electronics

MDPI

Article

An Approach to Maximize the Admitted Device-to-Device Pairs in MU-MIMO Cellular Networks

Yubo Wang [1], Fang Liu [2,*], Zhixin Li [2], Songchao Chen [2] and Xu Zhao [1,*]

[1] Beijing Smart-Chip Microelectronics Technology Co., Ltd., Beijing 100192, China; wangyubo@sgchip.sgcc.com.cn
[2] School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China; ljzx@bupt.edu.cn (Z.L.); csongchao@bupt.edu.cn (S.C.)
* Correspondence: lf@bupt.edu.cn (F.L.); zhaoxu@sgchip.sgcc.com.cn (X.Z.)

Abstract: Due to the shortage of wireless resources and the emergence of a large number of users, determining how to guarantee the quality-of-service (QoS) requirements of users and make more users work in the same spectrum has become an urgent research topic. In this paper, we study a multi-user MIMO (MU-MIMO) cellular network system model in which cellular users (CUs) share the same spectrum resource with multiple device-to-device (D2D) pairs. To maximize the number of admitted D2D pairs sharing the same spectrum with the CUs, a joint power allocation and channel gain (JPACG) algorithm is proposed. The optimization problem is divided into two steps to be solved. First, the power allocation of CUs without D2D pairs admitted is solved. Then, the optimization problem is transformed into minimizing the interference to CUs when CUs are treated as primary users. The admittance order of D2D pairs is determined by the transmission power and channel gain. The proposed algorithm uses a convex optimization algorithm to solve the problem of power allocation joint interference channel gain in order to maximize the number of admitted D2D pairs under the constraints of the signal-to-interference-plus-noise ratio (SINR) threshold and maximum transmission power. In addition, the effect of the number of admitted D2D pairs on the total sum rate of all users is also analyzed. The simulation results show that the proposed JPACG algorithm can achieve better performance in admitting D2D pairs.

Keywords: device-to-device; multi-user MIMO; power allocation; cellular networks

check for updates

Citation: Wang, Y.; Liu, F.; Li, Z.; Chen, S.; Zhao, X. An Approach to Maximize the Admitted Device-to-Device Pairs in MU-MIMO Cellular Networks. *Electronics* **2024**, *13*, 1198. https://doi.org/10.3390/electronics13071198

Academic Editor: Adão Silva

Received: 16 January 2024
Revised: 11 March 2024
Accepted: 21 March 2024
Published: 25 March 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The combination of underlaid device-to-device (D2D) communication and multi-input and multi-output (MIMO) is a popular research topic in cellular networks [1–4]. They are also promising technologies for 6G wireless communication networks [5], which are adopted to achieve higher data rate, higher spectral efficiency (SE), and higher energy efficiency (EE) with lower delay. D2D communications enable direct communication between two short-distance mobile users without traversing the base station (BS) [6], which allows for lower power consumption to transmit a higher data rate [7]. Two mobile users form a D2D pair, which can share the same spectrum resource with a cellular user (CU) in underlaid networks [8,9]. The underlaid D2D pair can improve the spectral efficiency of the entire network, but it can also introduce additional interference to CUs. In addition, multi-user MIMO (MU-MIMO) technology can support wireless communication between BS with multiple antennas and multiple cellular users and reduce the interference between CUs in order to provide higher performance for cellular wireless communication [10–13]. Due to the emergence of massive machine-type communication (mMTC) in 5G, many studies consider combining these two technologies to support the scenarios with high-density communication equipment, reasonable transmission rate, and low transmission power. The combination of D2D and MU-MIMO can improve spectral efficiency and reduce energy consumption. At the same time, however, the interference is more complex when multiple

D2D pairs work in an MU-MIMO cellular system. Therefore, there are many studies on how to reduce the interference through power optimization in mixed MU-MIMO and D2D scenarios [2].

The interference found in MU-MIMO cellular systems with D2D communication mainly involves the inter-user interference between MIMO CUs and the inter-link interference between CUs and D2D pairs sharing the same spectrum [14,15]. Precoding schemes can reduce the inter-user interference among the CUs in MU-MIMO systems [16]. Typical precoding schemes include zero forcing (ZF) [17] and minimum mean square error (MMSE) [18].

In order to determine the number of users that can share a spectrum with minimal inference, some studies have examined the selection of the admittance order of shared users [19–25]. Among these studies, the research target of [19–22] is the number of admitted users, while [23–25] mainly focuses on maximizing the sum rate, which is achieved by adjusting the order of the users admitted. Notably, the all channel state information (AllCSI) algorithm is proposed in [20], which considers the problem of joint power and admission control in uplink cellular networks where both primary and secondary users have quality of service (QoS) constraints. The number of admitted secondary users was maximized, and the total power required to serve them was minimized. However, this algorithm assumed the fixed power of a single primary user in order to solve the optimization problem, and it may be difficult for a MIMO cellular network to support multiple CUs for transmission with different power allocations.

M. Ali [21] developed a lower bound on the achievable user rate which was used to bound the maximum number of pairs that can be served by a two-way massive MIMO relay system. In this system, all users transmitted to the relay in the same time slot and received data from the relay in the next time slot. The MIMO relay applied maximum-ratio combing to the received signal and the re-transmitted data using maximum-ratio transmitting. Only inter-user interference in MIMO transmissions was considered by the algorithm, and further research should be conducted for D2D communication underlaying MIMO cellular networks. In [22], the authors recognized the correlation of the user channel and selected users by utilizing a real-time depth deterministic strategy gradient (RT-DDPG) in a single-cell downlink MU-MIMO network where the BS and users were equipped with multiple antennas. The algorithm aimed to select a subset of users among an active user set in order to minimize inter-user interference and maximize capability on each sub-band independently. The RT-DDPG showed the selected users and their frequency resources simultaneously across all sub-bands and met the requirement of minimum correlation between the selected users. However, this algorithm only considered the inter-user interference for MIMO transmission while not considering resource sharing within D2D user pairs.

In [23], a sequential admitted algorithm (SAA) was proposed to investigate three precoding methods and present a binary vector search algorithm used to admit D2D user pairs to a cellular network with multiple CUs and multiple direct D2D pairs underlaying communications with a central BS equipped with multiple antennas. The algorithm was used to solve the problem of maximizing the overall rate of the CUs and D2D pairs. It sequentially accessed the CUs in descending order of their signal-to-interference-plus-noise ratio (SINR) first, and then accessed the D2D user pair with the smallest channel gain norm to the accessed CU until the overall rate did not meet the required conditions. However, this algorithm did not consider the constraints of required rate placed on CUs and D2D users. In [24], a joint power and distance selection (JPDS) algorithm was proposed to maximize the overall sum rate of the network while guaranteeing the QoS requirements of CUs and admitted D2D pairs for uplink resource sharing between a CU and multiple D2D pairs. First, the CU located the largest distance from the BS was selected, after which the D2D pair the largest distance from the chosen CU was selected, and other D2D pairs were subsequently selected to re-use the resource block of the chosen CU based on the specific distance and power metric at each step, which ultimately required significant signal overhead to transmit

interference information. Moreover, this algorithm only considered the impact of distance, namely a large-scale fading of communication quality for single-antenna cellular systems, and there is still room for improvement in MIMO cellular systems. In [25], the closed-form expressions for the sum data rate of both cellular links and D2D links were derived in the D2D-aided underlaid cellular networks. The optimal and maximum numbers of activated D2D links corresponding to the maximum capacity and the minimum QoS requirements of the users, respectively, were identified. However, the close-form expression was derived for a cellular network with a central BS equipped with one antenna, which cannot directly be used in the MU-MIMO cellular network.

Some studies have also been conducted on analyzing power allocation in order to reduce the interference between users and improve the system throughput in D2D-underlaid cellular networks and the situation with MU-MIMO communication. In [26–30], several joint resource allocation and power control algorithms were proposed to maximize the energy efficiency while guaranteeing the QoS of CUs and D2D user pairs. Refs. [31,32] provided approximate concave–convex power control algorithms to maximize the minimum SE within D2D-underlaid MIMO cellular systems.

From the references provided above, we can see that there are few works jointly considering D2D-underlaid communication in MU-MIMO cellular networks for uplink resource sharing in order to solve the inter-user and inter-link interference problem, especially for the purpose of optimizing the number of shared D2D user pairs, which is very worthy of study as a means to improve the system capacity. In addition, the existing algorithms cannot provide a perfect solution, which consider the assumption and constraints of optimization problem either in a single way or with high complexity.Therefore, an optimization algorithm with a better effect and lower complexity is urgently needed.

In this paper, we study a shared channel to admit the maximal D2D user pairs for uplink MU-MIMO cellular networks. Specifically, we propose the joint power allocation and channel gain (JPACG) algorithm, which jointly considers the influence of user transmission power and channel gain. The main contributions of this article can be summarized as follows.

- We consider a system model for a single-cell uplink D2D communications underlaying an MU-MIMO cellular network. The CUs communicate with BS via uplink MU-MIMO using precoding technology.
- We consider complex interference scenarios including inter-user interference between MIMO CUs and inter-link interference between CUs and D2D pairs, and between D2D user pairs sharing the same spectrum, and derive the SINR expressions of MU-MIMO cellular communication and the admitted D2D user pairs sharing the same spectrum. The optimization challenge of maximizing the number of admitted D2D user pairs is formulated as minimizing the interference.
- To solve this problem, we transform it into two sub-problems: power allocation for CUs without D2D user pairs and admitted order selection for D2D user pairs. The JPACG algorithm is proposed to solve the problem of the admitted order of D2D user pairs.

The organization of this paper is as follows. In Section 2, the system model is presented for the uplink MU-MIMO cellular networks. The optimization problem is formulated in Section 3, and its solution is presented in Section 4. The simulation results and discussion are provided in Section 5. Finally, the conclusions are given in Section 6.

2. System Model

In a general scenario, we consider multiple D2D user pairs sharing the same spectrum with multiple uplink CUs in a single-cell MU-MIMO cellular network. As shown in Figure 1, a BS with M antennas is situated in the center of the cell, the coverage of which is a circle with radius R. M_C ($M_C \geq M$) CUs equipped with one antenna are randomly distributed in a circle with radius r centered on the BS. Therefore, BS can communicate with up to M CUs simultaneously by using MU-MIMO spatial multiplexing techniques.

The number of CUs M is determined by the antenna number of the BS, and the M CUs are selected according to the maximal reachable rate from M_C active CUs. Meanwhile, N pairs of D2D users are randomly distributed in the coverage area more than r meters away from BS. The interference caused by D2D user pairs to the BS is reduced by increasing the path loss of D2D user pairs to the BS, which helps the system to admit more users sharing the same spectrum. We consider that both the transmitter and receiver of the D2D pair are equipped with one antenna. We also consider at most K out of N D2D user pairs are admitted into the system and share the same spectrum with the uplink MU-MIMO CUs. The K pairs of D2D user in the ring range of radius r to R are selected according to the optimization targets. All D2D user pairs are potential alternative nodes, and the determination of K D2D user pairs is dependent on the D2D user pair selection algorithm, namely the JPACG algorithm. For easy expression, we use $\mathcal{C} = \{C_1, C_2, \cdots, C_{M_C}\}$ to represent the M_C CUs and $\mathcal{D} = \{D_1, D_2, \cdots, D_N\}$ to represent the N D2D user pairs. The transmitter and receiver of the n-th D2D user pair D_n are represented as T_n, R_n.

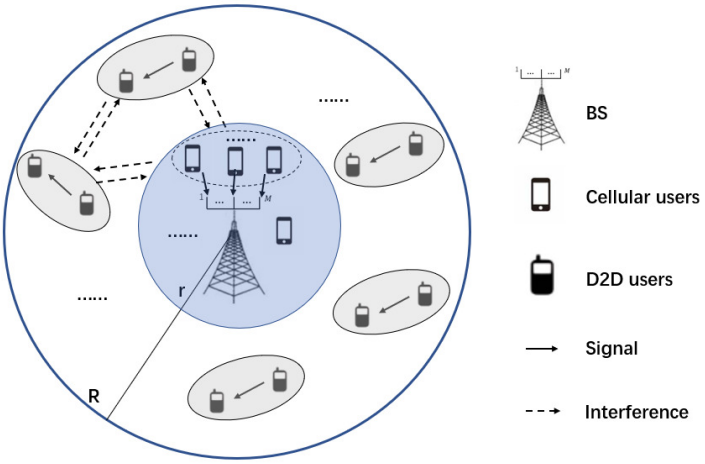

Figure 1. System Model.

According to the signal model and its interference problem, after admitting K D2D user pairs, BS receives the useful signal from C_m, the interference from other CUs working in the MU-MIMO, the interference from the admitted D2D pairs, and noise. Therefore, the received signal vector y_{C_m} from C_m at the BS is given as follows, similar to existing works [22–24].

$$y_{C_m} = \sum_{m=1}^{M} \sqrt{L_{C_m B} P_{C_m}} \mathbf{h}_{C_m B} s_{C_m} + \sum_{k=1}^{K} \sqrt{L_{T_k B} P_{D_k}} h_{T_k C_m} s_{D_k} + n_B \tag{1}$$

where s_{C_m} and s_{D_k} are the corresponding transmit signals from C_m and D_k , with $E[\|s_{C_m}\|^2] = 1$, $E[\|s_{D_k}\|^2] = 1$. $L_{lf} = {d_{lf}}^{-\alpha} (l = T_k, C_m; f = B, R_k)$ represents the large-scale fading coefficient of transmitter l to receiver f, where d_{lf} represents the distance between transmitter l and receiver f, and α is a path-loss fading exponent. P_{C_m} and P_{D_k} are the transmission power of C_m and D_k. $\mathbf{h}_{C_m B} \in C^{1 \times M}$ is the small-scale fading vector between C_m and the BS antennas. $h_{lf} \in C^{1 \times 1} (l = T_k, C_m; f = C_m, R_k; l \neq k)$ represents the channel coefficients between single antenna users, which follows an independent complex Gaussian distribution with zero mean and unit variance. Further, n_B is the additive white Gaussian noise (AWGN) at BS and follows CN $(0, \sigma^2)$ with zero mean and σ^2 variance.

In an MU-MIMO system, the ZF detector scheme is used at the BS to eliminate the inter-link interference between CUs, where the ZF detector matrix $\mathbf{W} = [\, \mathbf{w}_{C_1}, \mathbf{w}_{C_2}, \cdots, \mathbf{w}_{C_M} \,] \in C^{M \times M}$ is given by

$$\mathbf{W} = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \tag{2}$$

with $\mathbf{H} = [\ \mathbf{h}_{C_1B}; \mathbf{h}_{C_2B}; \cdots; \mathbf{h}_{C_MB}\ ] \in C^{M\times M}$ being the channel matrix between M CUs and BS. The M CUs are selected from the M_C CUs according to the goal of minimizing the total transmission power of M CUs while satisfying the required QoS of CUs. The selected M CUs can be taken as active users for MU-MIMO transmission. If the CUs and D2D pairs are not selected, they are inactive or allocated to the orthorgonal frequency. Thus, they will not introduce interference to active users. During the data transmission, the active M CUs communicate with the BS through uplink to the MU-MIMO, and the D2D user pairs transmit data to each other directly. The in-frequency interference occur between uplink MU-MIMO CUs, between admitted D2D user pairs and CUs, and between different admitted D2D user pairs. In order to resolve the interference between uplink CUs, the precoding technology is used to eliminate the interference between multiple uplink users. The interference to the BS caused by D2D user pairs is reduced by increasing the distance path loss. The interference of CUs to D2D pairs and between admitted D2D pairs is reduced by the selection algorithm of D2D user pairs.

After the ZF detector scheme is used to eliminate interference between active CUs, the interference to the received signal y_{C_m} is mainly from the admitted D2D user pairs, which can be expressed as:

$$y_{C_m} = \sqrt{L_{C_mB}P_{C_m}}\mathbf{h}_{C_mB}\mathbf{w}_{C_m}s_{C_m} + \sum_{k=1}^{K}\sqrt{L_{T_kB}P_{D_k}}h_{T_kC_m}s_{D_k} + n_B \tag{3}$$

According to the signal model and interference problem, the receiving signal $y_{D_{R_j}}$ at the receiver R_k of the k-th D2D user pair D_k is as follows:

$$\begin{aligned} y_{D_{R_k}} = &\sqrt{L_{T_kR_k}P_{D_k}}h_{T_kR_k}s_{D_k} + \sum_{n=1,n\neq k}^{K}\sqrt{L_{T_nR_k}P_{D_n}}h_{T_nR_k}s_{D_n} \\ &+ \sum_{m=1}^{M}\sqrt{L_{C_mR_k}P_{C_m}}\mathbf{h}_{C_mB}\mathbf{w}_{C_m}s_{C_m} + n_{D_{R_k}} \end{aligned} \tag{4}$$

In (4), the received signal of y_{R_k} at R_k includes the transmitted signal s_{D_k} from T_k, the in-frequency interference from other admitted D2D pairs and CUs, and noise. The P_{D_k}, P_{D_n} represent the transmission power of different D2D user pairs. n_{R_k} represents the zero-mean complex Gaussian noise at the k-th D2D pair receiver and follows $CN\ (0, \sigma^2)$.

Then, let $G_{lf} = L_{lf}|h_{lf}|^2 (l = T_k, C_m; f = B, R_k)$ represent the channel gain. According to the signal formula we obtained above in (3), we can calculate the received SINR γ_{C_m} of C_m at the BS side as

$$\gamma_{C_m} = \frac{P_{C_m}G_{C_mB}}{\sum_{k=1}^{K}P_{D_k}G_{T_kB} + \sigma^2} \tag{5}$$

$$\gamma_{D_k} = \frac{P_{D_k}G_{T_kR_k}}{\sum_{n=1,n\neq k}^{K}P_{D_n}G_{T_nR_k} + \sum_{m=1}^{M}P_{C_m}G_{C_mR_k} + \sigma^2} \tag{6}$$

From (5) and (6), it can be seen that the transmission performance of CUs and D2D users is mainly affected by transmitted power and channel gain.

3. Problem Formulation

According to the above signal expression and SINR derivation process, it can be found that the transmission power and channel state information of users are the key parameters affecting the communication quality. In this section, we investigate the joint power control and channel gain for the uplink MU-MIMO cellular system, aiming to achieve the maximal number of admitted D2D user pairs with the constraint of a predefined QoS. The optimization problem of maximizing the number of D2D pairs sharing frequency resources

with CUs is equivalent to minimizing the total interference of the system. This problem is formulated as follows.

$$\min \quad I_{sum} = I_{C-D} + I_{D-C} \tag{7a}$$
$$s.t. \quad \gamma_{C_m} \geq \gamma_{C_0} \quad m = 1, 2, \cdots, M \tag{7b}$$
$$\gamma_{D_k} \geq \gamma_{D_0} \quad k = 1, 2, \cdots, K \tag{7c}$$
$$0 \leq P_{C_m} \leq P_{C_{max}} \quad m = 1, 2, \cdots, M \tag{7d}$$
$$0 \leq P_{D_k} \leq P_{D_{max}} \quad k = 1, 2, \cdots, K \tag{7e}$$

In Equation (7a), the optimization goal is to minimize the total interference of CUs and the admitted D2D user pairs. I_{C-D} and I_{D-C} respectively denote the interference of CUs to admitted D2D pairs and the interference of admitted D2D pairs to cellular communication. The reason for setting this goal is to reduce the interference between users as much as possible so that the number of admitted D2D pairs can be increased for resource sharing. K denotes the maximum number of admitted D2D pairs. We chose SINR as the criterion to judge the quality of user communication service. Equations (7b) and (7c) denote that the SINR of each CU and each D2D pair should meet the minimum SINR requirements γ_{C_0} and γ_{D_0}, respectively, and (7d) and (7e) ensure that the transmission power of CUs and D2D pairs does not exceed the power budgets $P_{C_{max}}$ and $P_{D_{max}}$.

We can see that the problem in (7a) is difficult to solve directly. The major difficulty in solving (7a) arises from the fact that the formulaic problem is non-convex and that the transmission powers of uplink MU-MIMO CUs and admitted D2D pairs influence each other.

4. The Solution for the Formulated Problem

In this section, we propose a JPACG optimization algorithm for the formulated problem (7a). In order to simplify the solution process, we focus on reducing the interference of the admitted D2D pairs to the CUs in order to achieve more admitted D2D user pairs. We transform (7a) into two sub-problems to obtain the optimal result. The concrete realization process includes two parts: one subsection realizes the power allocation of CUs without D2D pairs admitted, while the other subsection presents the realization process of the JPACG algorithm in detail.

4.1. Power Allocation of CUs

As the system model introduced in Section 2. The total number of CUs M_C is larger than the number of receiving antennas at the BS M; therefore, we can select the M CUs matching the number of BS antennas to carry out MU-MIMO uplink communication. According to (7a), we can see that the interference received by the receiver of one admitted D2D user pair includes the interference from active CUs and the interference from other admitted D2D pairs. Therefore, if the appropriate CUs are selected, the interference from active CUs to the admitted D2D pairs will be reduced, which is helpful for achieving the optimization objective.

In order to achieve the QoS of the CUs in the initial scenario, we first allocate power to the CUs without D2D pairs admitted. Based on the criteria from the previous analysis, in order to decrease the interference from active CUs to admitted D2D pairs, we choose the M CUs with the lowest total transmission power after power allocation. In this case, the first sub-problem can be expressed as

$$\max_{P_{C_m}} \quad R_C = \sum_{m=1}^{M} \log_2(1 + \gamma_{C_m}) \tag{8a}$$
$$s.t. \quad \gamma_{C_m} \geq \gamma_{C_0} \quad m = 1, 2, \cdots, M \tag{8b}$$
$$0 \leq P_{C_m} \leq P_{C_{max}} \quad m = 1, 2, \cdots, M \tag{8c}$$

The problem used to solve the maximal sum rate of active CUs is a non-convex problem, which makes it difficult to solve directly. Therefore, we transform it into a convex problem through first-order Taylor expansion. After (8a) is expanded by the first-order Taylor function at point $P_{C_m 0}$, the approximate expression is

$$\begin{aligned} \max_{P_{C_m}} \quad & R_C = \sum_{m=1}^{M} \log_2(1+\gamma_{C_m}) \\ \approx & \sum_{m=1}^{M} \left\{ \log_2\left(1+\frac{P_{C_m 0} G_{C_m B}}{\sigma^2}\right) + \right. \\ & \left. (P_{C_m} - P_{C_m 0}) \left(\frac{G_{C_m B}}{\sigma^2 \ln 2 (1+P_{C_m 0})}\right) \right\} \end{aligned} \tag{9}$$

Equation (9) is a linear function of P_{C_m}, so we can obtain the power allocation when the R_C achieves the maximum value.

Considering that the number of CUs M_C is larger than the antenna number of BS M, we need to choose M CUs out of M_C CUs. The selection of M active CUs involves the design of a channel matrix and its corresponding ZF precoding matrix.

We use the following matrix expression as an example to express the selection process of active cellular users. The initial channel matrix $\mathbf{H}_C \in C^{M_C \times M_C}$ composed of M_C CUs is

$$\mathbf{H}_C = \begin{pmatrix} h_{11} & \cdots & h_{1M} & \cdots & h_{1M_C} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ h_{M1} & \cdots & h_{MM} & \cdots & h_{MM_C} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ h_{M_C 1} & \cdots & h_{M_C M} & \cdots & h_{M_C M_C} \end{pmatrix} \tag{10}$$

where h_{ij} represents the channel coefficients between C_i and C_j. In order to make full use of BS's receiving antennas, we need to select M active CUs to communicate with BS through uplink MU-MIMO communication. There are $C_{M_C}^{M}$ options for active CUs; we integrate the combination of each option into a matrix, which expressed as $\mathbf{Q} = [q_1, q_2, \cdots, q_i, \cdots, q_{C_{M_C}^{M}}]$, where q_i represents the set of active CUs.

From the newly formed channel matrix, we can obtain the ZF precoding matrix $\mathbf{W}$ following (2). Then, we can obtain the power allocation of M CUs according to (9) through convex optimization.

After the above derivation, the M active cellular users for MU-MIMO communication with BS will be selected. The goal is to maximize the sum rate of the uplink MU-MIMO cellular network with the minimal sum transmission power of the CUs.

Given that the uplink MU-MIMO CUs and the admitted D2D pairs share the same spectrum, interference exists between CUs and D2D users. In order to decrease the interference between active CUs and simplify the solving process of the problem, we fix the transmission power for CUs without an admitted D2D user pair. That is to say, in the process of solving the following equations, the transmission powers of active CUs are constant values.

4.2. The JPACG Algorithm

Having determined the power allocation for CUs, we then start to consider the admitted D2D pairs. It can be observed from (5) that the interference caused by D2D user pairs to CUs is mainly affected by the product of the transmission power and the gain of the jamming channel $P_{D_k} G_{T_k B}$. Therefore, we consider transforming the problem of minimizing the admitted D2D pairs' interference to CUs into the choice of the admittance order of D2D pairs so as to minimize the product sum of $P_{D_k} G_{T_k B}$. As the product sum of $P_{D_k} G_{T_k B}$ is a linear function of the transmission power P_{D_k}, it meets the conditions of convex

optimization. Therefore, according to the above problem transformation ideas, the objective (7a) of minimizing the interference of the admitted D2D pairs to CUs is rewritten into the following second sub-problem (11a):

$$\min_{P_{D_k}} \quad \sum_{k=1}^{K} P_{D_k} G_{T_k B} \tag{11a}$$

$$s.t. \quad \gamma_{C_m} \geq \gamma_{C_0} \quad m = 1, 2, \cdots, M \tag{11b}$$

$$\gamma_{D_k} \geq \gamma_{D_0} \quad k = 1, 2, \cdots, K \tag{11c}$$

$$0 \leq P_{D_k} \leq P_{D_{max}} \quad k = 1, 2, \cdots, K \tag{11d}$$

The main target we solved for was to get the maximum number of admitted D2D pairs, so we need to choose among the N pairs of D2D. As we assume in the system model, the initial set $\mathcal{D}$ of total N pairs of D2D is

$$\mathcal{D} = [D_1, D_2, D_3 \cdots D_N] \tag{12}$$

At this point, the admitted D2D pairs set $\mathcal{K}$ is empty. When we select the first D2D pair, there is no D2D inter-pair interference, so we only need to select the pair of D2D users with the least interference to the cellular link. To be more specific, all D2D pairs are admitted to the system individually. According to Equation (11a), the transmission power of a D2D user is solved through convex optimization, and whether the constraint condition is met at this time is judged. The D2D pair with the lowest product of transmission power and interference channel gain is selected as the first pair to admit, which is represented as DS_1. Now, the admitted D2D pairs set $\mathcal{K} = [DS_1]$ and the remaining D2D pairs sets $\mathcal{D}'$ have $(N-1)$ elements of $\mathcal{D}$, except for DS_1.

After the first D2D pair is admitted, we look for the second pair among the remaining D2D pairs. In this case, one D2D pair has been admitted to the system. There will be interference between D2D pairs. The D2D pairs already admitted to the system will not be eliminated, but it will consider adjusting the power of the second pair. We need to solve for the two D2D pairs admitted to the system again according to (11a). We can obtain $(N-1)$ groups of results. Then, we find the group that satisfies the constraints and has the smallest product sum. The selected group is our new set $\mathcal{K} = [DS_1, DS_2]$, and we get the next admitted D2D pair. In this case, there are two elements in the set $\mathcal{K}$, and the remaining D2D pairs have $(N-2)$ elements in the set $\mathcal{D}'$.

Based on this selection method, we provide a general process description. We need to select K eligible D2D pairs from N D2D pairs ($N \geq K$) to access the system. Assume that we have admitted n pairs of D2D users. The next step is to select the $(n+1)$-th D2D pair from the remaining $(N-n)$ pairs. The $(n+1)$-th pair satisfies the constraints and has the minimal sum $\sum_{k=1}^{n+1} P_{D_k} G_{T_k B}$.

When the set $\mathcal{K}$ has admitted n pairs of D2D user, it can be expressed as follows:

$$\mathcal{K} = [DS_1, DS_2, DS_3 \cdots DS_n] \tag{13}$$

In order to find the most suitable $(n+1)$-th pair of D2D, we need to select the DS_{n+1} from the remaining $(N-n)$ D2D pairs $\mathcal{D}'$ for power allocation.

$$\mathcal{D}' = \mathcal{D} - \mathcal{K}; \tag{14}$$

When the D_k is admitted as the $(n+1)$-th pair of D2D users, the channel gains G_{lf} ($l = D_{T_k}, C_m; f = B, D_{R_k}$) are updated based on the position and channel state information of D_k. As can be seen from (9), after the power allocation of CUs P_{C_m} is fixed, both the problem and the constraint conditions are linear functions of P_{D_k} which meet the solving conditions of convex optimization.

After we obtain the power allocation of the *(n + 1)*-th D2D pairs for the $(N-n)$ remaining D2D pairs, we can find their minimal results, and we set this new D2D pair as

DS_{n+1}. If the power allocation P_{D_k} satisfies the constraints (11b)–(11d), then the DS_{n+1} can be admitted into the system. At this time, $n = n + 1$. When any of three constraints are not met, the DS_{n+1} cannot be admitted into the system. At time, $K = n$, we obtain the maximal number of admitted D2D pairs K and the power allocation of each pair of admitted D2D user pair.

Therefore, our proposed JPACG algorithm can be summarized in Algorithm 1.

Algorithm 1: The Proposed JPACG Algorithm

Input: Parameters of the system, R, r, d, M, N, P_{C_m}, $P_{D_{max}}$, γ_{C_0}, γ_{D_0}, σ^2
Output: K, allocation of power P_{D_k}, for $k = 1, 2, \cdots, K$

```
Initialization: Power Allocation of CUs P_{C_m}
while n ⊂ N do
    for k ⊂ (N − n) do
        Update the channel gain G_{lf}(l = D_{T_k}, C_m; f = B, D_{R_k}) Obtain P_{D_{n+1}} by
         solving (11)
    end
    for k ⊂ (N − n) do
        Select the minimum ∑_{k=1}^{n+1} P_{D_k} G_{T_k B}
    end
    if and else;
    if (11a)–(11c) then
        n = n + 1
    else
        K = n
    end
end
```

5. Simulation Analysis

In this section, numerical simulation results are evaluated in order to show the performance of the proposed JPACG algorithm. The main simulation parameters are listed in Table 1. In the simulation, we analyze the effects of different parameters on the proposed JPACG algorithm and conventional algorithms, including CUs number, D2D user pairs, circle radius, and SINR budget of D2D pairs. In the simulation parameter settings, the cell radius, the D2D distance, and the circle radius are respectively set to 1000 m, 20 m, and 400 m. The related data required by the algorithms are generated randomly and collected in real time. In addition, considering that the more device nodes sharing the same frequency, the stronger the in-frequency interference, limited device nodes are assumed. Practically, though, our proposed algorithm has no restrictions on the number of device nodes.

Table 1. Simulation parameters.

Parameter	Value
Cell radius, R	1000 m
Circle radius, r	400–800 m
Distance between one D2D pair, d	20 m
Number of CUs, M_C	10
Number of D2D pairs, N	16, 20
BS antennas, M	4
Power budget of CUs, $P_{C_{max}}$	24 dBm
Power budget of D2D pairs, $P_{D_{max}}$	18 dBm
SINR budget of CUs,γ_{C_0}	15 dB
SINR budget of D2D pairs,γ_{D_0}	0–15 dB
Path loss exponent, α	3.5
Noise power, σ^2	−110 dBm

In order to evaluate the performance of the proposed JPACG algorithm, the following three algorithms are introduced to compare. The SAA, found in Ref. [23], determines whether D2D users can share by setting binary parameters λ_j, with $\lambda_j = 1$ meaning sharing and $\lambda_j = 0$ meaning not sharing. The SAA algorithm sequentially accessed the D2D user pairs in the ascending order of channel gain norm to the accessed CU until the constraint conditions are not met. The execution process is simple, and there are no options for varying communication conditions. Moreover, the randomness is high, and it has the most unstable performance. In the AllCSI algorithm [20], D2D users share the same spectrum with the CUs according to the value of the interference channel in order from small to large. According to the channel state information on the interference caused by D2D pairs to the CU communication when accessing the same spectrum, access is arranged in ascending order to reduce the in-frequency interference caused by D2D users to cellular users. Compared to the SAA algorithm, AllCSI has more choices for user state information, but it does not take into account the influence of factors such as user transmission power and distance fading, resulting in low complexity and improved performance. However, it is not an excellent algorithm. In Ref. [24], the JPDS algorithm was proposed to determine the sequence selection for admitted D2D users. By coordinating the selection of D2D pairs with lower transmission power and longer communication distance, which cause less co-frequency interference, the problem can be solved. This algorithm considers both the impact of user channel status on communication quality and the adjustment of communication user power. However, this algorithm only considers the impact of distance, that being a large-scale fading of communication quality, and there is still room for improvement. In addition, the traditional exhaustive searching algorithm to maximize the sum rate is also considered in the simulation in order to analyze the number of admitted D2D users versus the sum rate. The exhaustive searching algorithm is used to search for all possible D2D pairs so as to find the D2D pair with the least interference to the current communication and allow it access. Due to the exhaustive searching algorithm traversing all possibilities, it can achieve optimal performance of sum rate while greatly increasing computational complexity.

While our proposed algorithm comprehensively considers the influence of channel state information and transmission power, including not only large-scale fading but also small-scale fading, and tries to reduce the computational complexity of traversal execution as much as possible, achieving the maximal number of D2D users sharing the same frequency with cellular users under the constraints of rate threshold.

Figure 2 shows the effect of the number of total D2D user pairs on the number of admitted D2D pairs for different algorithms. With the increase of total D2D user pairs from 4 to 16, the number of D2D pairs admitted by the four algorithms also rises. This is because the number of available D2D pairs to choose from is gradually increasing, meaning that the number of D2D user pairs that can be admitted into the system in accordance with the constraint conditions will also increase. Moreover, the JPACG algorithm admits more D2D user pairs than other algorithms. This is because the JPACG algorithm considers both transmission power and channel gain, which can minimize interference to the BS as much as possible. JPDS selects the minimal interference to cellular communication and other admitted D2D pairs, which leads to the admitted D2D pairs causing less interference to other D2D pairs but more interference to the BS.

The order of device selection prioritizes user communication that shares the same frequency band and introduces interference. The less interference brought by the device, the higher the communication QoS, so a good user-selection algorithm is very important to improving the communication quality, which can be proved through the formula derivation and simulation.

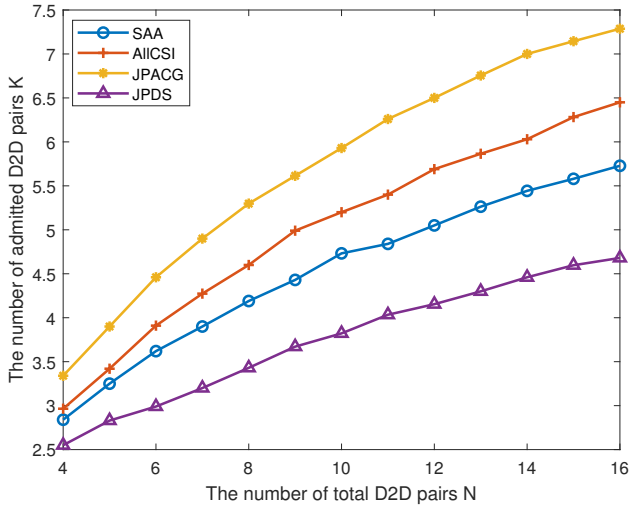

Figure 2. The number of admitted D2D pairs K versus the different number of total D2D pairs N for different algorithms (r = 600 m, M = 4, γ_{D_0} = 10 dB).

Figure 3 presents the effect of the SINR budget of D2D links on the number of admitted D2D pairs for four algorithms. With the increase of the SINR of D2D pairs γ_{D_0}, the constraints on the optimization problem become more and more stringent, so fewer and fewer admitted D2D user pairs can meet the requirements. Therefore, the numbers of admitted D2D user pairs given by the four algorithms show a decreasing trend. In addition, it can be seen from the simulation results that, among the four algorithms, the JPACG algorithm shares the largest number of D2D user pairs. This is because, when the JPACG algorithm selects the next D2D user pair, it selects the D2D user pair that satisfies the constraint conditions as much as possible and brings the least interference to cellular communication. The SAA algorithm and AllCSI algorithm obviously do not have a dynamic adjustment function. Although the JPDS algorithm also considers the influence of power allocation, it is easy to fail to meet the constraint conditions because it strictly selects the minimal distance of D2D user pairs, so the number of shared D2D user pairs is very small.

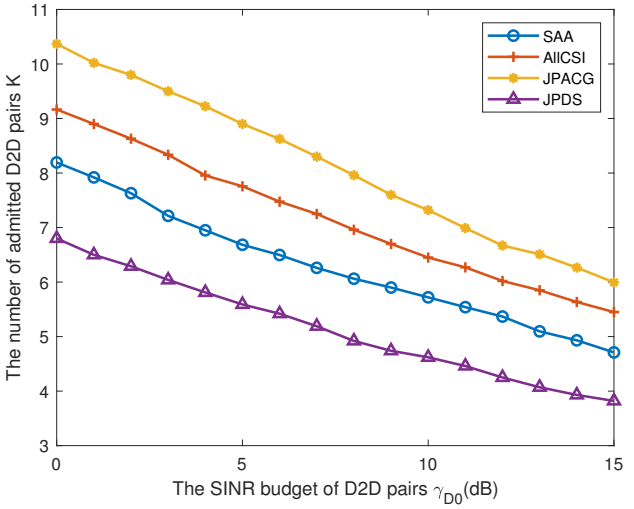

Figure 3. The number of admitted D2D pairs K versus the different SINR budgets of D2D pairs γ_{D_0} from different algorithms (r = 600 m, M = 4, N = 16).

Figure 4 shows the relationship between the number of admitted D2D pairs and the circle radius r. The circle radius r limits the distribution range of CUs and D2D user pairs and influences the interference between users from the perspective of large-scale fading.

With an increase of r, D2D user pairs will be distributed in a smaller range and farther away from the BS. Due to the path loss of large-scale fading, the admitted D2D users have less interference to the uplink signal received at the BS. Furthermore, because the total number of D2D user pairs is fixed, the number of D2D user pairs able to meet the constraint conditions will increase. As a result, the numbers of admitted D2D user pairs are on the rise for all four algorithms. In addition, as previously analyzed, it can be seen from the simulation results that the JPACG algorithm can admit the largest number of D2D user pairs, followed by the AllCSI algorithm and the SAA algorithm, while the JPDS algorithm admits the smallest number of D2D user pairs.

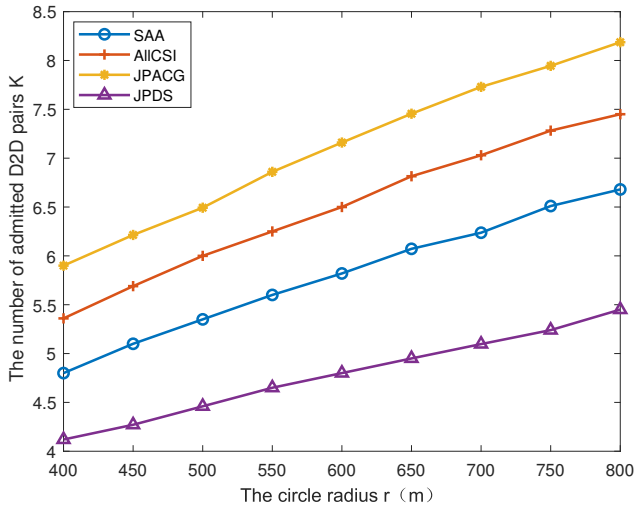

Figure 4. The number of admitted D2D pairs K versus the different circle radius r for different algorithms ($M = 4$, $N = 16$, $\gamma_{D_0} = 10$ dB).

Figures 5–7 show the relationship between the rate and the number of admitted D2D user pairs. In addition to comparing the previous four algorithms, an exhaustive searching algorithm with the goal of maximizing the system sum rate is also compared in the simulation in order to greatly explain the relationship between the sum rate and the number of admitted D2D user pairs.

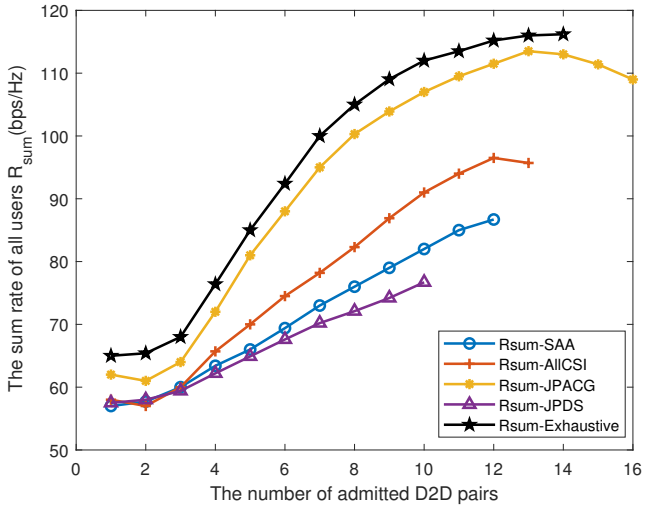

Figure 5. The sum rate of all users R_{sum} versus the number of admitted D2D pairs for different algorithms ($r = 600$ m, $M = 4$, $\gamma_{D_0} = 10$ dB, $N = 20$).

Figure 5 shows the changing trend of the sum rate as the number of admitted D2D users increases. It can be seen that different algorithms have different changing trends.

Since the exhaustive searching algorithm is used to search all user combinations with the goal of maximizing the sum rate, it overall shows an upward trend, and once the sum rate decreases, no new D2D user pairs will be admitted. As the number of admitted D2D user pairs increases, the sum rates of the SAA algorithm and JPDS algorithm decrease first and then increase. This is because the sum rate of the system includes the sum rate of CUs and the sum rate of admitted D2D user pairs. When the number of admitted D2D user pairs is small, the system sum rate is mainly affected by the sum rate of CUs. Since cellular communication is affected by the in-frequency interference of admitted D2D users, the sum rate of CUs decreases, resulting in a subsequent decrease in sum rate. When the number of admitted D2D user pairs increases to a certain number, the sum rate of D2D user pairs has a greater impact on the sum rate of the system. Therefore, the sum rate of the system increases with the increasing of the number of admitted D2D user pairs. When the number of D2D user pairs is not large enough, the changing trend of the JPACG and AllCSI algorithms is consistent with that of the SAA and JPDS algorithms, but they both show a downward trend in the end. This is because when the number of admitted D2D user pairs is too large, the interference between different D2D user pairs will increase and affect the communication quality of D2D user pairs, resulting in a decrease in sum rate. However, it can be proved that when the sum rate reaches the maximal value, the proposed JPACG can still support more users to share spectrum resources under certain QoS conditions.

It can also be seen from Figure 5 that with the increasing of admitted D2D user pairs, the sum rate of the JPACG algorithm is higher than that of the other three algorithms. This is because, with the increasing number of shared D2D user pairs, the sum rate of the system is mainly affected by the sum rate of admitted D2D user pairs. The SAA and AllCSI algorithms only allocate the minimal transmission power to the admitted D2D user pairs in order to meet the lowest constraint conditions. Thus, the admitted D2D user pairs only meet the lowest rate constraints. However, the JPACG algorithm allocates power to the admitted D2D user pairs with the goal of minimizing the product sum of the transmission power and channel gain, and the rate of each admitted D2D user pair achieved is higher than that of the SAA and AllCSI algorithms. Thus, it also achieves a higher sum rate. Although the JPDS algorithm does not allocate the minimal transmission power to the admitted D2D user pairs, the algorithm focuses more on reducing the interference between different D2D user pairs. Therefore, the number of admitted D2D user pairs is small, resulting in a low system sum rate.

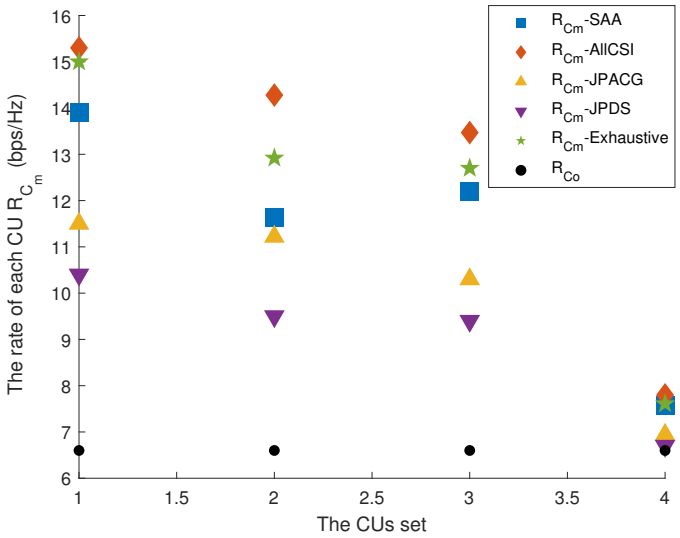

Figure 6. The rate of each CU R_{C_m} achieved by using different algorithms ($r = 600$ m, $M = 4$, $\gamma_{D_0} = 10$ dB, $N = 20$).

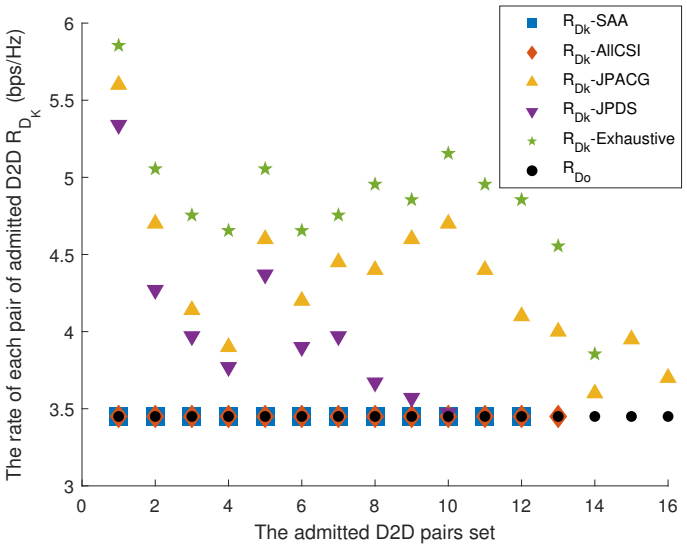

Figure 7. The rate of each pair of admitted D2D R_{D_k} achieved by using different algorithms (r = 600 m, M = 4, γ_{D_0} = 10 dB, N = 20).

To prove this, Figures 6 and 7 simulate the rate of each CU and each admitted D2D user pair for all algorithms when the maximal number of D2D user pairs is shared. The rate of all users is above the rate threshold and meets the constraint conditions.

It can be seen from Figures 6 and 7 that the AllCSI algorithm has a higher rate for CUs than other algorithms. This is because the AllCSI algorithm selects the D2D user pair with the least interference to the cellular link as the next admitted D2D user pair. However, the rate of admitted D2D user pairs only just reaches the rate threshold. In the SAA algorithm, both the CUs and the admitted D2D user pair are allocated the minimal amount of power that can satisfy the constraint conditions. However, because of its sequence characteristics, the rate of the CUs cannot be guaranteed to be large enough. Therefore, the sum rate achieved by the SAA algorithm is not high. Since the proposed JPACG algorithm is not meant to allocate the minimal transmission power to the admitted D2D user pairs, the interference of the admitted D2D user pairs to CUs in the algorithm will be greater than that of the SAA and AllCSI algorithms. Therefore, the rate of CUs in the JPACG algorithm is lower than that of the SAA and AllCSI algorithms, while the sum rate of its admitted D2D user pairs is higher than those of the other two algorithms. A similar scenario plays out for the JPDS algorithm. Since the JPDS algorithm takes into account the interference between different D2D user pairs, the rate of CUs and D2D user pairs cannot reach a high level. Since the exhaustive searching algorithm is meant to maximize the sum rate, the rate of both CUs and admitted D2D user pairs can reach a higher value.

In addition, from Figure 7, we can see that the sum rate of the JPACG algorithm is at most 5 bps/Hz lower than that of the exhaustive method, but the JPACG algorithm shares two more pairs of D2D users than the exhaustive method. In other words, the sum rate of the JPACG algorithm decreased by 4.7%, while the number of admitted D2D user pairs increased by 14.3%. Computational complexity is an important feature of observation methods. According to the algorithms introduced above, the computational complexities of both the SAA and AllCSI algorithms are **O** (n). The computational complexities of the JPACG and JPDS algorithms are **O** (n^2), while the exhaustive searching algorithm needs to traverse all cases, and its time complexity is **O** (n!). From the perspective of algorithms' performance, taking 13 pairs of admitted D2D users as an example, the exhaustive searching algorithm needs to be executed $C_{16}^{13} = 560$ times, while the JPACG algorithm only needs to be executed $\frac{(16+4)13}{2} = 130$ times, and the computational complexity is significantly reduced. It is verified that, compared with the exhaustive searching algorithm, the proposed JPACG algorithm can not only reduce the complexity, but also support more users to share

frequency resources with better communication quality. The SAA algorithm needs to be executed 13 times, the AllCSI algorithm needs to be executed 16 times, and the JPDS algorithm also needs to be executed 130 times. Compared to these algorithms, the JPACG algorithm has a better trade-off between complexity and performance.

6. Conclusions

In this paper, we consider an uplink multi-user MIMO cellular system where CUs and D2D user pairs are distributed in different areas of a cell. We propose the JPACG algorithm, which jointly investigates the power allocation and channel gain in order to maximize the number of admitted D2D pairs. To achieve this goal, we transform the problem into minimizing the interference between CUs and admitted D2D pairs, with CUs as the main users and all users satisfying their QoS. The proposed algorithm can reduce the computational complexity and achieve better performance. We also prove that when the system sum rate reaches the maximum, more users can still be admitted under the constraint conditions. This is helpful for future scenarios in which massive numbers of users access. In addition, the concepts of our proposed algorithm can be applied in mobile edge computing offloading to minimize the delay according to the inputting data of channel gain and user location which are used in this paper. In general, our proposed algorithm can greatly improve system capacity for massive machine type communication.

Author Contributions: Conceptualization, Y.W., F.L., Z.L., S.C. and X.Z.; investigation, S.C.; methodology, F.L.; software, Z.L.; writing—original draft, F.L. and Z.L.; writing—review and editing, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Industry and Information Technology of the People's Republic of China under grant number TC220H07A.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: Authors Yubo Wang and Xu Zhao were employed by the company Beijing Smart-Chip Microelectronics Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

QoS	Quality-of-Service
MU-MIMO	Multi-User Multiple Input Multiple Output
CU	Cellular User
D2D	Device-to-Device
JPACG	Joint Power Allocation and Channel Gain Selection Algorithm
SINR	Signal-to-Interference-plus-Noise Ratio
SE	Spectral Efficiency
EE	Energy Efficiency
BS	Base Station
mMTC	massive Machine-Type Communication
ZF	Zero Forcing
MMSE	Minimum Mean Square Error
AllCSI	the all Channel State Information
DDPG	Depth Deterministic Strategy Gradient
RA	Resource Allocation
AWGN	the Additive White Gaussian Noise
SAA	the Sequential Admitted Algorithm
JPDS	the Joint Power and Distance Selection Algorithm

References

1. Sangdeh, P.K.; Pirayesh, H.; Yan, Q.; Zeng, H. DM-COM: Combining Device-to-Device and MU-MIMO Communications for Cellular Networks. *IEEE Internet Things J.* **2021**, *8*, 13516–13527. [CrossRef]
2. Nie, X.; Zhao, F. Pilot Allocation and Power Optimization of Massive MIMO Cellular Networks With Underlaid D2D Communications. *IEEE Internet Things J.* **2021**, *8*, 15317–15333. [CrossRef]
3. Zhong, W.; Fang, B.; Qian, Z. Game Theoretic Resource Allocation for D2D MIMO Heterogenous Networks. *Wirel. Pers. Commun.* **2015**, *84*, 273–285. [CrossRef]
4. Wang, Q.; Zhou, T.; Zhang, H.; Hu, H.; Pignaton de Freitas, E.; Feng, S. Deep Learning-Based Detection Algorithm for the Multi-User MIMO-NOMA System. *Electronics* **2024**, *13*, 255. [CrossRef]
5. Zhang, Z.; Xiao, Y.; Ma, Z.; Xiao, M.; Fan, P. 6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies. *IEEE Veh. Technol. Mag.* **2019**, *14*, 28–41. [CrossRef]
6. Feng, D.; Lu, L.; Yuan-Wu, Y.; Li, G.Y.; Li, S.; Feng, G. Device-to-device communications in cellular networks. *IEEE Commun. Mag.* **2014**, *52*, 49–55. [CrossRef]
7. Hao, Y.; Ni, Q.; Li, H.; Hou, S.; Min, G. Interference-Aware Resource Optimization for Device-to-Device Communications in 5G Networks. *IEEE Access* **2018**, *6*, 78437–78452. [CrossRef]
8. Du, C.; Zhang, Z.; Wang, X.; An, J. Optimal Duplex Mode Selection for D2D-Aided Underlaying Cellular Networks. *IEEE Trans. Veh. Technol.* **2020**, *69*, 3119–3134. [CrossRef]
9. Han, L.; Zhang, Y.; Li, Y.; Zhang, X. Spectrum-Efficient Transmission Mode Selection for Full-Duplex-Enabled Two-Way D2D Communications. *IEEE Access* **2020**, *8*, 115982–115991. [CrossRef]
10. Jha, K.R.; Sharma, S.K. Multifunctional Antennas for 4G/5G Communications and MIMO Applications. In *Multifunctional Antennas and Arrays for Wireless Communication Systems*; Wiley: Hoboken, NJ, USA, 2021; pp. 279–320. [CrossRef]
11. Ayanoglu, E. Fifth generation (5G) cellular wireless: Vision, goals, and challenges. In Proceedings of the 2016 IEEE 35th International Performance Computing and Communications Conference (IPCCC), Las Vegas, NV, USA, 9–11 December 2017.
12. Sakai, M.; Kamohara, K.; Iura, H.; Nishimoto, H.; Ishioka, K.; Murata, Y.; Yamamoto, M.; Okazaki, A.; Nonaka, N.; Suyama, S.; et al. Experimental Field Trials on MU-MIMO Transmissions for High SHF Wide-Band Massive MIMO in 5G. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 2196–2207. [CrossRef]
13. Apiyo, A.; Izydorczyk, J. A Survey of NOMA-Aided Cell-Free Massive MIMO Systems. *Electronics* **2024**, *13*, 231. [CrossRef]
14. Ni, Y.; Wang, Y.; Zhu, H. Interference cancellation in device-to-device communications underlying MU-MIMO cellular networks. *Commun. China* **2019**, *16*, 75–88.
15. Chen, L.; Deng, N.; Wei, H. Performance Analysis of D2D and Cellular Coexisting Networks With Interference Management. *IEEE Access* **2020**, *8*, 82747–82759. [CrossRef]
16. Abu-Rgheff, M.A. *Linear Precoding Strategies for Multi-User Massive MIMO Systems*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2019.
17. Almoneer, M.; Mitran, P.; Boumaiza, S. Investigation of the Impact of Zero-Forcing Precoding on the Variation of Massive MIMO Transmitters' Performance with Channel Conditions. *IEEE Microw. Wirel. Components Lett.* **2021**, *31*, 802–804. [CrossRef]
18. Chen, C.E. MMSE One-Bit Precoding for MU-MIMO Systems With Enhanced Receive Processing. *IEEE Wirel. Commun. Lett.* **2019**, *9*, 548–552. [CrossRef]
19. Feng, W.; Wang, Y.; Yang, L. Resource Allocation Method of Device-to-Device Communication. *Commun. Netw.* **2013**, *5*, 338–343. [CrossRef]
20. Mitliagkas, I.; Sidiropoulos, N.D.; Swami, A. Convex Approximation-Based Joint Power and Admission Control for Cognitive Underlay Networks. In Proceedings of the International Wireless Communications & Mobile Computing Conference, Tangier, Morocco, 24–28 June 2008.
21. Ali Soliman, M.; Mehana, A.H.; Nafie, M. Users Capacity Upper Bound of Multi-Pair Massive MIMO AF Relay System under Pilot Contamination. In Proceedings of the 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Honolulu, HI, USA, 22–25 September 2019; pp. 1–5. [CrossRef]
22. Guo, X.; Li, Z.; Liu, P.; Yan, R.; Han, Y.; Hei, X.; Zhong, G. A Novel User Selection Massive MIMO Scheduling Algorithm via Real Time DDPG. In Proceedings of the GLOBECOM 2020—2020 IEEE Global Communications Conference, Taipei, Taiwan, 7–11 December 2020; pp. 1–6. [CrossRef]
23. Wei, L.; Hu, R.Q.; He, T.; Qian, Y. Device-to-device(d2d) communications underlaying MU-MIMO cellular networks. In Proceedings of the 2013 IEEE Global Communications Conference (GLOBECOM), Taipei, Taiwan, 7–11 December 2013; pp. 4902–4907. [CrossRef]
24. Bahonar, M.H.; Omidi, M.J. Centralized QoS-aware Resource Allocation for D2D Communications with Multiple D2D Pairs in One Resource Block. *arXiv* **2021**, arXiv:2112.10494.
25. Sun, J.; Li, Z.; Zhang, Z.; Xing, C. Maximum and Optimal Number of Activated Links for D2D-Aided Underlaying Cellular Networks. *IEEE Access* **2020**, *8*, 212776–212786. [CrossRef]
26. Özbek, B.; Pischella, M.; Le Ruyet, D. Energy Efficient Resource Allocation for Underlaying Multi-D2D Enabled Multiple-Antennas Communications. *IEEE Trans. Veh. Technol.* **2020**, *69*, 6189–6199. [CrossRef]
27. Khodamoradi, V.; Sali, A.; Messadi, O.; Salah, A.A.; Al-Wani, M.M.; Ali, B.M.; Abdullah, R.S.A.R. Optimal Energy Efficiency Based Power Adaptation for Downlink Multi-Cell Massive MIMO Systems. *IEEE Access* **2020**, *8*, 203237–203251. [CrossRef]

28. Kwon, J.H.; Cho, J.; Yu, B.; Lee, S.; Ko, Y.C. Spectral and energy efficient power allocation for MIMO broadcast channels with individual delay and QoS constraints. *J. Commun. Netw.* **2020**, *22*, 390–398. [CrossRef]
29. Reddy, M.K.K.; Kanishka, R.; Nandakumar, S.; Velmurugan, T. Enhanced Resource Blocks Management in D2D based Communication for 5G Networks. *Wirel. Pers. Commun.* **2022**, *126*, 367–383. [CrossRef]
30. Chandra, S.; Prateek.; Arya, R.; Verma, A.K. Lebesgue measures based power control annealing in 5G D2D networks under QoS constraints for IoT applications. *Wirel. Pers. Commun.* **2023**, *129*, 623–639. [CrossRef]
31. Saatlou, O.; Ahmad, M.O.; Swamy, M. Spectral Efficiency Maximization of a Single Cell Massive MU-MIMO Down-Link TDD System by Appropriate Resource Allocation. *IEEE Access* **2019**, *7*, 182758–182771. [CrossRef]
32. Amudala, D.N.; Sharma, E.; Budhiraja, R. Spectral Efficiency Optimization of Spatially-Correlated Multi-Pair Full-Duplex Massive MIMO Relaying. *IEEE Trans. Commun.* **2019**, *67*, 8346–8364. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.