A Joint Scheduling Scheme for Relay-Involved D2D Communications with Imperfect CSI in Cellular Systems

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Abstract. The introduction of device-to-device (D2D) communication brings many benefits to cellular systems, especially when relay-assisted (RA) D2D modes are included. This paper focuses on the joint scheduling problem when some channel state information (CSI) are not known, involving relay selection, probabilistic access control, power coordination, mode selection, and resource allocation. Since the fading components of the channel appear in the model as random variables in imperfect channels, we make some modifications to access control and channel allocation based on previous works. By using the existing algorithm and corresponding mathematical optimization theories, the transformed integer programming (IP) problem is decomposed into two stages to be solved separately. At the same time, in order to improve the solution efficiency, we transform the original NP-hard problem into a linear programming (LP) problem that can be easily solved. Simulation results validate the performance of the joint scheduling scheme and influence of imperfect CSI from the perspective of cell capacity.

Keywords: Device-to-device (D2D) communication · Joint scheduling · Imperfect CSI · Relay

1 Introduction

In order to cope with the massive connections of devices and a huge amount of data transmissions in the fifth generation (5G) cellular system, device-to-device (D2D) communication is proposed to achieve better performances in terms of spectrum efficiency and system capacity, which opens new horizons of device-centric communication. New research directions such as (vehicle-to-vehicle) V2V

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communication, D2D communications on mmWave spectrum band, and D2D network based on social trust, are also constantly proposed in the evolution of 5G D2D network. For two proximity D2D-capable user equipments (DUEs) who are relatively close to each other in the cell, their data can be transmitted directly bypassing the base station (BS) under unified scheduling. The introduced D2D pairs can switch communication modes flexibly and make efficient use of the limited wireless resources, so as to realize the significant improvement of data transmission performance of cellular system under controllable interference.

Most of the existing works on D2D communications included only dedicated and reused D2D modes [1] without fully exploiting the potential benefits of involving relay-aided (RA) D2D modes. A RA D2D mode demonstrates that two DUEs perform data transmissions with assistance of an idle relay-capable UE (RUE) to adapt to long distances and poor channel conditions. In this paper, we only consider the more implementable single-way RA D2D, as interference control and timing management for other RA D2D schemes are too complex [2]. Overall, the research on RA D2D are still in the stage of end-to-end transmission performance analysis, and few of them investigate the joint scheduling issue involving relay selection, power coordination, resource allocation, and mode selection. In [1], scheduling decisions obtained by such a heuristic scheme could not be strictly optimal, because all issues were not jointly modelled. The contribution of [3] was that the issue of mode selection involving RA and direct D2D modes was modeled as an integer programming (IP) problem which was then transformed into a linear programming (LP) problem for effective solution. The deficiency was that relay selection and power coordination were not considered. The branch and bound (BB) method mentioned in [4] can also be used to solve the mode selection problem in D2D communications, but the process was relatively complex and the solution efficiency was not high.

In the process of solving mode selection or power coordination, existing papers usually assumed that BS can acquire channel state information (CSI) of all relevant links. However, in actual situations, only those direct links between UEs and the BS correspond to easy CSI reporting, whereas the CSI acquisition for other links between UEs will correspond to severe signaling overhead. If the number of cellular UEs (CUEs) and D2D pairs are large enough, the severe signaling overhead can not be ignored, which means the assumption of a perfect CSI may be no longer reasonable. In order to better model the actual communications, we partially introduce imperfect CSI situation [5] to replace the traditional perfect CSI situation.

In conclusion, it is more reasonable to consider the assumption of imperfect CSI in designs of efficient joint scheduling schemes involving RA D2D modes, which is more suitable for real communication scenarios. Based on these considerations, this paper designs a more applicable scheduling scheme for a fully loaded single cell jointly considering relay selection, access control, power coordination, and mode selection. On the basis of [6], aiming to increase the cell-wise throughput, we form the joint scheduling issue into a mathematical optimization problem. First, the optimal relay node is selected from the candidate RUE set, which can maximize end-to-end transmission rate of the relay path. Access control then allows DUEs to meet the constraints on power and signal to interference plus noise ratio (SINR) before power coordination. Finally, in order to obtain the final result of channel allocation and mode selection, we relax the original IP problem to a LP problem and solve it further by simplex method or interior point method. Certainly, for some imperfect channels conditions, it is necessary to make corresponding modifications in access control and transmission rate calculation.

The rest of this paper is outlined as follows. Section 2 describes the system model and problem formation for the joint scheduling issue. The mathematical way to solve the formed problem is presented in Sect. 3. Section 4 depicts the simulation results, followed by conclusions in Sect. 5.

2 System Model and Problem Formation

In this section, we first introduce the fully loaded single-cell system model in which imperfect CSI situation is assumed, i.e., the BS does not know exact CSI for some channels, and then formulate the joint scheduling problem into a mathematical optimization model.

2.1 System Model

Considering a fully loaded single-cell with M CUEs, $C_1, C_2, \cdots, C_M$. There are K pairs of DUEs that can perform communications only by reusing the CUEs' uplink channels. In each D2D pairs, let $S_1, S_2, \cdots, S_K$ denote the source DUEs (SDUEs) and $D_1, D_2, \cdots, D_K$ denote the destination DUEs (DDUEs), respectively. In the full loaded cell, all channels have been occupied by the CUEs, and each channel has the same bandwidth, which can only be reused by one new D2D pair. Apart from directly multiplexing the uplink channel of CUEs in direct D2D mode, two distant DUEs can also establish connections with assistance of a selected RUE. But the source-to-relay and relay-to-destination transmissions must performed in two time segments and the two hops use the same channel. $R_{k,1}, R_{k,2}, \cdots, R_{k,R}$ are R uniformly distributed candidate relays for the k-th D2D pair and we denote the optimal RUE for the k-th D2D pair as R_k. On this basis, the types of UEs, available modes, and corresponding data and interference links in the cell are depicted in Fig. 1.

In this scenario, DUEs can measure the link qualities between D2D pairs during the device discovery process. The CSI is fed back to BS when a D2D connection is requested. Meanwhile, BS can obtain the CSI of the links that directly connects itself and UEs through channel estimation method, so channel gains $g_{C_m,B}$, $g_{S_k,B}$, g_{S_k,R_k}, g_{R_k,D_k}, and g_{S_k,D_k} can be assumed to be known. The subscripts in these symbols represents corresponding link's source and destination node, respectively.

However, for the channel gains of the interference links, i.e., g_{C_m,D_k} and g_{C_m,R_k}, acquiring their exact values in each scheduling subframe will lead to very

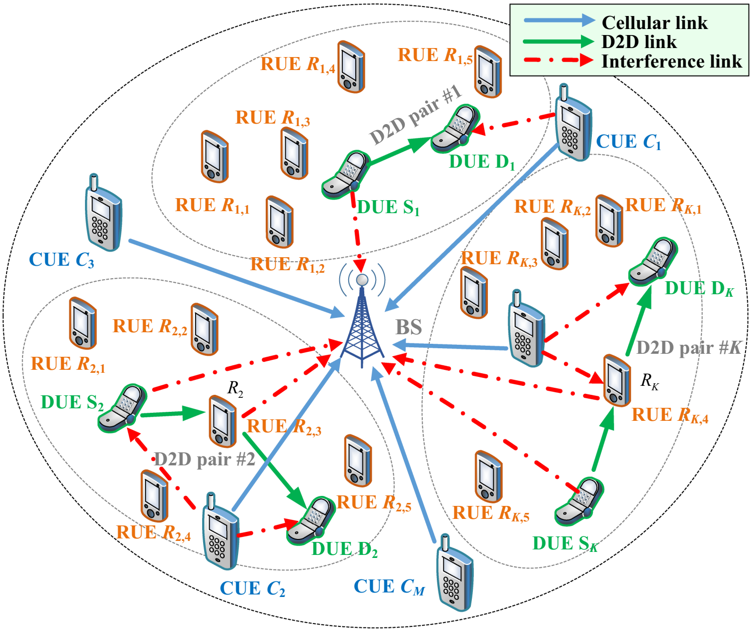

Fig. 1. Fully loaded single-cell scenario involving direct and relay-assisted D2D communications.

severe signaling overhead. Hence, to make the model closer to actual situations, it can be assumed that BS only grasps partial channel information of these interference links according to the distance based path loss, instead of the perfect CSI containing instantaneous channel fading. Therefore, such channels are called imperfect channels. The instantaneous channel gain can be expressed as:

$$g_{i,j} = K \cdot \beta_{i,j} \cdot L_{i,j}^{-\alpha} \tag{1}$$

where K is a constant for path loss, $L_{i,j}$ is the distance between transmitter i and receiver j, and α is the path loss exponent. $\beta_{i,j}$ denotes fading component of the channel, which is a stationary ergodic random variable. The part of the formula based on path loss is $\bar{g}_{i,j} = K \cdot L_{i,j}^{-\alpha}$.

In a Rayleigh fading channel, $\beta_{i,j}$ obeys exponential distribution whose mean is λ, and its cumulative probability function and probability density function are respectively represented as $F(\beta_{i,j})$ and $f(\beta_{i,j})$. $F(\beta_{i,j})$ can be expressed as follows.

$$F(\beta_{\mathrm{i,j}}) = 1 - e^{-\lambda\beta_{i,j}},\ \beta_{i,j} \geq 0 \tag{2}$$

2.2 Problem Formation

For CUE C_m whose uplink channel is not reused, since its radio resource is orthogonal to other UEs in the cell, its transmission rate can be expressed as follows:

$$Q_m^{(C)} = \log_2(1 + \frac{p_m^C g_{C_m,B}}{\delta_N^2}) \tag{3}$$

where p_m^C is the transmit power of C_m when its uplink is not reused, δ_N^2 is the power of additive white Gaussian noise, and B in the subscript denotes BS.

However, once the channel is reused, as the channel fading components in CUE-DDUE and CUE-RUE links are random variables, it is difficult for the base station to know their accurate values, leading to that the given SINR requirements can not be assured. Therefore, only under a certain outage probability threshold can the calculated average transmission rate be accurate.

In direct D2D mode, the data rates of a CUE can be expressed as

$$Q_{k,m}^{(C1)} = \log_2(1 + \frac{p_{k,m}^{C1} g_{C_m,B}}{p_{k,m}^{D1} g_{S_k,B} + \delta_N^2}) \tag{4}$$

where $p_{k,m}^{C1}$ and $p_{k,m}^{D1}$ denote the transmit powers of C_m and S_k, respectively, when CUE's channel is reused by the k-th D2D pair working in direct mode. Correspondingly, data rate of the direct D2D link [5] can be depicted as

$$\begin{aligned}
EQ_{k,m}^{(D1)} &= \{\log_2(1 + \frac{p_{k,m}^{D1} g_{S_k,D_k}}{p_{k,m}^{C1} \bar{g}_{C_m,D_k} \beta_{k,m} + \delta_N^2}) \,|\xi_k^{D1} \geq \xi_{k,\min}^{D1}\} \\
&= \{\log_2(1 + \frac{p_{k,m}^{D1} g_{S_k,D_k}}{p_{k,m}^{C1} \bar{g}_{C_m,D_k} \beta_{k,m} + \delta_N^2}) \left| \frac{p_{k,m}^{D1} g_{S_k,D_k}}{p_{k,m}^{C1} \bar{g}_{C_m,D_k} \beta_{k,m} + \delta_N^2} \geq \xi_{k,\min}^{D1}\right\} \\
&= \{\log_2(1 + \frac{p_{k,m}^{D1} g_{S_k,D_k}}{p_{k,m}^{C1} \bar{g}_{C_m,D_k} \beta_{k,m} + \delta_N^2}) \,|\beta_{k,m} \leq \eta\} \\
&= \int_0^\eta [\log_2(1 + \frac{p_{k,m}^{D1} g_{S_k,D_k}}{p_{k,m}^{C1} \bar{g}_{C_m,D_k} \beta_{k,m} + \delta_N^2})] \frac{f(\beta_{k,m})}{F(\eta)} d\beta_{k,m}
\end{aligned} \tag{5}$$

where, $\eta = \frac{p_{k,m}^{D1} g_{S_k,D_k} - \delta_N^2 \xi_{k,min}^{D1}}{p_{k,m}^{C1} \bar{g}_{C_m,D_k} \xi_{k,min}^{D1}}$ is the cutoff value of $\beta_{k,m}$.

In RA D2D mode, the transmission rate of a CUE is as

$$Q_{k,m}^{(C2)} = \frac{1}{2} \left[\log_2(1 + \frac{p_{k,m}^{C2_1} g_{C_m,B}}{p_{k,m}^{R2_1} g_{S_k,B} + \delta_N^2}) + \log_2(1 + \frac{p_{k,m}^{C2_2} g_{C_m,B}}{p_{k,m}^{R2_2} g_{R_k,B} + \delta_N^2}) \right] \tag{6}$$

where $p_{k,m}^{C2_1}$ and $p_{k,m}^{C2_2}$ are the transmit powers of C_m when its channel is reused by the source-to-relay and relay-to-destination links of the k-th D2D pair, respectively. $p_{k,m}^{R2_1}$ and $p_{k,m}^{R2_2}$ denote transmit powers of the SDUE S_k and the selected RUE R_k of the k-th D2D pair in RA D2D mode, respectively, while reusing a CUE's channel. In such a case, date rate of the RA D2D path within a scheduling time slot can be estimated as

$$EQ_{k,m}^{(SR)} = \{\log_2(1 + \frac{p_{k,m}^{R2_1} g_{S_k,R_k}}{p_{k,m}^{C2_1} \bar{g}_{C_m,R_k} \beta_{k,m} + \delta_N^2}) \,|\xi_k^{SR2} \leq \xi_{k,\min}^{SR2}\} \tag{7}$$

$$EQ_{k,m}^{(RD)} = \{\log_2(1 + \frac{p_{k,m}^{R2_2} g_{R_k,D_k}}{p_{k,m}^{C2_2} \bar{g}_{C_m,D_k} \beta_{k,m} + \delta_N^2}) \,|\xi_k^{RD2} \leq \xi_{k,\min}^{RD2}\} \tag{8}$$

$$EQ_{k,m}^{(D2)} = \frac{1}{2} \min\left\{EQ_{k,m}^{(SR)}, EQ_{k,m}^{(RD)}\right\} \tag{9}$$

Based on the expressions of data rates, we can formulate an optimization problem for joint scheduling, whose objective is to maximize the cell-wise throughput while ensuring the minimum SINR requirements of all links. Use $\mathbf{X} = \{\mathbf{X^{(1)}}, \mathbf{X^{(2)}}\}$ to represent the mode selection and channel allocation matrix. $\mathbf{X^{(1)}}$ and $\mathbf{X^{(2)}}$ are $K \times M$ indicator matrices of channel allocation in direct and RA D2D modes respectively. $x_{k,m}^{(1)}$ ($x_{k,m}^{(2)}$) is an element of $\mathbf{X^{(1)}}$ ($\mathbf{X^{(2)}}$), whose value is 0 or 1. If $x_{k,m}^{(1)} = 1$ ($x_{k,m}^{(2)} = 1$), it indicates that the k-th D2D pair works in direct (RA) D2D mode and reuses the channel of C_m; otherwise it indicates that the D2D pair is not allowed to resue the channel of CUE. Use $\mathbf{P}$ to denote the power matrix.

Therefore, the joint scheduling problem at the BS side can be formulated as

$$\begin{aligned}(\mathbf{P}^*, \mathbf{X}^*) = \arg\max_{\mathbf{P},\mathbf{X}} \sum_{k=1}^{K} \sum_{m=1}^{M} [(Q_{k,m}^{(C1)} + EQ_{k,m}^{(D1)}) x_{k,m}^{(1)} + (Q_{k,m}^{(C2)} + EQ_{k,m}^{(R2)}) x_{k,m}^{(2)}] \\ + \sum_{m=1}^{M} (1 - \sum_{k=1}^{K} x_{k,m}^{(1)} - \sum_{k=1}^{K} x_{k,m}^{(2)}) Q_m^{(C)}\end{aligned} \tag{10}$$

subject to:

$$x_{k,m}^{(1)}, x_{k,m}^{(2)} \in \{0, 1\} \quad \forall k, m \tag{11}$$

$$\sum_{k=1}^{K} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \leq 1 \quad \forall m \tag{12}$$

$$\sum_{m=1}^{M} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \leq 1 \quad \forall k \tag{13}$$

$$x_{k,m}^{(1)} p_{k,m}^{D1} + x_{k,m}^{(2)} \cdot \max\left\{p_{k,m}^{R2_1} p_{k,m}^{R2_2}\right\} \leq P_{\max}^{D} \;\forall k, m \tag{14}$$

$$\begin{aligned}(1 - \sum_{k=1}^{K} x_{k,m}^{(1)} - \sum_{k=1}^{K} x_{k,m}^{(2)}) p_m^C + \sum_{k=1}^{K} x_{k,m}^{(1)} p_{k,m}^{C_1} \\ + \sum_{k=1}^{K} x_{k,m}^{(2)} \cdot \max\left\{p_{k,m}^{C2_1}, p_{k,m}^{C2_2}\right\} \leq P_{\max}^{C} \;\forall m\end{aligned} \tag{15}$$

$$\begin{aligned}& x_{k,m}^{(1)} \cdot \min\left\{\frac{p_{k,m}^{D1} g_{S_k,D_k}}{p_{k,m}^{C1} g_{C_m,D_k} + \delta_N^2}, \frac{p_{k,m}^{C1} g_{C_m,B}}{p_{k,m}^{D1} g_{S_k,B} + \delta_N^2}\right\} + x_{k,m}^{(2)} \cdot \\ & \min\left\{\frac{p_{k,m}^{C2_1} g_{C_m,B}}{p_{k,m}^{R2_1} g_{S_k,B} + \delta_N^2}, \frac{p_{k,m}^{C2_2} g_{C_m,B}}{p_{k,m}^{R2_2} g_{R_k,B} + \delta_N^2}, \frac{p_{k,m}^{R2_1} g_{S_k,R_k}}{p_{k,m}^{C2_1} g_{C_m,R_k} + \delta_N^2}, \frac{p_{k,m}^{R2_2} g_{R_k,D_k}}{p_{k,m}^{C2_2} g_{C_m,D_k} + \delta_N^2}\right\} \\ & \geq \xi_{\min} \;\forall k, m\end{aligned} \tag{16}$$

where $P_{\max}^{C}$ and $P_{\max}^{D}$ denote the maximum transmit powers of CUEs and DUEs/RUEs, respectively. $\xi_{\min}$ is the minimum SINR/SNR requirement for each link.

3 Joint Scheduling Algorithm

In this section, we further decompose the formulated optimization problem into two solvable sub-problems and derive the optimal scheduling results. We will ensure the SINR of all involved links while maximizing the overall throughput of the system through relay selection, access control, and power coordination in the first stage and joint mode selection and channel allocation in the second stage.

3.1 Relay Selection

With a goal of maximizing the end-to-end data rate of the RA D2D mode, the optimal RUE is selected from the candidate set. Since the end-to-end transmission of RA D2D mode consists of two hops, i.e., the source-to-relay (first hop) and relay-to-destination (second hop) transmissions, objective function for optimal relay selection for the k-th D2D pair can be formulated as

$$f(R_k) = \max_{R_{k,r}} \left\{ Q^{(D2)} \right\} = \max_{R_{k,r}} \left\{ \frac{1}{2} \min \left\{ Q_{k,m}^{(SR)}, Q_{k,m}^{(RD)} \right\} \right\} \tag{17}$$

where $Q_{k,m}^{(SR)} = \log_2(1 + \frac{p_{k,m}^{S} g_{S_k, R_{k,r}}}{\delta_N^2})$, $Q_{k,m}^{(RD)} = \log_2(1 + \frac{p_{k,m}^{R} g_{R_{k,r}, D_k}}{\delta_N^2})$. The result obtained from the formulation is considered as the optimal RUE for the k-th D2D pair, and the all selected RUEs are marked as $R_1, R_2, R_3, \cdots, R_R$.

3.2 Probabilistic Access Control

For DUEs who want to access the full-loaded cell, they must reuse the uplink channels occupied by CUEs. In order to meet quality of service (QoS) requirements, the following constraints [5] must be met, i.e.,

$$\begin{cases} \frac{p_{k,m}^{C} g_{C_m, B}}{p_{k,m}^{D} g_{S_k, B} + \delta_N^2} \geq \xi_{m,\min}^{C} \\ \Pr \left\{ \frac{p_{k,m}^{D} g_{S_k, D_k}}{p_{k,m}^{C} g_{C_m, D_k} + \delta_N^2} < \xi_{k,\min}^{D} \right\} \leq \psi \\ p_{k,m}^{C} \leq P_{\max}^{C}, p_{k,m}^{D} \leq P_{\max}^{D} \end{cases} \tag{18}$$

where $\Pr\{\cdot\}$ denotes probability, $\xi_{k,\min}^{D}$ and $\xi_{m,\min}^{C}$ denote the minimum SINR required for the k-th D2D pair and C_m, respectively, and ψ denotes the maximum acceptable outage probability for D2D users.

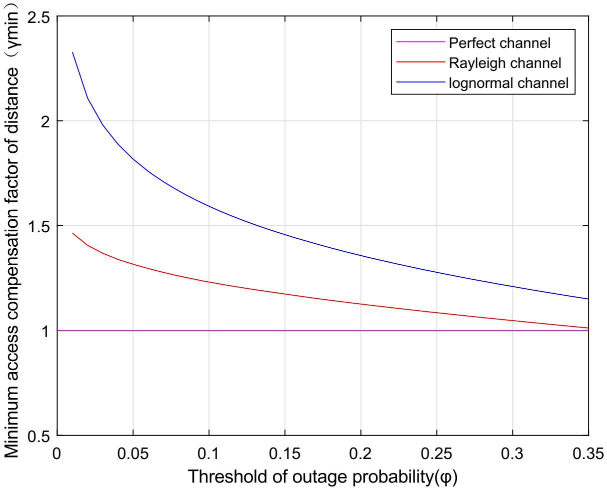

Fig. 2. The minimum access distance compensation factors under under different fading channels

According to [5], the shortest access distance corrected according to the imperfect channel condition is

$$\hat{L}_{C_{\mathrm{m}},D_k}^{\min} = \begin{cases} \gamma_{\min}\left[\frac{K\xi_{\min}^{C}\xi_{\min}^{D}P_{\max}^{C}g_{S_k,B}}{(P_{\max}^{C}g_{C_m,B}-\xi_{\min}^{C}\delta_N^2)g_{S_k,D_k}-\xi_{\min}^{C}\xi_{\min}^{D}\delta_N^2 g_{S_k,B}}\right]^{\frac{1}{\alpha}} \\ if\ \frac{P_{\max}^{C}g_{C_m,B}}{P_{\max}^{D}g_{S_k,B}+\delta_N^2} < \xi_{\min}^{C} \\ \gamma_{\min}\left[\frac{K\xi_{\min}^{C}\xi_{\min}^{D}(\delta_N^2+P_{\max}^{D}g_{S_k,B})}{g_{C_m,B}(P_{\max}^{D}g_{S_k,D_k}-\xi_{\min}^{D}\delta_N^2)}\right]^{\frac{1}{\alpha}} \\ if\ \frac{P_{\max}^{C}g_{C_m,B}}{P_{\max}^{D}g_{S_k,B}+\delta_N^2} \geq \xi_{\min}^{C} \end{cases} \tag{19}$$

Only when $L_{C_{\mathrm{m}},D_k} \geq \hat{L}_{C_{\mathrm{m}},D_k}^{\min}$ is satisfied, can DUEs reuse the channel of CUEs to access the cellular network.

The minimum access distance compensation factor $\gamma_{\min}$ is dependent on the probability distribution of channel fading components $\beta_{k,m}$. Figure 2 shows the minimum access compensation factors corresponding to different thresholds of outage probability under different fading channels. In Rayleigh fading channel, it can be expressed as $\gamma_{\mathrm{rayleigh}} = \left[\frac{1}{\lambda}\ln\left(\frac{1}{\psi}\right)\right]^{\frac{1}{\alpha}}$.

3.3 Power Coordination

For the DUEs who are allowed to access, power coordinations are performed based on the algorithm presented in [7]. According to the minimum SINR requirements for different communication links, we can derive the optimal transmit powers of different UEs in different situations. The derivation for the optimal transmit powers can be finally expressed as follows.

$$(P_m^{C^*}, P_k^{D^*}) = \begin{cases} \underset{(p_m^C, p_k^D)\in \mathbf{\Omega_1}}{\arg\max} \ f(P_m^C, P_k^D), if \frac{P_{\max}^C g_{C_m,B}}{p_{\max}^D g_{S_k,B}+\sigma_N^2} \leq \xi_{m,\min}^C \\ \underset{(p_m^C, p_k^D)\in \mathbf{\Omega_2}}{\arg\max} \ f(P_m^C, P_k^D), \\ if \frac{P_{\max}^C g_{C_m,B}}{p_{\max}^D g_{S_k,B}+\sigma_N^2} > \xi_{m,\min}^C \ and \ \frac{p_{\max}^D g_{S_k,D_k}}{P_{\max}^C g_{C_m,D_k}+\sigma_N^2} < \xi_{m,\min}^D \\ \underset{(p_m^C, p_k^D)\in \mathbf{\Omega_3}}{\arg\max} \ f(P_m^C, P_k^D), \\ if \frac{P_{\max}^C g_{C_m,B}}{p_{\max}^D g_{S_k,B}+\sigma_N^2} > \xi_{m,\min}^C \ and \ \frac{p_{\max}^D g_{S_k,D_k}}{P_{\max}^C g_{C_m,D_k}+\sigma_N^2} \geq \xi_{m,\min}^D \end{cases} \tag{20}$$

where $\mathbf{\Omega_1} = \{(P_{\max}^C, P_1), (P_{\max}^C, P_2)\}$, $\mathbf{\Omega_2} = \{(P_3, P_{\max}^D), (P_4, P_{\max}^D)\}$, and $\mathbf{\Omega_3} = \{(P_{\max}^C, P_1), (P_{\max}^C, P_{\max}^D), (P_4, P_{\max}^D)\}$, in which we have
$P_1 = \frac{(P_{\max}^C \bar{g}_{C_m,D_k} F^{-1}(1-\psi)+\sigma_N^2)\xi_{k,\min}^D}{g_{S_k,D_k}}$, $P_2 = \frac{P_{\max}^C g_{C_m,B} - \xi_{m,\min}^C \sigma_N^2}{\xi_{m,\min}^C g_{S_k,B}}$,
$P_3 = \frac{P_{\max}^D g_{S_k,D_k} - \xi_{m,\min}^D \sigma_N^2}{\xi_{m,\min}^D \bar{g}_{C_m,D_k} F^{-1}(1-\psi)}$, and $P_4 = \frac{(P_{\max}^D g_{S_k,B}+\sigma_N^2)\xi_{m,\min}^C}{g_{C_m,B}}$

For the direct D2D pair reusing a CUE's uplink channel, the optimal powers for the source DUE and the corresponding CUE can be obtained directly according to the above method. For RA D2D pair reuse a CUE's uplink channel, since both the source-to-relay and relay-to-destination links reuse the same channel, the optimal powers for the source DUE, the RUE, and the corresponding CUE can also be calculated in each time slot using the above method.

3.4 Mode Selection and Resource Allocation

Based on the results of the relay selection, access control, and power coordination in the first stage, we can further simplify the original optimization problem by removing the constraints on transmit powers and minimum SINR requirements. Accordingly, the simplified optimization problem covers only the issues on resource allocation and communication mode selection, which can be expressed as follows.

$$\begin{aligned} (\mathbf{X}^*) = \arg\max_{\mathbf{X}} \Bigg\{ & \sum_{k=1}^{K}\sum_{m=1}^{M} (Q_{k,m}^{(C1)} + Q_{k,m}^{(D1)} - Q_m^{(C)}) x_{k,m}^{(1)} \\ & + \sum_{k=1}^{K}\sum_{m=1}^{M} (Q_{k,m}^{(C2)} + Q_{k,m}^{(R2)} - Q_m^{(C)}) x_{k,m}^{(2)} \Bigg\} \end{aligned} \tag{21}$$

subject to:

$$\begin{aligned} & x_{k,m}^{(1)}, x_{k,m}^{(2)} \in \{0,1\}, \quad \forall k, m; \\ & \sum_{m=1}^{M} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \leq 1, \quad \forall k; \\ & \sum_{k=1}^{K} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \leq 1, \quad \forall m. \end{aligned} \tag{22}$$

It can be easily identified that the above optimization problem is a $0-1$ integer programming problem and we can rewrite it into a general form as

$$\begin{aligned} &\max \mathbf{C}^T\mathbf{X} \\ &\text{subject to}: \mathbf{A}\mathbf{X} \leq \mathbf{B}, \\ &\qquad\qquad \mathbf{X} \in \{0,1\}^{2MK}, \end{aligned} \tag{23}$$

where $\mathbf{C}^T$ is a row vector with $2MK$ elements corresponding to the coefficients of $x_{k,m}^{(1)}$ and $x_{k,m}^{(2)}$ in (21). $(\cdot)^T$ denotes the transpose operation. $\mathbf{X}$ is a column vector with $2MK$ elements corresponding to the values of $x_{k,m}^{(1)}$ and $x_{k,m}^{(2)}$. $\mathbf{A}$ is the constraint matrix with a size of $(K+M)\times 2MK$, which corresponds to the left sides of the two inequalities of (22). $\mathbf{B}$ is a right-hand-side vector with a length of $(K+M)$, and all its elements are 1.

It is known that such an IP problem is NP-hard owing to its large feasible domain and branch-and-bound (BB) method is generally used to search the optimal solution. As the BB method can be considered as an improved exhaustive solution, it corresponds to extremely high computational complexity. In contrast, if we can transform the above IP problem into a LP problem mathematically, the optimal solution might be able to be easily obtained, as there have been some very efficient ways to solve LP problems. For the IP problem depicted by (23), its feasible domain's characteristic is determined by the constraint matrix $\mathbf{A}$, and it can be proved that if $\mathbf{A}$ is a totally unimodular matrix (TUM), the above IP problem can be completely transformed into a LP problem whose optimal solution is definitely the optimal solution for the initial IP problem. The definition of TUM and corresponding judgement conditions are demonstrated as follows.

Definition 1: If every square sub-matrix of matrix $\mathbf{Z}_{I\times J}$ is with a determinant of -1, 0, or 1, $\mathbf{Z}$ can be called totally unimodular matrix.

Whether a matrix $\mathbf{Z}_{I\times J}$, with each element z_{ij} equal to -1, 0, or 1, is a TUM or not can be decided according to the following conditions [8]: (a) Each column of $\mathbf{Z}$ has no more than two non-zero elements; (b) There exists a division $(\mathbf{Z}_{upper}, \mathbf{Z}_{lower})$ on the rows of $\mathbf{Z}$ such that in each column, the sum of non-zero elements in the upper part is equal to that in the lower part, i.e., $\sum_{i\in\mathbf{Z}_{upper}} z_{ij} = \sum_{i\in\mathbf{Z}_{lower}} z_{ij}$, $\forall j$.

It can be easily proved that the constraint matrix $\mathbf{A}$ in (23) can satisfy the two judgement conditions of TUM, so the original IP problem can be further relaxed to a LP problem which is expressed as (24).

For such a LP problems, there are some mature and effective solving schemes, such as simplex method and interior point method. In this paper, the widely used simplex method is adopted to obtain the final solution. When the final indicator matrix for channel allocation and communication mode selection is fixed, combining with the optimal transmit powers derived in the first stage, we can say the whole optimization problem has been solved. The solving process corresponds definitely to the design of the joint scheduling scheme.

$$
\begin{aligned}
(\mathbf{X}^*) = \arg\max_{x} \Bigg\{ & \sum_{k=1}^{K}\sum_{m=1}^{M} (Q_{k,m}^{(C1)} + Q_{k,m}^{(D1)} - Q_{m}^{(C)}) x_{k,m}^{(1)} \\
& + \sum_{k=1}^{K}\sum_{m=1}^{M} (Q_{k,m}^{(C2)} + Q_{k,m}^{(R2)} - Q_{m}^{(C)}) x_{k,m}^{(2)} \Bigg\}
\end{aligned}
\tag{24}
$$

subject to:

$$
\begin{aligned}
& 0 \le x_{k,m}^{(1)} \le 1 \quad 0 \le x_{k,m}^{(2)} \le 1 \quad \forall k, m \\
& \sum_{m=1}^{M} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \le 1 \quad \forall k \\
& \sum_{k=1}^{K} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \le 1 \quad \forall m
\end{aligned}
$$

4 Performance Evaluation

In this section, the performance of the joint scheduling scheme are evaluated via simulations. We establish the simulation scenario according to fully loaded single-cell system model shown in Fig. 1. The influences of some major parameters, such as the number of D2D pairs, the maximum transmit power of UEs, and the distance between the source and destination DUEs, on the cell-wise throughput performance are simulated and analyzed. The major parameters used in the simulations are listed in Table 1.

Table 1. Major parameters used in performance evaluation.

Parameter	Value
Path loss exponent (α)	4
Path loss constant (K_0)	0.01
Cell radius	500 m
D2D cluster radius	Uniformly distributed in [10, 200] m
Number of active CUEs (M)	20
Number of D2D pairs (K)	10(if fixed)
Noise power spectral density	−174 dBm/Hz
Maximum transmition power of UEs	24 dBm (if fixed)
Minimum SNR/SINR for each link	10 dB
Outage probability threshold	0.01

The established simulation scenario is a single cell with a radius of 500 meters. BS is located in the center, and all CUEs and D2D pairs are randomly distributed in the cell. For each D2D pair, the destination DUE is randomly located on a circle centered on the source DUE, and a certain amount of RUEs are assumed for each D2D pair as candidate relay UEs to ensure the possibility on performing RA D2D communication. The candidate RUEs for each D2D pair are randomly distributed in the circle area bounded by the possible location of the destination DUE. Note that for a set of predefined parameters, 1 000 tests are performed to get and average result. We mainly analyze the effect of bringing the imperfect channel condition and the advantage of further considering RA D2D mode in the joint scheduling.

Figure 3 shows the influence of UE's maximum transmit power on the total capacity of the cell under different scheduling scenarios, where "Perfect channel" means the BS can acquire precisely all its needed CSI, while "Imperfect channel" means that the precise CSI for the interference links between UEs are not known at the BS. "CUEs without D2D" means D2D communications are not included, "Direct D2D" means only direct D2D mode is considered, and "Direct and RA D2D" means both the direct and RA D2D modes are considered. It is seen that, with the increase of the maximum transmit power of UEs in the five cases, the cell-wise system capacity increases greatly, and further introduction of the RA D2D mode is helpful to improving the cell-wise system capacity. In case of the channel reuse between a CUE and a D2D pair, increasing all UEs' maximum transmit power means increasing the feasible region of the power optimization problem, which may leads to further improvements on the power coordination results. For CUE whose uplink channel is not reused by D2D links, its optimal transmit power is just CUE's maximum transmit power. Therefore, when the maximum transmission power increases, the system performance will definitely increase. At the same time, due to the imperfection of CSI, the performance of system capacity under imperfect channel conditions are slightly worse than that under perfect channel conditions.

Figure 4 illustrates the performance of cell-wise system capacity increase with varying distances between SDUEs and DDUEs. To describe the distance variation, all D2D pairs are set the same separation distance between the source and destination DUEs. It is seen from Fig. 4, when the source DUE is closer to the destination DUE, the increase of system capacity brought in by D2D communication is larger. With the supplement of RA D2D mode, the system capacity can be further improved. The more RUEs available for each D2D pair, the more obvious the advantage. However, as the source to destination distance for all D2D pairs increases, the system capacity increase brought in by the D2D communication decreases. Therefore, if the such a separation distance is further enlarged, the cell-wise capacity gain might reduce to zero. When the channel capacity generated by D2D communications can not compensate for the channel capacity loss caused by channel reuse, there is no capacity growth on the whole.

Figure 5 shows the increase in cell-wise system capacity versus the number of D2D pairs. It can be seen that increase of the number of D2D pairs leads to obvious increase of the cell-wise system capacity, and the system capacity with the introduction of relay D2D mode increases more. Such a advantage is more significant when increasing of the number of D2D pairs in the cell. In addition, comparing the performance on cell-wise system capacity increase

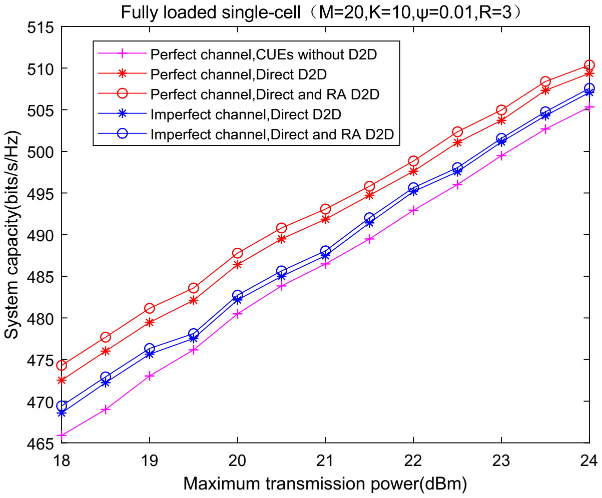

Fig. 3. System capacity versus maximum transmit power of UEs, where the distances between SDUEs and DDUEs are randomly selected from 10 to 200 m.

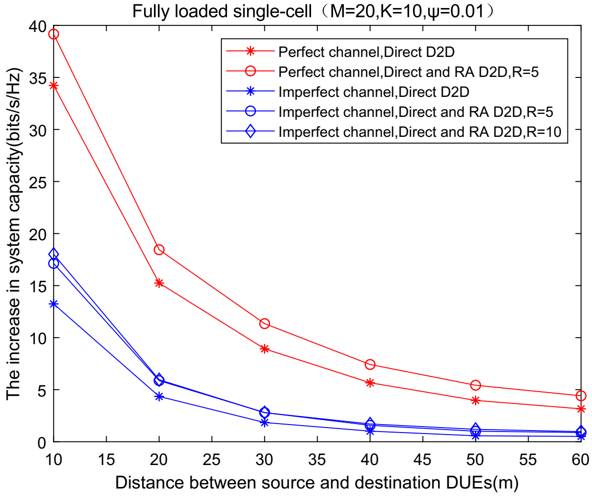

Fig. 4. Increase in system capacity versus distance between SDUEs and DDUEs, where $P_{\max}^{C} = P_{\max}^{D} = 24$ dBm.

under the imperfect CSI conditions with that under the perfect CSI conditions, we can observe that the gap becomes larger when the number of D2D pairs is increased. This is reasonable, as increase of the number of D2D pairs means more uncertainties on the interference links are involved, which might limit the improvement space for the cell-wise system capacity. But such a result clearly shows us the influence of channel uncertainties on the accuracy of the scheduling,

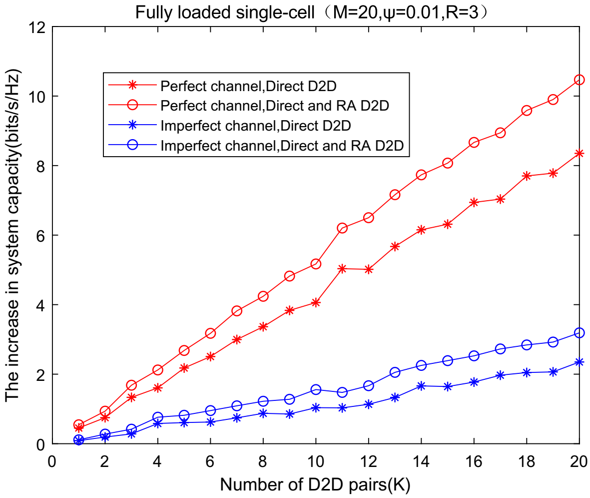

Fig. 5. Increase in system capacity versus number of D2D pairs, where distances between SDUEs and DDUEs are randomly selected from 10 to 200 m and $P^C_{\max} = 10\,P^D_{\max} = 24$ dBm.

and it prompts us to seek more effective solutions to overcome the influences of imperfect CSI on the accuracy of the jointly scheduling at the BS side.

5 Conclusions

This paper investigated the joint scheduling issue for cellular multi-mode D2D communications involving both direct and RA D2D modes under imperfect CSI condition. With an aim to maximize the cell-wise system capacity, joint scheduling on relay selection, access control, power coordination, mode selection, and resource allocation at the BS side in a fully loaded single-cell was formulated as an optimization problem which was then solved in two stages. The relay selection, access control, and power coordination issues were solved in the first stage, while the mode selection and channel allocation issues were solved in the second stage. By using probabilistic model to depict the fading component of uncertain interference channels, the condition of imperfect CSI was taken into account in the design of joint scheduling schemes. By transforming the IP problem into LP problem, the joint mode selection and resource allocation problem was solved with low complexity. Simulation results showed that including RA D2D mode into the scheduling can further increase the cell-wise system capacity, even under the imperfect CSI condition. Moreover, under both the perfect and imperfect CSI conditions, the cell-wise system capacity increased when the number of candidate RUEs for each D2D pair and the maximum transmit powers for involved UEs were increased. Meanwhile, the imperfect CSI condition did have influence on the accuracy of the joint scheduling and such an influence was more obvious while the number of D2D pairs was increased.

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