IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 24 April 2024, accepted 27 May 2024, date of publication 30 May 2024, date of current version 10 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3407345

RESEARCH ARTICLE

D2D Spectrum Efficiency Optimization Algorithm for Many-to-One Reusing Scenarios

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This work was supported in part by Zhengzhou University of Light Industry Doctoral Research Fund Project under Grant 2021BSJJ026 and Grant 2020BSJJ068, and in part by the Science and Technology Research Projects of Henan Province under Grant 242102210112.

ABSTRACT In order to solve the spectrum efficiency optimization problem of device-to-device (D2D) communication in many-to-one reusing mode, the channel allocation and power control problem in the frequency-selective channel environment is investigated. A resource allocation algorithm based on hierarchical optimization is proposed. The highly coupled resource allocation problem is decoupled by introducing the layering idea. Firstly, in the outer layer, a power control algorithm based on discrete power selection and two fast channel allocation algorithms based on priority setting are proposed. By using discrete power control for cellular users, the problem of multiple local optimal solutions is solved, which makes the power control algorithm of the whole system converge. Meanwhile, the proposed channel allocation algorithm reduces the complexity by setting priorities for D2D users, and at the same time realizes the suppression of cross-layer interference. In the inner layer, a resource allocation algorithm based on a non-cooperative game is proposed. By modeling D2D users share the same channel as a non-cooperative game model and introducing the cost function in term of same-layer interference, it achieves the suppression of same-layer interference while improving the spectrum efficiency. And the Nash equilibrium solution of the game is obtained by solving the KKT condition. Simulation experiments show that the proposed algorithm not only improves the spectrum efficiency of the system compared with the existing algorithms, but also proves the superiority of the algorithm in ultra-dense D2D communication scenarios.

INDEX TERMS Spectrum efficiency, ultra-dense D2D, many-to-one, discrete power control, non-cooperative game, cost function.

I. INTRODUCTION

The rapid development of information technology provides more convenience for our life, and also makes the mobile communication system face more severe challenge [1]. According to Huawei's communications whitepaper, in the streaming media field, services represented by Augmented Reality (AR) [2], Virtual Reality (VR) [3], and Ultra High Definition (UHD) video require a transmission rate of more than 500 Mbps and a transmission delay of less than 5 ms. The total market for AR and VR is expected to reach \$292 billion by 2025 (\$151 billion for AR and \$141 billion for VR). In the field of autonomous driving [4], [5], [6], [7], more than 50 million+ connections are expected by 2025. In the Industrial Internet of Things (IIoT) [8], [9], [10], mobile devices, represented by smart manufacturing and industrial robots, will be widely used, with 18 million state-monitoring connections globally as of the end of 2017, rising to 88 million by 2025. In addition, areas such as connected drones [11], smart homes [12], smart cities, and mobile wearables [13] will all be massively used in real working life in the coming years. All these new applications require mobile communication networks to have higher spectrum efficiency (SE), lower transmission delay, more device connections, and higher transmission energy efficiency, in order to achieve transmission speeds

The associate editor coordinating the review of this manuscript and approving it for publication was Rui Wang.

beyond Giga, real-time capabilities beyond industrial buses and all-space connectivity. In order to meet the above challenges to mobile communication systems, various standardization organizations, scientific research institutes and mobile communication enterprises have proposed various new technologies and solutions. Among them, D2D technology, as a short-range transmission technology, achieves higher channel gain by allowing users in close proximity to communicate directly with each other. Unlike cellular users who use uplink and downlink spectrum resources for data transmission, D2D users can access the network by reusing the channel resources of the cellular network, thus further improving the SE and energy efficiency of the network.

The SE optimization problem for D2D communication systems is more mature and correspondingly more fruitful compared to energy efficiency optimization. This is due to the fact that the SE optimization problem is not a fractional planning problem. Depending on whether a cellular user allows multiple D2D users to share its channel resources simultaneously, the D2D communication spectrum efficiency optimization problem can be divided into single-user reuse mode and multi-user reusing mode. Among them, in single-user reusing mode [14], [15], [16], [17], [18], each channel allows at most one pair of D2D users to share their channels, while each pair of D2D users share the channel resources of at most one cellular user. The multi-user reusing scenario can be further categorized into many-to-many and many-to-one reusing modes [19], [20], [21], [22], [23], [24], [25], [26].

The resource allocation problem for D2D communication in one-to-one reusing mode is a class of mixed integer nonlinear programming problems. In [14], the authors proposed that D2D communication utilizes the uplink resources of the cellular network for data transmission, considering that when D2D users reuse the uplink resources, the interference generated by the D2D users is received by the receiving antenna of the base station (BS), and the interference from D2D transmitting users can be minimized due to the strong interference cancellation techniques of the BS. In [15], the authors similarly studied the interference problem between D2D users and cellular users in the uplink and proposed two mechanisms to avoid the interference from cellular users to D2D users. Wang et al. proposed a fast channel allocation algorithm [16]. Unlike the traditional Hungarian allocation algorithm [17], the algorithm enhances the access probability of D2D communication by setting high allocation priority for the cellular user with the worst channel state and the D2D user with the worst channel gain. The algorithm is a worst and worst combination, which has a high loss of SE performance for D2D communications, despite the low complexity of the algorithm. In [18], the authors investigated the resource allocation algorithm in a non-perfect channel state information (CSI) environment for the one-to-one reusing mode and proposed a joint channel allocation and power control algorithm based on the interruption probability guarantee of location information.

In order to cope with the ultra-dense user distribution scenario of future mobile communication networks, authors in [19] propose a distributed power control and channel assignment algorithm to ensure that the interference to the cellular users is less than a threshold value while maximizing the SE of the D2D users. Authors in [20] proposes a Stackelberg game algorithm based on interference price updating, in which the authors construct a utility function in terms of cross-tier and co-tier interference suffered by D2D users by assuming that the D2D users have a discrete power policy space, and use an uncoupled stochastic learning algorithm to obtain the Nash equilibrium of the game. Similarly, literature [21] proposes a distributed power control algorithm and introduces the idea of power collaboration in the Stackelberg model. In order to harmonize the homogeneous interference among D2D user. This paper demonstrates that the algorithm converges to the KKT point. However, the algorithm implicitly covers scenarios where the cell contains only one cellular user channel. In [23], the authors studied the resource allocation problem under multi-user systems and proposed a distributed algorithm based on coalition formation game. In this algorithm, the literature utilizes different transmission modes to construct the utility functions of D2D users by incorporating the cooperative interference cost as well as the resource allocation mechanism, and the D2D users decide the reused channel resources based on their utility functions. In [24], the authors propose a distributed resource allocation algorithm based on the inverse iterative combinatorial auction game. unlike the existing auction game models, the authors consider channel resources as bidders who compete for D2D user packages by giving bidding prices, and the D2D users are regarded as commodities to be bid, and the utility function of the bidders is modeled as the difference between the channel capacity gain brought by the D2D users and the bidding price paid. A non-monotonic descending price auction algorithm is proposed in the paper and it is shown that the proposed auction game can converge after a finite number of iterations. In [25], the authors proposed a distributed resource allocation algorithm based on a non-cooperative game, where the authors consider allowing D2D users to reuse the channel resources of multiple cellular users at the same time, while each cellular user's channel resources can be reused by multiple D2D users. The utility function of a D2D user is expressed as the sum of the transmission rates minus the cost function of the cross-layer interference to cellular users and the cost function of the same-layer interference between D2D users. the cost function of inter-layer interference between D2D users. In [26], the authors model the SE optimization problem as a potential game model and propose an iterative algorithm using the convergence of the potential game with the transmit power as a constraint, and prove the convergence of the algorithm to a local optimal solution. In [27], the authors use evolutionary games to solve the spectrum efficiency optimization problem for D2D communications. In [28], the authors assume that the BS acts as the leader of the game by setting the interference price for each cellular user's channel, which is released to the D2D users, who in turn adjust their own transmit power on different cellular user's channels by observing the price factor of the reused channel. The paper assumes that the utility function of the BS is the interference price paid by the D2D user for reusing the different channels, while ensuring that the total interference to the BS is bounded, and the utility function of the D2D user is modeled as the difference between its transmission rate and the interference price paid. The authors consider scenarios with a uniform interference price factor and different interference price factors for each channel, as well as the optimization problem under sparse and dense scenarios for D2D users, respectively, and give closed-form expressions for the optimal transmit power under sparse scenarios.

However, in dense scenarios, the authors point out that there are multiple Nash equilibrium solutions for this Stackelberg game model, when it is not possible to determine which Nash equilibrium solution the algorithm converges to. Similarly, Liu et al. proposed an interference-constrained price updating algorithm using the Stackelberg game [29]. The difference is that the authors first narrowed the iteration space by analyzing the interference price of the BS and obtaining a range of values for the BS price. In the non-cooperative subgame model consisting of D2D users, depending on whether the BS has channel information of all links and whether the BS price is uniform or not, the literature proposes a semi-distributed power control algorithm and a fully-distributed power control algorithm to reduce signaling overload, respectively.

By analyzing the existing literature on solving the SE optimization problem using a game approach in the multiuser reusing mode, it is found that none of the existing algorithms consider the channel allocation problem under multiuser reusing. In the literatures [27] and [28], the authors have pointed out that the proposed algorithms are suitable for flat fading channels or single channel environments. This is due to the fact that the user's power control problem is strongly coupled with the channel allocation problem in the multiuser reusing mode. Therefore, in this paper, we address the problems in the existing literature and study the joint channel allocation and power control problem in the many-to-one reusing mode, in order to apply to the frequency-selective channel environment and the multichannel environment, which are more closely related to the actual one.

Aiming at the deficiencies of the existing algorithms, this paper investigates the D2D spectrum efficiency optimization problem in the many-to-one reusing mode, with the optimization objective of maximizing the spectrum efficiency of D2D users while guaranteeing the quality of service (QoS) requirements of cellular users. It can be found through the analysis that the problem is still a MINLP problem, and compared with the one-to-one reusing mode, the power control problem in the many-to-one mode is more coupled with the channel allocation problem, which makes it impossible to split the original optimization problem into independent optimization subproblems. The main contributions of this work are summarized as follow:

1) This paper considers decoupling the coupled SE optimization problem into two layers of resource allocation problems based on the same-layer interference and cross-layer interference by introducing the idea of layering. Then we solve the different layered optimization problems respectively.
2) In the outer layer resource allocation problem, a power control algorithm based on discrete power selection and two fast channel allocation algorithms based on priority setting are proposed. By using discrete power control for cellular users, the problem of multiple local optimal solutions for many-to-one reusing power control in frequency-selective channel environment is solved, which makes the power control algorithm of the whole system converge.
3) In the inner layer resource allocation problem, D2D users reusing the same channel adjust their own transmit power through a non-cooperative game and solve the Nash equilibrium to obtain the optimal transmit power when the utility function of the D2D users is maximized.

The remainder of this paper is organized as follows. Section II presents the system model and the mathematical formulation. Section III develops a new two-tier power control and resource allocation algorithm. Section IV presents the simulation used to validate the propose algorithm. The paper is concluded in section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Since the uplink of cellular networks is characterized by low spectrum utilization, it makes possible for D2D communications to use many-to-one reusing mode to further improve the system spectrum efficiency. Although this scenario makes the interference environment more complicated, unlike the cellular users at the receiving end of the downlink, the BS at the receiving end of the uplink has stronger anti-interference performance than the cellular users with handheld mobile devices. Therefore, considering the optimization of the SE of D2D communication in uplink with many-to-one reusing mode is not only achievable, but also can bring great practical application value. In this section, the D2D communication system model in many-to-one reusing mode is firstly given, and then the resource allocation problem with the optimization objective of maximizing the SE of D2D users is defined.

As shown in Fig. 1, the D2D communication system in uplink many-to-one reusing mode is given. It is assumed that there exist N cellular users with M pairs of D2D users in the uplink of a cellular cell and satisfy $M >> N$, denoted by the sets $\mathbf{C} = \{i\,|i = 1, 2, \ldots, N\}$ and $\mathbf{D} = \{j\,|j = 1, 2, \ldots, M\}$, respectively. This paper also considers the resource allocation problem under full load, i.e., N cellular users occupy all the available channel resources in the uplink, and the channel allocation for cellular users has been completed, and at the same time, the spectrums between the uplink channels are orthogonal and equipartitioned, and there is no co-channel interference problem between cellular users. Unlike one-to-one reuse, this paper assumes the channel resources of each cellular user can be reused by multiple pairs of D2D users at the same time, and each pair of D2D users reuses the channel resources of at most one cellular user. This paper also assumes that the cellular users in the uplink use discrete transmit powers $P_{i,l}^c \in [P_1, P_2, \cdots, P_L]$. In order to suppress the cross-layer interference from D2D users when the cellular users choose different fixed power, the maximum number of D2D users that can be reuse by the cellular users is limited to different number levels $num_{i,l} \in [c_{size}, 2c_{size}, \cdots, Lc_{size}]$, where $c_{size} = \left\lfloor \frac{M}{NL} \right\rfloor$, $\lfloor\rfloor$ are upward rounding functions. That is, when the cellular user employs a larger fixed transmit power, the cellular user allows more D2D users to reuse its channel simultaneously, and vice versa, limits the number of D2D users reusing its channel. Obviously, this assumption in this paper is consistent with the actual situation.

In this paper, a multi-channel environment is considered and the channel is modeled as a frequency-selective channel, and the channel gain is modeled as including a large-scale path loss model based on the transmission distance and a small-scale fading model based on multipath transmission with the Doppler effect. Similarly, it is assumed that the channel gain of all channels exhibits time-scale fading as block fading, i.e., the channel gain remains constant within each transmission time slot but varies between different time slots. In this case, the channel gain between the cellular user i and the BS $g_{i,B}$ is denoted as:

$$g_{i,B} = \kappa \chi_{i,B} d_{i,B}^{-\alpha} \tag{1}$$

where κ and α denote the path loss constant and path loss exponent, respectively, $d_{i,B}$ denotes the transmission distance between the cellular user i and the BS, and denotes the small-scale fading component of the channel.

Similarly it can be obtained that the D2D user j reuses the channel gain of the cellular user ig_j^i, the channel gain from the transmitter of the D2D user j to the BS $h_{j,B}^i$, the channel gain from the cellular user i to the receiving end of the D2D user $jh_{i,j}$, and the channel gain that the D2D user j receives from the transmitter of the other D2D user m that reuses the same uplink channel $h_{m,j}^i$.

Let P_j^d denote the transmit power of the D2D user j transmitter user, and the signal to interference plus noise ratio (SINR) of the BS and the D2D user j receiver user in the many-to-one reusing mode is denoted respectively:

$$\gamma_i^c = \frac{P_{i,l}^c g_{i,B}}{\sigma_n^2 + \sum_{j\in\mathbf{D}} f(i,j) P_j^d h_{j,B}^i} \tag{2}$$

$$\gamma_j^d = \frac{P_j^d g_j^i}{\sigma_n^2 + \sum_{i\in\mathbf{C}} f(i,j) P_{i,l}^c h_{i,j} + \sum_{m\in\mathbf{D}_i, m\neq j} P_m^d h_{m,j}^i} \tag{3}$$

where $\mathbf{D}_i$ denotes the set of D2D users reusing the same cellular subscriber channel i, m denotes the other D2D users reusing under the same channel, P_m^d denotes the transmit power of D2D user m. σ_n^2 denotes the additive white gaussian noise (AWGN) power in the channel, and $f(i,j)$ denotes the channel allocation indicator function with the following function expression:

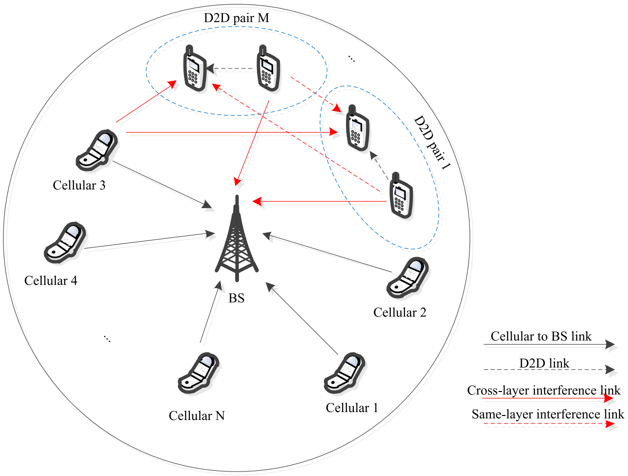

FIGURE 1. System mode of uplink D2D with many-to-one reusing mode.

$$f(i,j) = \begin{cases} 1 & \text{when D2D } j \text{ reuses channel } i \\ 0 & \text{other} \end{cases} \tag{4}$$

Unlike the channel allocation indicator function $f(i,j)$ constraint in one-to-one reusing mode, there is in many-to-one reusing mode:

$$\sum_{j\in\mathbf{D}} f(i,j) \geq 1 \tag{5}$$

Based on the above definition, an expression for the transmission rate of cellular users and D2D users in many-to-one reusing mode can be obtained:

$$R_i^c = \log_2(1 + \gamma_i^c) \tag{6}$$

$$R_j^d = \log_2(1 + \gamma_j^d) \tag{7}$$

Since cellular users as the primary users in the cell have higher priority than D2D users, the transmission rate demand of cellular users still needs to be guaranteed even in the many-to-one reusing mode. For D2D users, how to reasonably choose the reusing channel and transmit power is not only related to the strength of cross-layer interference from cellular users, but also to the size of co-layer interference from other D2D users. In this paper, the SE optimization problem for D2D communications is modeled as a joint channel allocation and power control problem in many-to-one reusing mode. Taking maximizing the total transmission rate of D2D communication as the optimization objective, the minimum transmission rate requirement of cellular users and the maximum transmit power of D2D users are considered as the constraints, and the channel allocation constraints in many-to-one reusing mode are satisfied at the same time. The mathematical expression of the optimization problem can be expressed as:

$$\max_{P_{i,l}^c, P_j^d, f(i,j)} \sum\nolimits_{i\in\mathbf{C}} \sum\nolimits_{j\in\mathbf{D}} f(i,j) R_j^d \tag{8}$$

$$\text{s.t. } \gamma_i^c = \frac{P_{i,l}^c g_{i,B}}{\sigma_n^2 + \sum\nolimits_{j\in\mathbf{D}} f(i,j) P_j^d h_{j,B}^i} \geq \gamma_{i,\min}^c, \ \forall i \in \mathbf{C} \tag{9}$$

$$\sum\nolimits_{j\in\mathbf{D}} f(i,j) \leq num_{i,l}, \ \forall i \in \mathbf{C} \tag{10}$$

$$\sum\nolimits_{i\in\mathbf{C}} f(i,j) \leq 1, \ \forall j \in \mathbf{D} \tag{11}$$

$$0 \leq P_j^d \leq P_{\max}^d, \ \forall j \in \mathbf{D} \tag{12}$$

where, $\gamma_{i,\min}^c$ represents the minimum SINR requirement of the cellular user i to guarantee its minimum transmission rate requirement and $P_{\max}^d$ represents the maximum transmit power of the D2D user. Equation (9) is used to guarantee the transmission rate requirement for the cellular user who is the primary user. Equation (10) is used to ensure that for each cellular user, the number of D2D users reusing its channel cannot exceed $num_{i,l}$. Equation (11) is used to ensure that each D2D user selects at most one cellular user's channel for reusing. Equation (12) is used to ensure that the transmit power of a D2D user cannot exceed its maximum transmit power.

By analyzing the above optimization problem, it can be found that the channel allocation optimization variables and power control variables in the many-to-one reusing mode are more coupled with each other compared to the one-to-one reusing mode, which is due to the fact that the selection of the cellular users transmit power not only affects the power control problem of the D2D users, but also affects the channel allocation problem of the D2D users. In addition, the D2D users affect each other's power control through the same-layer interference, and both the objective function and constraints are nonlinear functions that contain integer variables at the same time. Therefore, this optimization problem belongs to the mixed integer nonlinear programming (MINLP) problem, which is also an NP-hard problem, and it is not possible to directly find the optimal solution regarding channel allocation and power control. In this paper, we consider decoupling the above coupled optimization problem into a two-layer resource allocation problem based on the same-layer interference suppression and cross-layer interference suppression: in the outer resource allocation problem, the cross-layer interference suppression problem and the channel allocation problem are solved for the D2D users to cellular users; and in the inner resource allocation problem, the same-layer interference suppression problem is solved for the D2D users reusing the same channel.

III. COMMUNICATION SPECTRUM EFFICIENCY BASED ON TWO-TIER RESOURCE ALLOCATION

Unlike the D2D communication resource allocation problem in one-to-one reusing mod, which can be allocation problem in many-to-one reusing mode has stronger coupling and cannot be solved by splitting the channel allocation and power control problems into independent subproblems. Thus, this paper considers the layered idea to solve the resource allocation problem in many-to-one mode. First, in the outer layer resource allocation problem, the cellular user i, as the primary user, determines the number of D2D users that can be allowed to reuse its channel $num_{i,l}$ by adjusting its own transmit power $P_{i,l}^c$ and releases it to the D2D users through the BS. In order to increase the access rate of D2D users and improve the SE of the uplink, two different channel allocation algorithms are proposed in this paper; secondly, in the inner layer resource allocation problem, the problem of homogeneous interference between D2D users is solved by modeling the power control problem of D2D users who are reusing the same channel as a non-cooperative game model, and a distributed iteration-based power control algorithm is proposed.

A. CELLULAR USER POWER CONTROL AND CHANNEL ALLOCATION ALGORITHM

In the outer resource allocation problem, the feasible domain consisting of the constraints is shown as

$$\begin{cases} P_{i,l}^c \in [P_1, P_2, \cdots, P_L] \\ num_{i,l} \in [c_{size}, 2c_{size}, \cdots, Lc_{size}] \\ \gamma_i^c = \dfrac{P_{i,l}^c g_{i,B}}{\sigma_n^2 + \sum\nolimits_{j\in\mathbf{D}} f(i,j) P_j^d h_{j,B}^i} \geq \gamma_{i,\min}^c, \ \forall i \in \mathbf{C} \\ \sum\nolimits_{j\in\mathbf{D}} f(i,j) \leq num_{i,l}, \ \forall i \in \mathbf{C} \\ \sum\nolimits_{i\in\mathbf{C}} f(i,j) \leq 1, \ \forall j \in \mathbf{D} \end{cases} \tag{13}$$

From (13), when the cellular user i transmits information with smaller transmit power $P_{i,l}^c$, the BS will assign fewer D2D users for channel reusing in order to protect its minimum transmission rate requirement. At this time, the cellular user suffers less cross-layer interference from the D2D user's transmitter, and the problem of inter-layer interference between D2D users is simpler, and the D2D user can improve the SE by increasing the transmit power. As the cellular users continue to increase their transmit power, more D2D users are allowed to reuse the channel, at this time, although the access rate of D2D users is increased but more cross-layer and co-layer interference is introduced, and the SE performance of the system may still be degraded.

For the above to-be-solved cellular user power control and channel allocation problem in many-to-one reusing mode, this paper proposes fast resource allocation algorithms based on the minimum interference channel priority and based on the maximum gain interference ratio, respectively. The specific steps of the algorithms are shown in Algorithm 1 and Algorithm 2. In Algorithm 1, the main steps include: firstly, power control and D2D user reusing selection are performed for cellular users with poor transmission performance on their own, the cellular user traverses all the discrete transmit powers, and when the cellular user selects its fixed transmit power $P_{i,l}^c$, a different priority is set for the D2D users based on the cross-layer interference channel gain of the D2D users

Algorithm 1 Fast Resource Allocation Algorithm Based on Minimum Interference Channel Prioritization

```
for $i = 1 : N$ do
    Find the cellular user with the lowest channel $i = \arg\ \min\{g_{i,B}\}$;
    for $l = 1 : L$ do
        $P_{i,l}^c = P_l$ to determine the maximum number of D2Ds that can be accessed $num_{i,l}$;
        for $j = 1 : M$ do
            Find D2D $j = \arg\ \min\{h_{j,B}^i\}$ and assign it to $i$ until $|j| = num_{i,l}$;
        end for
    end for
    Delete paired users and update the queue.
end for
```

Algorithm 2 Fast Resource Allocation Algorithm Based on the Maximum Gain Interference Ratio

```
for $i = 1 : N$ do
    Find the cellular user with the lowest channel gain $i = \arg\ \min\{g_{i,B}\}$;
    for $l = 1 : L$ do
        $P_{i,l}^c = P_l$ to determine the maximum number of D2Ds that can be accessed $num_{i,l}$;
        for $j = 1 : M$ do
            Locate D2D $j = \arg\ \max\{\frac{g_j^i}{h_{j,B}^i}\}$ and assign it to $i$ until $|j| = num_{i,l}$;
        end for
    end for
    Delete paired users and update the queue.
end for
```

to the cellular user, and the $num_{i,l}$ D2D users with the smallest cross-layer interference channel gain are assigned to the cellular user. D2D users with the lowest cross-layer interference channel gain are assigned to the cellular users.

The advantage of the above algorithm is that by setting higher allocation priority for the cellular users with poor transmission performance, and at the same time allocating the D2D user reusing channel with the least cross-layer interference to them, each cellular user can get a good QoS guarantee. The specific flow is shown in Algorithm 1.

Unlike Algorithm 1, in order to achieve more SE gains per channel, Algorithm 2 sets a higher priority for D2D users with higher channel gains and cross-layer interference channel ratios to be assigned to cellular users. The specific flow is shown in Algorithm 2.

In this section, in order to solve the outer layer resource allocation problem in many-to-one reusing mode, two different resource allocation algorithms are proposed in this section, which are used to reduce the cross-layer interference suffered by cellular users versus to enhance the SE gain on each channel by setting different allocation priorities for D2D users, respectively.

B. NON-COOPERATIVE GAME-BASED POWER CONTROL ALGORITHM FOR D2D COMMUNICATION

In the previous section, the solution of the resource allocation problem for the outer cellular user is given, i.e., the cellular user's transmit power and the D2D user's channel allocation have been accomplished, and in this section, the inner resource allocation problem for the D2D user on the reuse identical channel will be solved, i.e., how the D2D user on the reuse identical channel can obtain higher SE by adjusting its own transmit power under the same channel. By introducing the idea of game theory, the power control problem of D2D users reusing the same channel can be modeled as a non-cooperative game to solve the inner resource allocation problem. According to the basic model of non-cooperative game, this game model can be expressed as:

$$G := \left\{\mathbf{D}_i; \left\{P_j^d\right\}; \{u_j\}\right\} \tag{14}$$

where $\mathbf{D}_i$ denotes the game participants consisting of D2D users on the reuse same channel i. $\{P_j^d\}$ denotes the strategy space of the game participants, and $\{u_j\}$ denotes the utility function of the game participants. For the D2D user j, its strategy space is composed of constraints consisting of the maximum transmit power and the QoS guarantee of the cellular user:

$$\begin{cases} 0 \leq P_j^d \leq P_{\max}^d \\ \dfrac{P_{i,l}^c g_{i,B}}{\sigma_n^2 + \sum_{j\in\mathbf{D}_i} P_j^d h_{j,B}^i} \geq \gamma_{i,\min}^c \end{cases} \tag{15}$$

In the many-to-one reusing mode, multiple D2D users reuse the same channel resources, if the D2D users do not take into account their own homogeneous interference problems to other D2D users, selfishly maximize their own transmission rate as the goal, will lead to a non-cooperative game each D2D user to continuously increase their own transmit power, the Nash equilibrium reached by the game is obviously not the system SE Optimization. In order to inhibit the deterioration of the co-layer interference environment brought about by the vicious competition among D2D users, this section considers introducing the co-layer interference cost as a penalty function in the non-cooperative game with its own transmission rate as the payoff function, so as to obtain more gains in SE.

Let the interference price factor that D2D user j on channel i receives from other D2D users on the reuse same channel be:

$$\mu_j = \frac{\sum_{m\in\mathbf{D}_i, m\neq j} h_{j,m}^i}{I_j^d} \tag{16}$$

where $h_{j,m}^i$ denotes the interference channel gain of D2D user j to the receiving end of other D2D user m reusing the same uplink channel. I_j^d denotes the total interference received by D2D user j:

$$I_j^d = \sigma_n^2 + P_{i,l}^c h_{i,j} + \sum\nolimits_{m\in\mathbf{D}_i, m\neq j} P_m^d h_{m,j}^i \tag{17}$$

The above interference price factor implies that when the co-layer interference I_j^d to the D2D user j increases, the interference price factor decreases, and then the D2D user j can increase its revenue by increasing its transmit power; when the co-layer interference of the D2D user j to other D2D users reusing the same channel increases, the interference price factor increases, and then the D2D user j needs to reduce its transmit power to minimize the interference price paid.

At this point, the utility function of the D2D user j can be expressed as follows:

$$\begin{aligned} u_j(P_j^d, P_{-j}^d) &= R_j^d - P_j^d \mu_j \\ &= \log_2\left(1 + \frac{P_j^d g_j^i}{I_j^d}\right) - \frac{P_j^d \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i}{I_j^d} \end{aligned} \tag{18}$$

where P_{-j}^d denotes the transmit power of other D2D users on channel i except D2D user j. The above assumptions on the utility function of D2D users take into account the suppression of interlayer interference among D2D users, preventing the worsening of interlayer interference among D2D users due to selfishly increasing their own transmit power, which in turn leads to the reduction of the system's SE.

According to the assumptions of the above non-cooperative game model, for the D2D user j, its objective is to maximize its utility function by choosing its own transmit power strategy, so its optimization problem can be expressed as follows:

$$\max_{P_j^d} u_j \tag{19}$$

$$\text{s.t. } 0 \leq P_j^d \leq P_{\max}^d \tag{20}$$

$$\frac{P_{i,l}^c g_{i,B}}{\sigma_n^2 + \sum_{j\in \mathbf{D}_i} P_j^d h_{j,B}^i} \geq \gamma_{i,\min}^c \tag{21}$$

For the optimization problem posed by the above non-cooperative game, the following lemmas are available:

Lemma 1: For a given cellular channel's transmit power $P_{i,l}^c$, there exists at least one Nash equilibrium solution to the noncooperative game $G := \{\mathbf{D}_i; \{P_j^d\}; \{u_j\}\}$.

The proof of *Lemma 1* is given in APPENDIX A.

For the above game model, the uniqueness problem of its Nash equilibrium can be given by the following lemma:

Lemma 2: For a given cellular subscriber's transmit power $P_{i,l}^c$, the non-cooperative game $G := \{\mathbf{D}_i; \{P_j^d\}; \{u_j\}\}$ has a unique Nash equilibrium solution.

The proof of **Lemma 2** is given in APPENDIX B.

Since in the utility function optimization problem expressed in (19), its objective function is a convex function and the policy space constituted by the constraints is a convex set, the optimization problem is a convex optimization problem, and the optimal solution can be obtained by constructing a Lagrangian function and solving the KKT condition, which is defined as follows:

$$\begin{aligned} &L_j(P_j^d, \varphi, v) \\ &= u_j + \varphi(P_{\max}^d - P_j^d) \\ &\quad + v\left(\frac{P_{i,l}^c g_{i,B}}{\gamma_{i,\min}^c h_{j,B}^i} - \frac{\sigma_n^2 + \sum_{m\in \mathbf{D}_i, m\neq j} P_m^d h_{m,B}^i}{h_{j,B}^i} - P_j^d\right) \end{aligned} \tag{22}$$

where φ, v are the Lagrange multipliers corresponding to constraints (20) and (21), respectively. where the inequalities:

$$\frac{P_{i,l}^c g_{i,B}}{\gamma_{i,\min}^c h_{j,B}^i} - \frac{\sigma_n^2 + \sum_{m\in \mathbf{D}_i, m\neq j} P_m^d h_{m,B}^i}{h_{j,B}^i} - P_j^d \geq 0 \tag{23}$$

is an equivalent transformation of (21). It can be obtained by taking the first order derivative of the Lagrangian function $L_j\left(P_j^d, \varphi, v\right)$ with respect to P_j^d and making it zero:

$$\begin{aligned} \frac{\partial L_j(P_j^d, \varphi, v)}{\partial P_j^d} &= \frac{\partial u_j}{\partial P_j^d} - \varphi - v \\ &= \frac{g_j^i}{\ln 2(I_j^d + P_j^d g_j^i)} - \frac{\sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i}{I_j^d} - \varphi - v \\ &= 0 \end{aligned} \tag{24}$$

In this case, the optimal transmit power P_j^{d*} of the D2D user j can be expressed as follows:

$$P_j^{d*} = \left[\frac{I_j^d}{\ln 2[\sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i + I_j^d\, (\varphi + v)]} - \frac{I_j^d}{g_j^i}\right]^+ \tag{25}$$

where the Lagrange multipliers φ, v corresponding to the constraints can be obtained by updating the gradient method, and the gradients of the Lagrange multipliers φ, v can be expressed as respectively:

$$\frac{\partial L_j(P_j^d, \varphi, v)}{\partial \varphi} = P_{\max}^d - P_j^d \tag{26}$$

$$\begin{aligned} \frac{\partial L_j(P_j^d, \varphi, v)}{\partial v} &= \frac{P_{i,l}^c g_{i,B}}{\gamma_{i,\min}^c h_{j,B}^i} \\ &\quad - \frac{\sigma_n^2 + \sum_{m\in \mathbf{D}_i, m\neq j} P_m^d h_{m,B}^i}{h_{j,B}^i} - P_j^d \end{aligned} \tag{27}$$

The Lagrange multipliers obtained by the gradient method of updating can be expressed as:

$$\varphi(t+1) = [\varphi(t) - \varepsilon_\lambda (P_{\max}^d - P_j^d)]^+ \tag{28}$$

$$\begin{aligned} v(t+1) = [v(t) - \varepsilon_v (&\frac{P_{i,l}^c g_{i,B}}{\gamma_{i,\min}^c h_{j,B}^i} \\ &- \frac{\sigma_n^2 + \sum_{m\in \mathbf{D}_i, m\neq j} P_m^d h_{m,B}^i}{h_{j,B}^i} - P_j^d)]^+ \end{aligned} \tag{29}$$

where t denotes the number of iterations, and ε_λ, ε_v represent the positive update steps, respectively.

Through the above analysis, this section addresses the inner layer resource allocation problem under many-to-one reusing mode by modeling the D2D communication power control problem on reuse identical channels as a non-cooperative game model with maximizing the utility function of the D2D users as the optimization objective, and proves the existence of a unique Nash equilibrium solution under this game model. For the power control problem of D2D users, this paper proposes an iterative power control

Algorithm 3 Iterative Power Control Algorithm Under Non-Cooperative Games

```
1. initialization, number of iterations $k = 1$, iteration termination error $\Delta$, update steps $\varepsilon_\lambda$ and $\varepsilon_v$, $\lambda(1)=0$, $v(1) = 0$;
2. repeat
3.     Calculate $I_j^d$ and the interference cost function $\mu_j$ according to (17) and (16);
4.     Update the transmit power $P_j^d(t+1)$ according to (25);
5.     Update $\varphi(t+1)$ and $v(t+1)$ according to equations (28) and (29);
6.     if $\left|P_j^d(t+1) - P_j^d(t)\right| \le \Delta$ then
7.         $P_j^{d*} = P_j^d(k+1)$;
8.         break
9.     else
10.        $k = k+1$ Return to step 3;
11.    end if
12. until the algorithm converges
13. return Optimal Transmit Power $P_j^{d*}$.
```

algorithm under the non-cooperative game, and the specific flow of algorithm is shown in Algorithm 3.

For the analysis of convergence of Algorithm 3, assuming that $(P_j^d(t), P_{-j}^d(t))$ is the combination of D2D user's transmit power during the first t iteration, for the D2D user j, the update to get the transmit power $P_j^d(t+1)$ for the $t+1$ th iteration given the other D2D user's transmit power $P_{-j}^d(t)$, and due to (25), $P_j^d(t+1)$ is the optimal response of the D2D user j at this point in time under $P_{-j}^d(t)$, therefore, there are

$$u(P_j^d(t+1), P_{-j}^d(t)) \ge u(P_j^d(t), P_{-j}^d(t)) \tag{30}$$

That is, the D2D user obtains a greater utility during each iteration until the maximum value of its own utility function is achieved, and therefore, Algorithm 3 converges.

In summary, for the spectrum efficiency optimization problem in the many-to-one reusing mode in (8), this paper solves it by a two-layer nested loop algorithm. In the outer layer resource allocation algorithm, the cellular users control the number of D2D users reusing their channels by adjusting their own transmit power, suppressing the cross-layer interference from the D2D users, and performing the channel allocation by two fast channel allocation algorithms; when the outer layer algorithm determines the transmit power and channel allocation of the cellular users, a non-cooperative game is adopted between the D2D users reusing the same channel for inner layer power control, and the optimal transmit power, i.e., the Nash equilibrium solution of the game, is obtained iteratively by solving the KKT condition. Finally, the cellular users iterate through the different discrete transmit powers to find the cellular user transmit power that maximizes the SE of the channel, the channel assignment, and the optimal transmit power of the D2D user that reuses this channel.

TABLE 1. System parameters.

Simulation parameters	value
Cell radius	1000 m
Cellular user discrete transmit power	[10, 15, 18, 20, 23] dBm
D2D maximum transmit power	21dBm
Number of cellular users	20
Number of D2D users	100
D2D link path loss	$148 + 40\lg(d / Km)$ dB
Path loss for other links	$128.1 + 37.6\lg(d / Km)$ dB
D2D communication distance	100 m
Multipath loss	Exponential distribution with mean 1
Minimum SINR requirement for cellular users	0dB ~ 20dB
Noise power	-114dBm

C. ALGORITHM COMPLEXITY ANALYSIS

The D2D spectrum efficiency optimization algorithm for many-to-one reusing scenarios proposed in this paper consists of an outer cellular user power control and channel assignment algorithm and an inner iterative power algorithm for D2D communication under non-cooperative games, respectively. Among them, the required computational complexity in the outer layer loop process is $O(MNL)$. During the inner layer loop, let T denote the maximum number of iterations of the iterative power algorithm, then the maximum required computational complexity of the inner layer loop is at most $O(MT)$. Therefore, the total computational complexity of the proposed SE optimization algorithm based on the layering idea in this paper is $O(M^2NLT)$.

IV. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In the simulation environment of this paper, a single cell uplink network environment is considered, where the BS is located in the center of the cell with a coverage radius of R.

All cellular users and D2D user transmitters are randomly distributed on any radius at any angle within the cell. Meanwhile, the receiving ends of D2D users are randomly distributed at any angle in any radius within the circle centered on the transmitting end of D2D users with a maximum transmission distance of d. Among them, the number of D2D users is much larger than the number of cellular users, and multiple D2D users are allowed to reuse the same channel. The specific parameter settings in the simulation experiment are shown in Table 1.

In order to better illustrate the performance advantages of the proposed D2D spectrum efficiency optimization algorithms in the many-to-one reusing scenario in this paper, the following typical algorithms with spectrum efficiency as the optimization objective are selected for comparison in

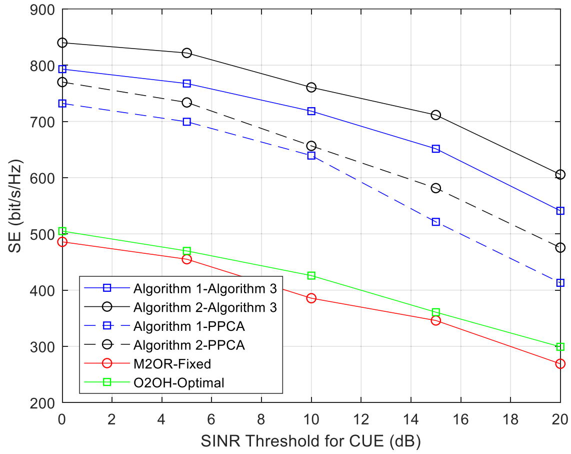

FIGURE 2. SE under different SINR requirements of cellular user.

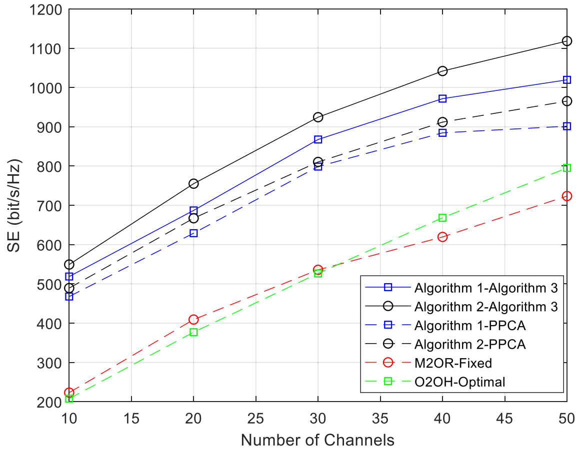

FIGURE 3. SE under different number of channels.

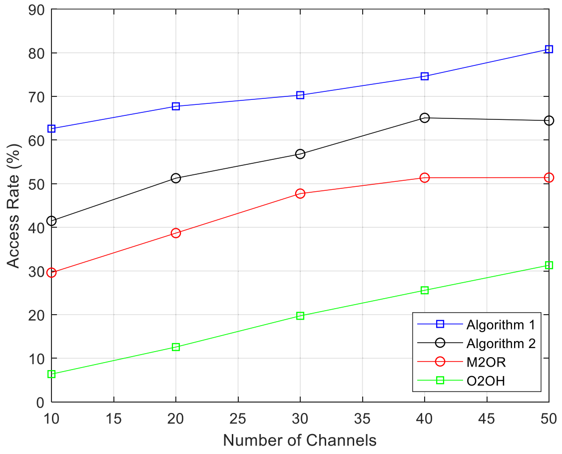

FIGURE 4. Access rate under different number of channels.

this paper, including: price-based power control algorithm (PPCA) [29], in which the D2D communication resource allocation problem in many-to-one reusing mode is modeled as a Stackelberg game, where the BS acts as a leader and gains by setting the interference price, and the D2D users maximize their gains by adjusting their own transmit power. Since the algorithm does not involve channel allocation, this paper assumes that Algorithm 1 and Algorithm 2 are executed for channel allocation and then PPCA is used for power control in the case of cellular users employing the maximum transmit power, respectively, as well as the Many-to-one Random (M2OR) channel allocation algorithm under fixed maximum transmit power; the optimal power in one-to-one reusing mode control [30] with the Hungarian channel assignment algorithm (One-to-one and Hungary, O2OH) [31], under which the transmit power is continuous for both cellular and D2D users.

Fig. 2 compares the performance of the system SE performance under different resource allocation algorithms as the minimum SINR requirement of the cellular users' changes. It can be seen from the figure that the SE of the D2D users all shows a decreasing trend as the minimum SINR requirement of the cellular users increases, this is due to the fact that as a primary cellular user, the BS needs to ensure its QoS first, which results in the need for the D2D users who are accessing the network to transmit data at a lower transmit power. It can also be seen from the figure that the SE performance using the algorithm proposed in this paper shows a significant performance improvement compared to the optimal resource allocation algorithm in the random allocation and one-to-one mode. At the same time, under the same channel allocation algorithm, the system performance is still improved compared to the power control algorithm based on interference price update, this is due to the fact that the power control algorithm in [29] does not take into account the effect of the cellular user's transmit power on the SE of the D2D user, due to the cross-layer interference between the cellular user and all the D2D users on the reuse its channel, the cellular user using the maximum transmit power will increase the access rate of D2D users, but, on the one hand, the cross-layer interference from the cellular users to the D2D users will also increase, and at the same time, more D2D users accessing the same channel will lead to an increase in the same-layer interference to the D2D users, which will lead to the deterioration of the SE performance. In addition, the proposed algorithm in this paper consider the suppression of the co-layer interference, which further improves the performance of the algorithm. Compared to the channel assignment algorithm using Algorithm 1, Algorithm 2 brings more SE improvement, which is due to the prioritization of the D2D users by the gain-to-interference ratio, which allows the D2D users with better performance to access the network. This leads to higher SE.

Fig. 3 depicts a comparison of the SE performance of the different algorithms when increasing the number of channels in the uplink for a fixed number of D2D users $M = 100$, with a minimum SINR requirement of 10dB for cellular users. From the figure, it can be seen that the total SE of D2D users is improved as the number of channels is increased, which is due to more D2D users being accessed to the network. It can also be found that the SE growth rate of the proposed resource allocation algorithm is not significant compared to

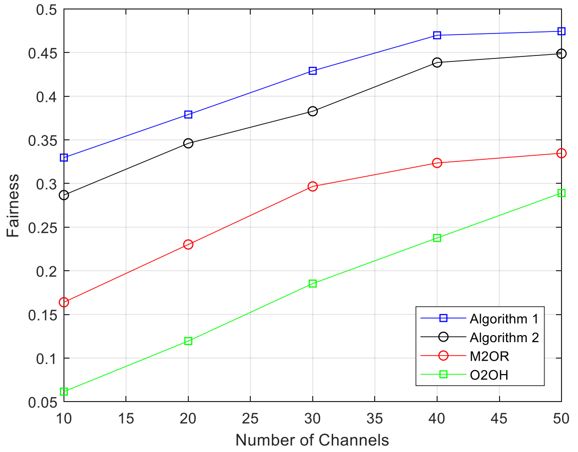

FIGURE 5. Fairness under different number of channels.

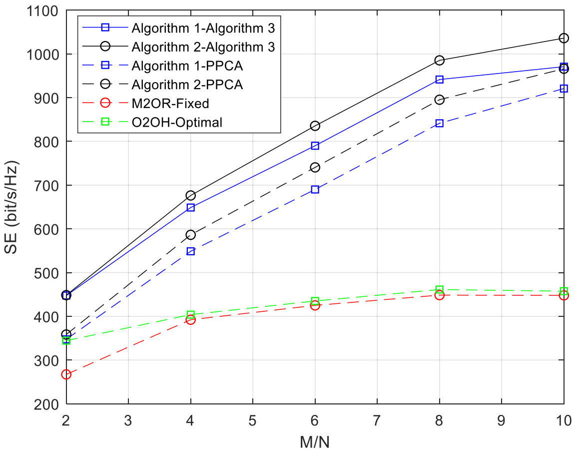

FIGURE 6. SE for different D2D user densities.

the optimal resource allocation algorithm in the one-to-one mode, this is due to the proposed algorithm itself has a higher access rate of D2D users, and also due to the fact that the cellular users are using the discrete transmit power rather than the optimal solution under the continuous power, which affects the performance, Fig. 3 further illustrates the proposed algorithm is more suitable for dense scenarios under the many-to-one reusing mode. one reusing mode. It can also be seen that the two-tier resource allocation algorithm proposed in this paper still has a performance advantage over the power control algorithm using interference price update based.

Fig. 4 and Fig. 5 validate the access rate and allocation fairness performance of the channel allocation algorithms proposed in this paper, respectively. As can be seen from Fig. 4, the access rates of both Algorithm 1 and Algorithm 2 increase with the increase of available channels in the uplink, but the increase is slower compared to the one-to-one matching algorithm, which is due to the fact that the algorithms proposed in this paper still have higher access rates with fewer channels, which also verifies the reason why the spectrum efficiency performance of the algorithms proposed in this paper grows slower in Fig. 4, as the number of D2D users in the uplink becomes sparse. efficiency performance grows at a slower rate. In Fig. 5, the better access performance makes the proposed algorithm also have a good allocation fairness, while Algorithm 1 has a better access rate and fairness compared to Algorithm 2 due to the guaranteed access to the poorer performing D2D users.

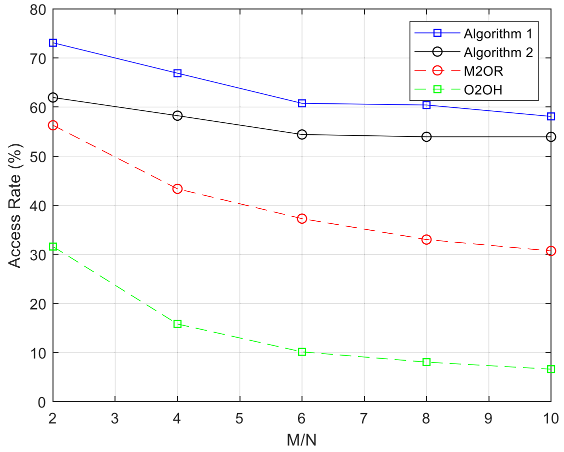

FIGURE 7. The impact of D2D density on access rate.

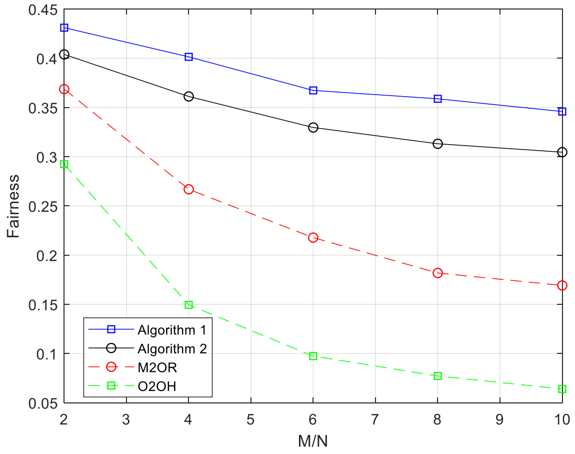

FIGURE 8. The impact of D2D density on fairness.

A comparison of the SE, access rate and allocation fairness performance of the system as the density of D2D users in the network increases is verified in Fig. 6, Fig. 7 and Fig. 8, respectively. Where the number of cellular users $N = 20$. As can be seen in Fig. 6, the proposed algorithm in this paper improves the system SE substantially as the D2D user density increases due to the increase in the number of D2D users that can be accessed. This is due to the fact that the many-to-one reusing mode allows multiple pairs of D2D users to reuse the channel simultaneously per cellular user channel, so that the access rate of D2D users does not decrease dramatically, and more D2D users are allowed to access in the cellular network, which improves the SE of the network. Meanwhile, compared to using the power control algorithm based on the interference price update, the resource allocation algorithm proposed in this paper performs better as the cross-layer interference suppression among D2D users is considered in the inner-layer

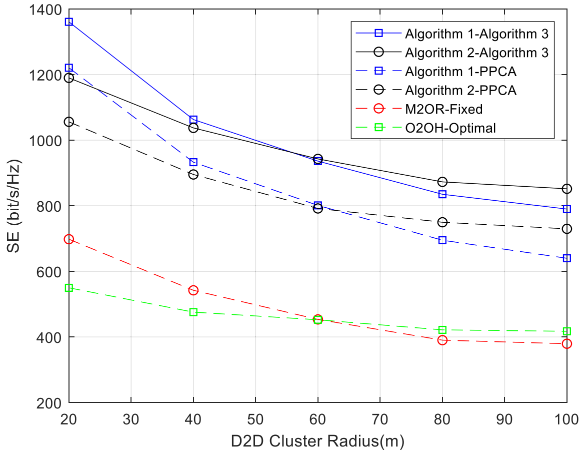

FIGURE 9. **The impact of D2D distance on SE.**

game, and thus the algorithm proposed in this paper performs better as the density of D2D users increases, the number of D2D users on each channel becomes more numerous, and the problem of same-layer interference becomes more serious. In addition, it can be seen from Fig. 7 and Fig. 8, the channel allocation algorithm proposed in this paper still maintains a very good access rate and allocation fairness, and does not cause a rapid deterioration of the access rate and fairness due to the access of a large number of D2D users, but rather decreases at a slower and less sensitive rate. The good performance of the proposed algorithm in this paper for ultra-dense D2D communication is further verified.

The SE performance of the D2D communication system is given in Fig. 9 for different D2D user maximum transmission distances, where $M = 100, N = 20$. From the figure, it can be seen that the SE performance of all the algorithms decreases to different degrees as the transmission distance increases. This is due to the decrease in channel gain of D2D communication itself. However, the decrease of Algorithm 1 is faster than that of Algorithm 2, which is due to the fact that when the transmission distance is close, Algorithm 1 ensures the access of D2D users with less cross-layer interference, so that the D2D users can be able to improve the SE by a large margin without jeopardizing the QoS guarantee of the cellular users, and at this time, due to the fact that the difference in the channel gain is not significant between D2D users due to the close transmission distance, which causes Algorithm 1 performs better than Algorithm 2 in terms of SE when the distance is close, while as the distance increases, Algorithm 2 ensures access to D2D users with better channel gains, which results in a significant improvement in SE compared to Algorithm 1.

V. CONCLUSION

In this paper, by introducing the idea of layering, the spectrum efficiency optimization problem for D2D communication in many-to-one reusing mode problem is divided into the power control and channel allocation problem of outer layer of cellular users, and the power control problem for the inner layer of D2D users. Two different channel allocation algorithms and a non-cooperative game are proposed in this paper. Through numerical simulation, it is demonstrated that the resource allocation algorithm proposed can further improve the SE performance of the network compared with the existing algorithms in many-to-one reusing mode. Moreover, with the increase of D2D user density, the performance of the proposed algorithm becomes better.

APPENDIX A

In a non-cooperative game, if for any D2D user j satisfies:

- The strategy space $\{P_j^d\}$ of a participant j is a nonempty, compact, convex subset on the Euclidean space.
- For any participant j, whose utility function $u_j(P_j^d, P_{-j}^d)$ is continuous on the strategy space $\{P_j^d\}$.
- For any participant j, the utility function $u_j(P_j^d, P_{-j}^d)$ is a proposed concave function about P_j^d.

Then the game has at least one pure strategy Nash equilibrium.

By analyzing the above optimization problem, it can be found that the second order derivative of its utility function $u_j(P_j^d, P_{-j}^d)$ with respect to P_j^d can be expressed as:

$$\frac{\partial^2 u_j(P_j^d, P_{-j}^d)}{\partial (P_j^d)^2} = \frac{-(g_j^i)^2}{\ln 2(P_j^d g_j^i + I_j^d)^2} \tag{31}$$

It can be found that (31) is less than 0 constant, so the utility function $u_j(P_j^d, P_{-j}^d)$ of D2D users is a concave function about P_j^d and is continuous. Meanwhile, the strategy space of D2D users consisting of (20) and (21) can be rewritten as:

$$\begin{cases} 0 \le P_j^d \le P_{\max}^d \\ P_j^d \le \dfrac{P_{i,l}^c g_{i,B}}{\gamma_{i,\min}^c h_{j,B}^i} - \dfrac{\sigma_n^2 + \sum_{m \in \mathbf{D}_i, m \neq j} P_m^d h_{m,B}^i}{h_{j,B}^i} \end{cases} \tag{32}$$

It can be found that the strategy space represented by (32) is the set enclosed by the affine function about P_j^d. The strategy space $\{P_j^d\}$ of the transmit power of the D2D user j is a tightly convex set and the set is non-empty. By analyzing the strategy space and utility function of the game $G := \{\mathbf{D}_i; \{P_j^d\}; \{u_j\}\}$ as described above, it can be obtained that the noncooperative game constructed in this paper satisfies the above conditions. Therefore, there exists a Nash equilibrium solution for the game $G := \{\mathbf{D}_{i;\{P_j^d\};\{u_j\}}\}$. Proof completes.

APPENDIX B

The utility function $u_j(P_j^d, P_{-j}^d)$ about P_j^d for the D2D user represented by (18) can be obtained by solving for the first-order partial derivative and making the first-order partial derivative equal to zero:

$$\begin{aligned} \frac{\partial u_j(P_j^d, P_{-j}^d)}{\partial P_j^d} &= \frac{g_j^i}{\ln 2(I_j^d + P_j^d g_j^i)} - \frac{\sum_{m \in \mathbf{D}_i, m \neq j} h_{j,m}^i}{I_j^d} \\ &= 0 \end{aligned} \tag{33}$$

$$P_j^{d*} = [\frac{I_j^d}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{I_j^d}{g_j^i}]^+ \tag{34}$$

where $[x]^+ = \max\{0, x\}$. The obtained optimal transmit power P_j^{d*} of the D2D user j is the optimal response function $P = B(P)$ of the D2D user j when the transmit power P_{-j}^d of other D2D users is determined.

It is known that a noncooperative game has a unique pure strategy Nash equilibrium if, for any participant in the game j, its optimal response function $P = B(P)$ is a standard function. $P = B(P)$ is a standard function if it is satisfied in its domain of definition:

- Positivity: $B(P) > 0$
- Monotonicity: if $P \geq P'$, then there are $B(P) \geq B(P')$
- Scalability: for any $\lambda > 1$, there are $\lambda B(P) > B(\lambda P)$

Since for any D2D user j, its optimal response function satisfies $B(P) > 0$, the optimal response function $P = B(P)$ satisfies positivity. And for any $P \geq P'$, we can get

$$\begin{aligned} B(P) - B(P') = {} & I_j^d(P)[\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & - I_j^d(P')[\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & = [I_j^d(P) - I_j^d(P')][\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & > 0 \end{aligned} \tag{35}$$

holds and the optimal reaction function $P = B(P)$ satisfies monotonicity. For any $\lambda > 1$, we can get

$$\begin{aligned} & \lambda B(P) - B(\lambda P) \\ & = \lambda I_j^d(P)[\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & \quad - I_j^d(\lambda P)[\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & = [\lambda I_j^d(P) - I_j^d(\lambda P)][\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & = [\lambda(\sigma_n^2 + P_{i,l}^c h_{i,j} + \sum_{m\in \mathbf{D}_i, m\neq j} P_m^d h_{m,j}^i) \\ & \quad - (\sigma_n^2 + P_{i,l}^c h_{i,j} + \lambda \sum_{m\in \mathbf{D}_i, m\neq j} P_m^d h_{m,j}^i)] \\ & \quad \times [\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & = [\lambda(\sigma_n^2 + P_{i,l}^c h_{i,j}) - (\sigma_n^2 + P_{i,l}^c h_{i,j})] \\ & \quad \times [\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & = [(\lambda - 1)(\sigma_n^2 + P_{i,l}^c h_{i,j})][\frac{1}{\ln 2 \sum_{m\in \mathbf{D}_i, m\neq j} h_{j,m}^i} - \frac{1}{g_j^i}]^+ \\ & > 0 \end{aligned} \tag{36}$$

holds and the optimal reaction function $P = B(P)$ satisfies scalability. Therefore, the reaction function $P = B(P)$ is a standard function. Proof completes.

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