Opportunistic Interference Alignment Approach in Device-to-Device Communications Underlaying Cellular Networks

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***Abstract*—We consider Device-to-Device (D2D) communications underlaying cellular networks with multiple cellular users (CUs) and multi-pair direct D2D users (DUs). In this considered scenario, we propose a novel opportunistic interference alignment (OIA) scheme to improve the sum rate of the whole networks. DUs are opportunistically selected based on the reference signal space (RSS) of the CUs. According to the RSS, the DUs can calculate the scheduling metric which represents the strength of D2D interference to CUs. Then, we select the DUs according to the computing result. Unlike most of the existing methods, the proposed OIA scheme relies on the local channel state information, which is more realistic in practice. In addition, in view of the angle between the interference caused by each DU and the RSS, several scheduling strategies are designed to enhance the performance. Numerical results show that the proposed scheme can improve the performance of the network.**

I. Introduction

In recent years, wireless communication is in continuous evolution due to the rapidly increasing demands for communication service. Meanwhile, the increasing number of users leads to the spectrum shortage [1], [2], which impedes the further improvement in the field of wireless communications. Device-to-Device (D2D) communications were first proposed in [3]. Unlike traditional cellular communications, D2D communications have the potential to reduce energy consumption [4], [5], it is because that D2D users can communicate directly with each other without transmitting data via the base station (BS). However, because D2D and cellular communications share the the same resources, new interference between the cellular and D2D communications needs to be dealt with. Of course, the new interference is the most important issue in the D2D communications underlaying cellular networks [6].

There are some recent researches on the interference mitigation for the D2D communications underlaying cellular networks. Aiming to decrease the complexity of the network, an interference limited areas based resource allocation scheme is proposed in [7], [8]. In this scheme, the cellular users (CUs) in the interference limited areas do not share the same resource with D2D pairs. So, this scheme cannot be applied to the scenarios with densely deployed D2D pairs. The interference is mitigated by a simple interference alignment (IA) scheme in [9], [10], and this method can improve the degrees-of-freedom (DoF) performance of the whole system. However, the IA scheme needs global channel state information (CSI) to mitigate interference in the whole system. To further improve the sum rate of the whole network, a user selection method is proposed in [11]. However, it is limited to the situation where all users are deployed with a single antenna. Besides, the complexity is high for the D2D user selection when there is a large number of active D2D users. For a D2D multiple-input multiple-output (MIMO) underlaying cellular network [12], an IA scheme is proposed to simplify the energy efficiency problem, then achieve maximal energy efficiency. The major interference between cellular users has significant influence on the performance. However, the major interference between cellular users, which has significant influence on the performance, is not taken into consideration in [12], and it is difficult to guarantee D2D and cellular networks can be reliable. Most existing schemes, like [9]–[12], assume that the global CSI is known at each user. However, in practice, the assumption might be unrealistic in D2D communications underlaying cellular networks. So, we need to propose a novel scheme to improve the performance of the D2D communications underlaying cellular networks without global CSI and calculation iteration or other complex methods proposed in other schemes.

The idea of opportunistic IA (OIA) scheme is to combine the IA and opportunistic selection of users. Inspired by IA, OIA can overcome the limitation of IA. For instance, OIA scheme can operate with local CSI and enjoy a significantly reduced implementation complexity. In [13]–[15], OIA scheme is applied to the cellular networks and can further improve the achievable sum rate. Then, [16] proposes a novel OIA scheme and achieves a comparable performance to the centralized user scheduling in a multi-way relay network. The OIA scheme can also be implemented in a two-tier heterogeneous network [17], [18], and it can obtain multiuser diversity and achieve a better sum rate. Due to the fact that OIA scheme is successfully applied in many different networks, and the performance of these networks is further improved, OIA is expected to be beneficial for the D2D communications as well.

In this work, we propose a novel OIA scheme for D2D

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communications. We consider D2D communications underlaying cellular networks with only one BS equipped with multiple antennas. In order to improve the spectrum efficiency of the whole networks, multi-D2D links reuse the same resource with cellular users. Then, there exists the interference from D2D links to CUs. In particular, as the number of D2D pairs admitted to the networks is constrained in each transmission block, D2D users need to be opportunistically selected to facilitate alignment between D2D networks and cellular networks. Because BS is lack of CSI among CUs and D2D pairs, BS cannot decide how to select these D2D users without any scheduling metric. So, by introducing a reference signal space (RSS), which can be determined by offline [19], we can calculate the scheduling metric which represents the D2D interference to the CUs. Therefore, we can use RSS to guide the D2D users selection and further improve the sum rate of the system. Also, we investigate the influence of different scheduling strategies of D2D users on the sum rate performance of the system. In this scheme, although IA cannot be completely achieved, we can approximately achieve IA by relying on multiuser diversity when there are a lot of D2D users. So, it is simple and convenient to find the suitable D2D candidates. Numerical simulations show that the several proposed schemes can outperform the existing methods.

Notation: $\mathbf{I}$ and $\mathbf{0}$ represent the identity matrix and the all zeros matrix, respectively. The operator $\mathbf{A}^H$ indicates Hermitian matrix of $\mathbf{A}$. Matrix operation $[\cdot]^{\mathrm{T}}$ means transpose.

II. System Model

We consider a D2D communication system underlaying a downlink cellular network, which has multiple CUs and D2D links. In this scenario, the D2D pairs share the same resource with all the CUs. Therefore, different kinds of interference in our networks may occur. In Fig. 1, there exists interference among D2D links, each CU receives both desired signals from BS and interference signals from BS and D2D links as well. The BS is equipped with M antennas. There are K cellular users (i.e., $CU_1, CU_2, ..., CU_K$) and S D2D pairs (i.e., $DU_1, DU_2, ..., DU_S$). Each CU is equipped with N_C antennas. Each D2D pair has one transmitter and one receiver. For the sake of convenience, we first focus on the scenario in which the BS transmits only one data stream and the transmitters and receivers of D2D pairs are all equipped with a single antenna. Then, we extend the proposed scheme to a more general model later in Section III-B. We assume that the generated interference caused by BS to D2D users and CUs can be eliminated completely by zero-forcing (ZF) method, which is discussed in Section III-A. Then, the number of the selected D2D links, i.e., L, can be determined according to the condition of applying ZF method. Therefore, we need to select L D2D pairs out of these S D2D pairs. These selected pairs are denoted as $D_1, D_2, ..., D_L$, where $L < M < S$.

In this paper, the model for path-loss is designed as $H = G_D \cdot (d)^{-\alpha} h$, where H is an element of the channel vector, h is the Gaussian channel coefficient with the distribution $\mathcal{N}(0,1)$. α is a path loss exponent, d is the distance between the two

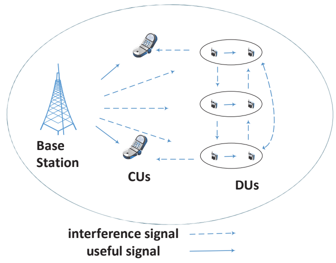

Figure 1. D2D communications underlaying downlink cellular networks.

nodes, G_D is the channel gain at a distance of $1m$. We assume that BS only knows the CSI from the BS to all D2D links and all CUs, each D2D user only knows the CSI from all CUs. So, we just need local CSI to select the users.

When we do not deal with the interference in this system model, the received signals at the CU_k and the receiver of DU_s can be presented as

$$\begin{aligned} Z_{C,k} &= \sum_{i=1}^{K} \sqrt{P_B^{C,i}} \mathbf{U}_{C,k} \mathbf{H}_B^{C,k} \mathbf{F}_i x_i \\ &+ \sum_{s=1}^{S} r(s) \sqrt{P_{D,s}^{s}} \mathbf{U}_{C,k} \mathbf{H}_{D,s}^{C,k} y_s + \mathbf{U}_{C,k} z_{C,k}, \end{aligned} \quad (1)$$

$$\begin{aligned} Z_{D,s} &= \sum_{m=1}^{S} r(m) \cdot \sqrt{P_{D,m}} H_{D,m}^{s} y_m \\ &+ \sum_{k=1}^{K} \sqrt{P_B^{C,k}} \mathbf{H}_B^{D,s} \mathbf{f}_k x_k + z_{D,s}, \end{aligned} \quad (2)$$

where x_k is transmit signal from BS to CU_k, y_s is the transmit signal from the s-th D2D link, with $E\{|x_k|^2\} = 1$ and $E\{|y_s|^2\} = 1$. If $r(s) = 0$, DU_s is admitted to share the resource with the cellular networks; otherwise, not admitted. $\mathbf{H}_B^{C,k}$ is the $N_C \times M$ channel matrix from BS to CU_k; $\mathbf{H}_B^{D,s}$ is the $1 \times M$ channel vector from BS to the receiver of DU_s; $H_{D,s}^{m}$ is the channel gain from the transmitter of DU_s to the receiver of DU_m; $\mathbf{H}_{D,s}^{C,k}$ is the $N_C \times 1$ channel vector from the transmitter of DU_s to CU_k.

Let $\mathbf{F}_k$ represent the precoding vector at the BS for CU_k. $\mathbf{U}_{C,k} \in \mathbb{C}^{1 \times N_C}$ represents the decoding vector or a signal direction of corresponding CU_k, where $\mathbf{U}_{C,k} \mathbf{U}_{C,k}^H = \mathbf{I}$. $P_B^{C,k}$ and $P_{D,s}$ are the transmission power from the BS to the CU_k and the DU_s. $z_{C,k}$ and $z_{D,s}$ are the normalized additive white Gaussian noise with distribution $\mathcal{N}(0,1)$ at CU_k and the receiver of DU_s, σ^2 is the noise power.

Then we can calculate the SINR at the CU_k and DU_s according to (1) and (2).

III. The OIA -Based Scheme

In this section, as we cannot completely eliminate the D2D interference to CUs. We need to adopt a method to reduce the interference. Then, we apply a scheduling metric about RSS to the user selection.

A. One Data Stream Case

We briefly describe the overall procedure of selecting the D2D pairs as follows. Three steps are involved to solve the problem.

1) The design of RSS:

In this network, CU_k has predefined a normalized interference direction $\mathbf{Q}_{C,k} \in \mathbb{C}^{N_C \times 1}$, and a signal direction $\mathbf{U}_{C,k} \in \mathbb{C}^{N_C \times 1}$, where $\left\|\mathbf{U}_{C,k}^T \mathbf{Q}_{C,k}\right\| = 0$. It is assumed that $\{\mathbf{Q}_{C,k}\}_{k=1}^{K}$, i.e., RSS. Then, the RSS is broadcast by the CUs to the DUs.

2) The selection of D2D pairs:

Aiming to cancel the interference of CUs and the interference caused by BS to D2D, the ZF method can be applied to BS. And it should satisfy the following conditions [20],

$$\begin{aligned} \mathbf{U}_{C,k}\mathbf{H}_B^{C,k}\mathbf{F}_i &= 0, \ \forall i \neq k, k = 1, ..., K, i = 1, ..., K \quad \text{and} \\ \mathbf{H}_B^{D,l}\mathbf{F}_i &= 0, \ \forall = 1, ..., L, i = 1, ..., K. \end{aligned} \tag{3}$$

To guarantee the solution of (3) exists, $L < M - (K-1)$ should be satisfied [21].

As the selection method for D2D pairs can influence the system performance evidently. Therefore, with the knowledge of the RSS, we can define the interference-reference angle $\theta_{s,k}$ between generated interference to CU_k caused by DU_s and the interference direction of CU_k as

$$\theta_{s,k} = \angle\left(\mathbf{H}_{D,s}^{C,k}, \mathbf{Q}_{C,k}\right), \tag{4}$$

where $\angle(\mathbf{h}, \mathbf{q}) = arccos\left(\frac{|\mathbf{h} \cdot \mathbf{q}|}{|\mathbf{h}| \cdot |\mathbf{q}|}\right)$, and $\mathbf{h}$ and $\mathbf{q}$ are vectors. $\theta_{s,k}$ can represent the strength of interference to CU_k caused by DU_s. Fig. 2 shows the angles θ_2, θ_1 and θ_3 between the channel vectors $\mathbf{H}_1$, $\mathbf{H}_2$, $\mathbf{H}_3$ from D2D links to CU_1 and the interference direction of CU_1. We can find $\mathbf{H}_2$ is the most aligned channel vector to the interference space of CU_1, i.e., the interference caused by DU_2 to CU_1 is the smallest. Based on this metric, we propose two strategies to select the D2D pairs.

Minimize total interference of each D2D (MIE): In this strategy, we tend to select L D2D pairs in the consideration of the total interference of each D2D pair to all CUs. From (4), the scheduling metric is expressed as

$$\Delta_s = \sum_{k=1}^{K} \theta_{s,k}. \tag{5}$$

According to Δ_s, we can select the DUs which cause less interference to the cellular networks.

Minimize interference to one CU (MIO): This strategy is designed to select D2D links by φ_s and φ_s is given by

$$\varphi_s = \min_{k \in \{1,...,K\}} \theta_{s,k}. \tag{6}$$

So, the selected DUs can cause less interference to one CU at least in the cellular networks.

Then, DUs send these computing result to BS. So, BS can allow L D2D pairs to access the cellular networks.

3) Transmit beamforming of BS:

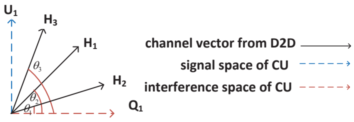

Figure 2. Demonstration of angles between D2D signals and reference signal space of CUs.

Let's define

$$\overline{\mathbf{U}_i} \triangleq [(\mathbf{U}_{C,1}^T \mathbf{H}_B^{C,1})^H, ..., (\mathbf{U}_{C,K}^T \mathbf{H}_B^{C,K})^H, (\mathbf{H}^{D,1})^H, ...(\mathbf{H}^{D,L})^H]^H,$$

where $i \neq k$, and $\mathbf{H}^{D,l} \in \mathbb{C}^{1 \times M}$ is the channel vector between the receiver of D_l and the BS. Then, the precoding matrix of BS can be designed as

$$\mathbf{F}_i \in \text{Null}(\overline{\mathbf{U}_i}), \tag{7}$$

where $\text{Null}(\cdot)$ is an orthonormal basis of the null space.

Then we can calculate the SINR at the CU_k and DU_s. $\text{SINR}_{C,k}$ and $\text{SINR}_{D,s}$ are given by (8) and (9).

$$\text{SINR}_{C,k} = \frac{P_B^{C,k} |\mathbf{U}_{C,k}\mathbf{H}_B^{C,k}|^2}{1 + \sum_{l=1}^{L} r(s) \cdot P_{D,s}^{s} |\mathbf{U}_{C,k}\mathbf{H}_{D,s}^{C,k}|^2}, \tag{8}$$

$$\text{SINR}_{D,s} = \frac{r(s) \cdot P_{D,s}^{s} |H_{D,s}^{s}|^2}{1 + \sum_{m=1, m \neq s}^{S} r(m) \cdot |\sqrt{P_{D,m}} H_{D,m}^{s}|^2}. \tag{9}$$

So, let us define R as the the sum rate of the whole network.

$$R = \sum_{k=1}^{K} \log_2(1 + \text{SINR}_{C,k}) + \sum_{s=1}^{S} \log_2(1 + \text{SINR}_{D,s}). \tag{10}$$

B. Multi-Data Streams Case

With a slight modification, the proposed scheme can be extended to a more general system model supporting $d > 1$ data transmission, where N_t-antenna BS transmits d data streams to each N_r-antenna CU and d data streams are transmitted between each d-antenna D2D pair. Similar as the idea in Section III, D2D pairs are selected with the help of the interference space of each CU and local CSI. Specifically, the signal space of CU_i and the signal from DU_j to CU_i are generalized as $\mathbf{U}_{C,i} \in \mathbb{C}^{N_r \times d}$ and $\mathbf{R}_{D,j}^{i} \in \mathbb{C}^{N_r \times d}$. Furthermore, as an extension of angle between vectors, the chordal distance is introduced as an orthogonality measure of the two subspaces $\mathbf{A}$ and $\mathbf{B}$, where $d(\mathbf{A}, \mathbf{B}) = \sqrt{N_T - trace(\mathbf{A}\mathbf{A}^H\mathbf{B}\mathbf{B}^H)}$, where $\mathbf{A}, \mathbf{B} \in \mathbb{C}^{N_R \times N_T}$, and $\mathbf{A}^H\mathbf{A} = \mathbf{B}^H\mathbf{B} = \mathbf{I}_{N_T \times N_T}$ [22]. The larger value of d means the better orthogonality between $\mathbf{A}$ and $\mathbf{B}$. For the proposed scheme, the basic angle based scheduling metric is replaced by the chordal distance based metric, i.e., $d(\mathbf{U}_{C,i}, \mathbf{R}_{D,j}^{i})$. Then, with the redefined metric and the same procedures in Section III-A, the proposed scheme can be implemented for $d > 1$. However, the difference is that we should select the D2D pairs with the first L maximum values of the scheduling metrics.

$Remark$: It should be pointed out that, for the $d > 1$ case, the proposed scheme cannot achieve the same performance improvement over the reference scheme compared with the

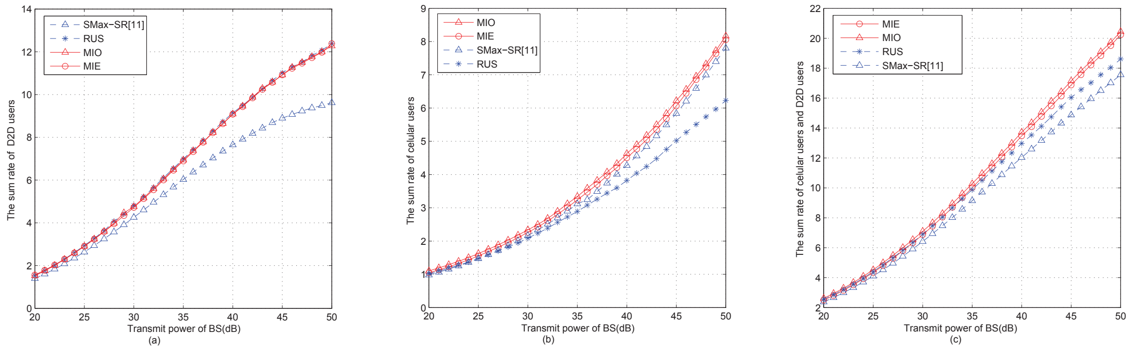

Figure 3. (a) The sum rate of the D2D users. (b) The sum rate of the cellular networks. (c) The sum rate of the whole networks.

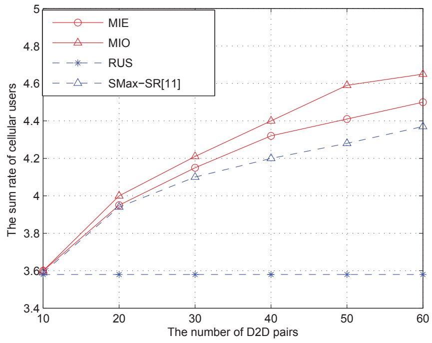

Figure 4. User scaling performance.

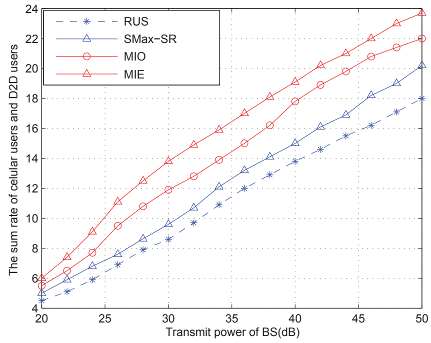

Figure 5. Sum rate of the whole networks, where $M = 8$, $N_C = 4$, $N_D = 2$, $D = 2$.

$d = 1$ case, which will be shown later in the simulation part. The reason is that precisely charactering the orthogonality between the two subspaces with high dimensionality is very difficult, which restricts the performance improvement of the proposed scheme.

Based on the above, we know that our proposed scheme can improve the performance of the whole system well. Combined with result of the Currently, we are still working on the rigorous theoretical analysis for the user scaling law in the general system model, and the DoF analysis for the multi-data transmission will be shown in our future work.

IV. Simulations

In this section, we provide numerical results to validate the proposed scheme by evaluating the performance of D2D communications underlaying the cellular networks. There is a base station which is equipped with 8 antennas. And two cellular users with 3 antennas and 60 D2D links are located in a circular area centered at BS with radius 200 m, D2D pairs are selected in our two strategies. The distance between each D2D pair is 10 m, the path-loss exponent is $\alpha = 3$, and the transmission power of each D2D pair is $E_D = E_B/10$ where E_B is the transmission power of BS [11].

In Fig. 3, we can see that the total sum rates in the different networks with our proposed strategies are higher than that with the other two existing schemes. Compared with the other schemes in [11], the SMax-SR scheme in [11] has the best performance. In Fig. 3 (a), we can observe the sum rates of D2D networks with different schemes. The sum rates of DUs with the different schemes (except for SMax-SR) are overlapped. It is because that the number of selected DUs in these schemes are equal and the D2D user selection cannot effect the performance in D2D networks. Although the SMax-SR scheme assumes that the global CSI is known to the BS, the performance of D2D pairs is not better than other schemes. It is because that with SMax-SR scheme, the interference among BS and DUs is not eliminated. In Fig. 3 (b), our strategies and the SMax-SR scheme are designed to protect the cellular networks. In the MIO strategy, each selected DU pair can cause less interference to the cellular networks than other schemes. Because the interference between cellular and D2D communications play a significant role in the whole networks, even if the SMax-SR scheme can protect the performance of cellular networks better, in Fig. 3 (c), the sum rate of cellular networks with the SMax-SR scheme cannot be higher than the random user selection (RUS) scheme. Fig. 3 demonstrates that our strategies can protect the the performance of cellular networks better than that with other schemes.

Figure 4 presents the comparison between our strategies and other schemes with different number of D2D pairs. We fix the SINR of BS as 40 dB. We can see that the MIE and MIO strategies achieve better performance with corresponding scheduling metrics. It is because that with the SMax-SR scheme, the D2D pairs are selected in the consideration of the sum rate of the whole networks. However, the SMax-SR scheme cannot guarantee the selected D2D pair is the best one to protect the cellular networks. It is because that when using the scheduling metric, interference from BS to the D2D networks exists. Even if the sum rate of the whole system increase, the sum rate of cellular networks may decrease a lot. For the MIE and MIO strategies, they are just considered to protect the cellular networks. So, the performance of the cellular networks with these two strategies is better than other schemes. Also, because the DUs are randomly selected, the RUS scheme cannot obviously improve the sum rate.

Fig. 5 presents the performance of the whole system with supporting $d > 1$ data transmission. It is shown that, the sum rate of the whole system with our scheme still higher than with the the SMax-SR scheme. It is because that there are multi-data streams, the interference among D2D and cellular networks still exist, and the performance of our user selection method is excel to other existing schemes. Different from figure 3 (a), the sum rate of the whole system with the SMax-SR scheme is higher than the RUS scheme. It is because that as the BS transmit multi-data streams and DUs pairs are equipped with $N_D > 1$ antenna, the performance of the cellular networks with the SMax-SR scheme improved faster. And the user selection method can influence the performance of the whole system obviously.

V. Conclusions

In this paper, an OIA scheme is proposed for the D2D communications underlaying cellular networks. In this proposed scheme, two angle-based strategies are designed to measure the interference caused by D2D users. Compared with the existing schemes, the our strategies just requires local CSI, and they are also very easy to implement. By selecting the appropriate D2D users according to our proposed OIA scheme, we achieve a better sum rate performance of the cellular network and the whole networks with the MIO strategy. And the more in-depth analysis for the user scaling law and the DoF of the more general system model will be a future work.

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