IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 6, 2021, accepted May 16, 2021, date of publication June 4, 2021, date of current version June 14, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3086148

Joint Interference Alignment and Power Allocation Based on Stackelberg Game in Device-to-Device Communications Underlying Cellular Networks

DAN WANG[1,2], **SHUNLIANG ZHANG**[1], **QIAN CHENG**[1,2], **AND XIAOHUI ZHANG**[1]
[1]Institute of Information Engineering, Chinese Academy of Sciences, Beijing 100093, China
[2]School of Cyber Security, University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding author: Shunliang Zhang (zhangshunliang@iie.ac.cn)

This work was supported by the National Research and Development Program of China under Grant 2019YFB1005204.

ABSTRACT As a promising wireless communication technique, Device-to-Device (D2D) can improve the utilization of spectrum resources, overall system throughput and reduce end-to-end delay, energy consumption by exploiting the direct radio link between local devices. Meanwhile, introducing D2D in cellular networks is very challenging due to the complex interference problem. To deal with the complex interference of D2D Underlying Cellular Networks, Interference alignment (IA) as an efficient interference management technique is extensively studied for D2D communications underlaying the cellular networks. However, most of the previous researches on IA only consider the equal power allocation for users, which leads to suboptimal overall system throughput. In order to further improve the system performance, in this paper, we propose a joint power allocation based on stackelberg game and interference alignment algorithm (STPA-IA) to eliminate the complex interference in D2D communications underlaying cellular networks. In this joint approach, the base station (BS) is modeled as the leader while the D2D pairs are followers. The performance of network system and that of D2D users are regarded as the revenues of leader and followers in stackelberg game. The strategy of the leader (BS) is to get the maximum benefits by reducing the interference, while the followers tend to (D2D pairs) maximize their own utility according to leader's strategy. The non-cooperative game is proved to get the nash equilibrium by the above strategies. Moreover, the close-form expression of the allocated power by maximum the unity function of leader and followers is derived. Extensive simulation results demonstrate that the proposed algorithm outperforms previous works in terms of sum-rate with lower time complexity.

INDEX TERMS Device-to-device communication, interference alignment, power allocation, stackerberg game.

I. INTRODUCTION

Device-to-Device (D2D) communications underlaying cellular networks [1] enable two devices communicate directly without the help of the base station (BS). The promising technique was first proposed by Lin [2]. D2D communication can achieve high sum-rate, low delay and low power consumption [3], [4]. Introducing D2D into cellular networks [5] means the D2D users reuse the wireless resource of cellular networks. Therefore, the interferences of cellular networks with D2D communications include the interference between device users, the interference between device users and cellular users and the interference between cellular users, which is more complex than that of conventional cellular networks.

Numerous interference management approaches have been developed to deal with the complex interference problem. For example, Xu *et al.* [6] studied both beam-forming (BF) and interference cancellation (IC) pre-coding strategies at the base station (BS). The performance with perfect and quantized channel state information (CSI) is derived with closed-form expressions. Successive interference cancellation (SIC) is one of the famous interference cancellation

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

techniques, which can cancel the interference between device users and cellular users. Li and Huang [7] investigated SIC scheduling for D2D communication in a multi-cell network to maximize the time-average total throughput of network. Moreover, the concept of power control can also be used to deal with this complex interference problem. Ramezani-Kebrya *et al.* [8] considered a power control algorithm to maximize the sum-rate of D2D underlaying cellular networks. The allocated power matrix of users depends on the severity of inter-cell interference (ICI) at a neighboring BS that device users and cellular users cause. In addition, the topological interference management (TIM) technique is a promising solution. Doumiati *et al.* [9] formulated a novel TIM problem for D2D communication, also proposed a novel solution based on semi-definite programming (SDP).

However, the aforementioned interference management approaches have some shortcomings. Firstly, some approaches only apply to the situation that the intensity of the interference is very low or the source of interference is single. Secondly, Some approaches need to orthogonalize interference and desired signal, which may lead to the waste of spectrum resources. Thirdly, Some approaches need to decode the complex signals at receivers. Finally, some approaches need data sharing between all users. Therefore, among these interference management methods, interference alignment (IA) [10] is a promising method because of its unique advantages:

Firstly, there is no concern about the intensity of the interference. Secondly, there is no need to ensure that the spectrum is orthogonal between users. Thirdly, there is low-complexity design of receivers. Finally, there is no need of data sharing between users [11]–[13].

Therefore, Several researchers have devoted to employing IA to eliminate the complex interference of D2D communications underlaying cellular networks. Elkotby *et al.* [14] are one of the first groups to study this problem, the extra degrees of freedom (DoF) that IA offers is used to enhance the capacity of D2D communication underlaying macro cells. As we all known, in D2D communication, device users (DUs) reuse the resource of cellular users (CUs). Therefore, there are two scenarios of this network, one is that some sub-channel of BS are not occupied by CUs and the other one is that all sub-channels of BS are occupied by CUs. In this case, Yang *et al.* [15] proposed ‘‘interference-free’’ IA scheme and ‘‘interference-limiting’’ IA scheme to solve the interference problem, which are generated by the above two scenarios respectively. Moreover, Wang *et al.* [16] proposed an iterative IA algorithm to solve the interference problem in D2D Local Area Network (LAN) with the scenario that some sub-channel of BS are not occupied by cellular networks, which is corresponding to the first scenario above. Furthermore, Li *et al.* [17] proposed a lower complexity three-step-based scheme for the case that the available spectrum is fully reused among different cells, which is corresponding to the second scenario above.

However, the above IA algorithms only consider the situation that all users have the same transmission power, which is unrealistic because the strength of different signals and the quality of the different channels are unequal. Therefore, exploring flexible power allocation into IA algorithm instead of equal power assignment can further manage the interference to improve the sum-rate of communication system. Several power allocation (PA) algorithms have been developed. For example, Yang *et al.* [18] derived an optimal power allocation schemes, which allocate the power according to the optimal preamble length and the channel estimate power. Teng *et al.* [19] proposed a two-layer power control algorithm to maximize the sum utility, in which the outer layer consists of updates for power constraints across the users in different cells, while the inner layer consists of the updates for that CUs and DUs in one cell. Moreover, Yin *et al.* [20] presented a centralized resource allocation scheme via the convex approximation method and Farhadi *et al.* [21] computed the required power values in a distributed fashion at each destination and informed the associated source via the feedback link.

Unfortunately, these power allocation approaches only consider the problem such as maximizing the signal to interference plus noise ratio (SINR) of single side, e.g. D2D or BS. In contrast, game theory can consider the problem comprehensively with the joint optimization on both sides, which means that the D2D users can communicate effectively as well as the cellular network can get the optimal performance. Therefore, game theory has been employed as a popular power allocation method to maximize the sum-rate of communication system. Liu *et al.* [22] presented a two-game analytical framework, where the IA and power allocation are modeled as two game processes. Especially, as one of the promising game theory methods, stackelberg game is often used to deal with the problems in communications. When uplink frequency is shared by different users, Xia *et al.* [23] proposed a stackelberg game algorithm based to jointly allocate power and resources. Furthermore, to deal with the fundamental problem of flexibility for distributed resource allocation, Sawyer and Smith [24] proposed a distributed algorithm with multiple objective stackelberg game which without any scalarization across the different objectives. For D2D communication, several researches about stackelberg game were given. For example, Yu *et al.* [25] presented a price-based power allocation scheme based on stackelberg game with a limitation on the total allocated power of the BS, a cooperative user as the data distributer and several requesting users as the buyers. And Wang *et al.* [26] proposed a multi-agent hierarchical learning (MAHL) algorithm based on multi-leader and multi-follower stackelberg game to maximize the performance of system.

Combining the suitable power allocation algorithm and interference alignment algorithm can improve the system performance effectively. In previous IA related works, the stackelberg game has rarely been considered to allocate the power of user devices. The game is suitable to research the interactions between two types of players and is benefit to both side, which are alike to the D2D communication and cellular network. Therefore, in this paper, we combine the power allocation based on stackelberg game and IA algorithm (STPA-IA) to improve the sum-rate of D2D communication underlaying cellular networks. The base station (BS) is regarded as the leader while the D2D pairs are regarded as the followers, which are two sides in stackelberg game. Specifically, the main contributions of this paper can be summarized as follows:

- We present a stackelberg model framework to achieve IA in D2D communications underlaying cellular networks, in which BS and DUs are modeled as leaders and followers of game respectively.
- An effective interference alignment algorithm in D2D LAN underlaying cellular networks is developed by deriving the pre-coding matrix by the reference vectors and designing two sub-post-processing matrices to eliminate the interference from device users and cellular users respectively.
- The effectiveness of the proposed algorithms is demonstrated by system simulations. Extensive simulation results reveal that this algorithm can improve the sum-rate of D2D LAN underlaying cellular networks considerably with lower the complexity compared with the existed algorithms.

The remainder of this paper is organized as follows. Section II introduces the system model for D2D communication underlaying cellular networks and gives the problem formulation. Section III develops a novel power allocation based on stackelberg game and IA algorithm (STPA-IA) to improve the sum-rate of D2D communication underlaying cellular networks. Extensive simulation results are discussed to verify the effectiveness of the solution. in Section IV, and Section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first introduce the system model of D2D LAN underlaying cellular networks. Next, the problem formulation is presented.

Notation: $\mathbb{E}(\cdot)$, $(\cdot)^\dagger$ represent the expectation and conjugate transpose respectively. $\mathbb{C}^{m\times n}$ denotes a set of all $m \times n$ complex matrices. $\mathbf{I}_m$ and $\mathbf{0}_{m\times n}$ are defined as $m \times m$ identity matrix and $m \times n$ zero matrix respectively. Bold upper case and lower case letters denote matrices and vectors respectively.

A. SYSTEM MODEL

As shown in figure 1, we consider the uplink resource sharing in the one-cell with a base station (BS) and two types of users, which are cellular users (CUs) and D2D users (DUs). The DUs come in pairs, which one D2D pair consists of one transmitter (DT) and one receiver (DR). In this network, the BS has M antennas, each CU and DU has N antennas. This cell has K_c CUs and K_d D2D pairs. Moreover, the subscripts b, $ci(i = 1, 2, \ldots, K_c)$ and $dj(j = 1, 2, \ldots, K_d)$ denote the BS, i-th cellular user and j-th D2D pair. The k-th DT reuses the resource of the k-th CU. Then the received signals at BS and k-th DR can be expressed as

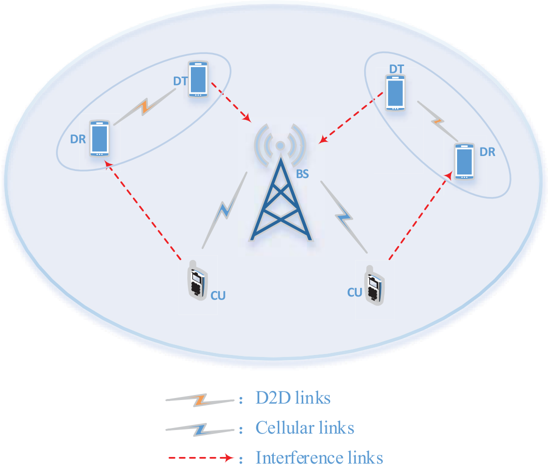


FIGURE 1. System model of D2D LAN underlaying cellular networks.

$$\begin{aligned}\mathbf{y}_b &= \sum_{i=1}^{K_c} \mathbf{H}_{ci,b}\mathbf{v}_{ci}p_{ci}s_{ci}\\ &\quad + \sum_{j=1}^{K_d} \mathbf{H}_{dj,b}\mathbf{v}_{dj}p_{dj}^{cj}s_{dj} + \mathbf{n}_b \qquad (1)\\ \mathbf{y}_{dk} &= \mathbf{H}_{dk,dk}\mathbf{v}_{dk}p_{dk}^{ck}s_{dk}\\ &\quad + \sum_{j=1,j\neq k}^{K_d} \mathbf{H}_{dj,dk}\mathbf{v}_{dj}p_{dj}^{cj}s_{dj}\\ &\quad + \mathbf{H}_{ck,dk}\mathbf{v}_{ck}p_{ck}s_{ck} + \mathbf{n}_{dk} \qquad (2)\end{aligned}$$

where $\mathbf{H}_{ci,b} \in \mathbb{C}^{M\times N}$ and $\mathbf{H}_{dj,dk} \in \mathbb{C}^{N\times N}$ denote the channels from user ci to BS and user dj to k-th DR respectively. $\mathbf{v}_{ci} \in \mathbb{C}^{N\times 1}$ and $\mathbf{v}_{dj} \in \mathbb{C}^{N\times 1}$ denote the pre-coding vectors of cellular user ci and device transmitter dj. $\mathbf{V}_c = [\mathbf{v}_{c1}\mathbf{v}_{c2}\ldots\mathbf{v}_{cK_c}]$ and $\mathbf{V}_d = [\mathbf{v}_{d1}\mathbf{v}_{d2}\ldots\mathbf{v}_{dK_d}]$, which satisfy ${\mathbf{V}_c}^\dagger\mathbf{V}_c = \mathbf{I}$ and ${\mathbf{V}_d}^\dagger\mathbf{V}_d = \mathbf{I}$. s_{ci} and s_{dj} denotes the message of user ci and dj, p_{ci} and p_{dj}^{cj} denote the power allocation of i-th CU and j-th DT respectively, and $\mathbf{n}_b \in \mathbb{C}^{M\times 1}$, $\mathbf{n}_{dk} \in \mathbb{C}^{N\times 1}$ denote the additive white gaussian noise of BS and k-th DR respectively.

Essentially, the main idea of interference alignment is that design the pre-coding vector $\mathbf{v}$ and the post-processing matrix $\mathbf{U}$. The pre-coding vectors ensure that the interference can be aligned into finite dimension as well as the post-processing matrices ensure that the interference can be eliminated at the receivers.

Therefore, to eliminate the interference effectively, the received signals at BS and k-th DR after the post-processing matrix can be expressed as

$$\begin{aligned}
\mathbf{U}_b{}^{\dagger}\mathbf{y}_b &= \mathbf{U}_b{}^{\dagger}\sum_{i=1}^{K_c}\mathbf{H}_{ci,b}\mathbf{v}_{ci}p_{ci}s_{ci} \\
&\quad + \mathbf{U}_b{}^{\dagger}\sum_{j=1}^{K_d}\mathbf{H}_{dj,b}\mathbf{v}_{dj}p_{dj}^{cj}s_{dj} + \mathbf{U}_b{}^{\dagger}\mathbf{n}_b \qquad (3) \\
\mathbf{u}_{dk}{}^{\dagger}\mathbf{y}_{dk} &= \mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{dk,dk}\mathbf{v}_{dk}p_{dk}^{ck}s_{dk} \\
&\quad + \mathbf{u}_{dk}{}^{\dagger}\sum_{j=1,j\neq k}^{K_d}\mathbf{H}_{dj,dk}\mathbf{v}_{dj}p_{dj}^{cj}s_{dj} \\
&\quad + \mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{ck,dk}\mathbf{v}_{ck}p_{ck}s_{ck} + \mathbf{u}_{dk}{}^{\dagger}\mathbf{n}_{dk} \qquad (4)
\end{aligned}$$

where $\mathbf{U}_b \in \mathbb{C}^{M\times K_c}$ is the post-processing matrix of BS. Moreover, $\mathbf{U}_d \in \mathbb{C}^{N\times K_d}$ is the post-processing matrix of DRs and $\mathbf{u}_{dk}$ is the $k-th$ column of $\mathbf{U}_d$. Both post-processing matrices satisfy $\mathbf{U}_b{}^{\dagger}\mathbf{U}_b = \mathbf{I}$ and $\mathbf{U}_d{}^{\dagger}\mathbf{U}_d = \mathbf{I}$.

B. PROBLEM FORMULATION

It should be noted that the k-th DT (dk) reuses the resource of the k-th CU (ck). The objective function and constraints are as follows:

$$\begin{aligned}
&max\ R \\
&s.t. \\
&\quad \mathbf{U}_b{}^{\dagger}\mathbf{H}_{cj,b}\mathbf{V}_c = 0, \quad j = 1,\ldots,K_c,\ j\neq i \\
&\quad \mathbf{U}_b{}^{\dagger}\mathbf{H}_{dk,b}\mathbf{V}_d = 0, \quad k = 1,\ldots,K_d \\
&\quad rank(\mathbf{U}_b{}^{\dagger}\mathbf{H}_{ci,b}\mathbf{V}_c) = d \\
&\quad \mathbf{U}_d{}^{\dagger}\mathbf{H}_{dj,dk}\mathbf{V}_d = 0, \quad j = 1,\ldots,K_d,\ j\neq k \\
&\quad \mathbf{U}_d{}^{\dagger}\mathbf{H}_{ci,dk}\mathbf{V}_c = 0, \quad i = 1,\ldots,K_c \\
&\quad rank(\mathbf{U}_d{}^{\dagger}\mathbf{H}_{dk,dk}\mathbf{V}_d) = d \\
&\quad 0 \leqslant p_{dj} \leqslant p_{max}. \qquad (5)
\end{aligned}$$

where p_{max} is the maximum transmit power of users, which is the total transmit power in this situation. R is the sum-rate of D2D communication underlaying cellular networks, which can be expressed as

$$R = \sum_{i=1}^{K_c} Blog_2(1+SINR_{ci}^{di}) + \sum_{j=1}^{K_d} Blog_2(1+SINR_{dj}^{cj}) \qquad (6)$$

where B is the bandwidth. Moreover, $SINR_{ci}^{di}$ and $SINR_{dj}^{cj}$ are the received signal to interference plus noise ratio (SINR) of k-th CU (ck) and k-th DT (dk), which can be written as follows respectively:

$$SINR_{ck}^{dk} = \frac{|(\mathbf{u}_{bk})^{\dagger}\mathbf{H}_{ck,b}(\mathbf{v}_{ck})|^2 p_{ck}}{|(\mathbf{u}_{bk})^{\dagger}\mathbf{H}_{dk,b}(\mathbf{v}_{dk})|^2 p_{dk}^{ck} + (\sigma_{ck})^2} \qquad (7)$$

$$SINR_{dk}^{ck} = \frac{|(\mathbf{u}_{dk})^{\dagger}\mathbf{H}_{dk,dk}(\mathbf{v}_{dk})|^2 p_{dk}^{ck}\alpha_{ck,dk}}{|(\mathbf{u}_{dk})^{\dagger}\mathbf{H}_{ck,dk}(\mathbf{v}_{ck})|^2 p_{ck} + (\sigma_{dk})^2} \qquad (8)$$

where $\mathbf{u}_{bk}$ is the $k-th$ column of $\mathbf{U}_b$. Moreover, $\alpha_{ci,dj} \in (0,1)$, which means the situation of uplink resource allocation. When the k-th DT (dk) reuses the resource of the i-th CU (ci), $\alpha_{ci,dk} = 1$, otherwise, $\alpha_{ci,dk} = 0$. In the formula (7), $\alpha_{ck,dk} = 1$. Moreover, $\sigma_{ck}{}^2$ and $\sigma_{dk}{}^2$ denote the noise power of ck and dk, which can be expressed as

$$\sigma_{ck}{}^2 = (\mathbf{u}_{bk})^{\dagger}\mathbf{n}_{ck}(\mathbf{n}_{ck})^{\dagger}\mathbf{u}_{bk} \qquad (9)$$

$$\sigma_{dk}{}^2 = (\mathbf{u}_{dk})^{\dagger}\mathbf{n}_{dk}(\mathbf{n}_{dk})^{\dagger}\mathbf{u}_{dk} \qquad (10)$$

III. INTERFERENCE ALIGNMENT AND POWER ALLOCATION BASED ON STACKELBERG GAME

This section presents the joint power allocation based stackelberg game and interference alignment algorithm (STPA-IA), which can eliminate the complex interference among D2D LAN underlaying cellular networks. First, the iterative interference alignment algorithm is given to compute the pre-coding vectors and the post-processing matrices with the certain power allocation matrix. Second, the power allocation algorithm based on stackelberg game is given to compute the power allocation matrix with the certain pre-coding vectors and post-processing matrices. Last, the STPA-IA algorithm steps will be given.

A. ITERATIVE INTERFERENCE ALIGNMENT

This subsection shows the double post-processing iterative interference alignment, which can eliminate the complex interference in D2D communication underlying cellular networks. By designing the pre-coding vectors, the interference signals can be aligned in limited dimensions. In addition, by designing the post-processing matrices, the aligned interference signals can be eliminated. The main idea of interference alignment algorithm with i-th CU (ci) and k-th DT (dk) can be expressed as the follow formulas:

$$\begin{aligned}
\mathbf{U}_b{}^{\dagger}\mathbf{H}_{cj,b}\mathbf{V}_c &= 0, \quad j = 1,\ldots,K_c, j\neq i \\
\mathbf{U}_b{}^{\dagger}\mathbf{H}_{dk,b}\mathbf{V}_d &= 0, \quad k = 1,\ldots,K_d \\
rank(\mathbf{U}_b{}^{\dagger}\mathbf{H}_{ci,b}\mathbf{V}_c) &= d \qquad (11) \\
\mathbf{U}_d{}^{\dagger}\mathbf{H}_{dj,dk}\mathbf{V}_d &= 0, \quad j = 1,\ldots,K_d, j\neq k \\
\mathbf{U}_d{}^{\dagger}\mathbf{H}_{ci,dk}\mathbf{V}_c &= 0, \quad i = 1,\ldots,K_c \\
rank(\mathbf{U}_d{}^{\dagger}\mathbf{H}_{dk,dk}\mathbf{V}_d) &= d \qquad (12)
\end{aligned}$$

The main idea of IA algorithm is embodied in three formulas. The first two formulas of (11) and (12) ensure that the interference from CUs and DUs can be eliminated, the third formula ensures that the desired signal can be decoded, where d is the degree of freedom (DoF) of users.

1) THE DESIGN OF PRE-CODING MATRIX

First, BS and DRs choose the reference vectors ρ_c and ρ_d respectively at random. Then, the pre-coding vectors can be designed according to the reference vectors as follows:

$$\mathbf{v}_{ci} = (\mathbf{H}_{ci,di})^{-1}\rho_c \qquad (13)$$

$$\mathbf{v}_{dj} = (\mathbf{H}_{dj,b})^{-1}\rho_d \qquad (14)$$

Then, the $\mathbf{v}_{ci}$ and $\mathbf{v}_{dj}$ are substituted in the formula (3), (4), the signals at BS and DRs can be expressed as

$$\begin{aligned}\mathbf{U}_b{}^{\dagger}\mathbf{y}_b = \mathbf{U}_b{}^{\dagger}\sum_{i=1}^{K_c}\mathbf{H}_{ci,b}(\mathbf{H}_{ci,di})^{-1}\rho_c p_{ci} s_{ci}\\ +\mathbf{U}_b{}^{\dagger}\sum_{j=1}^{K_d}\mathbf{H}_{dj,b}(\mathbf{H}_{dj,b})^{-1}\rho_d p_{dj}^{cj} s_{dj}+\mathbf{U}_b{}^{\dagger}\mathbf{n}_b \quad (15)\end{aligned}$$

$$\begin{aligned}\mathbf{u}_{dk}{}^{\dagger}\mathbf{y}_{dk} = \mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{dk,dk}(\mathbf{H}_{dk,b})^{-1}\rho_d p_{dk}^{ck} s_{dk}\\ +\mathbf{u}_{dk}{}^{\dagger}\sum_{j=1,j\neq k}^{K_d}\mathbf{H}_{dj,dk}(\mathbf{H}_{dj,b})^{-1}\rho_d p_{dj}^{cj} s_{dj}\\ +\mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{ck,dk}(\mathbf{H}_{ck,dk})^{-1}\rho_c p_{ck} s_{ck}+\mathbf{u}_{dk}{}^{\dagger}\mathbf{n}_{dk} \quad (16)\end{aligned}$$

The simplification formulas can be obtained as follows,

$$\begin{aligned}\mathbf{U}_b{}^{\dagger}\mathbf{y}_b &= \mathbf{U}_b{}^{\dagger}\sum_{i=1}^{K_c}\mathbf{H}_{ci,b}\mathbf{H}_{ci,b}(\mathbf{H}_{ci,di})^{-1}\rho_c p_{ci} s_{ci}\\ &\quad +\mathbf{U}_b{}^{\dagger}\sum_{j=1}^{K_d}\rho_d p_{dk}^{ck} s_{dk} + \mathbf{U}_b{}^{\dagger}\mathbf{n}_b \qquad (17)\\ \mathbf{u}_{dk}{}^{\dagger}\mathbf{y}_{dk} &= \mathbf{u}_{dk}{}^{\dagger}\sum_{j=1}^{K_d}\mathbf{H}_{dj,dk}\mathbf{H}_{dj,dk}(\mathbf{H}_{dj,b})^{-1}\rho_d p_{dj}^{cj} s_{dj}\\ &\quad +\mathbf{u}_{dk}{}^{\dagger}\rho_c p_{ck} s_{ck} + \mathbf{u}_{dk}{}^{\dagger}\mathbf{n}_{dk} \qquad (18)\end{aligned}$$

From these two formulas, the inter-layer interferences are already aligned into finite dimensional.

2) THE DESIGN OF POST-PROCESSING MATRIX

Considering the complex interferences in D2D underlying cellular networks, the post-processing matrix is divided into two sub-matrices to eliminate the interferences from different type of users respectively, which are cellular users and device users. Therefore, the post-processing matrix of BS and all DRs can be designed as

$$\mathbf{U}_b = \mathbf{U}_b^1\mathbf{U}_b^2 \qquad (19)$$

$$\mathbf{U}_d = \mathbf{U}_d^1\mathbf{U}_d^2 \qquad (20)$$

The main ideas of the first post-processing sub-matrices $\mathbf{U}_b^1$ and $\mathbf{U}_d^1$ are to maximize the power of desired signals, the desired signals $\mathbf{D}_b$ and $\mathbf{D}_d$ can be expressed as

$$\mathbf{D}_b = [\mathbf{H}_{c1,b}\mathbf{v}_{c1}\ \ldots\ \mathbf{H}_{ci,b}\mathbf{v}_{ci}\ \ldots\ \mathbf{H}_{cK_c,b}\mathbf{v}_{cK_c}] \qquad (21)$$

$$\mathbf{D}_d = [\mathbf{H}_{d1,d1}\mathbf{v}_{d1}\ \ldots\ \mathbf{H}_{di,di}\mathbf{v}_{di}\ \ldots\ \mathbf{H}_{dK_d,dK_d}\mathbf{v}_{dK_d}] \qquad (22)$$

Then, the power of desired signals p_b^1 and p_d^1 can be expressed as

$$p_b^1 = trace(\mathbf{U}_b{}^{\dagger}\mathbf{D}_b\mathbf{D}_b{}^{\dagger}\mathbf{U}_b) \qquad (23)$$

$$p_d^1 = trace(\mathbf{U}_d{}^{\dagger}\mathbf{D}_d\mathbf{D}_d{}^{\dagger}\mathbf{U}_d) \qquad (24)$$

To maximize the power of desired signals, the first post-processing sub-matrices can be calculated as

$$\mathbf{U}_b^1 = arg\ \max_{\mathbf{U}_b^1} p_b^1 \qquad (25)$$

$$\mathbf{U}_d^1 = arg\ \max_{\mathbf{U}_d^1} p_d^1 \qquad (26)$$

Moreover, the second post-processing sub-matrix is designed to eliminate the interference from two types of users. The interferences for all CUs and the k-th DT (dk) can be expressed as

$$\begin{aligned}\mathbf{IN}_b &= [\mathbf{U}_b{}^{\dagger}\mathbf{H}_{d1,b}\mathbf{v}_{d1}\ \mathbf{U}_b{}^{\dagger}\mathbf{H}_{c2,b}\mathbf{v}_{c2}\ldots\mathbf{U}_b{}^{\dagger}\mathbf{H}_{cK_c,b}\mathbf{v}_{cK_c},\ldots,\\ &\quad\times\mathbf{U}_b{}^{\dagger}\mathbf{H}_{c1,b}\mathbf{v}_{c1}\ \ldots\ \mathbf{U}_b{}^{\dagger}\mathbf{H}_{c(k-1),b}\mathbf{v}_{c(k-1)}\\ &\quad\times\mathbf{U}_b{}^{\dagger}\mathbf{H}_{dk,b}\mathbf{v}_{dk}\ \mathbf{U}_b{}^{\dagger}\mathbf{H}_{c(k+1),b}\mathbf{v}_{c(k+1)}\ \ldots\\ &\quad\times\mathbf{U}_b{}^{\dagger}\mathbf{H}_{cK_c,b}\mathbf{v}_{cK_c},\ldots,\\ &\quad\times\mathbf{U}_b{}^{\dagger}\mathbf{H}_{c1,b}\mathbf{v}_{c1}\ \ldots\ \mathbf{U}_b{}^{\dagger}\mathbf{H}_{c(K_c-1),b}\mathbf{v}_{(K_c-1)}\ \ldots\\ &\quad\times\mathbf{U}_b{}^{\dagger}\mathbf{H}_{dK_c,b}\mathbf{v}_{dK_c}] \qquad (27)\\ \mathbf{IN}_{dk} &= [\mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{d1,dk}\mathbf{v}_{d1}\ \ldots\ \mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{d(k-1),dk}\mathbf{v}_{d(k-1)}\\ &\quad\times\mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{ck,dk}\mathbf{v}_{ck}\quad\mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{d(k+1),dk}\mathbf{v}_{d(k+1)}\ \ldots\\ &\quad\times\mathbf{u}_{dk}{}^{\dagger}\mathbf{H}_{dK_d,dk}\mathbf{v}_{dK_d}] \qquad (28)\end{aligned}$$

To eliminate the interferences, the second post-processing matrices can be calculated as

$$\mathbf{U}_b^2 = (\mathbf{IN}_b{}^{\dagger}\mathbf{IN}_b)^{-1}\mathbf{IN}_b{}^{\dagger} \qquad (29)$$

$$\mathbf{u}_{dk}^2 = \mathbf{IN}_{dk}{}^{\dagger}\mathbf{IN}_{dk})^{-1}\mathbf{IN}_{dk}{}^{\dagger} \qquad (30)$$

where $\mathbf{U}_d^2 = [\mathbf{u}_{d1}^2\ \ldots\ \mathbf{u}_{dk}^2\ \ldots\ \mathbf{u}_{dK_d}^2]$.

3) THE UPDATE OF REFERENCE VECTORS

According to the previous analyse, the reference vectors should be updated to get the iterative pre-coding vectors and post-processing matrices. Due to $\mathbf{U}_b^1$ and $\mathbf{U}_d^1$ are used to maximize the power of desired signals, according to formulas (17) and (18), we can known that $\mathbf{U}_b^1\rho_d = \mathbf{0}$ and $\mathbf{U}_d^1\rho_c = \mathbf{0}$. Therefore, ρ_c and ρ_d should minimize the interference, which can be updated as follows:

$$\rho_c = \lambda_M^c \qquad (31)$$

$$\rho_d = \lambda_M^d \qquad (32)$$

where λ_M^c and λ_M^d are the smallest eigenvectors corresponds the smallest eigenvalue of $\mathbf{D}_b\mathbf{D}_b{}^{\dagger}$ and $\mathbf{D}_d\mathbf{D}_d{}^{\dagger}$.

B. POWER ALLOCATION WITH STACKELBERG GAME

This subsection details the computing processes of the power allocation matrix by using stackelberg game. This stackelberg game should ensure that the D2D communication is available and the sum-rate of system can be increased when the device users are added to the network. We consider the one-leader and multi-follower model, in which the BS is the leader and device users are the followers. The design of power allocation with stackerberg game will be given.

1) THE UTILITY FUNCTION OF LEADER AND FOLLOWERS

First, we consider the utility function of leader and followers. The utility function means the quantitative relationship between the consumer goods and the utility obtained by the consumer in the process of consumption, which can measure the customer satisfaction from a given combination of goods.

In this section, the utility function of leader means the system revenue of sum-rate in the condition that the D2D users reuse the resource of cellular users, which compared with the cellular networks without D2D users. The utility function of leader $UL_{ci,dj}$ can be expressed as

$$\begin{aligned} UL_{ci,dj} &= Blog_2(1+SINR_{ci}^{dj}) + Blog_2(1+SINR_{dj}^{ci}) \qquad (33)\\ &\quad - Blog_2(1+SNR_{ci}^{dj}) \\ &\Rightarrow \\ UL_{ci,dj} &= Blog_2\Big(1+\frac{|(\mathbf{u}_{bi})^{\dagger}\mathbf{H}_{ci,b}(\mathbf{v}_{ci})|^2 p_{ci}}{|(\mathbf{u}_{bi})^{\dagger}\mathbf{H}_{dj,b}(\mathbf{v}_{dj})|^2 p_{dj}^{ci} + (\sigma_{ci})^2}\Big) \\ &\quad + Blog_2\Big(1+\frac{|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2 p_{dj}^{ci}\alpha_{ci,dj}}{|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{ci,dj}(\mathbf{v}_{ci})|^2 p_{ci} + (\sigma_{dj})^2}\Big) \\ &\quad - B\,log_2\Big(1+\frac{|(\mathbf{u}_{bi})^{\dagger}\mathbf{H}_{ci,b}(\mathbf{v}_{ci})|^2 p_{ci}}{(\sigma_{dj})^2}\Big) \qquad (34) \end{aligned}$$

Moreover, the utility function of followers in this section means the followers' revenue. In other words, this function is the difference between the rate of the D2D user and its consumed signal power. The utility function of followers UF_{dj} can be expressed as

$$\begin{aligned} UF_{dj,ci} &= Blog_2(1+SINR_{dj}^{ci}) - \omega|U_d^{\dagger}H_{dj,dj}V_{dj}|^2 P_{dj}^{ci} \qquad (35)\\ &\Rightarrow \\ UF_{dj,ci} &= Blog_2\Big(1+\frac{|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2 p_{dj}^{ci}\alpha_{ci,dj}}{|(\mathbf{u}_{dj})^{\dagger}H_{ci,dj}(\mathbf{v}_{ci})|^2 p_{ci} + (\sigma_{dj})^2}\Big) \\ &\quad - \omega|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2 p_{dj}^{ci} \qquad (36) \end{aligned}$$

where ω is the matching factor.

2) OPTIMIZATION FORMULAS

When the utility function of the leader and the followers are deduced, the optimization formulas can be expressed as

$$max\ UL_{ci,dj}, \quad i=1,\ldots,K_c,\ j=1,\ldots,K_d. \qquad (37)$$

$$max\ UF_{dj,ci},\ j=1,\ldots,K_d \quad s.t.\ 0 \leqslant p_{dj} \leqslant p_{max}. \qquad (38)$$

where p_{dj} is the variable for these two problems and p_{max} is the maximum transmit power of users, which is the total transmit power P. To deal with the optimization problems, we take the derivation of the utility function of the followers $UF_{dj,ci}$, which can be expressed as

$$\frac{\partial UF_{dj,ci}}{\partial p_{dj}^{ci}} = 0 \qquad (39)$$

$$\Rightarrow$$

$$\frac{B|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2}{In2|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{ci,dj}(\mathbf{v}_{ci})|^2 p_{ci} + \sigma_{dj}^2 + |(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2 p_{dj}^{ci}\alpha_{ci,dj}} - \omega|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2 = 0 \qquad (40)$$

$$\Rightarrow$$

$$p_{dj}^{ci} = \frac{B - In2\omega|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{ci,dj}(\mathbf{v}_{ci})|^2 p_{ci} - In2\omega(\sigma_{dj})^2}{In2\omega|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2\alpha_{ci,dj}} \qquad (41)$$

Now, the optimal signal power of D2D users can be calculated. Next, one more derivative here is needed to prove the uniqueness of the results, which is to take the derivative of the derivative.

From formula (42), as shown at the bottom of the next page, it can be seen that the quadratic derivative is negative, which means the function is convex. Therefore, the result is one and only.

3) NASH EQUILIBRIUM

This subsection shows the nash equilibrium of the stackelberg game. The optimal signal power of D2D users can be calculated by formula (41). However, this paper should consider not only the performance of device users but also the interests of the whole communication system. As mentioned above, the utility function of leader means the system revenue of sum-rate in the condition that the D2D users reuse the resource of cellular users, which compared with the cellular networks without D2D users. Therefore, the utility function of leader must ensure that

$$UL_{ci,dj} \geqslant 0 \qquad (43)$$

Otherwise, the addition of device users will reduce the system performance, rather than bring revenue to the system. The goal of this game is to achieve nash equilibrium condition under which the leader and followers can both maximize their own revenue. Therefore, all p_{dk}^{ci} should be calculated towards the k-th DU ($k = 1,\ldots,K_d$) to get the all $UL_{ci,dk}$ ($i = 1,\ldots,K_c$). Then, the maximal $UL_{ck,dk}$ should be chosen to get the optimal cellular users whose resource are reused by the k-th DU and manage the $\alpha_{ck,dk} = 1$. Last, all optimal pairs of cellular users and device users are calculated and analysed to share the same cellular resources. So far, the game reaches nash equilibrium, which not only the allocated powers of device users are optimal but also the interests of the whole system are maximal.

C. STPA-IA ALGORITHM

Now, we get the pre-coding vectors, the post-processing matrices and the allocated power of users. In this section, the steps of the STPA-IA algorithm and the complexity of the proposed algorithm are given.

1) STEP OF STPA-IA ALGORITHM

2) THE TIME COMPLEXITY ANALYSIS

This subsection shows the time complexity of the proposed algorithm. Moreover, the comparisons of complexity with other interference alignment algorithms are also analysed. Due to matrix operations, all tpyes of interference alignment algorithms have high complexity.

It is assumed that the input data set is n. From the above algorithm analysis, we can konwn that the proposed algo-

Algorithm 1 Joint Power Allocation Based Stackelberg Game and Interference Alignment Algorithm

```
Input: all channel matrix $\mathbf{H}_{ci,b}$, $\mathbf{H}_{ci,dk}$, $\mathbf{H}_{dj,b}$ and $\mathbf{H}_{dj,dk}$, the maximum total user transmit power $P$
    Step 1. Initialize the reference vectors of pre-coding vectors $\rho_c$, $\rho_d$, and user power $p_{ci} = p_{dj}^{ci} = \frac{P}{(K_c+K_d)}$;
    Step 2. Compute the pre-coding vectors $\mathbf{v}_{ci}$, $\mathbf{v}_{dj}$ by (13), (14);
    Step 3. Compute the first post-processing matrices $\mathbf{U}_b^1$, $\mathbf{U}_d^1$ by (25), (26), and compute the second post-processing matrices $\mathbf{U}_b^2$, $\mathbf{U}_d^2$ by (29), (30);
    Step 4. Update the reference vectors of pre-coding matrices $\rho_c$, $\rho_d$ by (31), (32);
    Step 5. Go to step 2 and repeat till convergence;
    Step 6. Compute the full post-processing matrices $\mathbf{U}_b$, $\mathbf{U}_d$ by (19), (20);
    Step 7. Manage $k = 1$;
    Step 8. Compute all optimal user power $p_{dk}^{ci}$ $(i = 1, \ldots, K_c)$ towards the $k-th$ DU by (41);
    Step 9. Substitute $p_{dk}^{ci}$ into formula (34) to get all $UL_{ci,dk}$;
    Step 10. Choose the maximal $UL_{ck,dk}$, then manage $\alpha_{ck,dk} = 1, \alpha_{ci,dk} = 0$ $(i = 1, \ldots, K_c, i \neq k)$;
    Step 11. Manage $k = k + 1$ and then go to step 7, till $k = K_d$.
Output: all pre-coding vectors $\mathbf{v}_{ci}$, $\mathbf{v}_{dj}$, all post-processing matrices $\mathbf{U}_b$, $\mathbf{U}_d$, user power $p_{ci}$, $p_{dk}^{ck}$.
```

rithm need a for loop, which is an $\mathbf{O}(i)$ operation (i is the number of iteration). And there are matrix operations in the for loop, such as matrix multiplication, matrix inverse, SVD and so on, which are the $\mathbf{O}(n^3)$ operations. Moreover, K_c and K_d are constants, which do not affect the algorithm complexity. Therefore, the complexity of STPA-IA is $\mathbf{O}(i * n^3)$.

Next, we choose two existing interference alignemnt algorithms to give the comparisons of complexity. The maxSINR [27] is the classic interference alignment algorithm without power allocation, which also need iterative calculation repeatedly. Thus, its algorithm process need a for loop and matrix operations, which is same as STPA-IA. Therefore, the time complexity of maxSINR is $\mathbf{O}(i * n^3)$. Moreover, the Iter-IA [22] is a joint water-filling and interference alignment algorithm, which has double loops to allocate powers of users (iterate for $i1$ and $i2$ times respectively). The matrix operations are same as maxSINR and STPA-IA. Therefore, the time complexity of Iter-IA is $\mathbf{O}(i1 * i2 * n^3)$.

From the theoretical analysis, we can know that the complexity of proposed STPA-IA algorithm is lower than Iter-IA while close to maxSINR as shown in table 1.

TABLE 1. The comparisons of complexity of different IA algorithms.

STPA-IA	maxSINR[27]	Iter-IA[22]
$\mathbf{O}(i * n^3)$	$\mathbf{O}(i * n^3)$	$\mathbf{O}(i1 * i2 * n^3)$

IV. SIMULATION RESULTS

In this section, the simulation and discussion of the proposed STPA-IA algorithm is presented in the D2D LAN underlaying cellular networks. In this simulation, $K_d = 3$, $K_c = 3$. Moreover, all channel coefficients are independently and identically distributed (i.i.d.) complex gaussian random variables with zero mean and unit variance.

Figure 2 demonstrates the sum-rates performance comparison of STPA-IA and other interference management schemes, such as the maxSINR, the iterative IA with the power allocation (Iter-PA) [22] and time division multiple access (TDMA). With the increase of the sum-power of CUs and DUs, the system sum-rates of D2D LAN underlaying cellular networks are also increased. At the same time, the proposed STPA-IA shows the superior performance compared with existing algorithms, which are max-SINR, Iter-PA and TDMA. The reason is that the STPA-IA not only eliminates the interference from both cellular user and device user, but also ensures that the D2D communication is available and the sum-rate can be increased when devices are added to network.

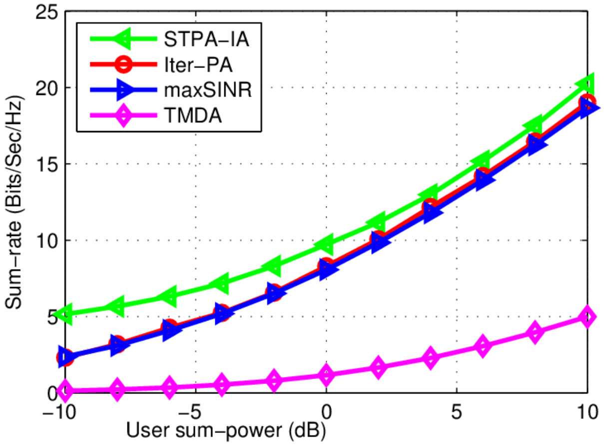


FIGURE 2. Sum-rates performance of different algorithms.

Figure 3 and figure 4 demonstrate the sum-rate performance of STPA-IA and Iter-PA as the number of iteration increases respectively. From figure 3, we can see that the sum-rate performance increases with the iteration number. Moreover, the performance curves overlap when the iterative number is 4 and 5, which means the proposed algorithm converges when the iteration number is 4. As for Iter-PA

$$\frac{\partial^2 UF_{dj,ci}}{\partial {p_{dj}^{ci}}^2} = -\frac{B}{In2} \times \frac{(|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2\alpha_{ci,dj})^2}{(|(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{ci,dj}(\mathbf{v}_{ci})|^2 p_{ci} + \sigma_{dj}^2 + |(\mathbf{u}_{dj})^{\dagger}\mathbf{H}_{dj,dj}(\mathbf{v}_{dj})|^2 p_{dj}^{ci}\alpha_{ci,dj})^2} < 0 \tag{42}$$

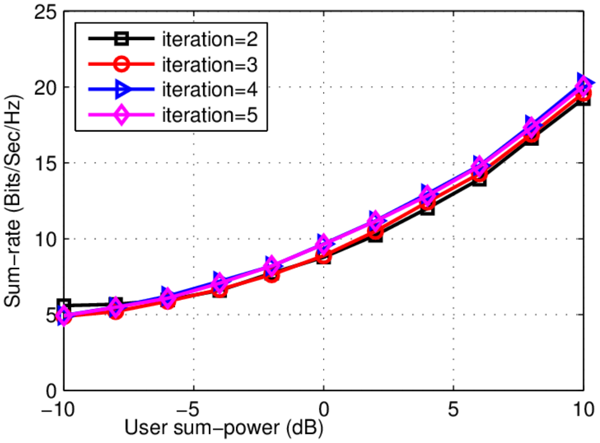


FIGURE 3. The sum-rate performance of STPA-IA algorithm with different iteration numbers.

algorithm, due to it need both outer iteration and inner iteration, in this simulation, Iter 1 means the outer iteration while Iter 2 means the inner iteration. From figure 4, we can see that the sum-rate performance curve when $\text{Iter1} = 3$, $\text{Iter2} = 6$ overlaps with the curve when $\text{Iter1} = 4$, $\text{Iter2} = 6$, which means Iter-PA algorithm converges when the outer iterative number is 3 and the outer iterative number is 6. It can be seen from the comparison of the two figures that the proposed STPA-IA algorithm converges faster than Iter-PA algorithm.

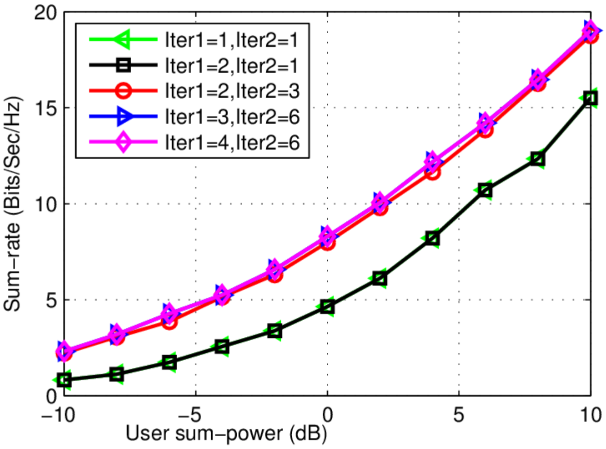


FIGURE 4. The sum-rate performance of Iter-PA algorithm with different iteration numbers.

V. CONCLUSION

In this paper, we propose a joint power allocation based stackelberg game and interference alignment algorithm (STPA-IA) to eliminate the complex interference in D2D LAN underlaying cellular networks. The algorithm is developed by deriving the pre-coding vectors by reference vectors and the double post-processing matrices to eliminate the interference not only from cellular users, but also from device users. This power allocation algorithm based stackelberg game ensures that the D2D communication is available and the sum-rate of system can be increased when the device users are added to the network. Therefore, the utility functions of leader and that of followers are designed to represent the performance revenues of communication system and D2D users. The problems of maximizing the two utility functions are formulated. By taking the derivative of utility functions and comparison of the results, the optimal allocated power of users can be calculated to achieve optimum system performance. Simulation results reveal that the proposed STPA-IA outperforms existing algorithms in terms of sum-rate. It's also demonstrated that the algorithm complexity of STPA-IA is acceptable. Meanwhile, the proposed algorithm and previous algorithms mentioned in this paper all need the full channel state information (CSI), which is hard to acquire in real scenario. Thus, how to improve the system performance without the accurate CSI information could be an interesting topic for future work.

REFERENCES

[1] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, Dec. 2009.

[2] Y.-D. Lin and Y.-C. Hsu, "Multihop cellular: A new architecture for wireless communications," in *Proc. IEEE INFOCOM Conf. Comput. Commun. 19th Annu. Joint Conf. IEEE Comput. Commun. Societies*, Mar. 2000, pp. 1273–1282.

[3] F. Jameel, Z. Hamid, F. Jabeen, S. Zeadally, and M. A. Javed, "A survey of device-to-device communications: Research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2133–2168, 3rd Quart., 2018.

[4] J. Lee and J. H. Lee, "Performance analysis and resource allocation for cooperative D2D communication in cellular networks with multiple D2D pairs," *IEEE Commun. Lett.*, vol. 23, no. 5, pp. 909–912, May 2019.

[5] W.-K. Lai, Y.-C. Wang, H.-C. Lin, and J.-W. Li, "Efficient resource allocation and power control for LTE–A D2D communication with pure D2D model," *IEEE Trans. Veh. Technol.*, vol. 69, no. 3, pp. 3202–3216, Mar. 2020.

[6] W. Xu, L. Liang, H. Zhang, S. Jin, J. C. F. Li, and M. Lei, "Performance enhanced transmission in device-to-device communications: Beamforming or interference cancellation?" in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 4296–4301.

[7] J. Li and S. Huang, "Delay-aware power control for D2D communication with successive interference cancellation and hybrid energy source," *IEEE Wireless Commun. Lett.*, vol. 6, no. 6, pp. 806–809, Dec. 2017.

[8] A. Ramezani-Kebrya, M. Dong, B. Liang, G. Boudreau, and S. H. Seyedmehdi, "Joint power optimization for device-to-device communication in cellular networks with interference control," *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 5131–5146, Aug. 2017.

[9] S. Doumiati, M. Assaad, and H. A. Artail, "Topological interference management framework for device-to-device communication," *IEEE Wireless Commun. Lett.*, vol. 7, no. 4, pp. 602–605, Aug. 2018.

[10] V. R. Cadambe and S. A. Jafar, "Interference alignment and degrees of freedom of the K-user interference channel," *IEEE Trans. Inf. Theory*, vol. 54, no. 8, pp. 3425–3441, 2008.

[11] L. Wang and Q. Liang, "Partial interference alignment for heterogeneous cellular networks," *IEEE Access*, vol. 6, pp. 22592–22601, 2018.

[12] M. Zhou, H. Li, N. Zhao, S. Zhang, and F. R. Yu, "Feasibility analysis and clustering for interference alignment in full-duplex-based small cell networks," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 807–819, Jan. 2019.

[13] N. Zhao, F. R. Yu, M. Jin, Q. Yan, and V. C. M. Leung, "Interference alignment and its applications: A survey, research issues, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1779–1803, 3rd Quart., 2016.

[14] H. E. Elkotby, K. M. F. Elsayed, and M. H. Ismail, "Exploiting interference alignment for sum rate enhancement in D2D-enabled cellular networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2012, pp. 1624–1629.

[15] L. Yang, W. Zhang, and S. Jin, "Interference alignment in device-to-device LAN underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3715–3723, Jul. 2015.

[16] D. Wang, Q. Cheng, W. Liu, S. Zhang, and Y. Wang, "Iterative interference alignment in device-to-device LAN with cellular networks," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–6.

[17] X.-Y. Li, C. He, H.-S. Shan, J. Li, and Z. J. Wang, "Feasibility-aware partial interference alignment for hybrid D2D and cellular communication networks," *IEEE Access*, vol. 6, pp. 71069–71083, 2018.

[18] G. Yang, C. K. Ho, and Y. L. Guan, "Dynamic resource allocation for multiple-antenna wireless power transfer," *IEEE Trans. Signal Process.*, vol. 62, no. 14, pp. 3565–3577, Jul. 2014.

[19] F. Teng, D. Guo, M. L. Honig, W. Xiao, and J. Liu, "Power control based on interference pricing in hybrid D2D and cellular networks," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 676–680.

[20] R. Yin, C. Zhong, G. Yu, Z. Zhang, K. K. Wong, and X. Chen, "Joint spectrum and power allocation for D2D communications underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2182–2195, Apr. 2016.

[21] H. Farhadi, C. Wang, and M. Skoglund, "Distributed transceiver design and power control for wireless MIMO interference networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1199–1212, Mar. 2015.

[22] W. Liu, S. Zhang, X. Zhang, and Y. Wang, "Iterative power allocation for throughput maximisation in IA-based cellular networks: Two-game approach," *IET Commun.*, vol. 12, no. 14, pp. 1678–1685, Aug. 2018.

[23] C. Xia, S. Xu, and K. S. Kwak, "Resource allocation for device-to-device communication in LTE-A network: A stackelberg game approach," in *Proc. IEEE 80th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2014, pp. 1–5.

[24] N. Sawyer and D. B. Smith, "Flexible resource allocation in device-to-device communications using stackelberg game theory," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 653–667, Jan. 2019.

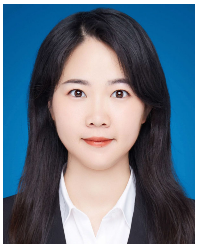
[25] X. Yu, S. Ma, and P. Zhang, "Stackelberg game based social-aware power allocation for cooperative D2D communications," *IEEE Access*, vol. 6, pp. 49877–49885, 2018.

[26] J. Wang, Y. Sun, B. Wang, B. Wang, A. Wang, S. Li, and Z. Sun, "Resource allocation for D2D video multicast using multi-leader multi-follower stackelberg game with personalized incentives," *IEEE Access*, vol. 7, pp. 117019–117028, 2019.

[27] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "Approaching the capacity of wireless networks through distributed interference alignment," in *Proc. GLOBECOM-IEEE Global Telecommun. Conf.*, Nov. 2008, pp. 1–6.

DAN WANG received the B.S. degree in electronic information engineering from the Hefei University of Technology, Hefei, China, in 2016, and the M.S. degree in communication and information system from the Institute of Information Engineering, Chinese Academy of Sciences, Beijing, China, where she is currently pursuing the Ph.D. degree in signal and information processing. Her current research interests include interference alignment, D2D communications, communication signal processing, and 5G wireless networks.

SHUNLIANG ZHANG received the Ph.D. degree in computer science from Zhejiang University, Hangzhou, China, in 2004. From 2005 to 2011, he worked as a Research Engineer on LTE-A standardization at Nokia Siemens networks. From 2011 to 2016, he was with Ericsson as a Technical Expert on 5G packet core networks. He is currently a Senior Engineer with the Institute of Information Engineering, Chinese Academy of Sciences. He has filed more than 50 PCT patent applications on mobile communication systems and holds U.S./EU 30 granted patents. He has published around 30 academic articles. His research interest includes mobile communication systems and security.



QIAN CHENG received the B.S. degree in communication engineering from the Communication University of China, Beijing, China, in 2016. She is currently pursuing the Ph.D. degree with the Institute of Information and Engineering, Chinese Academy of Science, Beijing. Her current research interests include communication engineering, next-generation wireless access technology, and signal processing technology.

XIAOHUI ZHANG received the master's degree from the Beijing University of Posts and Telecommunications, in 2015. She is currently pursuing the Ph.D. degree with the Institute of Information Engineering, Chinese Academy of Sciences. She has been an Engineer with the Institute of Information Engineering, Chinese Academy of Sciences, since 2015. Her current research interests include physical layer security of wireless communication and cyberspace security.

• • •