Bithas et al. [16]. However, scheduling and resource allocation were considered individually. By exploiting D2D communication for enabling user collaboration and reducing the edge server's load, the D2D-assisted and nonorthogonal multiple access based mobile edge computing system was investigated by Diao et al. [17], which just considered power, channel allocation, and computing resources without taking D2D access control problem into account. The resource allocation problem for uplink multicarrier nonorthogonal multiple access in D2D underlay cellular networks was investigated by Zheng et al. [18], which did not consider D2D access control and energy minimization. A kind of power allocation scheme was put forward by Wang et al. [19] to maximize the energy efficiency of the relay-aided D2D link while satisfying the minimum data transmission rates of the cellular links, which did not consider the minimum data rate requirements of D2D links and the number of admitted D2D links.

Although some current works [6, 7, 16, 20, 21] considered access control and resource allocation, access control and resource allocation were optimized individually. Firstly, they determined whether a D2D pair can be admitted under the SINR requirements of both D2D users and cellular users. Secondly, they allocated resources to D2D users and cellular users to maximize the overall throughput or energy efficiency. In our research, access control and resource allocation were optimized jointly, not individually. While ensuring the minimum transmission rates of cellular links and D2D links, we not only minimize the power consumed by D2D users but also maximize the number of D2D users. Besides, each D2D link can reuse all subcarriers of cellular users. Specifically, the main contributions of this paper are listed as follows:

(1) The optimization objective is to maximize the number of admitted D2D links and minimize the total power consumption of D2D links while meeting the minimum transmission rate requirements of D2D users and common cellular users. This optimization problem is transformed into a one-stage problem. It is proved that joint access control and resource allocation can not only maximize the number of admitted D2D links but also minimize the total power consumption of D2D links.

(2) In order to solve this problem, a continuous function is used to approximate binary discrete access control variable. The joint access control and resource allocation problem is transformed into a monotone optimization problem, which is worked out by reverse polyblock approximation algorithm. Besides, we prove that choosing appropriate parameters can maximize the number of admitted D2D links. In order to reduce computation complexity, a kind of iterative convex optimization algorithm is proposed.

(3) Via numerical simulation, we demonstrate that the proposed algorithms can maximize the number of admitted D2D links and minimize the total power consumption of D2D links. The performance of two algorithms is better than that of the energy efficiency optimization algorithm.

This paper is organized as follows. In Section 2, we present the system model. The access control and energy minimization problem is transformed into a one-stage problem in Section 3. In Section 4, the solving algorithm of access control and energy minimization is put forward. Numerical results are presented in Section 5 followed by the conclusions in Section 6.

2. System Model

In the uplink transmission of a single-cell wireless cellular network as shown in Figure 1, the set $\mathscr{K} = \{1, \ldots, K\}$ denotes K cellular links, $\mathscr{L} = \{K+1, \ldots, K+L\}$ denotes L D2D links, and K cellular links share N orthogonal subcarriers in the set $\mathscr{N} = \{1, \ldots, N\}$. L D2D links reuse N orthogonal subcarriers. $\mathscr{M} = \mathscr{K} \cup \mathscr{L}$ denotes the set of all

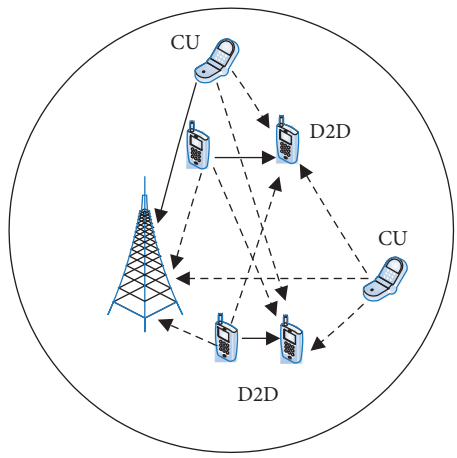

Figure 1: System model.

links, $K = |\mathscr{K}|$, $L = |\mathscr{L}|$, $M = |\mathscr{M}|$, $N = |\mathscr{N}|$, and $|\cdot|$ denotes cardinality of the set. h_{kl}^n denotes channel coefficient from transmitting link l to receiving link k on subcarrier n, and p_m^n represents transmitting power of link $m \in \mathscr{M}$ on subcarrier n. $\mathbf{p} = [\mathbf{p}_m]$, $\forall m \in \mathscr{M}$ represents transmitting power vector of all links; $\mathbf{p}_m = [p_m^n]$, $\forall n \in \mathscr{N}$ represents power allocation vector of link $m \in \mathscr{M}$ on all subcarriers. We introduce a binary variable ρ_k^n for the cellular link $k \in \mathscr{K}$. $\rho_k^n = 1$ represents that subcarrier n is assigned to link k; otherwise, $\rho_k^n = 0$. $\boldsymbol{\rho} = [\boldsymbol{\rho}^n]$, $\forall n \in \mathscr{N}$ represents allocation vectors of all subcarriers; $\boldsymbol{\rho}^n = [\rho_k^n]$, $\forall k \in \mathscr{K}$ represents allocation vectors of all cellular links on subcarrier n.

Signal to interference plus noise ratio of cellular link k on subcarrier n is

$$\gamma_k^n(\boldsymbol{\rho}, \mathbf{p}) = \frac{p_k^n |h_{kk}^n|^2}{\sigma_k^n + \sum_{l \in \mathscr{L}} p_l^n |h_{kl}^n|^2}, \tag{1}$$

where $\sum_{l \in \mathscr{L}} p_l^n |h_{kl}^n|^2$ represents interference from D2D link to cellular link k when reusing subcarrier n and σ_k^n represents noise power on subcarrier n of cellular link k. Signal to interference plus noise ratio of D2D link l on subcarrier n is

$$\gamma_l^n(\boldsymbol{\rho}, \mathbf{p}) = \frac{p_l^n |h_{ll}^n|^2}{\sigma_l^n + \sum_{l' \in \mathscr{L} \setminus l} p_{l'}^n |h_{ll'}^n|^2 + \sum_{k \in \mathscr{K}} \rho_k^n p_k^n |h_{lk}^n|^2}, \tag{2}$$

where $\sum_{k \in \mathscr{K}} \rho_k^n p_k^n |h_{lk}^n|^2$ represents interference from cellular link to D2D link l when reusing subcarrier n. $\sum_{l' \in \mathscr{L} \setminus l} p_{l'}^n |h_{ll'}^n|^2$ represents interference from other D2D links except for link l. σ_l^n represents noise power of D2D link l on subcarrier n. The spectrum efficiency of cellular link $k \in \mathscr{K}$ and D2D link $l \in \mathscr{L}$ is expressed, respectively, as

$$\begin{aligned} R_k(\boldsymbol{\rho}, \mathbf{p}) &= \sum_{n \in \mathscr{N}} \rho_k^n \log_2(1 + \gamma_k^n(\boldsymbol{\rho}, \mathbf{p})), \\ R_l(\boldsymbol{\rho}, \mathbf{p}) &= \sum_{n \in \mathscr{N}} \log_2(1 + \gamma_l^n(\boldsymbol{\rho}, \mathbf{p})). \end{aligned} \tag{3}$$

3. Problem Transformation

3.1. Access Control Problem and Energy Minimization Problem. The first problem is access control of D2D links, which maximizes the number of admitted D2D links through subcarrier allocation, power allocation, and link access control while ensuring the transmission rates of cellular users and D2D users. A binary link access control vector $\mathbf{s} = [s_1, s_2, \ldots, s_L]^T$ is introduced to represent whether D2D link l meets the demand of minimum data rate. For any $l \in \mathscr{L}$, $s_l = 0$ means that the corresponding D2D link is scheduled; otherwise $s_l = 1$. The optimization goal is to make as many as possible s_l equal to 0, which means the sum of all elements in the vector $\mathbf{s}$ is as small as possible. The access control problem is formulated as P1:

$$\min_{\boldsymbol{\rho}, \mathbf{p}, \mathbf{s}} \sum_{l \in \mathscr{L}} s_l, \tag{4}$$

$$\text{s.t.} \quad s_l = \begin{cases} 0, & R_l(\boldsymbol{\rho}, \mathbf{p}) \geq R_l^{\min}, \\ 1, & \text{otherwise}, \end{cases} \quad \forall l \in \mathscr{L}, \tag{5}$$

$$R_k(\boldsymbol{\rho}, \mathbf{p}) \geq R_k^{\min}, \quad \forall k \in \mathscr{K}, \tag{6}$$

$$\sum_{n \in \mathscr{N}} p_l^n \leq (1 - s_l) P_{\max}, \quad \forall l \in \mathscr{L}, \tag{7}$$

$$\sum_{n \in \mathscr{N}} \rho_k^n p_k^n \leq P_{\max}, \quad \forall k \in \mathscr{K}, \tag{8}$$

$$\sum_{k \in \mathscr{K}} \rho_k^n \leq 1, \quad \forall n \in \mathscr{N}, \tag{9}$$

$$\rho_k^n \in \{0, 1\}, \quad \forall k \in \mathscr{K}, \forall n \in \mathscr{N}, \tag{10}$$

where $R_k^{\min}$ and $R_l^{\min}$ represent the minimum rate requirement of cellular user $k \in \mathscr{K}$ and D2D user $l \in \mathscr{L}$, respectively, $P_{\max}$ denotes the maximum power of each link, and $\rho_k^n \in \{0, 1\}$ and $\sum_{k \in \mathscr{K}} \rho_k^n \leq 1$ mean that each subcarrier can only be assigned to one cellular link. Problem P1 can give the set of admitted D2D links $\mathscr{L}^* = \{l \mid s_l^* = 0\}$.

The second problem is to minimize total power consumption of the admitted D2D links $\mathscr{L}^* = \{l \mid s_l^* = 0\}$, which can be expressed as P2:

$$\min_{\boldsymbol{\rho}, \mathbf{p}} \sum_{l \in \mathscr{L}^*} \sum_{n \in \mathscr{N}} p_l^n, \tag{11}$$

$$\text{s.t.} \quad R_l(\boldsymbol{\rho}, \mathbf{p}) \geq R_l^{\min}, \quad \forall l \in \mathscr{L}^*, \tag{12}$$

$$R_k(\boldsymbol{\rho}, \mathbf{p}) \geq R_k^{\min}, \quad \forall k \in \mathscr{K}, \tag{13}$$

$$(9)\text{–}(11), \tag{14}$$

$$\sum_{n \in \mathscr{N}} p_l^n \leq P_{\max}, \quad \forall l \in \mathscr{L}^*, \tag{15}$$

$$p_l^n = 0, \quad \forall l \notin \mathscr{L}^*, \forall n \in \mathscr{N}. \tag{16}$$

(12) and (15) ensure that each admitted D2D link meets the minimum transmission rate and maximum power requirement, respectively. (13) and (14) can ensure that each cellular link meets the minimum transmission rate and maximum power requirement, respectively.

3.2. One-Stage Problem. Both P1 and P2 are NP problems [22, 23], which makes us can no longer find their global optimum in polynomial time. We have to use a high quality approximation method to solve these two problems in polynomial time. Therefore, effective suboptimal approximation is carried out to convert this two-stage problem into a one-stage problem P3:

$$\min_{\boldsymbol{\rho},\mathbf{p},\mathbf{s}} \quad \alpha \sum_{l\in\mathscr{L}} s_l + \sum_{l\in\mathscr{L}}\sum_{n\in\mathscr{N}} p_l^n, \tag{17}$$

$$\text{s.t.} \quad R_l(\boldsymbol{\rho},\mathbf{p}) + \delta_l^{-1} s_l \geq R_l^{\min}, \quad \forall l \in \mathscr{L}, \tag{18}$$

$$\sum_{n\in\mathscr{N}} p_l^n \leq (1-s_l)P_{\max}, \quad \forall l \in \mathscr{L}, \tag{19}$$

$$R_k(\boldsymbol{\rho},\mathbf{p}) \geq R_k^{\min}, \quad \forall k \in \mathscr{K}, \tag{20}$$

$$\sum_{n\in\mathscr{N}} \rho_k^n p_k^n \leq P_{\max}, \quad \forall k \in \mathscr{K}, \tag{21}$$

$$\sum_{k\in\mathscr{K}} \rho_k^n \leq 1, \quad \forall n \in \mathscr{N}, \tag{22}$$

$$\rho_k^n \in \{0,1\}, \quad \forall k \in \mathscr{K}, \forall n \in \mathscr{N}, \tag{23}$$

$$s_l \in \{0,1\}, \quad \forall l \in \mathscr{L}. \tag{24}$$

Proposition 1. *By selecting appropriate α ($\alpha \geq LP_{\max}$) and $\delta_l^{-1} \geq R_l^{\min}$ ($\forall l \in \mathscr{L}$), P3 can not only maximize the number of admitted D2D links but also minimize the total power consumed by D2D links. The proof process is as follows.*

Proof. Suppose that $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is a feasible solution to problem P3, which satisfies constraint (18)–(24). The link vector $\mathbf{s}^*$ that can be scheduled belongs to the set $\mathscr{L}^* = \{l \mid s_l^* = 0\}$. For $l \notin \mathscr{L}^*$, $\forall n \in \mathscr{N}$, $p_l^{n*} = 0$; for $\rho_k^{n*} = 0$, $p_k^{n*} = 0$; for $\rho_k^{n*} = 1$, $p_k^{n*} > 0$. So $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is also a feasible solution to problem P1. Similarly, suppose that $(\boldsymbol{\rho}', \mathbf{p}', \mathbf{s}')$ is a feasible solution to problem P1, which satisfies constraint (5)–(10), and the link vector $\mathbf{s}'$ that can be scheduled belongs to the set $\mathscr{L}' = \{l \mid s_l' = 0\}$. For $l \notin \mathscr{L}'$, $\forall n \in \mathscr{N}$, $p_l^{n'} = 0$, the corresponding link rate $R_l(\boldsymbol{\rho}', \mathbf{p}') = 0$; for $\rho_k^{n'} = 0$, $p_k^{n'} = 0$; $\rho_k^{n'} = 1$, $p_k^{n'} > 0$. As long as it does satisfy $\delta_l^{-1} \geq R_l^{\min}$, $(\boldsymbol{\rho}', \mathbf{p}', \mathbf{s}')$ is also a feasible solution to problem P3. So, problem P1 and problem P3 have the same feasible set.

It is assumed that $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is the optimal solution of problem P3, but it cannot maximize the number of admitted D2D links. However, there is another solution $(\boldsymbol{\rho}', \mathbf{p}', \mathbf{s}')$ that makes $\sum_{l\in\mathscr{L}} s_l^* \geq \sum_{l\in\mathscr{L}} s_l' + 1$, so that the following inequality is obtained:

$$\begin{aligned}\alpha \sum_{l\in\mathscr{L}} s_l^* + \sum_{l\in\mathscr{L}}\sum_{n\in\mathscr{N}} p_l^{n*} &\geq \alpha \sum_{l\in\mathscr{L}} s_l^* \geq \alpha\left(\sum_{l\in\mathscr{L}} s_l' + 1\right) \geq \alpha \sum_{l\in\mathscr{L}} s_l' \\ &+ \mathrm{LP}_{\max} \geq \alpha \sum_{l\in\mathscr{L}} s_l' + \sum_{l\in\mathscr{L}}\sum_{n\in\mathscr{N}} p_l^{n'}.\end{aligned} \tag{25}$$

It can be seen from inequality (25) that the new feasible solution $(\boldsymbol{\rho}', \mathbf{p}', \mathbf{s}')$ can obtain smaller objective function value than the optimal solution, which is inconsistent with the fact that $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is the optimal solution of problem P3, so problem P3 can maximize the number of admitted D2D links. The next step is to prove that P3 can minimize the power consumption of D2D links. Suppose that there is a feasible solution $(\boldsymbol{\rho}', \mathbf{p}', \mathbf{s}')$ which can maximize the number of admitted D2D links and can get lower D2D power consumption than $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ so that the following inequality can be obtained:

$$\alpha \sum_{l\in\mathscr{L}} s_l' + \sum_{l\in\mathscr{L}}\sum_{n\in\mathscr{N}} p_l^{n'} \leq \alpha \sum_{l\in\mathscr{L}} s_l^* + \sum_{l\in\mathscr{L}}\sum_{n\in\mathscr{N}} p_l^{n*}. \tag{26}$$

Inequality (26) is inconsistent with the fact $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is the optimal solution of P3, so P3 can maximize the number of admitted D2D links and minimize the power consumed by D2D links. Proposition 1 is proved completely.

In order to force cellular links to use orthogonal spectrum, the interference effects of other cellular links are considered, which is implemented by an introduced very large channel gain h_v between cellular links [24] so that the signal to interference plus noise ratio of cellular link k on subcarrier n is reformulated as

$$\overline{\gamma_k^n}(\mathbf{p}) = \frac{p_k^n \left|h_{kk}^n\right|^2}{\sigma_k^n + \sum_{k'\in\mathscr{K}\setminus k} p_{k'}^n h_v + \sum_{l\in\mathscr{L}} p_l^n \left|h_{kl}^n\right|^2}, \tag{27}$$

where $\sum_{k'\in\mathscr{K}\setminus k} p_{k'}^n h_v$ represents interference from other cellular links on subcarrier n. Similarly, the signal to interference plus noise ratio of D2D link l on subcarrier n is

$$\overline{\gamma_l^n}(\mathbf{p}) = \frac{p_l^n \left|h_{ll}^n\right|^2}{\sigma_l^n + \sum_{l'\in\mathscr{L}\setminus l} p_{l'}^n \left|h_{ll'}^n\right|^2 + \sum_{k\in\mathscr{K}} p_k^n \left|h_{lk}^n\right|^2}. \tag{28}$$

The spectral efficiency of cellular link $k \in \mathscr{K}$ and D2D link $l \in \mathscr{L}$ is expressed, respectively, as

$$\begin{aligned}\overline{R}_k(\mathbf{p}) &= \sum_{n\in\mathscr{N}} \log_2\left(1 + \overline{\gamma_k^n}(\mathbf{p})\right), \\ \overline{R}_l(\mathbf{p}) &= \sum_{n\in\mathscr{N}} \log_2\left(1 + \overline{\gamma_l^n}(\mathbf{p})\right).\end{aligned} \tag{29}$$

So, problem P3 can be converted into P4:

$$\min_{\mathbf{p},\mathbf{s}} \quad \alpha \sum_{l\in\mathscr{L}} s_l + \sum_{l\in\mathscr{L}}\sum_{n\in\mathscr{N}} p_l^n, \tag{30}$$

$$\text{s.t.} \quad \overline{R}_l(\mathbf{p}) + \delta_l^{-1} s_l \geq R_l^{\min}, \quad \forall l \in \mathscr{L}, \tag{31}$$

$$\sum_{n\in\mathscr{N}} p_l^n \leq (1-s_l)P_{\max}, \quad \forall l \in \mathscr{L}, \tag{32}$$

$$\overline{R}_k(\mathbf{p}) \geq R_k^{\min}, \quad \forall k \in \mathscr{K}, \tag{33}$$

$$\sum_{n\in\mathscr{N}} p_k^n \leq P_{\max}, \quad \forall k \in \mathscr{K}, \tag{34}$$

$$s_l \in \{0,1\}, \quad \forall l \in \mathscr{L}. \tag{35}$$

Suppose that $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is the optimal solution of P3, $(\mathbf{p}^*, \mathbf{s}^*)$ is a feasible solution of problem P4. If $(\mathbf{p}^*, \mathbf{s}^*)$ is an optimal solution of P4, the subcarrier allocation satisfies

$$\rho_k^{n*} = \begin{cases} 1, & p_k^{n*} > 0, \\ 0, & \text{otherwise}. \end{cases} \tag{36}$$

Each subcarrier is allocated to one cellular link at most, so $(\boldsymbol{\rho}^*, \mathbf{p}^*, \mathbf{s}^*)$ is an optimal solution of P3. Therefore, the optimal solution of problem P4 is also the optimal solution of problem P3. □

4. Problem Solution

4.1. Joint Access Control and Power Allocation Based on Monotone Optimization. $s_l \in \{0,1\}$ makes the solution of problem P4 very difficult. In order to solve this problem, a continuous function $q(s_l)$: $[0,1] \longrightarrow [0,1]$ is used to approximate binary discrete variable s_l as shown in the following equation:

$$q(s_l) = \frac{\log(1 + (s_l/Q))}{\log(1 + (1/Q))}, \tag{37}$$

where Q is a small enough constant larger than 0, and this approximate function satisfies monotone increasing property, for $s_l = 0$, $q(s_l) = 0$; for $s_l = 1$, $q(s_l) = 1$. Problem P4 is converted into problem M1:

$$\min_{\mathbf{p},\mathbf{s}} \quad \alpha \sum_{l\in\mathscr{L}} q(s_l) + \sum_{l\in\mathscr{L}} \sum_{n\in\mathscr{N}} p_l^n, \tag{38}$$

$$\text{s.t.} \quad (31), (32), (33), (34), \tag{39}$$

$$s_l \in [0,1], \quad \forall l \in \mathscr{L}. \tag{40}$$

Problem M1 is a nonconvex optimization problem, and the solving process is very complicated, but it has implied monotonicity. After appropriate transformation, this problem is transformed into a monotone optimization problem, which can be solved by reverse polyblock approximation method [25]. The regular monotone optimization has the following form:

$$\max\{f(\mathbf{x}) \mid \mathbf{x} \in G \cap H\}, \tag{41}$$

where $f(\mathbf{x})$: $R_+^n \longrightarrow R$ is a monotone increasing function, $G \subset [0,\mathbf{b}] \subset R_+^n$ is a nonempty normal set, and H is the inverse normal set belonging to $[0,\mathbf{b}]$.

If $g(\mathbf{x})$: $R_+^n \longrightarrow R$ and $h(\mathbf{x})$: $R_+^n \longrightarrow R$ are both increasing functions, G and H satisfying (42) are normal set and inverse normal set, respectively.

$$\begin{aligned} G &= \{\mathbf{x} \in R_+^n \mid g(\mathbf{x}) \leq 0\}, \\ H &= \{\mathbf{x} \in R_+^n \mid h(\mathbf{x}) \geq 0\}. \end{aligned} \tag{42}$$

The objective function (38) is an increasing function. In order to transform M1 into a monotone optimization problem, all constraints in M1 need to be converted into the form of (42). $\overline{R}_l(\mathbf{p})$ and $\overline{R}_k(\mathbf{p})$ are nonincreasing functions of $\mathbf{p}$. So, a new vector $\mathbf{z}= [z_m^n]_{\forall m\in\mathscr{M},\forall n\in\mathscr{N}}$ is defined. The variable $z_m^n = \overline{\gamma_m^n}(\mathbf{p})$ represents the signal to interference plus noise ratio of the link $m \in \mathscr{M}$ on the channel $n \in \mathscr{N}$. $\mathscr{P} = \{\mathbf{p} \mid \sum_{n\in\mathscr{N}} p_m^n \leq P_{\max}, m \in \mathscr{M}\}$ represents the maximum power constraint of the link $m \in \mathscr{M}$, and $\mathbf{x} = (\mathbf{z}, \mathbf{s})$ represents the optimization vector with dimension of $D = L + (K + L)N$. M1 is converted into the following form:

$$\min_{\mathbf{x}} \quad f(\mathbf{x}) = \alpha \sum_{l\in\mathscr{L}} q(s_l) + \sum_{l\in\mathscr{L}} \sum_{n\in\mathscr{N}} p_l^n, \tag{43}$$

$$\text{s.t.} \quad s_l \geq 0, \quad \forall l \in \mathscr{L}, \tag{44}$$

$$\sum_{n\in\mathscr{N}} \log_2(1 + z_l^n) + \delta_l^{-1} s_l - R_l^{\min} \geq 0, \quad \forall l \in \mathscr{L}, \tag{45}$$

$$\sum_{n\in\mathscr{N}} \log_2(1 + z_k^n) - R_k^{\min} \geq 0, \quad \forall k \in \mathscr{K}, \tag{46}$$

$$z_m^n \geq 0, \quad \forall m \in \mathscr{M}, \forall n \in \mathscr{N}, \tag{47}$$

$$z_m^n \leq \overline{\gamma_m^n}(p), \quad \forall m \in, \mathscr{M} \forall n \in, \mathscr{N} \forall \mathbf{p} \in \mathscr{P}, \tag{48}$$

$$\sum_{n\in\mathscr{N}} p_l^n - P_{\max} + s_l P_{\max} \leq 0, \quad \forall l \in \mathscr{L}, \tag{49}$$

$$s_l \leq 1, \quad \forall l \in \mathscr{L}. \tag{50}$$

This problem needs to minimize a monotone increasing function, G denotes the normal set which satisfies the constraints (48)–(50), and H denotes the reverse normal set which satisfies the constraints (44)–(47). The optimal solution of problem of M1 is located on the boundary of $\mathscr{X} = G \cap H$, so we can take advantage of the reverse polyblock approximation method to solve problem M1 as shown in Algorithm 1, where $\mathbf{e}^d$ is a vector the elements of which are all zeros except that the d-th element is one and $\odot$ represents the Hadamard product.

After Algorithm 1 is completed, binary access control vector $\overline{\mathbf{s}}$ is obtained by carrying out rounding operation according to

$$\overline{s_l} = \begin{cases} 0, & s_l^* \leq \varepsilon, \\ 1, & \text{otherwise}. \end{cases} \tag{51}$$

According to obtained $\mathbf{z}^*$, we can work out $(p_m^n)^*$ using

$$(z_m^n)^* = \frac{(p_l^n)^* |h_{ll}^n|^2}{\sigma_l^n + \sum_{l'\in\mathscr{L}\setminus l} (p_{l'}^n)^* |h_{ll'}^n|^2 + \sum_{k\in\mathscr{K}} (p_k^n)^* |h_{lk}^n|^2}. \tag{52}$$

Initialization: The number of iterations is $i = 1$. Vertex set is $\mathscr{V}^{(1)} = \{\mathbf{x}^{(1)}\}$ with $\mathbf{x}^{(1)} = (\mathbf{z}^{(1)}, \mathbf{s}^{(1)}) = \{0\}$. Set $\mathrm{CBV}_0 = +\infty$.
Repeat
Step 1. Calculate $\mathbf{x}^{(i)} = \arg\min_{\mathbf{x}\in\mathscr{V}^{(i)}} f(\mathbf{x})$.
Update the lower boundary $f_{\mathrm{low}} = f(\mathbf{x}^{(i)})$.
Step 2. Work out $\rho_H(\mathbf{x}^{(i)})$ according to Algorithm 2. If $f(\rho_H(\mathbf{x}^{(i)})) \le \mathrm{CBV}_{i-1}$ and $\rho_H(\mathbf{x}^{(i)})$ satisfies (48)–(50) judged by execution of Algorithm M1-1, update the current optimal value $\mathrm{CBV}_i = f(\rho_H(\mathbf{x}^{(i)}))$ and the optimal solution $\mathbf{x}^{(i)*} = \rho_H(\mathbf{x}^{(i)})$; otherwise, $\mathbf{x}^{(i)*} = \mathbf{x}^{(i-1)*}$, $\mathrm{CBV}_i = \mathrm{CBV}_{i-1}$.
Step 3. Calculate the auxiliary vertex set $\overline{\mathscr{V}_i} = \{\overline{\mathbf{x}_1^{(i)}}, \ldots, \overline{\mathbf{x}_D^{(i)}}\}$, $\overline{\mathbf{x}_d^{(i)}} = \mathbf{x}^{(i)} + (\rho_H(\mathbf{x}^{(i)}) - \mathbf{x}^{(i)}) \odot \mathbf{e}^d, \forall d \in \{1, \ldots, D\}$. Update the vertex set for the next iteration $\mathscr{V}^{(i+1)} = (\mathscr{V}^{(i)} - \{\mathbf{x}^{(i)}\}) \cup \overline{\mathscr{V}_i}$ and increase the number of iterations $i = i + 1$.
Until $\mathrm{CBV}_i - f_{\mathrm{low}} < \delta$.
Output $\mathbf{x}^* = (\mathbf{z}^*, \mathbf{s}^*)$.

Algorithm 1: Joint access control and power allocation based on monotone optimization.

Input: $\mathbf{x}^{(i)}$, H
Output: $\lambda = \arg\max\{\lambda > 0 \mid \mathbf{b} + \lambda(\mathbf{x}^{(i)} - \mathbf{b}) \in H\}$
Step 1. Initialize $\lambda_{\min} = 0$, $\lambda_{\max} = 1$, and $\delta > 0$ represents a small positive number.
Step 2. Repeat the following steps
$\overline{\lambda} = (\lambda_{\min} + \lambda_{\max})/2$
Judge whether $\overline{\lambda}$ is feasible, which is equivalent to judge whether $\mathbf{b} + \overline{\lambda}(\mathbf{x}^{(i)} - \mathbf{b}) \in H$ is true. If it is true, $\lambda_{\min} = \overline{\lambda}$; otherwise, $\lambda_{\max} = \overline{\lambda}$.
Until $\lambda_{\max} - \lambda_{\min} \le \delta$.
Step 3. Output $\lambda = \lambda_{\min}$, $\rho_H(\mathbf{x}^{(i)}) = \mathbf{b} + \lambda(\mathbf{x}^{(i)} - \mathbf{b})$.

Algorithm 2: Calculation process of $\rho_H(\mathbf{x}^{(i)})$.

In order to judge whether $\mathbf{b} + \overline{\lambda}(\mathbf{x}^{(i)} - \mathbf{b}) \in H$ is true in Algorithm 2, it needs to judge whether $\mathbf{b} + \overline{\lambda}(\mathbf{x}^{(i)} - \mathbf{b})$ meets the constraints

$$\begin{aligned}
&\sum_{n\in\mathscr{N}} \log_2\left(1 + \frac{P_{\max}|h_{ll}^n|^2}{\sigma_l^n} + \overline{\lambda}\left((z_l^n)^{(i)} - \frac{P_{\max}|h_{ll}^n|^2}{\sigma_l^n}\right)\right) \\
&\quad + \delta_l^{-1}\left(1 + \overline{\lambda}\left((s_l)^{(i)} - 1\right)\right) - R_l^{\min} \ge 0, \quad \forall l \in \mathscr{L}, \\
&\sum_{n\in\mathscr{N}} \log_2\left(1 + \frac{P_{\max}|h_{kk}^n|^2}{\sigma_k^n} + \overline{\lambda}\left((z_k^n)^{(i)} - \frac{P_{\max}|h_{kk}^n|^2}{\sigma_k^n}\right)\right) \\
&\quad - R_k^{\min} \ge 0, \quad \forall k \in \mathscr{K},
\end{aligned} \tag{53}$$

where $(z_l^n)^{(i)}$ and $(s_l)^{(i)}$, respectively, represent the values of z_l^n and s_l in the i-th iteration. In order to determine whether $\rho_H(\mathbf{x}^{(i)})$ meets constraints (48)–(50), the solution of problem M1-1 is as follows:

$$\min_{\mathbf{p}\in\mathscr{P}} \quad 0, \tag{54}$$

$$\text{s.t.} \quad \frac{P_{\max}|h_{kk}^n|^2}{\sigma_k^n} + \lambda\left((z_k^n)^{(i)} - \frac{P_{\max}|h_{kk}^n|^2}{\sigma_k^n}\right) \le \overline{\gamma_m^n}(\mathbf{p}), \quad \forall m \in \mathscr{M}, \forall n \in \mathscr{N}, \tag{55}$$

$$\sum_{n\in\mathscr{N}} p_l^n - P_{\max} + \left(1 + \lambda\left((s_l)^{(i)} - 1\right)\right)P_{\max} \le 0, \quad \forall l \in \mathscr{L}, \tag{56}$$

$$1 + \lambda\left((s_l)^{(i)} - 1\right) \le 1, \quad \forall l \in \mathscr{L}. \tag{57}$$

If the constraints of problem M1-1 are feasible, it returns the value 0. Otherwise, it returns $+\infty$, where the numerator and denominator of $\overline{\gamma_m^n}(\mathbf{p})$ are linear functions of $\mathbf{p}$, $\overline{\gamma_m^n}(\mathbf{p}) = \Gamma_{nm}^{\mathrm{num}}(\mathbf{p})/\Gamma_{nm}^{\mathrm{den}}(\mathbf{p})$, $\forall m \in \mathscr{M}$:

$$\begin{aligned}
&\Gamma_{nm}^{\mathrm{num}}(\mathbf{p}) = p_m^n|h_{mm}^n|^2, \quad \forall m \in \mathscr{M}, \forall n \in \mathscr{N}, \\
&\Gamma_{nk}^{\mathrm{den}}(\mathbf{p}) = \sigma_k^n + \sum_{k'\in\mathscr{K}\setminus k} p_{k'}^n h_v + \sum_{l\in\mathscr{L}} p_l^n|h_{kl}^n|^2, \quad \forall k \in \mathscr{K}, \\
&\Gamma_{nl}^{\mathrm{den}}(\mathbf{p}) = \sigma_l^n + \sum_{l'\in\mathscr{L}\setminus l} p_{l'}^n|h_{ll'}^n|^2 + \sum_{k\in\mathscr{K}} p_k^n|h_{lk}^n|^2, \quad \forall l \in \mathscr{L}.
\end{aligned} \tag{58}$$

So, (55) can be converted into

$$\left(\frac{P_{\max}|h_{kk}^n|^2}{\sigma_k^n} + \lambda\left((z_k^n)^{(i)} - \frac{P_{\max}|h_{kk}^n|^2}{\sigma_k^n}\right)\right)\Gamma_{nm}^{\mathrm{den}}(\mathbf{p}) \le \Gamma_{nm}^{\mathrm{num}}(\mathbf{p}). \tag{59}$$

For a given λ, M1-1 is transformed into the following linear programming problem:

$$\begin{aligned} \min_{\mathbf{p}\in\mathscr{P}} \quad & 0, \\ \text{s.t.} \quad & (59), \forall m \in, \mathscr{M} \forall n \in \mathscr{N} \\ & (56), (57). \end{aligned} \tag{60}$$

The above linear programming problem can be solved by the simplex method or interior point method.

Proposition 2. *In problem M1, s_l^* could be a fractional number, which is clearly not the optimal solution to problem P4. Then, Algorithm 1 can maximize the number of admitted D2D links by choosing appropriate ε satisfying $(\sqrt[L-1/L]{1+1/Q}-1)Q<\varepsilon<1$. The proof process is as follows.*

Suppose that $(\mathbf{z}^*, \mathbf{s}^*)$ is the optimal solution of problem M1 and $\mathbf{p}^*$ is the corresponding optimal power vector; if s_l^* is an integer, the proposition is proved. If s_l^* is a fractional number, suppose that $\mathbf{s}^0$ and $\mathbf{p}^0$ are the optimal access control vector and power allocation vector of problem P4, respectively. $\mathbf{s}^* \neq \mathbf{s}^0$, $\mathbf{z}^0 = [(z_m^n)^0]_{\forall m\in\mathscr{M}}$, $\forall n \in \mathscr{N}$, $(z_m^n)^0 = \overline{\gamma_m^n}(\mathbf{p}^0)$. $(\mathbf{z}^0, \mathbf{s}^0)$ is a feasible solution of the problem M1, and we can obtain

$$\alpha \sum_{l\in\mathscr{L}} q(s_l^*) + \sum_{l\in\mathscr{L}} \sum_{n\in\mathscr{N}} (p_l^n)^* < \alpha \sum_{l\in\mathscr{L}} q(s_l^0) + \sum_{l\in\mathscr{L}} \sum_{n\in\mathscr{N}} (p_l^n)^0, \tag{61}$$

where $\alpha \geq \mathrm{LP}_{\max}$, $(p_l^n)^*$ and $(p_l^n)^0$ are bounded variables, and we can obtain

$$\sum_{l\in\mathscr{L}} q(s_l^*) \leq \sum_{l\in\mathscr{L}} q(s_l^0), \tag{62}$$

where $\bar{\mathbf{s}} = [\overline{s_l}]_{\forall l\in\mathscr{L}}$ represents the binary access control solution after rounding according to (62). The admitted D2D link should meet the following equation:

$$\overline{s_l} = \begin{cases} 0, & s_l^* \leq \varepsilon, \\ 1, & \text{otherwise}. \end{cases} \tag{63}$$

Then, inequality (63) is established:

$$\sum_{l\in\mathscr{L}} q(s_l^*) \geq \sum_{l\in\mathscr{L}} q(\overline{s_l}) + L\frac{\log(1+(\varepsilon/Q))}{\log(1+(1/Q))} - L. \tag{64}$$

Since $(\sqrt[L-1/L]{1+1/Q}-1)Q<\varepsilon<1$, $-1<L((\log(1+(\varepsilon/Q)))/(\log(1+1/Q)))-L<0$ holds, and we can obtain

$$\sum_{l\in\mathscr{L}} q(\overline{s_l}) \leq \sum_{l\in\mathscr{L}} q(s_l^0). \tag{65}$$

Therefore, Algorithm 1 can maximize the number of admitted D2D links.

I represents the total number of iterations in Algorithm 1. The computational complexity of calculating the lower boundary of step 1 in each iteration is $O(D)$, where D represents the dimension of optimization vector. The computational complexity of step 2 is $O(M^{3.5}N^{3.5})$, which adopts interior point method to calculate linear programming. The computational complexity of Algorithm 1 is $O(I(D+M^{3.5}N^{3.5}))$ in polynomial time.

4.2. Access Control and Resource Allocation Algorithm Based on Iterative Convex Optimization. As discussed in the last paragraph of the previous section, the algorithm based on monotone optimization can achieve the asymptotically optimal solution, but the computational complexity is high. So, we propose an iterative convex optimization approximation algorithm with low complexity. s_l in problem P4 is relaxed, the value of which belongs to $[0, 1]$. In the constraint condition, $\overline{R}_m(\mathbf{p})$, $m \in \mathscr{K} \cup \mathscr{L}$ is a nonconvex function, which can be expressed as $\overline{R}_m(\mathbf{p}) = f_m(\mathbf{p}) - g_m(\mathbf{p})$.

For $m \in \mathscr{K}$,

$$\begin{aligned} f_m(\mathbf{p}) &= \sum_{n\in N} \log_2\left(\sigma_m^n + p_m^n|h_{mm}^n|^2 + \sum_{k'\in K\backslash mm} p_{k'}^n h_v + \sum_{l\in L} p_l^n|h_{ml}^n|^2\right), \\ g_m(\mathbf{p}) &= \sum_{n\in N} \log_2\left(\sigma_m^n + \sum_{k'\in K\backslash mm} p_{k'}^n h_v + \sum_{l\in L} p_l^n|h_{ml}^n|^2\right). \end{aligned} \tag{66}$$

For $m \in \mathscr{L}$,

$$\begin{aligned} f_m(\mathbf{p}) &= \sum_{n\in\mathscr{N}} \log_2\left(\sigma_m^n + \sum_{l'\in\mathscr{L}} p_{l'}^n|h_{ll'}^n|^2 + \sum_{k\in\mathscr{K}} p_k^n|h_{mk}^n|^2\right), \\ g_m(\mathbf{p}) &= \sum_{n\in\mathscr{N}} \log_2\left(\sigma_m^n + \sum_{l'\in\mathscr{L}\backslash m} p_{l'}^n|h_{ll'}^n|^2 + \sum_{k\in\mathscr{K}} p_k^n|h_{mk}^n|^2\right), \end{aligned} \tag{67}$$

where $f_m(\mathbf{p})$ and $g_m(\mathbf{p})$ are concave functions, $\overline{R}_m(\mathbf{p})$ has the difference form of concave functions [26], and $g_m(\mathbf{p})$ satisfies the inequality

$$g_m(\mathbf{p}) \leq g_m(\mathbf{p}^{(k)}) + \nabla g_m^T(\mathbf{p}^{(k)})(\mathbf{p} - \mathbf{p}^{(k)}). \tag{68}$$

The dimension of the vector $\nabla g_m^T(\mathbf{p})$ is $(K+L)N$, and $\nabla g_m^T(\mathbf{p}^{(k)})$ represents the gradient vector of function $g_m(\mathbf{p})$ at $\mathbf{p} = \mathbf{p}^{(k)}$. According to this approximation, the lower boundary of the rate for link m is $R_m(\mathbf{p}) \leq \overline{R}_m(\mathbf{p})$:

$$R_m(\mathbf{p}) = f_m(\mathbf{p}) - g_m(\mathbf{p}^{(k)}) - \nabla g_m^T(\mathbf{p}^{(k)})(\mathbf{p} - \mathbf{p}^{(k)}), \quad \forall m \in \mathscr{K} \cup \mathscr{L}. \tag{69}$$

According to the given power $\mathbf{p}^k$, problem P4 is converted into the following problem CP4:

$$\begin{aligned} \min_{\mathbf{p},\mathbf{s}} \quad & \alpha \sum_{l\in\mathscr{L}_i} s_l + \sum_{l\in\mathscr{L}_i} \sum_{n\in\mathscr{N}} p_l^n \\ \text{s.t.} \quad & R_l(\mathbf{p}) + \delta_l^{-1} s_l \geq R_l^{\min}, \quad \forall l \in \mathscr{L}_i, \\ & \sum_{n\in\mathscr{N}} p_l^n \leq (1-s_l)P_{\max}, \quad \forall l \in \mathscr{L}_i, \\ & R_k(\mathbf{p}) \geq R_k^{\min}, \quad \forall k \in \mathscr{K}, \\ & \sum_{n\in\mathscr{N}} p_k^n \leq P_{\max}, \quad \forall k \in \mathscr{K}, \\ & s_l \in [0,1], \quad \forall l \in \mathscr{L}_i. \end{aligned} \tag{70}$$

It is easy to verify that it is a convex optimization problem, which can be solved by standard convex optimization

Step 1. Given link $\mathscr{L}_1 = \mathscr{L}$, initial power $\mathbf{p}^{(0)} = 0$ and iteration times $i = 0$.
Step 2. Repeat
  $i = i + 1$, $k = 0$.
  repeat
  $k = k + 1$
  solve problem CP4 to obtain $\mathbf{p}^{(k)}$.
  update $\nabla g_m^T(\mathbf{p}^{(k)})$
  until convergence
 calculate $\overline{R}_l(\mathbf{p})$ according to obtained $\mathbf{p}^{(k)}$.
 calculate $l = \arg\min_{l \in \mathscr{L}_i} \overline{R}_l(\mathbf{p})/R_l^{\min}$, if $\overline{R}_l(\mathbf{p})/R_l^{\min} < 1$, $\mathscr{L}_i = \mathscr{L}_i \backslash l$.
 Until $\overline{R}_l(\mathbf{p}) \geq R_l^{\min}$, $\forall l \in \mathscr{L}_i$.
Output $\mathscr{L}_i$, $\mathbf{p}^* = \mathbf{p}^{(k)}$.

Algorithm 3: P4.

techniques, such as the interior point method. The solving process of problem P4 is described in Algorithm 3.

The complexity of iterative computation in this algorithm is $O(L)$, the complexity of solving convex optimization by using interior point method is $O(N^3M^{3.5})$, and the total computational complexity of solving problem P4 is $O(LN^3M^{3.5})$ in polynomial time.

5. Numerical Simulation

In order to test the performance of proposed algorithms, we perform numerical simulation based on MATLAB platform. In the wireless cellular network that supports D2D communication, the coverage radius of the base station is 500 m, the number of cellular links is $K = 4$, the number of D2D links is $L = 26$, and the number of subcarriers is $N = 5$. The maximum transmission power of the user is 23 dBm, the distance between D2D transmitting endpoint and receiving endpoint is randomly distributed between 10m and 50m, and the cellular users are evenly distributed in the cell. The numerical simulation parameters are shown in Table 1. The minimum rate requirement of each cellular link is $R_k^{\min} = 2$ bps/Hz, and the minimum rate requirement of each D2D link is $R_l^{\min} = 5$ bps/Hz. All numerical results are obtained by averaging 1000 randomly implemented channel gains. In the numerical simulation process, reverse polyblock approximation algorithm is used to solve monotone optimization problem, low complexity algorithm represents the iterative convex optimization algorithm with low complexity, and maximizing energy efficiency algorithm represents the method which can maximize energy efficiency [27]. The energy efficiency is defined as the ratio of total sum rate to overall consumed power of all D2D links [27]. The comparison of access ratio of different algorithms is shown in Figure 2. The reverse polyblock approximation algorithm has the highest access ratio, the access ratio of the iterative convex optimization algorithm with low complexity decreases about 5% on average compared with reverse polyblock approximation algorithm, and the maximizing energy efficiency algorithm has the lowest access ratio and is reduced by about 26% on average compared with reverse polyblock approximation algorithm.

The total power consumption comparison of different algorithms is shown in Figure 3. The power consumption of maximizing energy efficiency algorithm is greater than iterative convex optimization algorithm and reverse polyblock approximation algorithm. Iterative convex optimization algorithm consumes about 10% more power on average than reverse polyblock approximation algorithm. The power consumption of the maximizing energy efficiency algorithm is increased by about 30 times as much as that of reverse polyblock approximation algorithm. Figure 4 presents the objective function value of different algorithms. It can be seen from this figure that reverse polyblock approximation algorithm has the smallest objective function value, followed by the iterative convex optimization algorithm, and the maximum energy efficiency algorithm has the largest objective function value.

The relationship between objective function value and D2D bit rate requirement is shown in Table 2. As the bit rate requirement of D2D links increases, the objective function value of reverse polyblock approximation algorithm increases from 15.1827 to 34.2001, the objective function value of iterative convex optimization algorithm increases from 22.9407 to 38.8148, and the objective function value of maximizing energy efficiency algorithm increases from 134.9136 to 192.5249. The average objective function value of maximizing energy efficiency algorithm is about 5 times that of iterative convex optimization algorithm on average. The objective function value of reverse polyblock approximation algorithm is reduced by about 20% on average compared with iterative convex optimization algorithm.

In order to test the access ratio and power consumption of D2D links under different number of cellular users, we perform another experiment. The number of cellular links is varied from 4 to 10, and the number of subcarriers is 10. The access ratio and power consumption under different number of cellular users are shown in Figures 5 and 6, respectively. As the number of cellular links increases, the access ratio of D2D links decreases and

Table 1: Numerical simulation parameters.

Parameter	Value
Cell coverage	500 m
Subcarrier bandwidth	15 kHz
Noise power	−174 dBm/Hz
Path loss index	3
Path loss constant	0.01
Maximum transmission power of cellular user	23 dBm
Maximum transmission power of D2D user	23 dBm
Distance between D2D transmitting endpoint to receiving endpoint	10 m–50 m
Channel fast fading	Exponential distribution with mean value of 1
Shadow fading	Lognormal distribution with standard deviation of 8 dB

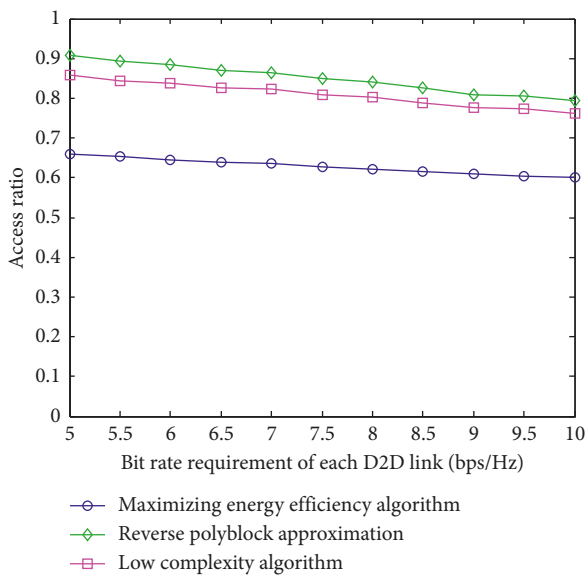

Figure 2: Comparison of access ratio of different algorithms.

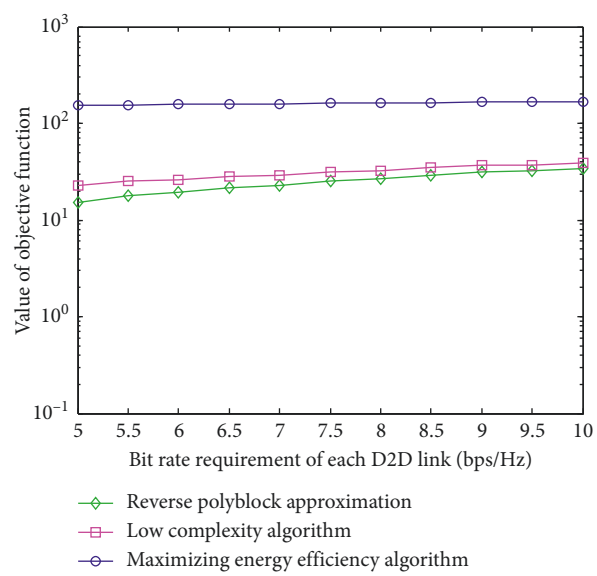

Figure 4: Objective function value of different algorithms.

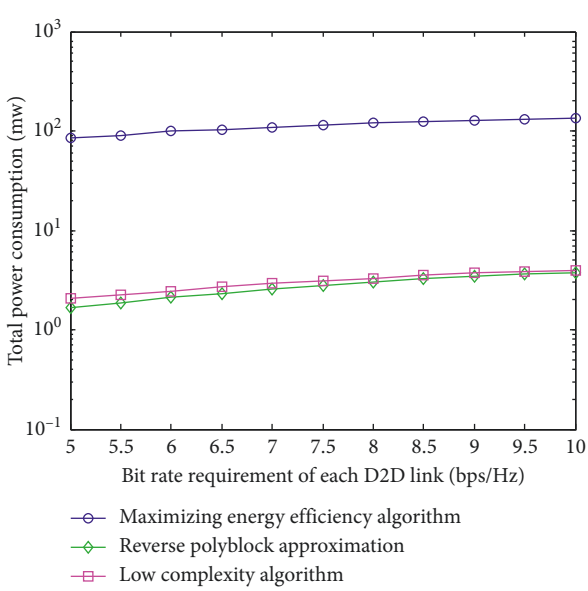

Figure 3: Comparison of total power consumption of different algorithms.

Table 2: The relationship between objective function value and bit rate requirement.

Bit rate requirement of D2D link (bps/Hz)	Maximizing energy efficiency algorithm	Low complexity algorithm	Reverse polyblock approximation algorithm
5	134.9136	22.9407	15.1827
5.5	141.6358	25.1183	17.6746
6	150.9760	26.2547	19.1253
6.5	157.0504	28.4875	21.6724
7	162.4909	29.0522	22.5515
7.5	168.8731	31.2595	25.0731
8	174.8789	32.3256	26.4536
8.5	179.6258	34.6119	29.0542
9	184.9805	36.7865	31.5431
9.5	189.7533	37.2876	32.3584
10	192.5249	38.8148	34.2001

total power consumption increases. In this case, the interference from the cellular link increases, resulting in a decrease in the access ratio of the D2D link. In order to

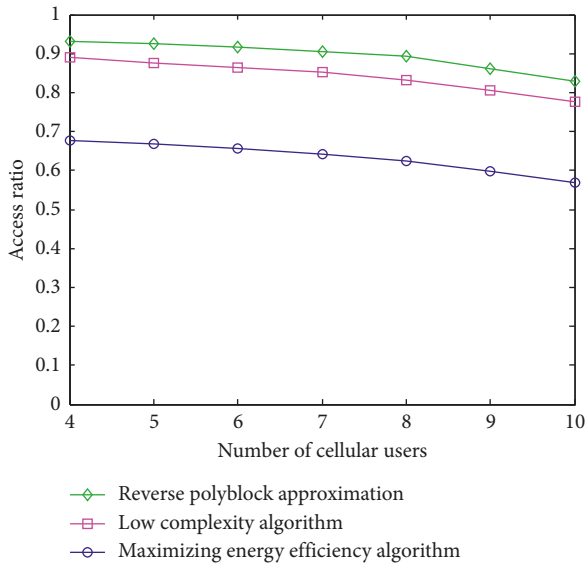

Figure 5: Access ratio versus the number of cellular users.

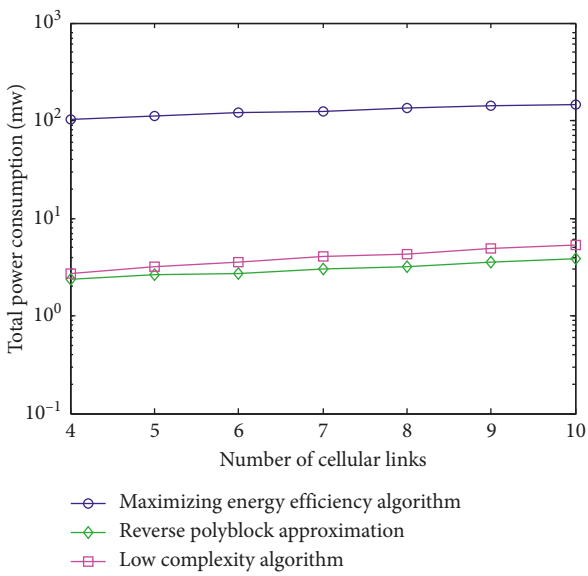

Figure 6: Total power consumption versus the number of cellular users.

meet transmission rate requirements of D2D links, more energy is required. It can be observed that reverse polyblock approximation algorithm and iterative convex optimization algorithm are superior to maximizing energy efficiency algorithm. The objective function value versus the number of cellular users is shown in Figure 7. Table 3 presents the numerical results, implying the relationship between objective function value and the number of cellular users. It is also validated that reverse polyblock approximation algorithm has the best performance, iterative convex optimization algorithm takes the second place, and maximizing energy efficiency algorithm has the worst performance.

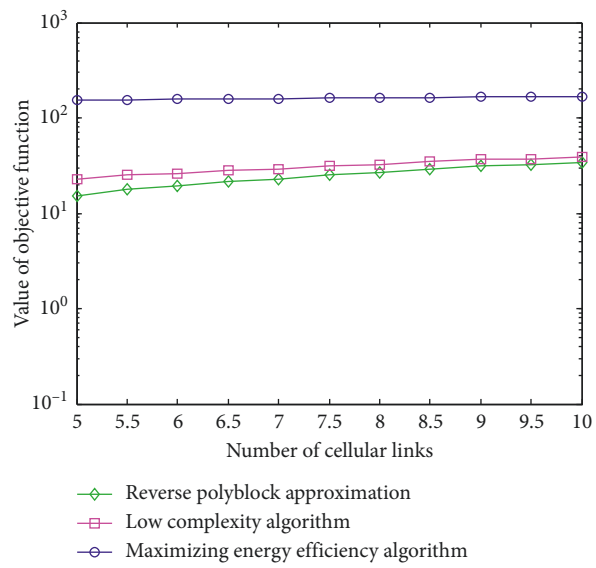

Figure 7: Objective function value versus the number of cellular users.

Table 3: The relationship between objective function value and the number of cellular users.

The number of cellular users	Maximizing energy efficiency algorithm	Low complexity algorithm	Reverse polyblock approximation algorithm
4	163.2548	26.1520	19.6916
5	173.0267	28.9304	20.8520
6	184.6074	30.9124	22.5116
7	189.6626	33.0678	24.4384
8	202.8289	36.3616	26.1478
9	213.8672	40.6358	31.4696
10	221.5871	45.4877	36.2362

6. Conclusions

In this paper, the problem of D2D link access control, subcarrier allocation, and power allocation in the uplink of single-cell D2D underlay cellular network is studied. The purpose is to maximize the number of admitted D2D links and reduce the power consumption of D2D links in the system while ensuring the minimum data transmission rate of cellular links and D2D links. It is difficult to solve the problem effectively, so it is transformed into monotone optimization problem. Then, reverse polyblock approximation algorithm is used to solve this monotone optimization problem. Because the monotone optimization problem has relatively high complexity, this paper proposes an algorithm based on iterative convex optimization with low complexity. The numerical results show that reverse polyblock approximation algorithm has the best performance, the low complexity algorithm based on iterative convex optimization has the suboptimal performance, and the algorithm based on energy efficiency maximization has the lowest access rate and the highest energy consumption.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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