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Feasibility-Aware Partial Interference Alignment for Hybrid D2D and Cellular Communication Networks

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ABSTRACT Device-to-Device (D2D) communication has been a promising technology for the fifth generation (5G) wireless network owing to the higher throughput, less energy consumption, and lower latency. As the 5G network becomes denser, the interference in a hybrid D2D and cellular communication system becomes much severe and more difficult to deal with. In this paper, a novel feasibility aware partial interference alignment (FA-PIA) scheme is investigated. Partial IA has already been studied to manage severe interference for symmetric interference network or simple asymmetric network with limited users. In this paper, we consider an asymmetric interference network with an arbitrary number of D2D users transmitting concurrently. We aim to boost the degrees of freedom and achievable sum rate. To achieve this goal, a lower complexity three-step-based scheme is proposed. Specifically, the pressure transfer tree-based interference selection algorithm is first developed, which is to select the appropriate interference links to be aligned under the IA feasibility constraints. Then, the minimum interference leakage-based iterative partial IA scheme is given to mitigate the selected interference. At last, a constrained concave convex procedure-based iterative power optimization algorithm is provided to further manage the residual interference. Numerical results demonstrate that the proposed three-step-based FA-PIA scheme can significantly improve the achievable sum rate.

INDEX TERMS Asymmetric interference channel, device-to-device (D2D), feasibility analysis, partial interference alignment.

I. INTRODUCTION

Device-to-Device (D2D) communication as one of the key technologies for fifth generation (5G) has attracted much research interest [1], [2]. In D2D communication, user equipments (UEs) located near each other are allowed to communicate directly rather than through the evolved NodeB (eNB). By reusing the radio spectrum of the conventional cellular network and reducing one hop through eNB, D2D communication can bring about the benefits of higher throughput, less power consumption and lower latency [3].

Since the aforementioned network encounters severe interference problems to support D2D communication including both the intra-cell and inter-cell interferences, interference management has become a critical issue. In recent years, many researchers have focused on dealing with the interference management problem from different aspects [4], such as mode selection [5], [6], resource allocation [7], [8], power control [9], or a joint scheme combining two or three of these aspects listed before [10]–[12].

However, in the future, the 5G wireless network will be highly dense and the interference situation will become more complex, so it will be not enough to rely only on the interference management approaches mentioned above [13]. For example, when the network is denser, more D2D communication links will reuse the same spectrum resource with a cellular mode UE (CUE) in each cell. In this case, resource allocation may be unable to effectively separate these D2D links, which will result in stronger interference and then the decrease of achievable rate. Therefore, it needs to incorporate other effective techniques into the hybrid D2D and cellular communication network to further manage the interference and improve the throughput performance.

Currently, combining some of the multi-input multi-output (MIMO) transmission techniques with D2D communication is a promising research area [14], such as beamforming [15] or interference alignment (IA) [16]–[23]. In [15], it designed two kinds of zero-forcing (ZF) beamforming vectors for eNB in a D2D communication underlaying cellular network, which can eliminate the interference between CUEs and the interference from eNB to D2D links, respectively. However, a lot of interferences still remain in the system, such as the interference from D2D transmitters to CUEs, which may lead to performance loss.

IA is another promising technique for D2D communication to effectively mitigate interference and improve the degrees of freedoms (DoFs) [24]. In [16] and [17], they proposed some grouping and clustering schemes for D2D links in order to apply IA technique to D2D communication. Their schemes can improve the capacity by reaping benefit from the additional DoF provided by IA. However, they exploit IA technique for D2D links only, and they do not manage the interference between D2D and cellular links. Then, in [18], it proposed an effective IA scheme for both D2D and cellular communication links. However, it arbitrarily ignored some interference in order to meet the IA feasibility constraints, which may not coincide with the real interference conditions. In [19], it proposed an IA based energy efficient algorithm for D2D underlaying cellular network. However, its scheme is valid only when the network configuration satisfies the IA feasibility conditions, which limits its application.

In [20], by alternately optimizing the pre-coding vector and post-processing matrix, they proposed an iterative IA scheme for D2D broadcasting communication system. However, the considered system is somewhat simple, which only consisted of two D2D transmitters, two cellular uses, one D2D receiver and one base station (BS). The feasibility condition of IA is also not considered in [20]. In [21], a power threshold based IA was proposed, in which only the interference with the power higher than the threshold would be aligned and the others were just treated as noise. However, the remaining interference can still bring negative effects on achievable rate. In [22], a multiuser D2D system that allows concurrent D2D transmission was considered. By proposing a bucket based DoF assignment algorithm and IA scheme, they aimed to contain as many D2D pairs as possible in the concurrent transmission group. However, they must guarantee that all the interferences can be aligned or eliminated in the concurrent transmission group no matter the interference power is high or low. In [23], a novel IA scheme assisted by D2D communication (DaIA) is proposed, which is focused on reducing the channel state information (CSI) feedback by using D2D communication to exchange CSI between paired users.

In this paper, we consider an asymmetric hybrid D2D and cellular communication systems, in which multiple D2D links communicate concurrently with the cellular links. Here, the symmetric network means that the number of antennas of all transmitters (or receivers) is the same; otherwise it is an asymmetric network [24]. However, aligning all the interference links in such system is unnecessary and is hard to guarantee the feasibility of IA. Since the transmit power levels of an eNB and a D2D transmitter as well as the path loss of different links are quite different, the interference in D2D communication underlaying cellular network can be divided into two categories, i.e., strong interference and weak interference. Then by ignoring some relatively weak interference from IA process, i.e., these interference links are viewed as unconnected links for IA, we can establish a partially connected interference network for IA.

For partially connected interference networks, some studies have found that the IA feasibility conditions can be ensured more easily and the achievable network DoF is much higher [25]–[31]. For symmetric network configuration, reference [25]–[27] proved that IA can be achieved for any network size in partially connected case. However, how to guarantee the feasibility conditions of IA for asymmetric situations is not given. In [28] and [29], they proposed IA algorithms for a partially connected multiple-input multiple-output (MIMO) network, in which the partial connectivity is introduced by path-loss, shadowing effects or spatial correlation. However, their algorithm may be very dependent on the real channel conditions, including the practical signal propagation characteristics as well as the maximum interference distance defined therein. For the cases that only a few interference links can be viewed as unconnected links, the benefit of partial connectivity contributed to system performance will be limited. In [30], a two-stage IA algorithm was proposed for partially connected downlink heterogeneous networks. They considered a specific scenario, in which the interference links had already been divided into weak and strong categories based on the kinds of interference sources. However, the actual interference level is not considered in differentiating the strong and weak interference. In [31], a partial interference alignment scheme for heterogeneous network was proposed, which can effectively improve the achievable rate at intermediate signal noise ratio (SNR). However, they just considered a three-user interference channel, and the feasibility condition is not considered.

Based on the above studies, the main challenge of employing IA in a dense hybrid D2D and cellular communication system is how to select proper interference links to be aligned meanwhile guaranteeing the IA feasibility conditions for the asymmetric network with arbitrary number of concurrent transmission links.

In summary, the main contributions of this work are summarized as follows:

- Interference is a serious barrier that limits the development of D2D technology especially in dense networks. As a promising technique to mitigate interference, partial IA has been investigated in some existing works. However, the research on partial IA scheme for asymmetric networks with arbitrary number of users is deficient. The key challenge in such scenario lies in the guaranteeing of feasibility. In this paper, we propose a novel three-step-based feasibility aware partial IA (FA-PIA) scheme for an asymmetric hybrid D2D and cellular communication network, which can support align relatively strong interference for arbitrary number of D2D and cellular communication links transmitting concurrently. Moreover, the residual relatively weak interference can be further managed by power optimization.

- As we know, feasibility condition is important for IA. In this paper, we develop a sufficient and necessary condition to judge the feasibility of partial IA for asymmetric networks with arbitrary number of D2D and cellular links communicating concurrently. Moreover, combining the pressure transfer tree based feasibility checking approach, a low complexity IA feasibility-aware interference selection algorithm is proposed, which can effectively select the relatively strong interference links to be aligned meanwhile guaranteeing the IA feasibility condition.
- For the residual relatively weak interference, we further propose a constrained concave convex procedure (CCCP) based iterative power optimization algorithm, which can further improve the system achievable rate.

Our contribution is mainly on devising an efficient and implementable feasibility aware partial IA scheme to manage interference and improve achievable sum rate for the asymmetric hybrid D2D and cellular communication network having arbitrary number of concurrent transmission links.

The remainder of this paper is organized as follows. Section II describes the system model and the transmission mode. In Section III, the feasibility aware partial IA problem is formulated. Section IV gives the three-step-based scheme. In Section V and VI, the practical deployment and overhead of the proposed scheme are provided. In Section VII, the numerical results are provided and the final conclusion is offered in Section VIII.

Notations: $\boldsymbol{I}_N$ denotes the $(N \times N)$ identity matrix. $\boldsymbol{X}^T, \boldsymbol{X}^\dagger$, $tr(\boldsymbol{X})$ and $\boldsymbol{X}_{*l}$ represent the transposition, Hermitian, trace and the lth column of matrix $\boldsymbol{X}$, respectively. $\upsilon_l(\boldsymbol{X})$ is the eigenvector that corresponds to the lth smallest eigenvalue of $\boldsymbol{X}$. $x \mid y$ denotes that y is divisible by x. $\mathbb{C}^{N\times M}$ represents the set of complex $(N \times M)$ matrices.

II. SYSTEM MODEL AND TRANSMISSION MODE

A. SYSTEM MODEL

We consider a hybrid D2D and cellular communication network, which is briefly plotted in Fig. 1. The set of cells is denoted as $\mathcal{L} \triangleq \{1, 2, \ldots, L\}$. In each cell, there are two kinds of UEs: 1) cellular mode UEs or called CUEs, which communicate with eNB, and 2) D2D mode UEs or called D2D pairs, which communicate with each other directly. Each

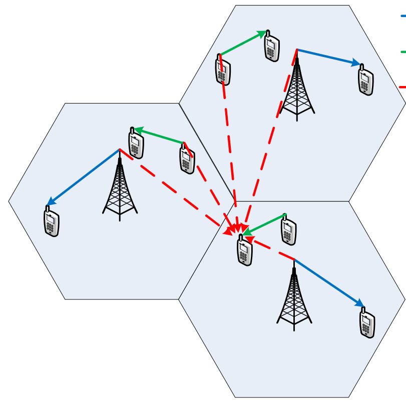


FIGURE 1. Illustration of a downlink hybrid D2D and cellular communication network.

kind of UEs is equipped with N antennas and each eNB has M antennas. Moreover, we assume the available spectrum is fully reused among different cells, while in one cell, different CUEs occupy orthogonal spectrum resources [32]. The set of D2D pairs reusing the same downlink spectrum resource with one CUE in each cell is $\mathcal{D}^{[l]} \triangleq \{1, 2, \ldots, D^{[l]}\}, \forall l \in \mathcal{L}$. Then, we denote the cellular and D2D communication links that make use of the same resources in this network by $\mathcal{C} \triangleq \{1, 2, \ldots, L\}$ and, $\mathcal{D} \triangleq \{L+1, L+2, \ldots, L+D\}$ respectively, where $D = \sum_{l\in\mathcal{L}} D^{[l]}$. In Fig. 1, we just plot the case where $L = 3$ and $D = 3$ for brevity.

For the convenience of mathematical analysis and presentation, all the communication links in this hybrid D2D and cellular communication network that occupy the same spectrum resource can be modeled as an asymmetric MIMO interference channel as shown in Fig. 2(a).

Since the power levels and antenna configurations are different between eNB and D2D transmitters, this interference network is hierarchical and asymmetric. We can let $(M \times N, d^{[m]})^L (N \times N, d^{[n]})^D$ denote this asymmetric MIMO interference network [24]. Specifically, the item $(M \times N, d^{[m]})^L$ stands for cellular communication links, while the item $(N \times N, d^{[n]})^D$ stands for D2D communication links. $d^{[m]}$ and $d^{[n]}$ denote the demanded DoFs for the link from the mth eNB transmitter to the mth CUE receiver (the mth cellular communication link) and the link from the nth D2D transmitter to the nth D2D receiver (the nth D2D communication link), respectively. Moreover, the dashed arrows in Fig. 2(a) represent all the interference links in this network, thus Fig. 2(a) illustrates the fully connected case. This fully connected case will be used for rate analysis of the whole network in the following.

Then, we introduce the concept of partial connectivity. As previously mentioned, the interference in this heterogeneous network can be classified into weak and strong interference due to heterogeneous path loss as well as different levels of transmit powers. If we remove some weak interference, the partially connected MIMO interference network can be shown as Fig. 2(b), where the dashed arrows represent the relatively strong interference links. We will use this partially

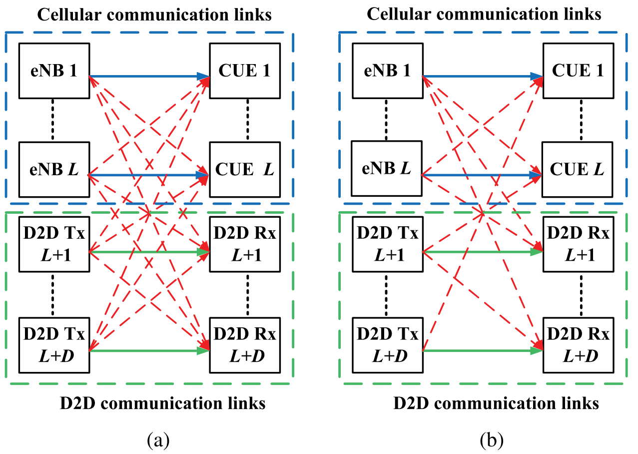


FIGURE 2. System model: (a) fully connected case for rate analysis, (b) partially connected case for IA analysis.

connected MIMO interference channel to analyze partial IA in the following.

Furthermore, we assume the eNB in each cell acts as a central entity, which can acquire the global CSI. Similar assumption on global CSI for eNBs can be found in many existing interference management schemes, such as [7] and [9]. As for D2D communication links, each D2D transmitter only knows their local CSI.

B. TRANSMISSION MODE

We consider exploiting IA technology for the asymmetric MIMO interference channel. Then, the received signal $y^{[k]}$ for the kth ($\forall k \in \mathcal{C} \cup \mathcal{D}$) receiver can be expressed as

$$\boldsymbol{y}^{[k]} = \boldsymbol{H}^{[kk]}\boldsymbol{V}^{[k]}\boldsymbol{x}^{[k]} + \sum_{\substack{j\in\mathcal{C}\cup\mathcal{D}\\ j\neq k}} \boldsymbol{H}^{[kj]}\boldsymbol{V}^{[j]}\boldsymbol{x}^{[j]} + \boldsymbol{z}^{[k]}, \quad (1)$$

where

- $\boldsymbol{H}^{kj} \in \mathbb{C}^{N_r^{[k]} \times N_t^{[j]}}$ is the channel matrix between the jth transmitter and the kth receiver, $N_r^{[k]} = N$ and $N_t^{[j]} = \begin{cases} M, & j \in [1, L] \\ N, & j \in [L+1, L+D] \end{cases}$ denote the number of receive antennas for the kth receiver and the number of transmit antennas for the jth transmitter, respectively. Moreover, we assume all the elements of each channel matrix $\boldsymbol{H}^{[kj]}$ are independent and random variables [33];
- $\boldsymbol{V}^{[j]} \in \mathbb{C}^{N_t^{[j]} \times d^{[j]}}$ is the IA precoding matrix for the jth transmitter, where $d^{[j]}$ is the DoF for the jth communication link;
- $\boldsymbol{x}^{[j]} \in \mathbb{C}^{d^{[j]} \times 1}$ is the data signal vector for the jth transmitter, moreover, $E[\boldsymbol{x}^{[j]\dagger}\boldsymbol{x}^{[j]} = P^{[j]}]$ is the transmit power of the jth transmitter;
- $\boldsymbol{z}^{[k]} \in \mathbb{C}^{N_r^{[k]} \times 1}$ is the additive white Gaussian noise (AWGN) vector at kth receiver with zero mean vector and covariance matrix of $(\sigma)^2\mathbf{I}_N$.

To suppress the interference from other transmitters, the kth receiver uses the IA decorrelator matrix $\boldsymbol{U}^{[k]} \in \mathbb{C}^{N_r^{[k]} \times d^{[k]}}$ to decode $\boldsymbol{y}^{[k]}$ and obtain the estimated signal $\widetilde{\boldsymbol{y}}^{[k]}$ as follows

$$\begin{aligned} \widetilde{\boldsymbol{y}}^{[k]} &= \boldsymbol{U}^{[k]\dagger}\boldsymbol{y}^{[k]} \\ &= \sum_{j\in\mathcal{C}\cup\mathcal{D}} \boldsymbol{U}^{[k]\dagger}\boldsymbol{H}^{[kj]}\boldsymbol{V}^{[j]}\boldsymbol{x}^{[j]} + \boldsymbol{U}^{[k]\dagger}\boldsymbol{z}^{[k]}. \end{aligned} \quad (2)$$

Here, we assume $\boldsymbol{V}^{[j]}$ and $\boldsymbol{U}^{[k]}$ satisfy $\boldsymbol{V}^{[j]\dagger}\boldsymbol{V}^{[j]} = \mathbf{I}_{d^{[j]}}$ and $\boldsymbol{U}^{[k]\dagger}\boldsymbol{U}^{[k]} = \mathbf{I}_{d^{[k]}}$, respectively [33].

Then, the maximum achievable data rate $R^{[k]}$ of the kth receiver can be expressed as [33]

$$R^{[k]} = \sum_{l=1}^{d^{[k]}} \log_2(1 + \frac{P^{[k]}}{d^{[k]}} \frac{\boldsymbol{U}_{*l}^{[k]\dagger}\boldsymbol{H}^{[kk]}\boldsymbol{V}_{*l}^{[k]}\boldsymbol{V}_{*l}^{[k]\dagger}\boldsymbol{H}^{[kk]\dagger}\boldsymbol{U}_{*l}^{[k]}}{\boldsymbol{U}_{*l}^{[k]\dagger}\boldsymbol{F}^{[kl]}\boldsymbol{U}_{*l}^{[k]}}), \quad (3)$$

where $\boldsymbol{F}^{[kl]} = \sum_{\substack{j\in\mathcal{C}\cup\mathcal{D}\\ j\neq k}} \frac{P^{[j]}}{d^{[j]}} \sum_{d=1}^{d^{[j]}} \boldsymbol{H}^{[kj]}\boldsymbol{V}_{*d}^{[j]}\boldsymbol{V}_{*d}^{[j]\dagger}\boldsymbol{H}^{[kj]\dagger} + (\sigma)^2\mathbf{I}_N$.

III. PROBLEM FORMULATION

In this section, we first discuss the IA feasibility conditions, and then the feasibility aware partial IA problem is established.

A. IA FEASIBILITY CONDITIONS

Firstly, the definition of connection factor is introduced. We use $\alpha^{[kj]}$ to denote the connection factor between the jth transmitter and the kth receiver (expressed as interference link $j \to k$), which is defined as

$$\alpha^{[kj]} = \begin{cases} 1, & j \to k \text{ is connected, align} \\ 0, & j \to k \text{ is unconnected, not align} \end{cases} \quad (4)$$

By introducing $\alpha^{[kj]}$, we can establish a partially connected interference network for IA application. According to [24], [34], we conclude that the following conditions should be guaranteed in order to obtain an IA solution for the partially connected interference network:

$$\boldsymbol{U}^{[k]\dagger}\alpha^{[kj]}\boldsymbol{H}^{[kj]}\boldsymbol{V}^{[j]} = \mathbf{0}, \forall k \neq j, \quad (5)$$

$$\text{rank}(\boldsymbol{U}^{[k]\dagger}\boldsymbol{H}^{[kk]}\boldsymbol{V}^{[k]}) = d^{[k]}, \forall k \in \mathcal{C} \cup \mathcal{D}. \quad (6)$$

To obtain some more practical conclusions, there have been a lot of papers investigating the necessary or sufficient conditions of IA for fully connected network. However, for general network configurations, there are no closed-form sufficient conditions [35], which may lead to the intractability of IA for practical applications. In this paper, we adopt the Corollary 3.4 in [34], which gives the necessary and sufficient condition for a special case of network configuration.

For the partially connected interference network, we can develop it as follows.

Theorem 1: When 1) $d^{[k]} = d$, $\forall k \in \mathcal{C} \cup \mathcal{D}$, and 2) $d \mid N$ or $d \mid M$, IA is feasible if and only if the following inequalities are satisfied:

$$\begin{aligned} \sum_{j:(\cdot,j)\in J_{sub}} (N_t^{[j]} - d) + \sum_{k:(k,\cdot)\in J_{sub}} (N_r^{[k]} - d) \\ \geq \sum_{(k,j)\in J_{sub}} (\alpha^{[kj]}d), \forall J_{sub} \in J, \end{aligned} \quad (7)$$

where $J = (k, j) : k, j \in \mathcal{C} \cup \mathcal{D}, k \neq j, (\cdot, j)\text{or}((k, \cdot)) \in J_{sub}$ represents that it can find a k (or j) so as to $(k, j) \in J_{sub}$. The proof of Theorem 1 is given in Appendix A.

Remark 3.1: From (7), we note that the introducing of connection factor $\alpha^{[kj]}$ makes the feasibility conditions easy to satisfy, i.e., proper setting of $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ can help a network to be feasible for IA.

Remark 3.2: Connection factors can also influence the achievable DoF d. When the elements of $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ are all 1, i.e., the fully connected case, d is the smallest. When some of the elements of $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ are 0, i.e., the partially connected case, d may become larger. In other words, for a given demanded d, we can find a proper configuration of $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ that guarantees the IA feasibility conditions for the partially connected interference network.

B. THE FEASIBILITY AWARE PARTIAL IA PROBLEM

Based on the previous analysis, we know that the connection factor set $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ affects both the feasibility of IA and the achievable DoF for the interference network. Moreover, aligning some very weak interference may be unnecessary since it may produce only limited benefit for the whole system performance at the cost of aggravating more computational burden. Thus, we consider only aligning the relatively strong interference, which can be expressed as

$$\alpha^{[kj]} = \begin{cases} 1, & \gamma^{[kj]} < \gamma_{min}, j \neq k \text{ or } k = j, \\ 0, & \gamma^{[kj]} \geq \gamma_{min}, j \neq k, \end{cases} \tag{8}$$

where $\gamma^{[kj]}$ is the signal-to-interference-ratio (SIR) of the interference link $j \to k$. γ_{min} is a given SIR threshold. The meaning of the expression is that if the SIR $\gamma^{[kj]}$ of the interference link $j \to k$ is higher than a given SIR threshold γ_{min}, i.e., the interference of this link is relatively weak, $\alpha^{[kj]}$ is 0 and the interference of $j \to k$ will not be eliminated by IA, otherwise $\alpha^{[kj]}$ is 1 and the interference from the $j \to k$ should be managed by IA. Moreover, if $k = j$, $\gamma^{[kk]} = 1$.

Given the above definition of $\alpha^{[kj]}$, we can infer that the configuration of $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ has an impact on the achievable DoF per user (or called the capacity pre-log [24]). Moreover, the transmit power determines the received signal-to-interference-plus-noise ratio (SINR) for each receiver, which affects the capacity in-log. Thus, in order to improve the sum capacity of the whole network, we need to find appropriate $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$ and optimal power allocation.

Then, by assuming $d^{[k]} = d, \forall k \in \mathcal{C} \cup \mathcal{D}$, and $d \mid N$ or $d \mid M$, we can establish a sum rate maximization programming as follows

$$\text{(P1)} \max_{\boldsymbol{\alpha},\boldsymbol{P}\boldsymbol{V},\boldsymbol{U}} \sum_{k\in\mathcal{C}\cup\mathcal{D}} \sum_{l=1}^{d^{[k]}=d} R^{[k]}, \tag{9a}$$

$$\text{s.t.} \sum_{j:(\cdot,j)\in J_{sub}} (N_t^{[j]} - d) + \sum_{k:(k,\cdot)\in J_{sub}} (N_r^{[k]} - d) \geq \sum_{(k,j)\in J_{sub}} (\alpha^{[kj]} d), \forall J_{sub} \in J, \tag{9b}$$

$$P^{[k]} \leq P^{[k]}_{\max}, k \in \mathcal{C} \cup \mathcal{D}, \tag{9c}$$

$$\alpha^{[kj]} = \begin{cases} 1, & \gamma^{[kj]} < \gamma_{min}, \\ 0, & \gamma^{[kj]} \geq \gamma_{min}, \end{cases}, j, k \in \mathcal{C} \cup \mathcal{D}, \tag{9d}$$

$$\boldsymbol{U}^{[k]}_{*l} = \upsilon_l(\boldsymbol{Q}^{[k]}), l = 1, 2, \ldots, d, k \in \mathcal{C} \cup \mathcal{D}, \tag{9e}$$

$$\boldsymbol{Q}^{[k]} = \sum_{j\in\mathcal{C}\cup\mathcal{D},\neq k} \frac{P^{[j]}}{d} \alpha^{[kj]} \boldsymbol{H}^{[kj]} \boldsymbol{V}^{[j]} \boldsymbol{V}^{[j\dagger]} \boldsymbol{H}^{[kj]\dagger}, \tag{9f}$$

where $\boldsymbol{\alpha} = [\alpha^{[kj]}]_{k,j\in\mathcal{C}\cup\mathcal{D}} \in \mathbb{C}^{K\times K}$, $\boldsymbol{P} = [P^{[1]}, \ldots, P^{[K]}] \in \mathbb{C}^{1\times K}$, $\boldsymbol{V} = \boldsymbol{V}^{[1]}, \ldots, \boldsymbol{V}^{[K]}$, $\boldsymbol{U} = \boldsymbol{U}^{[1]}, \ldots, \boldsymbol{U}^{[K]}$, are the connection factor matrix, power vector as well as the collections of all IA precoders and decoders, respectively. Here, $K = L + D$ is the total number of communication links. $P^{[k]}_{\max}$ is the maximum allowed transmit power for kth transmitter. Constraint (9b) ensures that IA is feasible. Constraint (9c) guarantees that the transmit power of each transmitter meets the power constraint. Constraint (9d) determines the values of connection factors. Constraint (9e) and (9f) calculates the IA decorrelator matrices by adopting the minimum interference leakage (MIL) algorithm in [33].

Unfortunately, the established problem (P1) is NP-hard [36] and difficult to solve directly since it has both continuous and integer variables to optimize. Consequently, finding a solution of problem (P1) with acceptable computational complexity for practical implementation is very necessary. In the next section, we will solve (P1) by dividing it into three sub-problems.

IV. THREE-STEP BASED FA-PIA ALGORITHM

In this section, we will solve problem (P1) by dividing it into three sub-problems. The first sub-problem is IA feasibility-aware interference links selection, in which we select an appropriate set of interference links to implement IA and meanwhile, the feasibility conditions are guaranteed. The second sub-problem is designing the IA precoding and decorrelator matrices for the established partially connected interference network. The third one is the power optimization for each eNB and D2D transmitter, which is aimed at maximizing the sum rate. By successively solving the three sub-problems, the three-step-based FA-PIA algorithm is finished.

A. IA FEASIBILITY-AWARE INTERFERENCE LINKS SELECTION

To solve (P1), we first find the proper set of interference links that should be aligned for each receiver under the IA feasibility constraints. In other words, we first determine the appropriate configuration of $\{\alpha^{[kj]}\}_{k,j\in\mathcal{C}\cup\mathcal{D}}$, and it must guarantee that the partially connected network will satisfy the IA feasibility conditions, that is

$$\sum_{j:(\cdot,j)\in J_{sub}} (N_t^{[j]} - d) + \sum_{k:(k,\cdot)\in J_{sub}} (N_r^{[k]} - d) \geq \sum_{(k,j)\in J_{sub}} (\alpha^{[kj]} d), \forall J_{sub} \in J, \tag{10a}$$

Algorithm 1 Pressure transfer tree based IA feasibility-aware interference selection algorithm

1: Arrange the elements of SIR set $\{\gamma^{[kj]}\}_{k\neq j\in\mathcal{C}\cup\mathcal{D}}$ from lowest to highest by using Insertion sort method for small scale networks [37] (for large scale networks, one can select to use more efficient sorting algorithms, such as Quicksort method [38]). The connection factors for all interference links are set to 0;

2: For the interference generated from each eNBs (i.e., $j \in \mathcal{C}$): select the first $n_{1\ L}$ ($n_{1\ L} = (M-d)/d$) lowest SIR interference links, which will be managed by IA (i.e., their corresponding connection factors are set to 1);

3: For the rest interference from all transmitters (i.e., $j \in \mathcal{C}\cup\mathcal{D}$): select the first $n_{1\ K}$ ($n_{1\ K} = (N-d)(2D+L)/d$) lowest SIR interference links, which will be mitigated by IA (i.e., their connection factors are also set as 1);

4: Feasibility check. If the partially connected network established by using the connection factors obtained in Step 2 and Step 3 is IA feasible, stop; else, go to Step 5;

5: For D2D transmitters (i.e., $j \in \mathcal{D}$), remove one link $j \rightarrow k$ from the above selected links in Step 2 and Step 3, where j, k is obtained by solving: $\max_{(k,j)} \gamma^{[kj]}(\sum_{j_1\in\mathcal{C}\cup\mathcal{D}} c^{[kj_1]})(\sum_{k_1\in\mathcal{C}\cup\mathcal{D}} c^{[k_1 j]})$, where $c^{[kj]} = \alpha^{[kj]}d^2$, $c^{[kk]} = 0$. Then return to Step 4.

$$\alpha^{[kj]} = \begin{cases} 1, & \gamma^{[kj]} < \gamma_{min}, \\ 0, & \gamma^{[kj]} \geq \gamma_{min}, \end{cases}, j,k \in \mathcal{C}\cup\mathcal{D}. \quad (10b)$$

However, it has exponential complexity in searching all J_{sub} to guarantee the feasibility of IA [28]. So we consider exploiting the pressure transfer tree based feasibility checking approach in [28] and [29] for its low complexity. Then the detailed algorithm of interference selection is as follows:

Remark 1: Step 2 and 3 in Algorithm 1 are aimed at selecting the maximum number of interference links to perform IA under the feasibility constraints for the set J. Moreover, Step 2 in Algorithm 1 is expected to take full advantage of the antennas at eNB, since eNB can usually be equipped with more antennas compared with UEs.

Remark 2: Step 5 in Algorithm 1 is to remove a link that has relatively high SIR and great influence on feasibility. The method to obtain j, k can be derived according to [29].

Remark 3: The selected interference links in Algorithm 1 is determined both by the SIR values and the IA feasibility conditions.

Example 1: We consider the $(4\times 2, d)^3(2\times 2, d)^3$ system as in Fig. 1 to illustrate the selection procedure in Algorithm 1. Here, d takes value of 1. We first randomly generate such a system as shown in Fig. 3(a).

Then, by using Insertion sort method, we can obtain the descending order of SIRs for all interference links as shown as in Fig. 3(b), where the number below each element in SIR set indicates the descending order.

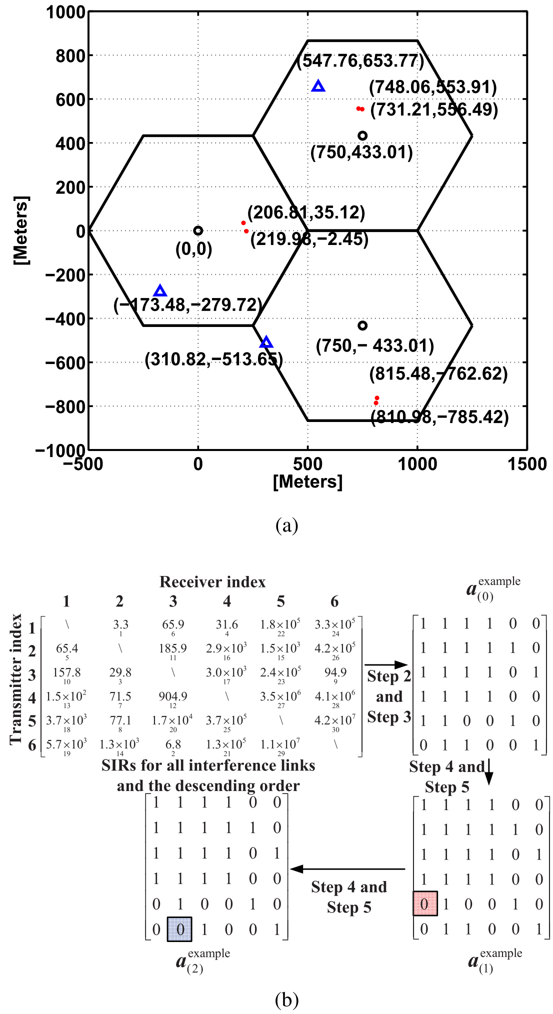


FIGURE 3. Illustration of Algorithm 1: (a) the cell configuration of example 1, where the circle, triangle and dot denote eNB, CUE and D2D users, respectively; (b) the detailed procedure of Algorithm 1.

Next, using Step 2 and Step 3 in Algorithm 1, we can get a connection factor matrix $\boldsymbol{\alpha}_{(0)}^{\text{example}}$ as shown in Fig. 3(b). Then, we can conclude the partially connected interference network established by $\boldsymbol{\alpha}_{(0)}^{\text{example}}$ is IA infeasible by using the feasibility checking method in Step 4 in Algorithm 1. Thus, we need to remove one interference link from the already selected links by using the method in Step 5 in Algorithm 1 as shown in Fig. 3(b) (i.e., the interference link corresponding to the element of $\boldsymbol{\alpha}_{(1)}^{\text{example}}$ in red box is removed). However, the partially connected interference network is still IA infeasible, so we continue removing one interference link as shown in Fig. 3(b) (i.e., the interference link corresponding to the element of $\boldsymbol{\alpha}_{(2)}^{\text{example}}$ in blue box is removed). Finally, the partially connected interference network is IA feasible and the selection procedure ends. The final connection factor matrix is $\boldsymbol{\alpha}_{(2)}^{\text{example}}$.

B. PRECODING AND DECORRELATOR MATRICES DESIGN

In the previous subsection, we have investigated how to select the appropriate interference links that should be aligned under the IA feasibility constraints. Based on the connection factor matrix $\boldsymbol{\alpha}$ obtained in the above, we can now adopt the MIL iteration approach in [33] to get the IA precoding and decorrelator matrices. The detailed algorithm to obtain $\boldsymbol{V}^{[k]}$ and $\boldsymbol{U}^{[k]}$, $k \in \mathcal{C} \cup \mathcal{D}$ is as follows:

(1) Generate initial precoding matrix $\boldsymbol{V}_{(i)}^{[j]}, j \in \mathcal{C} \cup \mathcal{D}, i \neq 0$;
(2) Calculate the decorrelator matrix $\boldsymbol{U}_{(i)}^{[k]}$, $k \in \mathcal{C} \cup \mathcal{D}$, by minimizing the interference leakage: $\boldsymbol{U}_{*l,(i)}^{[k]} = \upsilon_l(\boldsymbol{Q}_{(i)}^{[k]})$, $l = 1, 2, ..., d$, where $\boldsymbol{Q}_{(i)}^{[k]} = \sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} \frac{P^{[j]}}{d} \alpha^{[kj]} \boldsymbol{H}^{[kj]} \boldsymbol{V}_{(i)}^{[j]} \boldsymbol{V}_{(i)}^{[j]\dagger} \boldsymbol{H}^{[kj]\dagger}$;
(3) Calculate the new precoding matrix $\boldsymbol{V}_{(i+1)}^{[j]}, j \in \mathcal{C} \cup \mathcal{D}$, by minimizing the interference leakage for the reversed communication direction: $\boldsymbol{V}_{*l,(i+1)}^{[j]} = \upsilon_l(\boldsymbol{Q}_{(i)}^{[j]})$, $l = 1, 2, ..., d$, where $\boldsymbol{Q}_{(i)}^{[j]} = \sum_{k \in \mathcal{C} \cup \mathcal{D}, \neq j} \frac{P^{[k]}}{d} \alpha^{[jk]} \boldsymbol{H}^{[jk]} \boldsymbol{U}_{(i)}^{[k]} \boldsymbol{U}_{(i)}^{[k\dagger]} \boldsymbol{H}^{[jk]\dagger}$;
(4) Let $i = i + 1$ and repeat from (2) until convergence.

In the above iterations, we assume each transmitter use their maximum allowed transmit power, i.e., $P^{[k]} = P_{\max}^{[k]}$, $k \in \mathcal{C} \cup \mathcal{D}$. Note that the value of maximum allowed power does not influence the convergence of MIL iteration algorithm [33].

C. CCCP-BASED POWER OPTIMIZATION

In subsections A and B, we have proposed a low complexity interference selection method in Algorithm 1 and a MIL based iterative partial IA scheme. Upon the obtained connection factor matrix $\boldsymbol{\alpha}$ and the precoding and decorrelator matrices $\boldsymbol{V}^{[k]}$ and $\boldsymbol{U}^{[k]}$ ($k \in \mathcal{C} \cup \mathcal{D}$), we investigate the optimal power allocation for each transmitter to maximize the sum rate. The power optimization programming can be expressed as

$$\max_{\boldsymbol{P}} \sum_{k \in \mathcal{C} \cup \mathcal{D}} \sum_{l=1}^{d} \log_2(1 + \frac{P^{[k]}}{d} \frac{\widehat{g}_l^{[kk]}}{\sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} (1 - \alpha^{[kj]}) \frac{P^{[j]}}{d} \widehat{g}_l^{[kj]} + \widehat{\sigma}_{n,l}^2}), \quad (11a)$$

$$\text{s.t. } P^{[k]} \leq P_{\max}^{[k]}, k \in \mathcal{C} \cup \mathcal{D}, \quad (11b)$$

where $\widehat{g}_l^{[kk]} = \boldsymbol{U}_{*l}^{[k]\dagger} \boldsymbol{H}^{[kk]} \boldsymbol{V}_{*l}^{[k]} \boldsymbol{V}_{*l}^{[k]\dagger} \boldsymbol{H}^{[kk]\dagger} \boldsymbol{U}_{*l}^{[k]}$ is the effective channel gain for the lth stream of communication link $k \to k$. $\widehat{g}_l^{[kj]} = \sum_{l\acute{a}\acute{r}}^{d} \boldsymbol{U}_{*l}^{[k]\dagger} \boldsymbol{H}^{[kj]} \boldsymbol{V}_{*l\acute{a}\acute{r}}^{[j]} \boldsymbol{V}_{*l\acute{a}\acute{r}}^{[j]\dagger} \boldsymbol{H}^{[kj]\dagger} \boldsymbol{U}_{*l}^{[k]}$ is the effective channel gain of the interference link $j \to k$ suffered at the lth stream of kth receiver. $\widehat{\sigma}_{n,l}^2 = \sigma_n^2 \boldsymbol{U}_{*l}^{[k]\dagger} \boldsymbol{U}_{*l}^{[k]} = \sigma_n^2$ is the effective noise power for the lth stream of kth receiver. Besides, the item of $(1 - \alpha^{[kj]})$ is for the simplification of power optimization, which indicates the residual interference due to imperfect iterative IA is negligible and is not considered in the power allocation.

The optimization problem in (11a) is still difficult to solve directly since the objective function is not convex or concave. For convenience, we use $\varphi(\boldsymbol{P})$ to denote the objective function of (11a). Fortunately, we observe that the objective function $\varphi(\boldsymbol{P})$ can be rewritten as the 'Difference of Convex' (DC) form [39]. Then, the power optimization problem in (11a) can be transformed into the DC program as follows:

$$\min_{\boldsymbol{P}} \sum_{k \in \mathcal{C} \cup \mathcal{D}} \sum_{l=1}^{d} (f(\boldsymbol{P}) - g(\boldsymbol{P})), \quad (12a)$$

$$\text{s.t. } P^{[k]} \leq P_{\max}^{[k]}, k \in \mathcal{C} \cup \mathcal{D}, \quad (12b)$$

where $f(\boldsymbol{P}) = -\log_2(\sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} (1 - \alpha^{[kj]}) \frac{P^{[j]}}{d} \widehat{g}_l^{[kj]} + \widehat{\sigma}_{n,l}^2 + \frac{P^{[k]} \widehat{g}_l^{[kk]}}{d})$, $g(\boldsymbol{P}) = -\log_2(\sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} (1 - \alpha^{[kj]}) \frac{P^{[j]}}{d} \widehat{g}_l^{[kj]} + \widehat{\sigma}_{n,l}^2)$, and $\sum_{k \in \mathcal{C} \cup \mathcal{D}} \sum_{l=1}^{d} (f(\boldsymbol{P}) - g(\boldsymbol{P})) = -\varphi(\boldsymbol{P})$.

Since the optimal power vector is hard to be obtained by directly solving problem (11a), we seek to find a stationary solution. To achieve this, we adopt the CCCP in [39] to solve problem (12a) by successively solving a series of convex optimization problems. Specifically, in the n^{th} iteration, we approximate $g(\boldsymbol{P})$ by using its first order Taylor expansion $\widehat{g}(\boldsymbol{P}_{(n)}, \boldsymbol{P})$ at $\boldsymbol{P}_{(n)}$ [39]. The first order Taylor expansion $\widehat{g}(\boldsymbol{P}_{(n)}, \boldsymbol{P})$ at $\boldsymbol{P}_{(n)}$ is given by [39]

$$\widehat{g}(\boldsymbol{P}_{(n)}, \boldsymbol{P}) = -\log_2(\sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} (1 - \alpha^{[kj]}) \frac{P_{(n)}^{[j]}}{d} \widehat{g}_l^{[kj]} + \widehat{\sigma}_{n,l}^2) - \frac{1}{\ln 2} \frac{\sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} (1 - \alpha^{[kj]}) \widehat{g}_l^{[kj]} \frac{(P^{[j]} - P_{(n)}^{[j]})}{d}}{\sum_{j \in \mathcal{C} \cup \mathcal{D}, \neq k} (1 - \alpha^{[kj]}) \frac{P_{(n)}^{[j]}}{d} \widehat{g}_l^{[kj]} + \widehat{\sigma}_{n,l}^2} \quad (13)$$

Then, we only need to solve the following convex optimization problem in the n^{th} iteration:

$$\min_{\boldsymbol{P}} \sum_{k \in \mathcal{C} \cup \mathcal{D}} \sum_{l=1}^{d} (f(\boldsymbol{P}) - \widehat{g}(\boldsymbol{P}_{(n)}, \boldsymbol{P})), \quad (14a)$$

$$\text{s.t. } P^{[k]} \leq P_{\max}^{[k]}, k \in \mathcal{C} \cup \mathcal{D}, \quad (14b)$$

where $\sum_{k \in \mathcal{C} \cup \mathcal{D}} \sum_{l=1}^{d} (f(\boldsymbol{P}) - \widehat{g}(\boldsymbol{P}_{(n)}, \boldsymbol{P})) \triangleq -\widehat{\varphi}(\boldsymbol{P}_{(n)}, \boldsymbol{P})$ denotes the approximated convex objective function.

The detailed CCCP based algorithm for power optimization is as follows [39]:

(1) Generate a initial feasible power vector $\boldsymbol{P}_{(n)}$, $n = 0$;
(2) Approximate $g(\boldsymbol{P})$ as an affine function at $\boldsymbol{P}_{(n)}$ by using the Taylor expansion in (13);
(3) Solve the convex optimization problem (14a) and assign its optimal solution to $\boldsymbol{P}_{(n+1)}$;
(4) Let $n = n + 1$ and repeat from (2) until $|\varphi(\boldsymbol{P}_{(n)}) - \varphi(\boldsymbol{P}_{(n+1)})| < \varepsilon, \forall \varepsilon > 0$.

The convergence property of the CCCP-based power optimization algorithm can be obtained according to [40], [41], and [42]. We conclude it as follows:

Theorem 2: For any initial feasible point $\boldsymbol{P}_{(0)}$, the sequence $\boldsymbol{P}_{(n)}$ generated from the iterative power optimization algorithm can converge to a stationary point for the DC problem (12a) in finite iterations.

The proof of Theorem 2 can refer to [41], [42].

Finally, we can obtain a sub-optimal solution of the sum rate maximization programming (P1) by successively solving the above three sub-problems.

D. COMPLEXITY

In this part, the complexity of the three-step-based FA-PIA algorithm is calculated. As mentioned above, the FA-PIA algorithm contains three parts, i.e., interference selection, precoding and decorrelator IA matrices design as well as power allocation. We first calculate the complexity of each sub-problem respectively.

For the sub-problem of selecting proper interference links for IA, the worse case complexity is

$$\mathcal{O}\Bigg(\underbrace{\left(K(K-1)\right)^2}_{(a)}+\underbrace{K^3}_{(b)}\underbrace{\frac{(M-d)L+(N-d)(2K-L)}{d}}_{(c)}\Bigg), \tag{15}$$

where $K = L + D$ is the sum number of cellular and D2D communication links, part (a) is the worse case complexity of sort method (such as Insertion sort) [37], part (b) is the worse case complexity of feasibility checking [29], part (c) is the maximum number of interference links removed in Step 5 of Algorithm 1.

Next, for the sub-problem of precoding and decorrelator IA matrices design, the complexity is $\mathcal{O}(K)$. For the sub-problem of power optimization, it has polynomial complexity $\mathcal{O}(K\log K)$ [43]. Then, the complexity of the three-step-based algorithm can be expressed as

$$\mathcal{O}\Bigg(\left(K(K-1)\right)^2 + K^3\frac{(M-d)L+(N-d)(2K-L)}{d} +K\log K + K\Bigg), \tag{16}$$

If we fix the antenna configurations M, N as well as DOF d, (16) can be further reduced to $\mathcal{O}(K^4)$.We can see that the complexity has been decreased from exponential level to polynomial one.

E. UPPER BOUND

In this subsection, we analyze the possible upper bound of problem (P1). As we can see, for any given connection factor matrix $\boldsymbol{\alpha}$, we can get one maximum sum rate by interference alignment and optimal power allocation. Then, the optimal connection factor matrix $\boldsymbol{\alpha}^{\text{opt}}$ as well as IA beamforming matrices $\boldsymbol{V}_{\text{opt}}^{[k]}$ and $\boldsymbol{U}_{\text{opt}}^{[k]}, k \in \mathcal{C}\cup\mathcal{D}$ and power allocation vector $\boldsymbol{P}^{\text{opt}}$ can be obtained by comparing all the sum rates generated from different $\boldsymbol{\alpha}$. Moreover, the maximum one of all these sum rates is an upper bound. For a K-user interference network, the maximum number of all possible $\boldsymbol{\alpha}$ that guarantees the feasibility of IA is $2^{K(K-1)}-1$. Then the complexity of the exhaustive search method can be expressed as $\mathcal{O}(2^{K^2})$. Since the exhaustive search method has exponential computational complexity, it is not practical for large scale network.

V. PRACTICAL DEPLOYMENT AND APPLICATION

In this section, we will give some reasonable assumptions and illustrate the possible practical implementation of the proposed FA-PIA scheme. We first assume that:

(1) Each eNB acts as a control center.

(2) Each receiver (D2D receiver or CUEs) has an additional feedback channel to the eNB in its cell. Similar assumption can be found in [6].

(3) eNBs in different cells can exchange CSI and control information through low latency backhaul links. Similar assumption can be found in Coordinated Multipoint (CoMP) system [44].

Given the above assumptions, a possible way to implement the proposed three-step-based algorithm is as follows: At first, each transmitter (D2D transmitter or eNB) sends training sequences. Then, each receiver (D2D receiver or CUE) can estimate its local CSI of the effective channel as well as interference channels. The obtained CSI at each receiver would be fed back to the eNB in its cell. Since eNBs in different cells can exchange their CSI via the backhaul links, global CSI can be acquired at each eNB finally. As for D2D transmitters, the local CSI is obtained by the feedback from their corresponding D2D receivers. After the acquisition of CSI, the procedure of interference selection, IA beamforming matrices calculation and power allocation would be conducted successively.

Here, to reduce computational burden at UEs, we can choose one eNB as the central unit, which is responsible of calculating the connection factor matrix $\boldsymbol{\alpha}$, IA precoding and decorrelator matrices $\boldsymbol{V}^{[k]}$ and $\boldsymbol{U}^{[k]}$, $k \in \mathcal{C} \cup \mathcal{D}$ as well as power allocation vector $\boldsymbol{P}$. During the three-step process, no signaling is exchanged among different nodes. Although the above procedure increases the computational burden at the central unit, the signaling needed to be exchanged between all nodes during the distributed application process of iterative IA can be avoided [26]. Thus, we prefer to use the centralized algorithm to reduce the burden at UEs. Then, the obtained results would be sent to other eNBs through backhaul links. Each eNB can then distribute the corresponding allocated power and IA beamforming matrices to the D2D links in its cell. Finally the proposed FA-PIA algorithm is accomplished.

VI. OVERHEAD

As discussed in Section V, the central unit needs global CSI to perform interference selection, IA beamforming matrices design and power allocation. The signaling for CSI detection, feedback and exchange will be increased with the enlargement of network size. Moreover, the computational overhead for the central unit is also increased when the network size becomes larger. To reduce the overhead, advanced channel estimation and feedback technologies can be adopted [45]–[47]. Another possible way to reduce the overhead is to employ the concept of clustering [16], [48], [49]. Through dividing the large network into some clusters, we can respectively implement the proposed schemes in each cluster. However, in this paper, we are focused on obtaining a solution that is nearest to the optimal one. Therefore the clustering procedure would not be considered in this paper.

TABLE 1. Simulation parameters.

Carrier frequency	2 GHz
DL bandwidth	5 MHz
Cell radius	500 meters
Maximum transmit power	$P_{\text{eNB}}^{\max}$: 37, 40, 43, 46, 49 dBm;
	$P_{\text{D2D}}^{\max}$: 12, 15, 18, 21, 24 dBm
Thermal noise density	-174 dBm/Hz
Noise figure	eNB: 5 dB, UE: 9 dB
Antenna configurations	M(eNB): 2, 3, 4, 5, 6; N(UE): 1, 2, 3, 4, 5
Maximum D2D link distance	$l_{\text{D2D}}^{\max}$: 20, 40, 60, 80, 100 meters
Number of D2D pairs per cell	$D^{[l]}(\forall l \in \mathcal{L}) \triangleq n_{\text{D2D pairs}}$: 1, 2, 3, 4, 5

VII. NUMERICAL RESULTS

In this section, we will provide some numerical results to evaluate the performance of the proposed three-step-based FA-PIA algorithm. Moreover, some necessary analysis of the simulation results is also provided.

A. SIMULATION SCENARIO AND PARAMETERS

The simulation scenario we considered is a three-cell (i.e., $L = 3$) network. The CUEs and D2D mode UEs coexist in the network. In each cell, the CUEs are uniformly distributed throughout the cell. Since D2D communication is usually established for UEs within relatively short distances, we assume the maximum distance between a D2D transmitter and its receiver is $l_{\text{D2D}}^{\max}$. The way to generate such a D2D pair can refer to [11], where a D2D transmitter and its receiver are distributed uniformly in a randomly generated circular region with radius $0.5l_{\text{D2D}}^{\max}$. Moreover, we assume the appropriate resource blocks have already been assigned for different CUEs and D2D pairs by using some effective resource allocation schemes [8], [12]. In each cell, we assume $D^{[l]}$ D2D pairs reuse the same spectral resource with one CUE. According to the Third Generation Partnership Project (3GPP) standardization on D2D communication [50], we consider the WINNER+ urban micro-cell channel models for both D2D channel and cellular channel [51]. The simulation parameters are summarized in Table 1.

B. PERFORMANCE COMPARISON

In this part, we evaluate the achievable sum rate of the proposed FA-PIA scheme versus six parameters: the maximum D2D distance ($l_{\text{D2D}}^{\max}$,i.e., the maximum distance between the D2D transmitter and corresponding D2D receiver), the maximum transmit powers for eNBs and D2D transmitters ($P_{\text{eNB}}^{\max}$, $P_{\text{D2D}}^{\max}$), antenna configurations for eNBs and UEs (M, N) and the number of D2D pairs per cell ($n_{\text{D2D pairs}}$). Moreover, for each parameter, we take 500 Monte Carlo simulations and obtain the averaged performance result. We mainly compare the achievable sum rate of the FA-PIA algorithm with three different algorithms and three baselines:

1) **Scheme 1**: the ZF-beamforming scheme (**ZF-BF scheme**) proposed in [15], in which a ZF precoder is used by the eNB to eliminate its interference to all D2D receivers in each cell.

2) **Scheme 2**: the fixed interference links based IA scheme (**FI-IA scheme**) proposed in [18], in which the IA is carried out for a predetermined and fixed set of interference links.

3) **Scheme 3**: IA algorithm for the channel condition dependent partially connected networks (**C-PIA scheme**) in [29]. Here, to have a fair comparison, we only consider the partial connectivity caused by path-loss. Moreover, the maximum interference distance l defined in [29] is set to be 400 m or 600 m, which will generate an interference network with quite weak connectivity.

4) **Baseline 1**: the optimal power allocation scheme without IA (**PA scheme**), in which the SINR quality-of-service (QoS) requirement is satisfied.

5) **Baseline 2**: the first simplified proposed scheme, in which the interference links to be aligned is selected randomly (**RandS-simplified scheme**).

6) **Baseline 3**: the second simplified proposed scheme, in which maximum allowed transmit power is allocated for each transmitter. While the selection of interference links still uses the approach of Algorithm 1 (**MaxP-simplified scheme**).

7) **Baseline 4**: the upper bound of the network achievable sum rate (**Upper Bound**), which is obtained by an exhaustive search method as discussed in Part. E in Section IV.

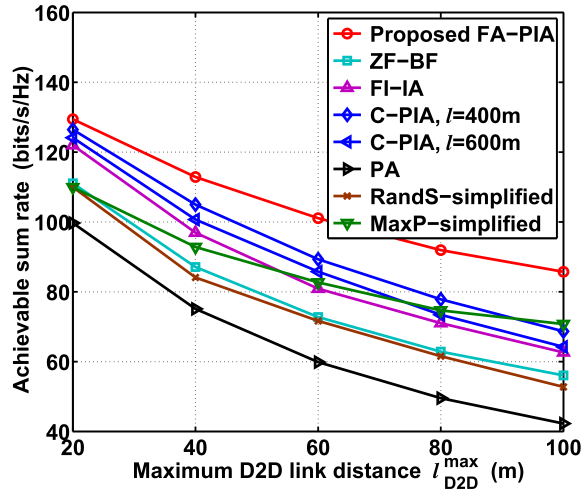
Here, to have a fair comparison, the total power consumed for scheme 1-3 and the proposed FA-PIA scheme is the same. Moreover, to guarantee the feasibility of IA for the partial connected interference network, the DoF d for each user is 1 for all antenna configurations except the cases $N = 4, 5$ and $M = 4$. We let d to be 2 when $N = 4, 5$ and $M = 4$. Moreover, we calculate the maximum achievable sum rate based on the Shannon Theory. One can use the modified Shannon's capacity to approximate the real LTE-Advanced system throughput performance [12], which is lower than half of the value obtained in this section.

Fig. 4(a) illustrates the achievable sum rates versus $l_{\text{D2D}}^{\max}$ of four different algorithms and three baselines for the D2D communication underlaying cellular network. As we can see from Fig. 4(a), the achievable sum rates for all the schemes decrease when $l_{\text{D2D}}^{\max}$ increases. The reason is that the channel gains of D2D communication links decline with the increase of $l_{\text{D2D}}^{\max}$, which will lead to the decrease of achievable received SINRs for D2D receivers. Moreover, from Fig. 4(a) we can see that the proposed FA-PIA scheme can achieve better achievable sum rates performance compared with other existing algorithms. Specifically, the descending order of achievable sum rates performances for all these schemes is: the FA-PIA, the C-PIA, the FI-IA, the MaxP-simplified ($l_{\text{D2D}}^{\max} < 54$ m), the ZF-BF, the RandS-simplified, and the PA schemes. Note that when $l_{\text{D2D}}^{\max} > 54$ m ($l_{\text{D2D}}^{\max} > 75$ m), the MaxP-simplified scheme has better achievable sum rate performance than the FI-IA (C-PIA) scheme. The reasons are as follows. Firstly, the FA-PIA scheme is much superior to the RandS-simplified one since our interference selection algorithm is devoted to the mitigation of the relatively strong interference for both D2D and cellular communications.

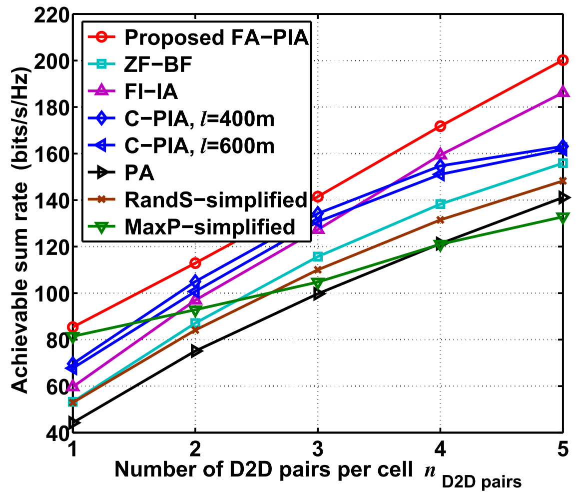
Thus, the remaining interference of the FA-PIA scheme is much weaker, which results in better achievable sum rate performance than that of the RandS-simplified one. Secondly, the FA-PIA scheme also has superiority compared with the MaxP-simplified one since the power allocation can mitigate the remaining weak interference and result in higher sum rate. In addition, the MaxP-simplified scheme uses the same maximum allowed power throughout the range of $l_{\text{D2D}}^{\max}$. So when the channel quality of D2D communications gets better, i.e., $l_{\text{D2D}}^{\max}$ is smaller, the MaxP-simplified scheme cannot fully take the advantages of D2D communications since the allocated power for D2D links do not change. As a result, the MaxP-simplified scheme has a more smooth curve and its achievable sum rate performance would be inferior to the C-PIA and FI-IA schemes when $l_{\text{D2D}}^{\max}$ is less than about 54 meters. Thirdly, PA scheme achieves the worst performance since it can not take advantage of the additional freedom brought about by IA or beamforming.

In addition, we can see from Fig. 4(a) that the ZF-BF scheme only has limited achievable sum rate gain than PA case since it only cancels out the interference from eNB to D2D receivers in each cell. As for the FI-IA scheme, it is better than the ZF-BF one but worse than the proposed FA-PIA algorithm. The reason is that it can eliminate additional interference compared with ZF-BF scheme. However, the set of interference links to be aligned for FI-IA scheme is fixed for any channel situation. So in some cases, the residual interference may be strong and the achievable sum rate will decrease. Finally, as we can see the achievable sum rate of C-PIA scheme decreases with the increase of the maximum interference distance, which is in accordance with [29]. Moreover, for C-PIA scheme, the partial connectivity state for a given network is fixed. To satisfy the IA feasibility conditions, it needs to decrease the DoFs for some communication links and a few of links may achieve 0 DoF, i.e., these links are shut down. Thus, for those cases with some communication links having lowered or even worse 0 DoF, their achievable sum rates may decrease and the averaged results will be inferior to the FA-PIA algorithm.

Fig. 4(b) illustrates the achievable sum rates versus $n_{\text{D2D pairs}}$ for four different algorithms and three baselines for the hybrid D2D and cellular network. As we can see from Fig. 4(b), the achievable sum rates for all the schemes are improved when $n_{\text{D2D pairs}}$ increases. Obviously, it can better take advantage of the benefit of higher data rates of D2D communications when the number of D2D pairs increases. Similarly, we can see the achievable sum rate of the MaxP-simplified scheme grows slower than other schemes. Here, the reason is the same as that in Fig. 4(a). Moreover, the achievable sum rate for the C-PIA scheme increases slowly when $n_{\text{D2D pairs}}$ is more than 3. As a result, the achievable sum rate gain of the proposed FA-PIA scheme against the C-PIA one is larger when $n_{\text{D2D pairs}} > 3$. That is because the averaged achievable DoF for the C-PIA scheme decreases as $n_{\text{D2D pairs}}$ increases. As for the proposed FA-PIA scheme, the averaged achievable DoF per user is fixed to be d.



(a)



(b)

FIGURE 4. Achievable sum rates for four different schemes and three baselines when (a): $l_{\text{D2D}}^{\max}$ changes from 20 m to 100 m given $n_{\text{D2D pairs}} = 2$, or (b): $n_{\text{D2D pairs}}$ changes from 1 to 5 given $l_{\text{D2D}}^{\max} = 40$ m. $P_{\text{eNB}}^{\max}$=40 dBm, $P_{\text{D2D}}^{\max}$=24 dBm, $M = 4$, and $N = 2$.

Consequently, when the number of D2D links increases, our proposed FA-PIA scheme has a higher achievable sum rate gain over the C-PIA one.

Fig. 5 illustrates the achievable sum rates for four different algorithms and three baselines under different $P_{\text{eNB}}^{\max}$ or $P_{\text{D2D}}^{\max}$. As we can see from Fig. 5(a), the achievable sum rates for all the schemes change little when $P_{\text{eNB}}^{\max}$ increases. The reason mainly comes from the inherent channel properties of the hybrid D2D and cellular communication system. In this heterogeneous network, the communication quality of D2D links is better than that of cellular links. The achievable sum rate improvement mainly comes from D2D communications. As $P_{\text{eNB}}^{\max}$ increases, the allocated power for cellular links will be increased, which would bring about the sum rate increase for cellular links. However, the interference from cellular links to D2D communications also becomes strong,

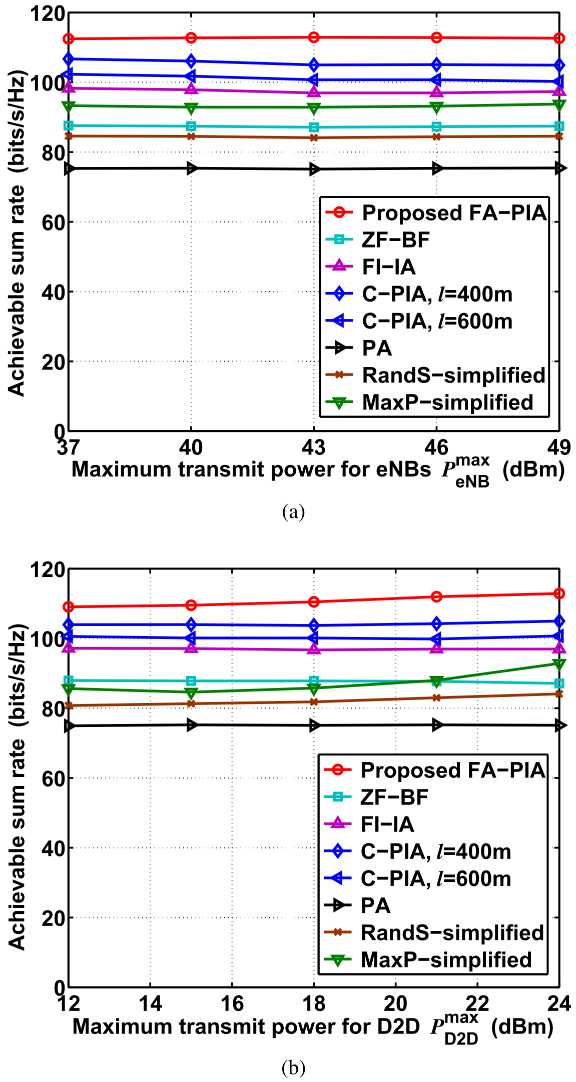


FIGURE 5. Achievable sum rates for four different schemes and three baselines when (a): $P_{\text{eNB}}^{\text{max}}$ changes from 37 dBm to 49 dBm with $P_{\text{D2D}}^{\text{max}}$=24 dBm, or when (b): $P_{\text{D2D}}^{\text{max}}$ changes from 12 dBm to 24 dBm with $P_{\text{eNB}}^{\text{max}}$=43 dBm. $l_{\text{D2D}}^{\text{max}}$=40 m, $n_{\text{D2D pairs}} = 2$, $M = 4$, and $N = 2$.

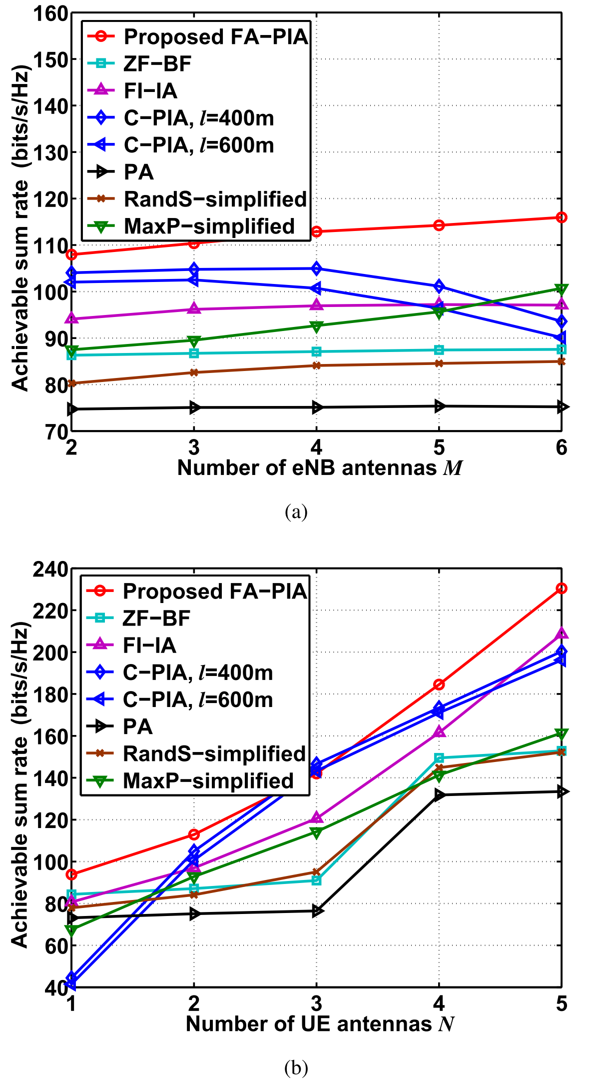


FIGURE 6. Achievable sum rates for the four different schemes and three baselines when (a): the number of eNB antennas M changes from 2 to 6 with $N = 2$, or when (b): the number of UE antennas N changes from 1 to 5 with $M = 4$. $P_{\text{eNB}}^{\text{max}}$=43 dBm, $P_{\text{D2D}}^{\text{max}}$=24 dBm, $l_{\text{D2D}}^{\text{max}}$=40 m, $n_{\text{D2D pairs}} = 2$.

which would decrease the sum rate for D2D communications. Moreover, given the inherent channel properties, the rate increment of cellular links is no higher than the rate decrease of D2D links. Thus, the integrated effect is that the achievable sum rate is almost unchanged with the increase of $P_{\text{eNB}}^{\text{max}}$.

In Fig. 5(b), we can see that the achievable sum rates of the FA-PIA, the MaxP-simplified and the RandS-simplified schemes grow smoothly as $P_{\text{D2D}}^{\text{max}}$ increases. The achievable sum rates of the other schemes are almost unchanged. The reasons are as follows. First, for our schemes (the FA-PIA, baseline 2, 3), the achievable sum rates of D2D communications will be improved as the transmit power of D2D links increases. For the MaxP-simplified scheme, the interference from D2D communications to cellular links also becomes strong, which would lead to the decrease of cellular sum rates. Given the inherent channel properties, the sum rate increment of D2D links is higher than the sum rate decrease of cellular links. So the integrated effect is that the achievable sum rates of the MaxP-simplified scheme grows smoothly with the increase of $P_{\text{D2D}}^{\text{max}}$. While, for the FA-PIA, baseline 2 and 3, to guarantee the performance of cellular links, more power would also be consumed at eNBs, which would increase the interference power to D2D links in turn. The integrated effect is that the achievable sum rates have a little increase when $P_{\text{D2D}}^{\text{max}}$ increases. As for other schemes, although the total power is increased, the interference between cellular and D2D communications also becomes stronger. Consequently, the separate sum rates for cellular or D2D is almost unchanged, i.e., the achievable sum rate changes little when $P_{\text{D2D}}^{\text{max}}$ increases.

Fig. 6 illustrates the achievable sum rates performance for four different algorithms and three baselines with

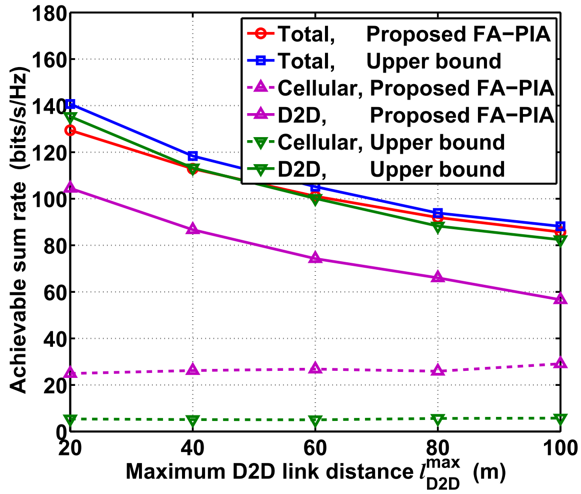


FIGURE 7. **The comparison between the achievable sum rates of the FA-PIA scheme and the upper bound when P_{eNB}^{max}=43 dBm, P_{D2D}^{max}=24 dBm, $n_{D2D\ pairs}$ = 2, M = 4, and N = 2.**

different antenna configurations. From Fig. 6(a), we can see that the achievable sum rates for the FA-PIA, the FI-IA and the RandS-simplified schemes increase smoothly when the number of antennas at eNBs M goes from 2 to 6. Moreover, the achievable sum rate of the MaxP-simplified scheme grows more rapidly when M increases. The reasons are as follows. The sum rate for D2D communications of the MaxP-simplified scheme is low since the interference from eNBs to D2D receivers is strong. When M becomes larger, more interference from eNBs to D2D receivers will be eliminated by IA. As a result, the D2D sum rate of the MaxP-simplified scheme increases relatively rapidly with the increase of M. As for the FA-PIA, the FI-IA scheme and the RandS-simplified scheme, the room for D2D sum rate growth is limited since they would have their nearest highest available D2D sum rate. Thus, the achievable sum rate improvement is limited.

As for the ZF-BF and the PA schemes, their achievable sum rates do not change with the increase of M since the DoF d for each user is unchanged. In addition, for the C-PIA scheme, the achievable sum rate decreases with the increases of M. The reason is as follows. With the increase of M, more DoFs will be allocated to cellular users by using the C-PIA scheme, which would lead to the decrease of sum rate for D2D communications. Moreover, the cellular sum rate has limited growth with the increased DoF since the channel quality of cellular links is worse than that of D2D links. The integrated effect is that the achievable sum rate decreases with the increase of M.

As we can see from Fig. 6(b), the achievable sum rates for the FA-PIA, the C-PIA, the FI-IA, the MaxP-simplified and the RandS-simplified schemes are all improved when the number of antennas at UEs N increases. The reason is that the feasibility of IA is easier to be guaranteed with the increase of N for a given per user DoF d on one hand. On the other hand, higher DoF d for each user can be achieved when N increases. As for our schemes (the proposed FA-PIA, baseline 2, 3, 4), more interference from other transmitters can be selected to participate in IA. Thus, the residual interference is weaker, which would lead to the increase of achievable sum rate. Moreover, when N is 4, 5, per user's DoF d can be selected as 2. The feasibility of IA can also be satisfied by properly selecting the interference links. Thus, the achievable sum rate is improved for the increase of DoF d. As for the ZF-BF and the PA schemes, their achievable sum rates do not change with the increase of N (N is 1, 2, 3, $d = 1$) unless the DoF d for each user is increased (N is 4, 5, $d = 2$). Moreover, we can see the achievable sum rate improvement of the proposed FA-PIA scheme against the C-PIA scheme is higher when N is smaller ($N \leq 2$). However, when N is 3, the achievable sum rate of the C-PIA scheme is almost the same as the proposed one. As N is larger than 3, our proposed scheme is superior to C-PIA scheme again. Here, the reason is as follows. Since the proposed FA-PIA algorithm is devoted to the selection of proper interference to accomplish IA for a given per user's DoF d, d is fixed to be 1 when $N < 4$ and 2 when $N = 4, 5$. As for the C-PIA scheme, it has different DoFs for different users. When N is 3, some users may get DoF of 2, which is higher than that of the proposed scheme. However, as N is larger than 3, all users can achieve DoF of 2 in our scheme, which will be higher than that of C-PIA one again.

In summary, the proposed FA-PIA scheme can on one hand achieve higher degree of freedoms than that of fully connected IA. On the other hand, the proposed scheme can further reduce the residual interference that is not aligned and achieve higher sum rate.

C. UPPER BOUND

According to the analysis in Section IV, we know an upper bound of achievable sum rate can be obtained by using the exhaustive search method. Since the exhaustive search method has exponential complexity, we only simulate it in the scenario that l_{D2D}^{max} ranges from 20 to 100 meters with $P_{eNB}^{max} = 43$dBm, $P_{D2D}^{max} = 24$dBm, $n_{D2D\ pairs} = 2$, $M = 4$, and $N = 2$. The achievable sum rates as well as the separate rates for D2D and cellular communications of the proposed FA-PIA scheme and the exhaustive search method are shown in Fig. 7. As shown in Fig. 7, the exhaustive search method can get higher achievable sum rate at the cost of sacrificing the rate of cellular links. As for the proposed FA-PIA scheme, both cellular and D2D communications have acceptable rates. Moreover, the superiority of the exhaustive search method compared to the proposed FA-PIA one becomes smaller when l_{D2D}^{max} increases. That is because the rate performance for D2D communication decreases with the increase of l_{D2D}^{max}. So the sum rate gain that is mainly from D2D communication for the exhaustive search method is limited.

VIII. CONCLUSION

In this paper, we propose a novel three-step-based FA-PIA algorithm for a multicell hybrid D2D and cellular communication network, which can support arbitrary number of D2D and cellular communication links to transmit concurrently. We firstly establish the necessary and sufficient feasibility condition of partial IA for the asymmetric hybrid D2D and cellular communication network. Then, the feasibility aware interference selection algorithm is proposed. Along with the MIL-based precoding and decorrelator partial IA matrices calculating algorithm, the relatively strong interference can be effectively eliminated. At last, the CCCP-based iterative power optimization scheme is given to mitigate the remaining weak interference. Finally, simulation results show the proposed three-step-based FA-PIA scheme can effectively improve the achievable sum rate compared with other existing schemes. In the future, we will investigate more general scenario which can support more general antenna configurations.

APPENDIX A
PROOF OF THEOREM 1

Firstly, we prove the "only if" side of Theorem 1. According to [24] and [34], if a network is IA feasible, the properness condition in the following must be satisfied [24].

$$N_v = \sum_{j:(\cdot,j)\in J_{\text{sub}}} (N_t^{[j]} - d)d + \sum_{k:(k,\cdot)\in J_{\text{sub}}} (N_r^{[k]} - d)d \geq N_e = \sum_{(k,j)\in J} \alpha^{[kj]} d^2, \forall J_{\text{sub}} \in J, \tag{17}$$

Apparently, we can see that (17) is just the properness condition (7). Thus, if a network is IA feasible, (17) must be satisfied. The proof of "only if" side is completed.

Secondly, we prove the "if" side of Theorem 1. Before the proof, we first give Lemma 1, which is an expansion of lemma 3.7 in [34].

Lemma 1: if we can find such variables $\left\{c_{kjpq}^r, c_{kjpq}^t \in \{0,1\}\right\}$, $k, j \in 1, \ldots, K$, $k \neq j$, $p, q \in 1, \ldots, d$, that satisfy the following constraints, the IA problem has solutions with probability 1,

$$c_{kjpq}^r + c_{kjpq}^t = 1, \text{ if } \alpha^{[kj]} = 1, \tag{18}$$

$$c_{kjpq}^r = c_{kjpq}^t = 0, \text{ if } \alpha^{[kj]} = 0, \tag{19}$$

$$\sum_{j=1,\neq k}^{K} \sum_{q=1}^{d} c_{kjpq}^r \leq N_r^{[k]} - d^{[k]}, \forall k, \tag{20}$$

$$\sum_{k=1,\neq j}^{K} \sum_{p=1}^{d} c_{kjpq}^t \leq N_t^{[j]} - d^{[j]}, \forall j, \tag{21}$$

$$\sum_{k=1,\neq j}^{K} \sum_{p=1}^{d} c_{kjpq}^t \leq N_t^{[j]} - d^{[j]}, \forall j, \tag{22}$$

$$c_{kj1q}^r = \ldots = c_{kjdq}^r, \forall k, j, q, \text{ or } \quad c_{kjp1}^t = \ldots = c_{kjpd}^t, \forall k, j, p. \tag{23}$$

Proof of Lemma 1: According to Theorem 3.2 in [34], if the matrix $\boldsymbol{H}_{\text{all}}$ defined in [34] is full row rank, the IA problem has solutions almost surely.

According to the definition of $\boldsymbol{H}_{\text{all}}$, we can obtain the corresponding $\boldsymbol{H}_{\text{all}}^{\text{partial}}$ in our system, which is a little different from $\boldsymbol{H}_{\text{all}}$ in [34]. The block elements in $\boldsymbol{H}_{\text{all}}^{\text{partial}}$ are $\alpha^{[kj]}\boldsymbol{H}_{kj}^{\text{U}}$ and $\alpha^{[kj]}\boldsymbol{H}_{kj}^{\text{V}}$ (the definition of $\boldsymbol{H}_{kj}^{\text{U}}$ and $\boldsymbol{H}_{kj}^{\text{V}}$ can refer to [34]). Since our system is partially connected for IA, some row blocks of $\boldsymbol{H}_{\text{all}}^{\text{partial}}$ are zero matrices. The number of non-zero rows is $N_e = \sum_{(k,j)\in J_{\text{sub}}} \alpha^{[kj]} d^2$. Thus, for our system, we have to prove the row rank of matrix $\boldsymbol{H}_{\text{all}}^{\text{partial}}$ is N_e. We can first remove all the zero rows from $\boldsymbol{H}_{\text{all}}^{\text{partial}}$ and get the new matrix $\boldsymbol{H}_{\text{all,no 0}}^{\text{partial}} \in \mathbb{C}^{N_e \times N_v}$. Now, we only need to prove the new matrix $\boldsymbol{H}_{\text{all,no 0}}^{\text{partial}}$ is full row rank. The proof is similar as that for $\boldsymbol{H}_{\text{all}}$ in [34]. The proof of Lemma 1 is completed.

We further have the conclusion that when (7) is true, the set of variables will satisfy (18)-(23). The proof is similar as that in [34]. Finally, given Lemma 1, we know IA is feasible when (7) is satisfied. The proof of the "if" side is completed.

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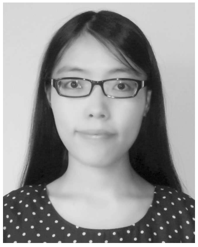

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