Joint Mode Selection and Resource Allocation for Device-to-Device Communications

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***Abstract*—*Device-to-device* (D2D) communications have been recently proposed as an effective way to increase both spectrum and energy efficiency for future cellular systems. In this paper, joint mode selection, channel assignment, and power control in D2D communications are addressed. We aim at maximizing the overall system throughput while guaranteeing the *signal-to-noise-and-interference ratio* of both D2D and cellular links. Three communication modes are considered for D2D users: cellular mode, dedicated mode, and reuse mode. The optimization problem could be decomposed into two subproblems: power control and joint mode selection and channel assignment. The joint mode selection and channel assignment problem is NP-hard, whose optimal solution can be found by the branch-and-bound method, but is very complicated. Therefore, we develop low-complexity algorithms according to the network load. Through comparing different algorithms under different network loads, *proximity gain*, *hop gain*, and *reuse gain* could be demonstrated in D2D communications.**

***Index Terms*—Device-to-device communications, mode selection, channel assignment, power control.**

I. Introduction

In recent years, *device-to-device* (D2D) communication underlaying cellular network has been widely studied as a promising technique to increase both spectral and energy efficiency for the LTE-Advanced systems [1]–[4]. This new technique has been proved to have the *hop gain*, the *proximity gain*, and the *reuse gain* [5]. The *hop gain* comes from the fact that D2D communications only need one hop by enabling users communicating directly instead of going through the infrastructure known as *evolved NodeBs* (eNBs). The *proximity gain* is achieved due to communications between nearby users. The *reuse gain* is introduced when *D2D users* (DUs) reuse the channels of existing *cellular users* (CUs) with proper interference management strategies.

Several interference coordination methods have been proposed for D2D communications recently. In [6], a simple power control method has been proposed to limit interference to co-channel CUs. In [7], *interference limited area* (δ-ILA) has been suggested to avoid reusing the resources of CUs in the area that could generate strong interference. Channel reusing strategies have been developed in [8] and [9] for cellular networks with fractional frequency reuse. The above methods basically exploit static channel information (path loss) based on the geographic locations of users. Adaptive resource allocation is another effective solution for interference mitigation in D2D communications, where both statistical and instantaneous channel state information can be used to further improve the performance. In this case, resource allocation will include three aspects: mode selection, channel assignment, and power control. Mode selection decides whether two users in proximity should communicate directly or not, and whether to use dedicated channels or reuse channels of CUs. There are basically three communication modes for D2D systems.

- Cellular mode: If two users select the cellular mode, they will communicate as conventional CUs through eNB. This mode would consume the most channel resource among all modes in general. It should be used only if the other two modes are not available.
- Dedicated mode: Two DUs communicate directly using a channel that is not currently used by CUs. DUs in this mode consume less channel resource compared to those in the cellular mode and can improve the energy efficiency due to user proximity.
- Reuse mode: Two DUs communicate directly by reusing a channel that is currently used by CUs. This mode could further improve the spectrum utilization, but co-channel interference needs to be properly managed so as not to degrade the performance of either DUs or CUs.

From the above, mode selection is very important in D2D communications. Therefore, there have been some works in this topic. In [10], mode selection taking into account the quality of both D2D and cellular links has been proposed to mitigate interference caused by D2D communications. Mode selection

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in [11] considers network information such as link gains, noise levels, and *signal-to-noise-and-interference ratio* (SINR). In [12], an opportunistic mode selection and subchannel scheduling algorithm has been developed for *orthogonal frequency division multiple access* (OFDMA) based D2D systems. Joint mode selection and power control has been investigated in [14]–[16] for further performance improvement. However, the above works consider the dedicated mode and the cellular mode only. For the reuse mode, the main challenge is how to properly assign the reusing channel and control the transmit power to mitigate the co-channel interference between the D2D links and the cellular links.

To this end, joint channel assignment and power control has been considered for D2D systems. Optimal resource allocation and power control for a single D2D pair and a single CU has been investigated in [17]. An interference-aware graph-based resource sharing algorithm has been developed in [18], which is nearly optimal but with low computational complexity. Interference can be further mitigated by exploiting the multiuser diversity inherent in the cellular network [19] or by reusing the proper CU resources [20]–[22]. Recently, joint power control and reuse partner selection have been investigated in [23] and [24]. However, the works mentioned above only address the resource allocation for the reuse mode, without jointly considering mode selection for further performance improvement. Although a joint mode selection and resource allocation to maximize the system throughput and guarantee the fairness is proposed in [13], the optimality of the method cannot be guaranteed since it is based on the evolutionary algorithm.

In this paper, we consider joint mode selection, channel assignment, and power control to maximize the overall system throughput. First, for each D2D pair, the optimal communication mode should be determined. Second, if a D2D pair works in the reuse mode, the reusing channel and the corresponding transmit powers of the DU and the co-channel CU should be carefully chosen to guarantee the *quality-of-service* (QoS) for both. Based on the above idea, an optimization problem is formulated, which is a nonconvex problem with 0–1 variables and NP-hard in general. To make the problem better tractable, we first decompose it into two subproblems: power control, and joint mode selection and channel assignment. Then, standard optimization methods can be used to solve the power control problem and the *branch-and-bound* (BB) method can be utilized for model selection and channel assignment. To further reduce the computational complexity, we propose two low-complexity heuristic algorithms based on the network loads: *heavy load*, *medium load*, or *light load*. The computational complexities of the proposed algorithms are analyzed and their sub-optimality is demonstrated by numerical simulations. Through the comparison of different scenarios, the *proximity gain*, the *hop gain*, and the *reuse gain* are demonstrated by D2D communications. The main contributions of this paper are twofold. First, we consider all the three modes mentioned above while other papers only consider resource allocation for one or two modes. Secondly, we will develop different low-complexity algorithms based on the network loads to achieve three types of gain. We will demonstrate that more throughput gains can be achieved if more communication modes are available.

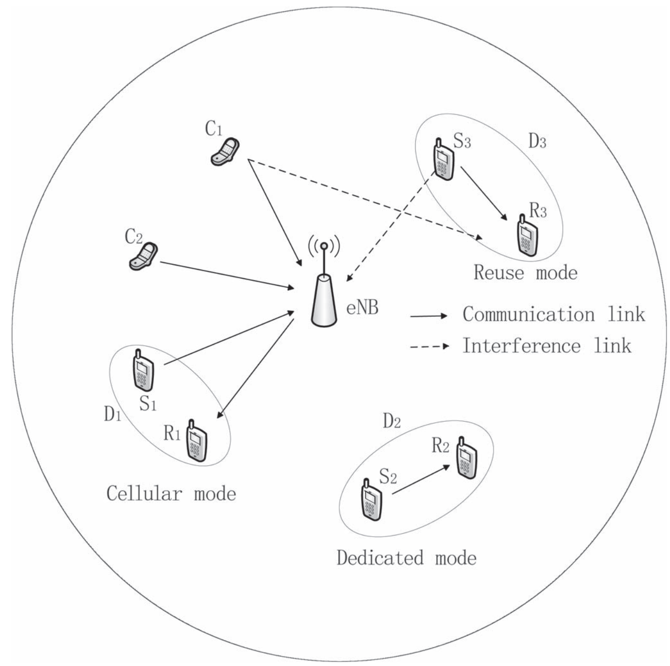

Fig. 1. System model for D2D communications.

The rest of the paper is organized as follows. In Section II, the system model is described and a joint mode selection, channel assignment, and power control problem is formulated. Then, low-complexity algorithms are developed in Section III. Section IV presents simulation results and Section V finally concludes the paper.

II. System Model and Problem Formulation

In this section, we first introduce the system model and various D2D communication modes, then formulate the joint mode selection, channel assignment, and power control problem for D2D systems.

A. System Model

Consider a single cell with M cellular users, $\{C_1, C_2, \ldots, C_M\}$, connecting to the eNB. There exist K pairs of potential DUs denoted by $\{D_1, D_2, \ldots, D_K\}$. Let S_k and R_k denote the transmitter and the receiver of D2D pair k, respectively. The D2D communication could be established by a certain neighbor discovery algorithm. Denote r as the maximum distance between each D2D pair, which is limited by the capability of neighbor discovery. As in [7], [21], [23], we further assume that the number of D2D pairs is smaller than that of CUs, i.e., $K < M$ since two users in the same cell communicate with each other will not often happen. Without loss of generality, we assume each CU is allocated with an orthogonal channel, and denote N_{U} and N_{D} as the numbers of unused uplink and downlink channels, respectively. Here, we focus on mode selection and channel allocation while the time-domain user scheduling has been discussed in [27], [29] and is beyond the scope of this paper (see Fig. 1).

As indicated before, each D2D pair will work in one of the three modes, depending on the network scenario. If the cellular mode is chosen, the D2D pair uses one of the N_{D} downlink channels and one of the N_{U} uplink channels. If the dedicated mode is chosen, only one dedicated channel (either downlink or uplink) will be assigned to the D2D pair. If the reuse mode is selected, the D2D pair only reuses the uplink channels of CUs since interference to the cellular network can be better handled in uplink than in downlink from [25], [26]. In this case, the transmit powers of both DUs and CUs should be appropriately controlled to guarantee their QoS. Due to severe co-channel interference, the scenario that more than one D2D pairs reusing a same channel rarely happens and therefore is not considered. This is also reasonable since the number of D2D pairs is less than that of CUs and channel reusing among D2D pairs is unnecessary.

We further assume that the eNB has full acquisition of the instantaneous *channel state information* (CSI) of links to all users, including the CSI of D2D links, which can be estimated by the D2D receiver and then feed back to the eNB via control channel. The joint mode selection, channel assignment, and power control is performed at the eNB based on available channel CSI. Our developed algorithms work in a centralized fashion, which require much control signaling overhead. However, the centralized algorithm generally achieves better performance than distributed one, and can be served as a benchmark for distributed algorithm.

All links are assumed to experience independent block fading. Hence, the instantaneous channel gain of the interference link between CU m and the receiver of D2D pair k can be expressed as

$$h_{k,m} = G\beta_{k,m} d_{k,m}^{-\alpha},$$

where G is the path loss constant, α is the path loss exponent, $\beta_{k,m}$ denotes the channel fading component, and $d_{k,m}$ is the distance between CU m and the receiver of D2D pair k. Similarly, we can express the channel gain between CU m and the eNB as $h_{m,\mathrm{B}}^{\mathrm{C}}$, the channel gain between D2D pair k as h_k^{D}, and the channel gain between the transmitter of D2D pair k and the eNB as $h_{k,\mathrm{B}}^{\mathrm{D}}$.

B. D2D Communication Modes

1) Cellular Mode: In this mode, two DUs communicate through eNB as conventional CUs and no D2D link is established. Intuitively, if two users are too far away from each other, this mode is preferred. In this case, two channels (one downlink and one uplink) will be allocated to a D2D pair. Although the D2D pairs working in the cellular mode perform the same as conventional cellular users, we assume that their channels are not reused by any other D2D pairs. This can simplify the optimization problem and also is reasonable since there are adequate cellular channels for reusing.

In the cellular mode, the uplink *signal-to-noise ratio* (SNR) of D2D pair k can be expressed as

$$\xi_{k,\mathrm{up}}^{(1)} = \frac{p_k^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}, \tag{1}$$

where $p_k^{(1)}$ is the transmit power of D2D pair k in the cellular mode, σ_N^2 is the power of the *additive white Gaussian noise* (AWGN). Similarly, the downlink SNR can be expressed as

$$\xi_{k,\mathrm{down}}^{(1)} = \frac{p_{k,\mathrm{B}}^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}, \tag{2}$$

where $p_{k,\mathrm{B}}^{(1)}$ is the transmit power of the BS. Then, the achievable rate of D2D pair k in the cellular mode will be

$$C_k^{(1)} = \min\left\{\log\left(1+\xi_{k,\mathrm{up}}^{(1)}\right), \log\left(1+\xi_{k,\mathrm{down}}^{(1)}\right)\right\}.$$

To guarantee the QoS of DUs, both uplink and downlink SNRs should be larger than a given threshold, $\xi_{\min}$, that is,

$$\min\left\{\xi_{k,\mathrm{up}}^{(1)}, \xi_{k,\mathrm{down}}^{(1)}\right\} \geq \xi_{\min}.$$

In this work, we focus on the power control of D2D pairs and assume that the eNB can coordinate its transmit power to ensure that $\xi_{k,\mathrm{down}}^{(1)}$ is no less than $\xi_{k,\mathrm{up}}^{(1)}$[16], [28]. This can also be guaranteed by the admission control strategy [23].

2) Dedicated Mode: In the dedicated mode, D2D pair communicates directly and only requires one dedicated channel, either uplink or downlink channel. The dedicated mode will be considered when two users are nearby and there are empty channels that are not currently used by CUs. In the dedicated mode, the SNR of D2D pair k can be expressed as

$$\xi_k^{(2)} = \frac{p_k^{(2)} h_k^{\mathrm{D}}}{\sigma_N^2}, \tag{3}$$

where $p_k^{(2)}$ is the transmit power of D2D pair k in the dedicated mode.

3) Reuse Mode: In this mode, two DUs communicate directly by reusing the channel of an existing CU. Therefore, the spectrum efficiency could be further improved. However, interference between the D2D pair and its co-channel CU will be incurred. In the reuse mode, the SINR of D2D pair k when reusing the uplink channel of CU m can be expressed as

$$\xi_{k,m}^{(3)} = \frac{p_{k,m}^{(3)} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}} h_{k,m} + \sigma_N^2}, \tag{4}$$

where $p_{k,m}^{(3)}$ and $p_{k,m}^{\mathrm{c}}$ are the transmit powers of D2D pair k and CU m, respectively, when CU m is reused by D2D pair k.

On the other hand, channel reusing will also cause interference to the co-channel CU. The SINR of CU m when interfered by D2D pair k can be expressed as

$$\xi_{k,m}^{\mathrm{c}} = \frac{p_{k,m}^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2}. \tag{5}$$

Since CUs have higher priority, their QoS should be guaranteed. Therefore, DU is allowed to reuse the channel only if $\xi_{k,m}^{\mathrm{c}} \geq \xi_{\min}$. That is, only when the SINR requirements of both the D2D pair and the interfering CU are satisfied, can a D2D pair share the channel with the CU.

C. Problem Formulation

We will maximize the overall system throughput while guaranteeing the SINR of both CUs and DUs by joint mode selection, channel assignment, and power control. Denote $\mathbf{x} = \{\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \mathbf{x}^{(3)}\}$ as a mode selection and channel assignment matrix. $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ are K dimensional indication vectors of the cellular mode and the dedicated mode, respectively, such that $x_k^{(1)} = 1$ $(x_k^{(2)} = 1)$ if D2D pair k works in the cellular (dedicated) mode. $\mathbf{x}^{(3)}$ is a $K \times M$ channel allocation indication matrix in the reuse mode, such that $x_{k,m}^{(3)} = 1$ if D2D pair k reuses the channel of CU m, and $x_{k,m}^{(3)} = 0$ otherwise. Denote $\mathbf{p} = \{\mathbf{p}^{(1)}, \mathbf{p}^{(2)}, \mathbf{p}^{(3)}, \mathbf{p}^{\mathbf{c}}\}$ as the power matrix. $\mathbf{p}^{(1)}$, $\mathbf{p}^{(2)}$, and $\mathbf{p}^{(3)}$ are with the same size as $\mathbf{x}^{(1)}$, $\mathbf{x}^{(2)}$, and $\mathbf{x}^{(3)}$, respectively, and indicate the transmit power when a mode is chosen (the corresponding element in $\mathbf{x}^{(1)}$, $\mathbf{x}^{(2)}$, or $\mathbf{x}^{(3)}$ is 1). $\mathbf{p}^{\mathrm{c}}$ is the transmit power of CUs, which is equal to $p_{k,m}^{\mathrm{c}}$ if CU m is reused by D2D pair k, and p_m^{c} if CU m is not reused by any D2D pair.

Then, the joint mode selection, channel assignment, and power control problem can be mathematically formulated as

$$
\begin{aligned}
(\mathbf{p}^*, \mathbf{x}^*) = \arg\max_{\mathbf{p},\mathbf{x}} \Bigg\{ & \sum_{k=1}^{K} x_k^{(1)} \log\left(1 + \frac{p_k^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}\right) \\
& + \sum_{k=1}^{K} x_k^{(2)} \log\left(1 + \frac{p_k^{(2)} h_k^{\mathrm{D}}}{\sigma_N^2}\right) \\
& + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(3)} \log\left(1 + \frac{p_{k,m}^{(3)} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}} h_{k,m} + \sigma_N^2}\right) \\
& + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(3)} \log\left(1 + \frac{p_{k,m}^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2}\right) \\
& + \sum_{m=1}^{M}\left(1 - \sum_{k=1}^{K} x_{k,m}^{(3)}\right) \log\left(1 + \frac{p_m^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{\sigma_N^2}\right) \Bigg\}, \quad (6)
\end{aligned}
$$

subject to

$$x_k^{(1)}, x_k^{(2)}, x_{k,m}^{(3)} \in \{0,1\},\ \forall k, m, \quad (6a)$$

$$\sum_{k=1}^{K} x_k^{(1)} \leq \min\{N_{\mathrm{U}}, N_{\mathrm{D}}\}, \quad (6b)$$

$$2\sum_{k=1}^{K} x_k^{(1)} + \sum_{k=1}^{K} x_k^{(2)} \leq N_{\mathrm{U}} + N_{\mathrm{D}}, \quad (6c)$$

$$x_k^{(1)} + x_k^{(2)} + \sum_{m=1}^{M} x_{k,m}^{(3)} \leq 1,\ \forall k, \quad (6d)$$

$$\sum_{k=1}^{K} x_{k,m}^{(3)} \leq 1,\ \forall m, \quad (6e)$$

$$x_k^{(1)} p_k^{(1)} + x_k^{(2)} p_k^{(2)} + x_{k,m}^{(3)} p_{k,m}^{(3)} \leq P_{\max}^{\mathrm{D}},\ \forall k, m, \quad (6f)$$

$$\left(1 - \sum_{k=1}^{K} x_{k,m}^{(3)}\right) p_m^{\mathrm{c}} + \sum_{k=1}^{K} x_{k,m}^{(3)} p_{k,m}^{\mathrm{c}} \leq P_{\max}^{\mathrm{C}},\ \forall m, \quad (6g)$$

$$
\begin{aligned}
& x_k^{(1)} \frac{p_k^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2} + x_k^{(2)} \frac{p_k^{(2)} h_k^{\mathrm{D}}}{\sigma_N^2} \\
& \quad + \sum_{m=1}^{M} x_{k,m}^{(3)} \frac{p_{k,m}^{(3)} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}} h_{k,m} + \sigma_N^2} \geq \xi_{\min},\ \forall k \quad (6h)
\end{aligned}
$$

$$
\begin{aligned}
& \sum_{k=1}^{K} x_{k,m}^{(3)} \frac{p_{k,m}^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2} \\
& \quad + \left(1 - \sum_{k=1}^{K} x_{k,m}^{(3)}\right) \frac{p_m^{\mathrm{c}} h_{m,B}^{\mathrm{C}}}{\sigma_N^2} \geq \xi_{\min},\ \forall m. \quad (6i)
\end{aligned}
$$

In the above, $P_{\max}^{\mathrm{D}}$ and $P_{\max}^{\mathrm{C}}$ denote the maximal transmit power of DUs and CUs, respectively, ξ_k^{d} and ξ_m^{c} denote the SINRs of D2D pair k and CU m, respectively. Constraint (6b) denotes that the number of D2D pairs in the cellular mode should not exceed the number of unused uplink channels or downlink channels. Constraint (6c) indicates that the channels used by D2D communications in the cellular mode and the dedicated mode should not exceed the total number of unused channels. Constraint (6d) implies that any D2D pair will choose at most one of the three modes. Constraint (6e) denotes that one CU can only be reused by one D2D pair at most. Constraints (6f) and (6g) indicate the transmit power of DUs and CUs cannot exceed their maximum values. Constraints (6h) and (6i) denote the SINR thresholds of DUs and CUs should be guaranteed.

It should be noted that our problem may be infeasible if not all D2D pairs can be admitted. Therefore, admission control should be carefully designed, which has been investigated in [23]. In this paper, we focus on the joint mode selection and resource allocation strategy, assuming that the problem is always feasible.

III. Joint Mode Selection and Resource Allocation Algorithm

In this section, we will solve the optimization problem formulated in (6). It is non-concave and contains binary variables, thus could not be solved directly. Therefore, we will decompose the problem into two subproblems and then solve them individually.

We can observe that the original optimization problem could be reformulated as

$$
\begin{aligned}
(\mathbf{p}^*, \mathbf{x}^*) = \arg\max_{\mathbf{x}} \Bigg\{ & \sum_{k=1}^{K} x_k^{(1)} Q_1 + \sum_{k=1}^{K} x_k^{(2)} Q_2 \\
& + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(3)} Q_3 + \sum_{m=1}^{M}\left(1 - \sum_{k=1}^{K} x_{k,m}^{(3)}\right) Q_4 \Bigg\}, \quad (7)
\end{aligned}
$$

where

$$Q_1 = \arg\max_{p_k^{(1)}} \left\{ \log\left(1 + \frac{p_k^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}\right) \right\},$$

$$Q_2 = \arg\max_{p_k^{(2)}} \left\{ \log\left(1 + \frac{p_k^{(2)} h_k^{\mathrm{D}}}{\sigma_N^2}\right) \right\},$$

$$Q_3 = \arg\max_{p_{k,m}^{(3)}, p_{k,m}^{\mathrm{c}}} \left\{ \log\left(1 + \frac{p_{k,m}^{(3)} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}} h_{k,m} + \sigma_N^2}\right) + \log\left(1 + \frac{p_{k,m}^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2}\right) \right\},$$

$$Q_4 = \arg\max_{p_m^{\mathrm{c}}} \left\{ \log\left(1 + \frac{p_m^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{\sigma_N^2}\right) \right\}.$$

From (7), we see that the optimization problem consists of two layers. The inner one is power control, denoted by Q_1, Q_2, Q_3, and Q_4 in (7), and determines the optimal transmit powers of DUs and CUs in each mode. The outer one is the decision process of communication mode and channel assignment. From (7), the two layers could be decoupled. Therefore, we can separately optimize both inner and outer layers to obtain the optimal solution.

Since there is no co-channel interference between DUs and CUs in the cellular mode and the dedicated mode, the maximum throughput could be achieved when both DUs and CUs transmit with their maximum powers, i.e., $P_{\max}^{\mathrm{D}}$ and $P_{\max}^{\mathrm{C}}$, respectively. That is,

$$P_{\max}^{\mathrm{D}} = p_k^{(1)^*} = \arg\max_{p_k^{(1)}} \log\left(1 + \frac{p_k^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}\right),$$

$$P_{\max}^{\mathrm{D}} = p_k^{(2)^*} = \arg\max_{p_k^{(2)}} \log\left(1 + \frac{p_k^{(2)} h_k^{\mathrm{D}}}{\sigma_N^2}\right),$$

$$P_{\max}^{\mathrm{C}} = p_m^{\mathrm{c}^*} = \arg\max_{p_m^{\mathrm{c}}} \log\left(1 + \frac{p_m^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{\sigma_N^2}\right),$$

for problems Q_1, Q_2, and Q_4, respectively.

Power control in the reuse mode, Q_3, is a little bit complicated and can be reformulated as

$$\left(p_{k,m}^{(3)*}, p_{k,m}^{\mathrm{c}*}\right) = \arg\max_{p_{k,m}^{(3)}, p_{k,m}^{\mathrm{c}}} f_{k,m}\left(p_{k,m}^{(3)}, p_{k,m}^{\mathrm{c}}\right), \tag{8}$$

subject to

$$0 \le p_{k,m}^{(3)} \le P_{\max}^{\mathrm{D}}, \tag{8a}$$

$$0 \le p_{k,m}^{\mathrm{c}} \le P_{\max}^{\mathrm{C}}, \tag{8b}$$

$$\frac{p_{k,m}^{(3)} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}} h_{k,m} + \sigma_N^2} \ge \xi_{\min}, \tag{8c}$$

$$\frac{p_{k,m}^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2} \ge \xi_{\min}, \tag{8d}$$

TABLE I
THREE CATEGORIES OF SYSTEM SCENARIO

$\max\{N_{\mathrm{U}}, N_{\mathrm{D}}\} = 0$	heavy load	reuse mode only	Hungarian algorithm
$\max\{N_{\mathrm{U}}, N_{\mathrm{D}}\} > 0$, $K > N_{\mathrm{U}} + N_{\mathrm{D}}$	medium load	reuse+dedicated mode	Algorithm 2
$\max\{N_{\mathrm{U}}, N_{\mathrm{D}}\} > 0$, $K \le N_{\mathrm{U}} + N_{\mathrm{D}}$	light load	dedicated+cellular mode	Algorithm 1

where

$$f_{k,m}\left(p_{k,m}^{(3)}, p_{k,m}^{\mathrm{c}}\right) = \log\left(1 + \frac{p_{k,m}^{(3)} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}} h_{k,m} + \sigma_N^2}\right) + \log\left(1 + \frac{p_{k,m}^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2}\right).$$

The optimal power control vector $(p_{k,m}^{(3)*}, p_{k,m}^{\mathrm{c}*})$ for the above problem can be obtained from the algorithm in [23].

With the optimal transmit powers, the optimization problem in (6) can be converted into

$$\mathbf{x}^* = \arg\max_{\mathbf{x}} \left\{ \sum_{k=1}^{K} x_k^{(1)} \gamma_k + \sum_{k=1}^{K} x_k^{(2)} \theta_k + \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(3)} \eta_{k,m} + \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(3)} \lambda_{k,m} + \sum_{m=1}^{M} \left(1 - \sum_{k=1}^{K} x_{k,m}^{(3)}\right) \tau_m \right\}, \tag{9}$$

subject to (6a), (6b), (6c), (6d), (6e), where,

$$\gamma_k = \log\left(1 + \frac{P_{\max}^{\mathrm{D}} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}\right),$$

$$\theta_k = \log\left(1 + \frac{P_{\max}^{\mathrm{D}} h_k^{\mathrm{D}}}{\sigma_N^2}\right),$$

$$\eta_{k,m} = \log\left(1 + \frac{p_{k,m}^{(3)*} h_k^{\mathrm{D}}}{p_{k,m}^{\mathrm{c}*} h_{k,m} + \sigma_N^2}\right),$$

$$\lambda_{k,m} = \log\left(1 + \frac{p_{k,m}^{\mathrm{c}*} h_{m,\mathrm{B}}^{\mathrm{C}}}{p_{k,m}^{(3)*} h_{k,\mathrm{B}}^{\mathrm{D}} + \sigma_N^2}\right),$$

$$\tau_m = \log\left(1 + \frac{P_{\max}^{\mathrm{C}} h_{m,\mathrm{B}}^{\mathrm{C}}}{\sigma_N^2}\right).$$

In (9), the binary variables $x_k^{(1)}, x_k^{(2)}, x_{k,m}^{(3)}$ are the only remaining variables to be optimized. Thus, it turns out to be a 0–1 integer optimization problem, which is NP hard in general. An effective way to solve this problem is using the BB method [30]. However its computational complexity is very high. Therefore, in the follows, we will develop some low computational complex algorithms, with the help of network load information.

We first classify the system into three categories based on the network load: heavy load, medium load, and light load, as shown in Table I. The *heavy load* case corresponds that all channels have already been occupied by CUs, that is, $\max\{N_{\mathrm{U}}, N_{\mathrm{D}}\} = 0$. In this case, only the reuse mode could be selected by D2D pairs and the optimal channel assignment problem can be solved by Hungarian algorithm [23]. In the *medium load* case, there are empty channels, but the number of D2D pairs is larger than the number of empty channels, i.e, $K > N_{\rm U} + N_{\rm D}$. Therefore, some of the DUs can use dedicated channels while others must work in the reuse mode and share channels with CUs. In the *light load* case, the number of empty channels is larger than that of D2D pairs, i.e, $K \le N_{\rm U} + N_{\rm D}$. In this case, channel reusing is unnecessary. Each DU can work in either the cellular mode or the dedicated mode and use orthogonal channel to avoid co-channel interference with CUs. Inspired by this, we propose two heuristic algorithms for the problem (9).

A. Algorithm 1

This algorithm is applicable only when the cellular mode and the dedicated mode are considered and reusing the channels of CUs is not allowed, which can solve the problem in the *light load* scenario. In this case, $x_{k,m}^{(3)} = 0,\ \forall k, m$, the optimization problem in (9) is simplified into

$$\mathbf{x}^* = \arg\max_{\mathbf{x}} \left\{ \sum_{k=1}^{K} x_k^{(1)} \gamma_k + \sum_{k=1}^{K} x_k^{(2)} \theta_k \right\}, \tag{10}$$

subject to (6a), (6b), (6c), and

$$x_k^{(1)} + x_k^{(2)} \le 1,\ \forall k.$$

A special case for this scenario is that empty channels are sufficient so that constraints (6b) and (6c) could be removed. In this case, the optimal mode selection for each D2D pair can be simply found by comparing the capacities of the cellular mode and the dedicated mode. That is, a D2D pair will choose the dedicated mode if the capacity of the dedicated mode is larger than that of the cellular mode, and vice versa.

If the empty channels are not sufficient, the mode selection should be performed jointly, which makes the problem more complicated. Since the cellular mode consumes twice the amount of channels as the dedicated mode, we compare the capacity in the cellular mode with twice the capacity in the dedicated mode for each D2D pair. Only under the circumstance that the capacity in the cellular mode is twice larger than that in the dedicated mode, the D2D pair would choose the cellular mode. Otherwise, the dedicated mode would be chosen. In the dedicated mode, for the purpose of balance, the D2D pair will choose a downlink channel if the number of downlink channels is larger than that of uplink channels. Otherwise, it will choose an uplink channel. The D2D pairs have to use the dedicated mode when neither downlink channel nor uplink channel is available. In this case, the D2D pairs with larger channel capacity would be selected. The details of the algorithm are summarized in Table II. Note that the main computational complexity of Algorithm 1 is the sorting of the K dimensional vector $\mathbf{T}$, which is with $O(K \log_2 K)$ complexity.

TABLE II
HEURISTIC ALGORITHM FOR THE LIGHT LOAD SCENARIO

Algorithm 1 Heuristic Algorithm for the Light Load Scenario

Calculate the capacity of each DU working in the cellular mode and the dedicated mode, as: $\mathbf{T^{(1)}} = \left(T_1^{(1)}, \cdots, T_k^{(1)}, \cdots, T_K^{(1)}\right)$, $\mathbf{T^{(2)}} = \left(T_1^{(2)}, \cdots, T_k^{(2)}, \cdots, T_K^{(2)}\right)$, where $T_k^{(1)} = \log\left(1 + \frac{P_{\max}^{\rm D} h_{k,B}^{\rm D}}{\sigma_N^2}\right)$ and $T_k^{(2)} = \log\left(1 + \frac{P_{\max}^{\rm D} h_k^{\rm D}}{\sigma_N^2}\right)$.
Construct a vector $\mathbf{T}$, whose element is the higher of $\mathbf{T^{(1)}}$ and $2\mathbf{T^{(2)}}$, $\mathbf{T} = \left(\max\left\{T_1^{(1)}, 2T_1^{(2)}\right\}, \cdots, \max\left\{T_K^{(1)}, 2T_K^{(2)}\right\}\right)$.
Initialize the allocated uplink channel counter $n_1 = 0$, the allocated downlink channel counter $n_2 = 0$.
while $n_1 < N_{\rm U}$ and $n_2 < N_{\rm D}$ **do**
  select $k^* = \arg\max_k T_k$.
  if $T_{k^*} = T_{k^*}^{(1)}$ **then**
    set $n_1 = n_1 + 1$, $n_2 = n_2 + 1$, and $x_{k^*}^{(1)} = 1$.
  else
    if $N_{\rm U} - n_1 > N_{\rm D} - n_2$ **then**
      set $n_1 = n_1 + 1$ and $x_{k^*}^{(2)} = 1$.
    else
      set $n_2 = n_2 + 1$ and $x_{k^*}^{(2)} = 1$.
    end if
  end if
  set $T_{k^*}^{(1)} = T_{k^*}^{(2)} = 0$, and update $\mathbf{T}$.
end while
for $i = 1$ to $\max\{N_{\rm U} - n_1, N_{\rm D} - n_2\}$
  select $k^* = \arg\max_k T_k^{(2)}$, and set $x_{k^*}^{(2)} = 1$.
end for

B. Algorithm 2

This algorithm is dedicated to the medium load scenario, where a D2D pair may select one of the three modes. However, we could further simplify the optimization by neglecting the cellular mode. The reasons are two-fold. First, for DUs in proximity, the channel gain between D2D pair is typically larger than that between DU and eNB. Therefore, D2D communications will improve both the system capacity and the energy efficiency. Secondly, each D2D pair in the dedicated mode only occupies one channel, which also increases the bandwidth utilization rate. The same conclusion has been made and proved through the numerical results in Section IV (Table V).

Let $x_k^{(1)} = 0,\ \forall k$ in (9), then we have

$$\mathbf{x}^* = \arg\max_{\mathbf{x}} \left\{ \sum_{k=1}^{K} x_k^{(2)} \theta_k + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(3)} \eta_{k,m} + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(3)} \lambda_{k,m} + \sum_{m=1}^{M} \left(1 - \sum_{k=1}^{K} x_{k,m}^{(3)}\right) \tau_m \right\}, \tag{11}$$

subject to

$$x_k^{(2)}, x_{k,m}^{(3)} \in \{0, 1\},\ \forall k, m, \tag{11a}$$

$$\sum_{k=1}^{K} x_k^{(2)} \le N_{\rm U} + N_{\rm D}, \tag{11b}$$

$$x_k^{(2)} + \sum_{m=1}^{M} x_{k,m}^{(3)} \le 1,\ \forall k, \tag{11c}$$

$$\sum_{k=1}^{K} x_{k,m}^{(3)} \le 1,\ \forall m. \tag{11d}$$

Further, the optimization problem can be reformulated by inserting constraint (11c) into the objective function as

$$\mathbf{x}^* = \arg\max_{\mathbf{x}} \left\{ \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(3)} (\eta_{k,m} + \lambda_{k,m} - \theta_k - \tau_m) \right\}, \quad (12)$$

subject to

$$x_{k,m}^{(3)} \in \{0,1\}, \ \forall k, m, \quad (12a)$$

$$\sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(3)} \geq K - N_{\mathrm{U}} - N_{\mathrm{D}}, \quad (12b)$$

$$\sum_{k=1}^{K} x_{k,m}^{(3)} \leq 1, \ \forall m, \quad (12c)$$

$$\sum_{m=1}^{M} x_{k,m}^{(3)} \leq 1, \ \forall k. \quad (12d)$$

We can easily see that $\eta_{k,m} + \lambda_{k,m} - \theta_k - \tau_m < 0$, $\forall k, m$, therefore constraint (12b) could be forced to be equal, i.e., $\sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(3)} = K - N_{\mathrm{U}} - N_{\mathrm{D}}$.

Define $\rho_{k,m} = \eta_{k,m} + \lambda_{k,m} - \theta_k - \tau_m$, and the matrix

$$\Theta = \begin{bmatrix} \rho_{1,1} & \cdots & \rho_{1,m} & \cdots & \rho_{1,M} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \rho_{k,1} & \cdots & \rho_{k,m} & \cdots & \rho_{k,M} \\ \cdots & \cdots & \cdots & \cdots & \\ \rho_{K,1} & \cdots & \rho_{K,m} & \cdots & \rho_{K,M} \end{bmatrix}. \quad (13)$$

The optimization problem is now changed to pick $K - N_{\mathrm{U}} - N_{\mathrm{D}}$ elements from the matrix Θ in the way that each row and each column have at most one element. If the total number of elements is equal to K, i.e., $N_{\mathrm{U}} = N_{\mathrm{D}} = 0$, then the problem would be an assignment problem and the optimal solution could be obtained by the well-known Hungarian algorithm with a computational complexity of $O(M^3)$. Otherwise, there is no algorithm to this problem that could be solved with polynomial times of calculation. One can find the optimal solution by exhaustively searching all the $\binom{K}{K-N_{\mathrm{U}}-N_{\mathrm{D}}}$ possible combinations, but the computational complexity is extremely high.

Therefore, we develop a suboptimal heuristic algorithm to solve the problem. The algorithm first utilizes the Hungarian algorithm to obtain the optimal channel assignment for each D2D pair. Since there are $N_{\mathrm{U}} + N_{\mathrm{D}}$ empty channels, we then select the $K - N_{\mathrm{U}} - N_{\mathrm{D}}$ best D2D pairs to work in the reuse mode and the remaining D2D pairs to work in the dedicated mode. The detail procedures are summarized in Table III. Note that the main computational complexity of this algorithm is the Hungarian algorithm in the first step, which is with $O(M^3)$ computational complexity.

C. Algorithm 3

As a benchmark for comparison, here we examine the conventional scenario, where D2D communications are not allowed and DUs communicate through the eNB. In this case, since each D2D pair turns to regular users now and will occupy one uplink channel and one downlink channel, the maximum number of admitted D2D pair is $\min\{N_{\mathrm{D}}, N_{\mathrm{U}}\}$. Denote π as the permutation on $\{1, 2, \cdots, K\}$ that rearranges $\xi_k^{(1)}$ into a non-ascending order, then the overall system throughput of the cellular mode is

$$T = \sum_{k=1}^{\min\{N_{\mathrm{U}}, N_{\mathrm{D}}\}} \log\left(1 + \frac{p_{\pi(k)}^{(1)} h_{k,\mathrm{B}}^{\mathrm{D}}}{\sigma_N^2}\right) + \sum_{m=1}^{M} \log\left(1 + \frac{p_m^{\mathrm{c}} h_{m,\mathrm{B}}^{\mathrm{C}}}{\sigma_N^2}\right). \quad (14)$$

Recall a system with K D2D pairs, if D2D communications are not allowed, only $\min\{N_{\mathrm{D}}, N_{\mathrm{U}}\}$ D2D pairs could be admitted into the system and the maximum throughput is achieved by (14). Even if all the DUs can be admitted by the cellular mode, i.e., $K \leq \min\{N_{\mathrm{D}}, N_{\mathrm{U}}\}$, the system throughput can still be improved by Algorithm 1 without using the reuse mode due to the *proximity gain*. When $K > \min\{N_{\mathrm{D}}, N_{\mathrm{U}}\}$, Algorithm 1 will admit more D2D pairs than Algorithm 3 and the system throughput would be further improved for the sake of the *hop gain*. As $K > N_{\mathrm{D}} + N_{\mathrm{U}}$, the *reuse gain* would be introduced by Algorithm 2.

TABLE III
HEURISTIC ALGORITHM FOR THE MEDIUM LOAD SCENARIO

Algorithm 2 Heuristic Algorithm for the Medium Load Scenario

1: Utilize the Hungarian algorithm for K D2D pairs and M CUs with cost matrix Θ.
2: Let $\omega = (\omega_{\mathbf{1}}, \cdots, \omega_{\mathbf{k}}, \cdots, \omega_{\mathbf{K}})$ ($\omega_k \in \{1, 2, \cdots, M\}, \forall k$) denote the resulting channel assignment vector by the Hungarian algorithm and $\mathbf{T} = (T_1, \cdots, T_k, \cdots, T_K)$, where $T_k = \rho_{k,\omega_k}$.
3: Denote π as the permutation on $\{1, 2, \cdots, K\}$ which rearranges $\mathbf{T}$ into a non-ascending order.
4: **for all** $k = 1 : K - N_{\mathrm{D}} - N_{\mathrm{U}}$ **do**
5: set $x_{\pi_k, \omega_{\pi_k}}^{(3)} = 1$.
6: **end for**
7: **for all** $k = K - N_{\mathrm{D}} - N_{\mathrm{U}} + 1 : K$ **do**
8: set $x_{\pi_k}^{(2)} = 1$.
9: **end for**

IV. Numerical Results

We consider a single cellular network with a radius of 500 m. The eNB is located in the center of the cell and conventional CUs are distributed uniformly in the cell. The DUs are located according to the clustered distribution model [31], where each D2D transmitter, S_k, is distributed uniformly in the cell and the D2D receiver, R_k, is distributed uniformly in a disk centered by the corresponding D2D transmitter, S_k, and with a radius of r. Our simulation parameters are summarized in Table IV.

For comparison, we consider the following two optimal algorithms.

- *OptAlg 1*: The optimal algorithm for the *light load* scenario problem (10) by the BB method.
- *OptAlg 2*: The optimal algorithm for problem (9) using the BB method. Note that this algorithm is also optimal to the original problem (6).

The probabilities of choosing the cellular mode for different scenarios with different K and r are shown in Table V, which

TABLE IV
SIMULATION PARAMETERS

Parameter	Value
Cell radius	500 m
D2D distance, r	20,...,100 m
Uplink bandwidth	3 MHz
Noise spectral density	-174 dBm/Hz
Path loss model for cellular links	128.1+37.6log(d[km])
Path loss model for D2D links	148+40log(d[km])
Shadowing standard deviation	10 dB
SINR threshold, $\xi_{\min}$	10 dB
Number of CUs, M	10–20
Number of D2D pairs, K	1–15
Maximum Tx power of CU, $P^{\mathrm{C}}_{\max}$	18–27 dBm
Maximum Tx power of DU, $P^{\mathrm{D}}_{\max}$	18–27 dBm
Number of uplink channels	20
Number of downlink channels	20

TABLE V
THE PROBABILITY OF THE CELLULAR MODE

	light load		medium load	
	$K=5$	$K=8$	$K=12$	$K=15$
$r=20$ m	2.89%	2.22%	0.14%	0.13%
$r=60$ m	16.96%	9.83%	2.10%	1.63%
$r=100$ m	30.81%	16.32%	5.51%	4.29%
$r=200$ m	54.44%	28.37%	14.06%	10.79%

are obtained by *OptAlg 1* and *OptAlg 2*. From the table, the *cellular mode probability* (CMP) decreases with the number of DUs for both scenarios since more DUs should work in the dedicated or the reuse mode in order to admit more DUs into the system for larger K. Also, the CMP increases with D2D distance, r, in that D2D communications are less competitive when the distance between D2D pairs is large. In the medium load scenario, the CMP is very small, as we have discussed in Section III. The above results demonstrate that it is reasonable to neglect the cellular mode in Algorithm 2.

Fig. 2 shows the overall system throughput of different algorithms in a medium load scenarios, where $N_{\mathrm{U}}=N_{\mathrm{D}}=2$, $K=8$, and $M=18$. In the medium load scenario, certain number of DUs could not be admitted by Algorithms 1 and 3. Hence, Algorithm 2 has the best performance and is very close to the optimal algorithm (OptAlg 2). Therefore, neglecting cellular mode has little impact on the performance, demonstrating that Algorithm 2 is effective for the medium load scenario. The performance of Algorithm 3 is the worst. The performance of Algorithm 1 is between that of Algorithms 2 and 3 and is also very close to the optimal algorithm (OptAlg 1). We also compare Algorithm 1 with the algorithm proposed in [16], which also considers dedicated and cellular modes only. From the figure, Algorithm 1 has a better performance than the existing one.

We now investigate the proximity gain, the hop gain, and the reuse gain in both the light and medium load scenarios. The maximum transmit powers of both DUs and CUs are fixed to 24 dBm. The overall system throughput is depicted in Fig. 3(a), where the numbers of both downlink channels and uplink channels are 20, the number of CUs is 15, and the number of D2D pairs varies from 1 to 15. In this case, the numbers of the empty channels of both downlink and uplink are 5, i.e., $N_{\mathrm{U}}=N_{\mathrm{D}}=5$. From the figure, when the system is with light load ($K\leq 10$), almost all D2D pairs could be admitted by Algorithm 1. Therefore, the performance of Algorithm 1 is close to that of Algorithm 2 since channel reusing is probably not required. As the system turns from light load into medium load ($K>10$), some of D2D pairs need to work in the reuse mode. Therefore, Algorithm 2 will outperform Algorithm 1 since it allows D2D pairs to reuse the channels of CUs. In this case, reuse gain could be achieved. When the system is with very light load ($K\leq 5$), all DUs could be admitted by Algorithm 3 as conventional CUs. In this case, the proximity gain is observed by comparing Algorithms 3 and 1 (or 2). The performance gap between Algorithms 1 and 3 increases quickly as the network load increases ($K>5$) due to the hop gain. Beside, for $K>5$, although the number of admitted D2D pairs in Algorithm 3 remains 5, the overall throughput still increases due to the inherent multiuser diversity. The same phenomenon can be observed in Algorithm 1 for $K>10$.

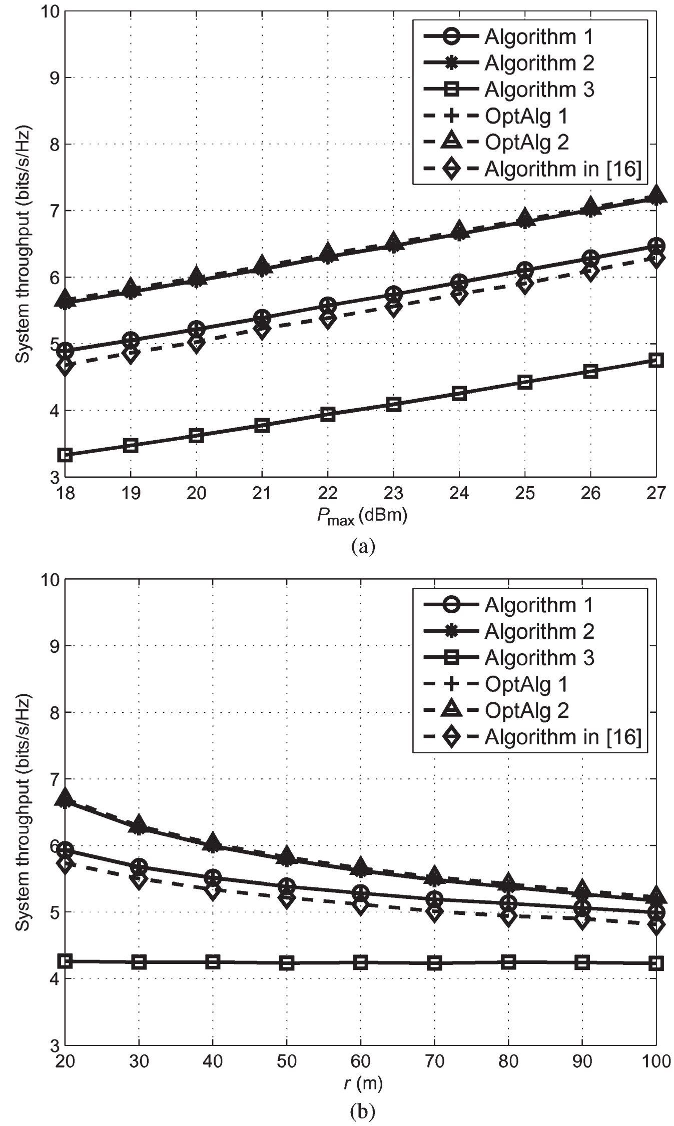

Fig. 2. Overall system throughput of different algorithms. $N_{\mathrm{U}}=2$, $N_{\mathrm{D}}=2$, $K=8$, and $M=18$. (a) Overall system throughput for different maximum transmit power. $r=20$ m. (b) Overall system throughput for different D2D distances. $P^{\mathrm{D}}_{\max}=P^{\mathrm{C}}_{\max}=24$ dBm.

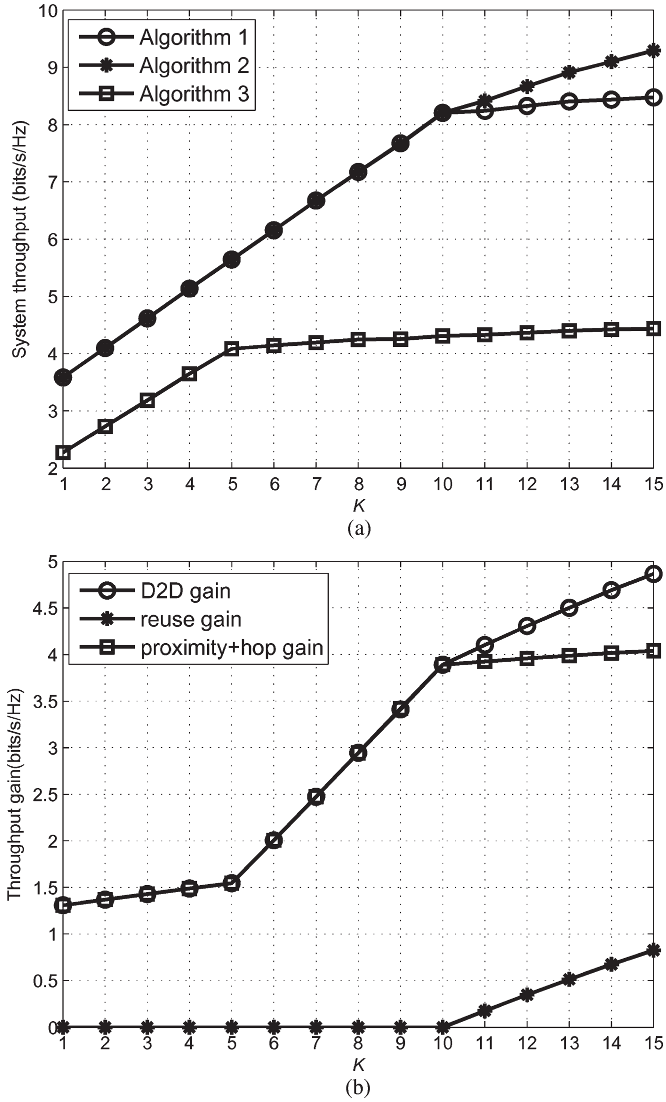

Fig. 3. Overall system throughput and throughput gain for different D2D numbers. $r = 20$ m, $N_{\mathrm{U}} = 5$, $N_{\mathrm{D}} = 5$, $P^{\mathrm{D}}_{\max} = 24$ dBm, $P^{\mathrm{C}}_{\max} = 24$ dBm, and $M = 15$. (a) Overall system throughput for different D2D numbers. (b) Throughput gain for different D2D numbers.

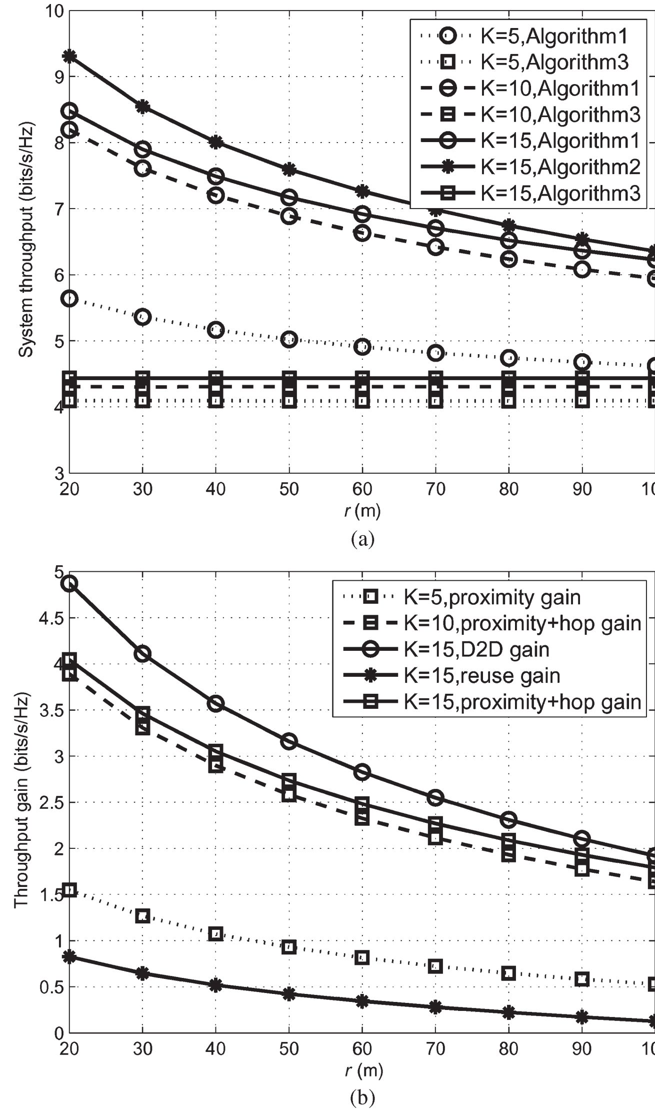

Fig. 4. Overall system throughput and throughput gain for different D2D distances. $N_{\mathrm{U}} = 5$, $N_{\mathrm{D}} = 5$, $P^{\mathrm{D}}_{\max} = 24$ dBm, $P^{\mathrm{C}}_{\max} = 24$ dBm, $M = 15$, $K = 5, 10, 15$. (a) Overall system throughput for different D2D distances. (b) Throughput gain for different D2D distances.

Fig. 3(b) plots various gains for the same scenario as Fig. 3(a). The reuse gain is achieved by comparing Algorithms 2 and 1 while the proximity gain plus the hop gain is achieved by comparing Algorithms 1 and 3. The D2D gain is the sum of the proximity gain, the hop gain, and the reuse gain. In the light load scenario $(K \leq 10)$, the D2D gain is dominated by the proximity gain and the hop gain since empty channels are enough and channel reusing is unnecessary. While for the medium load scenario $(K > 10)$, the increase of D2D gain is largely due to the reuse gain. In this case, the proximity gain and the hop gain is still slightly increased due to the multiuser diversity.

Fig. 4(a) plots the overall system throughput of Algorithms 1, 2, and 3 for different D2D distances. In the light load scenario ($K = 5$ and $K = 10$), Algorithm 2 is omitted since its performance is very close to Algorithm 1. From the figure, the system throughput decreases with the D2D distance for all algorithms. Fig. 4(b) demonstrates various throughput gains. The curve of $K = 5$ is obtained by comparing Algorithms 1 and 3. In this case, there is only the proximity gain, which decreases quickly as D2D distance increases. The curve of $K = 10$ is also obtained by comparing Algorithms 1 and 3. But different from the case of $K = 5$, there are both the proximity gain and the hop gain. For $K = 15$, the reuse gain is obtained by comparing Algorithms 2 and 1, the summation of the proximity and the hop gain is obtained by comparing Algorithms 1 and 3, and the D2D gain reflects the overall proximity gain, hop gain, and reuse gain.

Fig. 5 shows the D2D throughput versus different numbers of CUs, where the numbers of both downlink channels and uplink channels are 20, and the number of D2D pairs is 10. For Algorithm 3, D2D throughput decreases with M since less D2D pairs could be admitted as M increases from 10. For Algorithms 1 and 2, D2D throughput first remains same and then decreases with M since the empty channels are almost enough for all D2D pairs when $M \leq 15$ while channel reusing becomes necessary for $M > 15$. In this case, Algorithm 2 would perform closely to Algorithm 1 in the light load scenario,

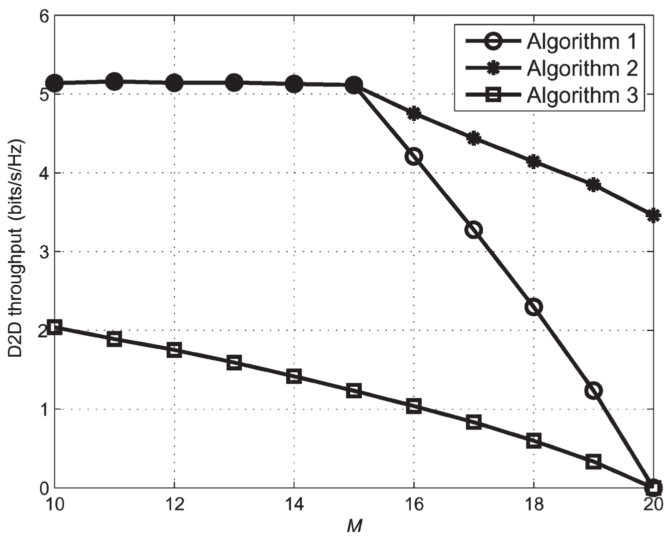

Fig. 5. D2D throughput versus different CU numbers. $r = 20$ m, $P_{\max}^{\mathrm{D}} = 24$ dBm, $P_{\max}^{\mathrm{C}} = 24$ dBm, and $K = 10$.

but would outperform Algorithm 1 in the medium load scenario. A larger D2D throughput could be achieved by Algorithms 1 and 2 than Algorithm 3 due to the proximity gain and the hop gain. When $M = 20$, the D2D throughput for both Algorithms 1 and 3 approaches 0. It is because that these algorithms do not allow channel reusing, no D2D pair could be admitted when the system is with heavy load as $M = 20$. In this case, Algorithm 2 can still achieve a certain system throughput, benefited from the reuse gain.

V. Conclusion

In this paper, we investigate the joint mode selection, channel assignment, and power control problem in D2D communication underlaying cellular networks. We optimize the overall system throughput while guaranteeing the SINR of both cellular and D2D links. The optimization problem is decomposed into two subproblems: transmit power control for both DUs and CUs, and joint mode selection and channel assignment for each DU. Joint mode selection and channel assignment is NP hard and usually very complicated to obtain the optimal solution. We then develop low-complexity algorithms according to different network loads. Through numerical simulation, we find that the proposed low-complexity algorithms perform very closely to the corresponding optimal algorithms. They can be effectively used in D2D communications to obtain the proximity gain, the hop gain, and the reuse gain. For the future work, we will develop distributed algorithms and consider the scenario where different D2D pairs can reuse the same channel of a CU.

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