Proceedings Paper:

Liu, M, Zhang, L and Gautam, PR (2020) Joint Relay Selection and Resource Allocation for Relay-Assisted D2D Underlay Communications. In: Proceedings of the 2019 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC). 2019 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC), 24-27 Nov 2019, Lisbon, Portugal. IEEE . ISBN 978-1-7281-5419-0

https://doi.org/10.1109/WPMC48795.2019.9096172

Joint Relay Selection and Resource Allocation for Relay-Assisted D2D Underlay Communications

Miaomiao Liu and Li Zhang
School of Electronic and Electrical Engineering
University of Leeds, UK.
Email:{ml13m2l, l.x.zhang}@leeds.ac.uk

***Abstract*—Relay-assisted D2D (Device-to-device) communication as a supplement to direct D2D communications for enhancing LTE-A system capacity has been proposed. In this paper, a joint mode selection, relay selection and resource allocation optimization in relay-assisted D2D communications is addressed. We aim at maximizing the overall system throughput while guaranteeing the power limitations and signal-to-noise-and-interference ratios (SINR) requirements of all cellular and active D2D links. After decomposing our original design problem into two sub-problems: 1) Optimal Power Allocation (*OPA*); 2) Joint Mode selection, Relay selection and Channel allocation (*JMRC*), we then propose the corresponding algorithms to solve them sequentially. Simulation results show that our proposed scheme significantly outperforms some existing schemes.**

***Index Terms*—Relay-assisted D2D communications; Mode Selection; Relay Selection; Power Allocation; Channel Allocation.**

I. Introduction

D2D (Device-to-device) communication is a promising technique for improving spectral energy and latency performance in next-generation cellular systems [1]. Many works have been done on resource allocation [1] for D2D communications [2]-[5]. We define the D2D pair communicate with each other directly as the direct mode (DM) in this paper.

However, only using direct D2D mode may limit the benefits brought in by D2D communications to LTE-A systems, because D2D transmitter and receiver may not be able to perform direct D2D communications due to long separation distance and poor channel condition between them [6]. In such cases, network-assisted transmission through relays could enhance the performance of D2D communication, which is called as relay-assisted D2D communications. We define the D2D pair communicate with each other supporting with the relay node as the relay mode (RM). Thus, D2D links can operate in either DM or RM in relay-assisted D2D communications. The mode selection is referred as the D2D link operates in which communication mode. Moreover, when operating in RM, the D2D link will select a relay node to assist its communication, which is defined as relay selection.

Recently, there are some researches on relay-assisted D2D communications. Authors in [7] propose a new radio protocol architecture (RPAs) to realize the relay-assisted D2D communications, and propose a joint scheduling in mode selection and resource allocation for D2D links without considering spectrum sharing. Authors in [8] [9] propose the joint mode selection and resource allocation problem for D2D underlaid cellular communication systems with each D2D link is supported only one relay node consideration. Although relay selection scheme is investigated in [10] [11], it always force D2D links to operate in RM. The relay selection is considered in [12], and Genetic Algorithm (GA) is applied to solve this combination problem, which is insufficient to achieve the optimal system performance.

Thus, in this paper, we propose a novel algorithm to optimally solve the joint mode selection, relay selection and resource allocation for relay-assisted D2D underlay communications while guaranteeing the QoS of all cellular and active D2D links. Our main contributions are as follows.

- We model the joint mode selection, relay selection and resource allocation problem to maximize the overall network throughput while subjecting to power and the signal-to-noise-and-interference ratios (SINR) limits for both cellular and active D2D links.
- In order to solve the above joint problem efficiently, we decompose our optimization problem into two subproblems: *OPA* (optimal power allocation) and *JMRC* (joint mode selection, relay selection and channel allocation), then solve them sequentially.
- The *OPA* are further divided into *OPA*-I and *OPA*-II for DM and RM, which can be optimally solved by proposed *OPA*-I algorithm and the existing algorithm in [8], respectively. In proposed *OPA*-I algorithm, the optimal power solution for cellular and D2D links which share the same channel resource can be obtained by comparing at most 4 feasible power solutions.
- Based on above optimal power allocation, we linearise *JMRC* into a integer linear programming (ILP) by introducing auxiliary variables. Then the *JMRC* problem can be solved directly by standard linear programming methods such as simplex method and Balas method.

Simulation results show that our proposed scheme can produce a better system performance than existing schemes. The rest of paper is organized as follows. Section II introduces the system model for relay-assisted D2D communications. Section III shows the problem formulation and decomposition. Our proposed solution approaches are explained in section IV. Simulation results and analysis are presented in section V.

[1] Here the resource allocation refer to power and channel allocation.

Section VI concludes this paper.

II. System Model

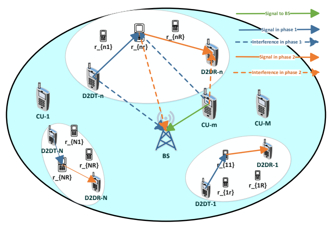

Fig. 1. A Single Cell System with M cellular links, N D2D links and the corresponding relay nodes.

The spectrum sharing relay-assisted D2D communications underlay cellular networks is shown in Fig.1, which has M cellular links, N D2D links. We use $\mathcal{M} = \{1, ...m, ...M\}$ and $\mathcal{N} = \{1, ...n, ...N\}$ to denote the index sets of cellular links and D2D links, respectively. For D2D link n, it has L corresponding relay nodes, which can be denoted as $L_n = \{r_{n1}, r_{n2}..., r_{nl}, ..., r_{nL}\}$. The relay node set of all D2D links is $\mathcal{L} = \{L_1, ...L_n, ...L_N\}$. We consider a fully loaded cellular network, in which M active cellular links occupy the M orthogonal channels and no spare spectrum. Moreover, we assume that each D2D link can only reuse no more than one channel resource of cellular link.

We denote $h_{a,b}$ as the channel gain from transmitter of link or relay node a to receiver of link or relay b. Each D2D link can operate in either direct or RM, which will be analysed in the following subsection.

A. Direct Mode

When D2D link n operates in DM, the D2D transmitter communicates directly with its D2D receiver. Thus, the SINRs of cellular link m and D2D links n can be expressed as

$$\gamma_{C_{m,n}}^{(d)} = \frac{p_{C_m}^{(d)} h_{m,B}}{\sigma^2 + p_{D_n}^{(d)} h_{n,B}}, \tag{1}$$

$$\gamma_{D_{m,n}}^{(d)} = \frac{p_{D_n}^{(d)} h_{n,n}}{\sigma^2 + p_{C_m}^{(d)} h_{m,n}}, \tag{2}$$

in where $p_{C_m}^{(d)}$ and $p_{D_n}^{(d)}$ are the transmitter powers of cellular link m and D2D link n in DM, respectively [2]. $h_{m,B}$ is the signal channel gain between cellular link m and BS, and $h_{n,B}$ is the interfering channel gain from D2D link n to BS. $h_{n,n}$ and $h_{m,n}$ are the signal channel gain between D2D link n and the interfering channel gain from cellular link m and D2D link n, respectively. The data rates in bits per second per hertz (i.e. normalized by the channel bandwidth) of cellular link m and D2D link n can be expressed as

$$R_{C_{m,n}}^{(d)} = \log_2(1 + \gamma_{C_{m,n}}^{(d)}), \tag{3}$$

$$R_{D_{m,n}}^{(d)} = \log_2(1 + \gamma_{D_{m,n}}^{(d)}), \tag{4}$$

[2]Here, the superscript (d) means DM, and (r) means RM for the next subsection.

respectively. Thus, the total data rates of channel m and D2D links n in DM is

$$R_{m,n}^{(d)} = R_{C_{m,n}}^{(d)} + R_{D_{m,n}}^{(d)}. \tag{5}$$

B. Relay Mode

When D2D link n operates in RM, D2D link n selects relay node r_{nl} when reusing the same channel resource of cellular link m. We assume that the Decode and Forward (DF) relaying strategy is employed, where each communication period is divided into two equal intervals corresponding to the D2D transmitter to relay node communication phase (phase 1) and relay node to D2D receiver communication phase (phase 2). Also, we assume that communications in phase 1 and phase 2 use the same cellular channel resource.

In phase 1, the SINRs of cellular link m and D2D link n can be expressed as

$$\gamma_{C1_{m,n,r_{nl}}}^{(r)} = \frac{p_{C_m}^{(r)} h_{m,B}}{\sigma^2 + p_{D_n}^{(r)} h_{n,B}}, \tag{6}$$

$$\gamma_{D1_{m,n,r_{nl}}}^{(r)} = \frac{p_{D_n}^{(r)} h_{n,r_{nl}}}{\sigma^2 + p_{C_m}^{(r)} h_{m,r_{nl}}}. \tag{7}$$

Similarly, in phase 2, the SINRs of cellular link m and D2D link n can be expressed as

$$\gamma_{C2_{m,n,r_{nl}}}^{(r)} = \frac{p_{C_m}^{(r)} h_{m,B}}{\sigma^2 + p_{R,r_{nl}}^{(r)} h_{r_{nl},B}}, \tag{8}$$

$$\gamma_{D2_{m,n,r_{nl}}}^{(r)} = \frac{p_{R,r_{nl}}^{(r)} h_{r_{nl},n}}{\sigma^2 + p_{C_m}^{(r)} h_{m,n}}, \tag{9}$$

where $p_{C_m}^{(r)}$, $p_{D,n}^{(r)}$ and $p_{R,r_{nl}}^{(r)}$ are the transmit powers of cellular link m, D2D link n and relay node r_{nl} in RM, respectively. $h_{n,r_{nl}}$ and $h_{m,r_{nl}}$ are the signal channel gain from D2D link n transmitter to relay node r_{nl} and the interfering channel gain from cellular link m to relay node r_{nl}, respectively. The signal channel gain from relay node r_{nl} to D2D link n receiver is denoted as $h_{r_{nl},n}$. The data rates of cellular link m and D2D links n RM can be expressed as

$$R_{C_{m,n,r_{nl}}}^{(r)} = \frac{1}{2}\log_2(1+\gamma_{C1_{m,n,r_{nl}}}^{(r)}) + \frac{1}{2}\log_2(1+\gamma_{C2_{m,n,r_{nl}}}^{(r)}), \tag{10}$$

$$R_{D_{m,n,r_{nl}}}^{(r)} = \frac{1}{2}\log_2(1+\min\{\gamma_{D1_{m,n,r_{nl}}}^{(r)}, \gamma_{D2_{m,n,r_{nl}}}^{(r)}\}). \tag{11}$$

Thus, the sum data rate of D2D link n and cellular link m when supported by relay node r_{nl} is

$$R_{m,n,r_{nl}}^{(r)} = R_{C_{m,n,r_{nl}}}^{(r)} + R_{D_{m,n,r_{nl}}}^{(r)}. \tag{12}$$

In addition, the data rate of cellular link m without being reused can be expressed as

$$R_{C,m}^{0} = \log_2(1 + \frac{P_{max}^{C} h_{m,B}}{\sigma^2}), \tag{13}$$

where P_{max}^{C} is the maximum transmission power of cellular link.

III. Problem Formulation and Decomposition

In this section, we formulate the joint mode selection, relay selection and resource allocation problem, which aims to maximize the sum data rate of all communication links while guaranteeing the required minimum SINRs and power limits of cellular and active D2D links. The problem can be expressed as

$$\begin{aligned}\max_{\boldsymbol{\chi},\boldsymbol{\rho},P} \sum_{m=1}^{M}[(1-\sum_{n=1}^{N}\chi_{mn})(1-\sum_{n=1}^{N}\sum_{l=1}^{L}\rho_{m,n,r_{nl}})R^{0}_{C,m}\\ +\sum_{n=1}^{N}(\chi_{mn}R^{(d)}_{mn}+\sum_{l=1}^{L}\rho_{m,n,r_{nl}}R^{(r)}_{m,n,r_{nl}})]\end{aligned} \tag{14}$$

s.t.

$$\gamma^{(d)}_{C_{m,n}} \geq \gamma^{C}_{min}; \gamma^{(r)}_{C1_{m,n,r_{nl}}}, \gamma^{(r)}_{C2_{m,n,r_{nl}}} \geq \frac{1}{2}\gamma^{C}_{min}, \forall m \in \mathcal{M}, \tag{14a}$$

$$\gamma^{(d)}_{D_{m,n}} \geq \gamma^{D}_{min}; \gamma^{(r)}_{D1_{m,n,r_{nl}}}, \gamma^{(r)}_{D2_{m,n,r_{nl}}} \geq \frac{1}{2}\gamma^{D}_{min}, \forall n \in \mathcal{N}, \tag{14b}$$

$$0 \leq p^{(d)}_{C_m}, p^{(r)}_{C_m} \leq P^{C}_{max}, \forall m \in \mathcal{M}, \tag{14c}$$

$$0 \leq p^{(d)}_{D_n}, p^{(r)}_{D,n} \leq P^{D}_{max}, \forall n \in \mathcal{N}, \tag{14d}$$

$$0 \leq p^{(r)}_{R,r_{nl}} \leq P^{D}_{max}, \forall r_{nl} \in \mathcal{L}, \tag{14e}$$

$$\sum_{m=1}^{M}(\chi_{mn}+\sum_{l=1}^{L}\rho_{m,n,r_{nl}}) \leq 1, \forall n \in \mathcal{N}, \tag{14f}$$

$$\sum_{n=1}^{N}(\chi_{mn}+\sum_{l=1}^{L}\rho_{m,n,r_{nl}}) \leq 1, \forall m \in \mathcal{M}, \tag{14g}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{m,n,r_{nl}} \leq 1, \forall r_{nl} \in \mathcal{L}, \tag{14h}$$

$$\chi_{mn}, \rho_{m,n,r_{nl}} \in \{0,1\}, \forall m \in \mathcal{K}, \forall n \in \mathcal{N}, \forall r_{nl} \in \mathcal{L}, \tag{14i}$$

where P is the power matrix. $\boldsymbol{\chi}$ and $\boldsymbol{\rho}$ are the binary channel allocation decision matrices for D2D in DM and RM, respectively. $\chi_{mn}=1$ if D2D link n operates in DM by reusing the same channel resource of cellular link m, otherwise, $\chi_{mn}=0$. $\rho_{m,n,r_{nl}}=1$ if D2D link n selects relay node r_{nl} by reusing the same channel resource with cellular link m, otherwise, $\rho_{m,n,r_{nl}}=0$. γ^{C}_{min} and γ^{D}_{min} are the minimum SINR requirements of cellular and D2D links, respectively. P^{D}_{max} is the maximum transmission power of D2D and relay transmitters. Constraints (14a)-(14b) show the minimum SINR requirement of each link is guaranteed in all transmission intervals. Constraints (14c)-(14e) express the limited transmission power of cellular, D2D links and relay transmitter, respectively. Constraint (14f) shows that each D2D link can reuse no more one channel and can operate in DM or RM. Constraint (14g) shows either in DM or RM, each channel resource of cellular link can only be shared by no more than one D2D link, and constraint (14h) shows that each D2D link can only be served by no more than one relay node. The final constraint (14i) means the value of resource allocation indicator should be binary.

Since the above design problem in (14) is a mixed-integer nonlinear programming (MINLP), which is an NP-hard problem. In order to solve it efficiently, we first attempt to decompose it into two sub-problems: *OPA* and *JMRC*. The *OPA* can be further divided into *OPA*-I and *OPA*-II sub-problems for DM and RM. Both *OPA*-I and *OPA*-II problems aim to maximize the sum data rate on the channel that cellular and D2D links reused by allocating the appropriate transmit power.

The *OPA*-I problem and *OPA*-II problem can be expressed as

$$\max_{(p^{(d)}_{C,m}, p^{(d)}_{D,n})} R^{(d)}_{mn} \tag{15}$$

s.t.

$$\gamma^{(d)}_{C_{m,n}} \geq \gamma^{C}_{min}, 0 \leq p^{(d)}_{C_m} \leq P^{C}_{max}, \tag{15a}$$

$$\gamma^{(d)}_{D_{m,n}} \geq \gamma^{D}_{min}, 0 \leq p^{(d)}_{D_n} \leq P^{D}_{max}, \tag{15b}$$

and

$$\max_{(p^{(r)}_{C,m}, p^{(r)}_{D,n}, p^{(r)}_{R,r_{nl}})} R^{(r)}_{m,n,r_{nl}} \tag{16}$$

s.t.

$$\gamma^{(r)}_{C1,m}, \gamma^{(r)}_{C2,m} \geq \frac{1}{2}\gamma^{C}_{min}; \gamma^{(r)}_{D1,n}, \gamma^{(r)}_{D2,n} \geq \frac{1}{2}\gamma^{D}_{min}, \tag{15b}$$

$$0 \leq p^{(r)}_{C_m} \leq P^{C}_{max}, 0 \leq p^{(r)}_{D,n}, p^{(r)}_{R,r_{nl}} \leq P^{D}_{max}. \tag{16d}$$

Based on above power allocations, the *JMRC* problem becomes

$$\begin{aligned}\max_{\boldsymbol{\chi},\boldsymbol{\rho}} \sum_{m=1}^{M}[(1-\sum_{n=1}^{N}\chi_{mn})(1-\sum_{n=1}^{N}\sum_{l=1}^{L}\rho_{m,n,r_{nl}})R^{0}_{C,m}\\ +\sum_{n=1}^{N}(\chi_{mn}R^{(d)*}_{m,n}+\sum_{l=1}^{L}\rho_{m,n,r_{nl}}R^{(r)*}_{m,n,r_{nl}})]\end{aligned} \tag{17}$$

s.t. constraints (14f)-(14i). $R^{(d)*}_{mn}$ and $R^{(r)*}_{m,n,r_{nl}}$ is the optimal sum data rates when cellular link m and D2D link n reuse the same channel in DM and RM, respectively.

IV. Proposed Optimal Algorithms

Both *OPA* and *JMRC* algorithms are discussed in this section.

A. The OPA Algorithm

We discuss the *OPA*-I and *OPA*-II algorithms individually in this subsections.

1) The OPA-I Algorithm: It has been proved in [4] that at least one user (CU or D2D transmitter) transmit on its maximum power can lead to the maximum system data rate in DM. We define Ω_{mn} is the feasible set of problem in (15), $\Omega 1_{mn}$ and $\Omega 2_{mn}$ are the feasible sets when cellular and D2D users transmit its maximum power, respectively. Thus, we can have the following proposition.

Proposition 1. If the problem in (15) is feasible, its optimal power allocation solution belongs to the set $\Omega_{mn} = \Omega 1_{mn} \cup \Omega 2_{mn}$*; otherwise,* $\Omega_{mn} = \phi$.

We first assume that $p_{C,m}^{(d)} = P_{max}^C$, then problem in (15) becomes

$$\begin{aligned}(P_{max}^C, p_{D,n}^{(d)*}) &= \arg \max_{(P_{max}^C, p_{D,n}^{(d)})} R_{m,n}^{(d)} \\ &= \arg \max_{(P_{max}^C, p_{D,n}^{(d)})} f(P_{max}^C, p_{D,n}^{(d)})\end{aligned} \tag{18}$$

s.t.

$$\frac{P_{max}^C h_{m,B}}{\sigma^2 + p_{D_n}^{(d)} h_{n,B}} \geq \gamma_{min}^C, \frac{p_{D_n}^{(d)} h_{n,n}}{\sigma^2 + P_{max}^C h_{m,n}} \geq \gamma_{min}^D, \tag{18a}$$

$$0 \leq p_{D,n}^{(d)} \leq P_{max}^D, \tag{18b}$$

where $f(P_{max}^C, p_{D,n}^{(d)}) = (1 + \frac{P_{max}^C h_{m,B}}{\sigma^2 + p_{D_n}^{(d)} h_{n,B}})(1 + \frac{p_{D_n}^{(d)} h_{n,n}}{\sigma^2 + P_{max}^C h_{m,n}})$. According to constraints ($18a$) - ($18b$), we can get the continuous closed and bounds feasible set of $p_{D,n}^{(d)}$, which is denoted as $[p_{low,D,n}^{(d)}, p_{up,D,n}^{(d)}]$. The lower and upper bounds $p_{low,D,n}^{(d)}$ and $p_{up,D,n}^{(d)}$ are expressed as

$$p_{low,D,n}^{(d)} = \max\{0, \frac{\gamma_{min}^D(\sigma^2 + P_{max}^C h_{m,n})}{h_{n,n}}\}, \tag{19}$$

$$p_{up,D,n}^{(d)} = \min\{P_{max}^D, \frac{(P_{max}^C h_{m,B} - \gamma_{min}^C \sigma^2)}{h_{n,B}\gamma_{min}^C}\}. \tag{20}$$

The problem in (18) is feasible only when $p_{low,D,n}^{(d)} \leq p_{up,D,n}^{(d)}$ holds.

When it holds, the optimal value of $f(P_{max}^C, p_{D,n}^{(d)})$ can be obtained by solving equation $f'(P_{max}^C, p_{D,n}^{(d)}) = 0$, which always has two negative solutions ($-\frac{h_{m,B}P_{max}^C + \sigma^2}{h_{n,B}}$ and $-\frac{h_{m,n}P_{max}^C + \sigma^2}{h_{n,n}}$). It means those two roots do not belong to the feasible set, and the function $f(P_{max}^C, p_{D,n}^{(d)})$ is monotonous in this feasible set. Thus, the optimal value of $f(P_{max}^C, p_{D,n}^{(d)})$ can be achieved in the bound $p_{low,D,n}^{(d)}$ or $p_{up,D,n}^{(d)}$.

Thus, $\Omega 1_{mn}$ can be expressed as

$$\Omega 1_{mn} = \{(P_{max}^C, p_{low,D,n}^{(d)}), (P_{max}^C, p_{up,D,n}^{(d)})\}. \tag{21}$$

If (18) is not feasible, we set $\Omega 1_{mn} = \phi$. The $\Omega 2_{mn}$ can be obtained in the similar way, so we omit the deviation of the $\Omega 2_{mn}$ due to the space limitation.

After that, Ω_{mn} is obtained. If $\Omega_{mn} = \phi$, we set the optimal data rate $R_{mn}^{(d)*}$ as Q, where Q is a sufficiently small value meaning that cellular link m can not reuse the same channel with D2D link n. Otherwise, the optimal power solution $(p_{C,m}^{(c)*}, p_{D,n}^{(d)*})$ can be determined by comparing at most 4 possible solutions in Ω_{mn}, which maximize (15). Meanwhile, $R_{mn}^{(d)*}$ can be obtained by substituting the optimal power solution into (5).

2) The OPA-II Algorithm: The *OPA*-II problem can be solved by the algorithm in [8] with the same technique that at least one user (cellular or D2D transmitter or relay node) transmit its maximum power can lead to the optimal system sum data rate in RM is applied. Thus, three cases (*Case1:* $p_{C_m}^{(r)} = P_{max}^C$, *Case2:* $p_{D_n}^{(r)} = P_{max}^D$, *Case3:* $p_{R_{r_{n,l}}}^{(r)} = P_{max}^D$) are considered to get the feasible power solution set. Then, the optimal power allocation and sum data rate can be obtained similar as in DM. More details can be found in [8], we omit this due to the space limitation.

Algorithm 1 : Proposed Joint Optimization Algorithm

Power Allocation:
for all $m \in \mathcal{M}, n \in \mathcal{N}$ **do**
  Obtain Ω_{mn} according to Proposition 1.
  if $\Omega_{mn} = \phi$ **then**
    $R_{mn}^{(d)*} = Q$
  else
    Obtain $R_{mn}^{(d)*}$ by substituting the $(p_{C,m}^{(d)*}, p_{D,n}^{(d)*})$ into (5), where $(p_{C,m}^{(d)*}, p_{D,n}^{(d)*}) = \arg\max_{(p_{C,m}^{(c)}, p_{D,n}^{(D)}) \in \Omega_{mn}} R_{mn}^{(d)}$.
  end if
end for
for all $m \in \mathcal{M}, n \in \mathcal{N}, l \in L$ **do**
  Obtain $R_{m,n,r_{nl}}^{(r)*}$ by solving *OPA*-II problem in (16) using the algorithm in [8]
end for
Obtain $R_{C,m}^0, \forall m \in \mathcal{M}$ according to (13)
JMRC:
Relay Selection
for all $m \in \mathcal{M}, n \in \mathcal{N}$ **do**
  Get $R_{m,n,r_{nl}^*}^{(r)*} = \max_{r_{nl} \in L_n}\{R_{m,n,r_{nl}}^{(r)}\}$
end for
Then, problem in (23) **can be solved by the standard linear programming method.**

B. The JMRC Algorithm

The relay selection is realized by letting the D2D link n selects the relay node r_{nl}^*, which can produce the maximum sum data rate. Thus, based on above *OPA* considering all the reuse possibilities for DM and RM, the *JMRC* can be further simplified into a join mode selection and channel allocation problem, which can be expressed as

$$\begin{aligned}\max_{(\boldsymbol{\alpha},\boldsymbol{\beta})} \sum_{m=1}^{M} [(1 - \sum_{n=1}^{N} \alpha_{mn}) R_{C,m}^0 + \sum_{n=1}^{N} \alpha_{mn}(\beta_n R_{m,n}^{(d)*} \\ + (1 - \beta_n) R_{m,n,r_{nl}^*}^{(r)*})]\end{aligned} \tag{22}$$

s.t.

$$\sum_{m=1}^{M} \alpha_{mn} \leq 1, \forall n \in \mathcal{N}, \tag{22a}$$

$$\sum_{n=1}^{N} \alpha_{mn} \leq 1, \forall m \in \mathcal{K}, \tag{22b}$$

$$\alpha_{mn}, \beta_n \in \{0, 1\}, \forall m \in \mathcal{K}, \forall n \in \mathcal{N}, \tag{22c}$$

where $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are channel allocation matrix and mode selection vector, respectively. $\alpha_{mn} = 1$, if D2D link n reuse channel m, otherwise, $\alpha_{mn} = 0$. $\beta_n = 1$, if D2D link n operate in DM, otherwise, $\beta_n = 0$. Constraint ($22a$) shows that each D2D link can reuse no more than one channel, and constraint ($22b$) shows that each channel resource of cellular link can be shared by no more than one D2D link. Constraint ($22c$) shows the channel allocation matrix and mode selection vector should be binary. Those three constraints are actually corresponding to ($14f$), ($14g$) and ($14i$), respectively.

Problem in (22) is an INLP (integer non-linear programming), where the only non-linear expressions are the multiplications of two binary variables ($\alpha_{mn}\beta_n$ and $\alpha_{mn}(1-\beta_n)$). According to [13], we linearise (22) by introducing auxiliary variables μ_{mn}, υ_{mn}, where $\mu_{mn} = \alpha_{mn}\beta_n$, $\upsilon_{mn} = \alpha_{mn}(1-\beta_n)$, respectively. Then, problem in (22) becomes an ILP, which is expressed as

$$\max_{(\boldsymbol{\mu},\boldsymbol{\upsilon})} \sum_{m=1}^{M} [(1-\sum_{n=1}^{N}\alpha_{mn})R_{C,m}^{0} + \sum_{n=1}^{N}(\mu_{mn}R_{mn}^{(d)} + \upsilon_{mn}R_{m,n,r_{nl}^{*}}^{(r)})], \tag{23}$$

s.t.

$$\mu_{mn} \le \alpha_{mn}, \mu_{mn} \le \beta_n, \tag{23a}$$
$$\mu_{mn} \ge \alpha_{mn} + \beta_n - 1, \tag{23b}$$
$$\upsilon_{mn} \le \alpha_{mn}, \upsilon_{mn} \le (1-\beta_n), \tag{23c}$$
$$\upsilon_{mn} \ge \alpha_{mn} - \beta_n, \tag{23d}$$

where constraints ($23a$) ensures that μ_{mn} will be 0 if either α_{mn} or β_n are 0, constraint ($23b$) makes sure that μ_{mn} will take 1 if both α_{mn} and β_n are 1. Similarly, constraints ($23c$) ensures that υ_{mn} will be 0 if either α_{mn} or $(1-\beta_n)$ are 0, constraint ($23d$) makes sure that υ_{mn} will take 1 if both α_{mn} and $(1-\beta_n)$ are 1. In this way, problem in (23) can be effectively solved by the standard ILP methods in [14] (e.g. simplex method and Balas method).

Algorithm 1 shows the details of our proposed joint optimization algorithm. The power allocation is conducted by considering all the reuse possibilities between cellular and D2D links in both DM and RM. Based on the results in RM, the relay selection is implemented as shown in Step 17. After that, the *JMRC* can be solved.

V. Simulation Results and Analysis

In this section, we use *Monte Carlo* simulation to evaluate the performance of our proposed design. We consider a single cellular network with a radius S. The BS is located in the centre of the cell, in where cellular users are uniformly distributed. Each D2D transmitter and receiver are uniformly distributed in a randomly located cluster with radius s_{max}, along with corresponding relay nodes which uniformly distributed in its concentric cluster with radius $2s_{max}$. The channel gain in our proposed model is modelled as $h_{a,b} = d_{a,b}^{-\alpha}\chi$ for all communication links, where $d_{a,b}$ is the distance between node a and b, α is the pathloss exponent[3]; χ represents the Rayleigh fading. Our simulation parameters are summarized in TABLE I.

[3] To demonstrate the benefit that relay can bring us, we will choose different pathloss exponent value for D2DT to Relay nodes and Relay nodes to D2D links.

TABLE I
SIMULATION PARAMETERS

Cell Radius S (m)	500
Maximum distance between D2D pairs s_{max} (m)	200 (if fixed)
Number of cellular links M	20
Number of D2D links N ($N \le M$)	10
Number of relay nodes for each D2D links L	4
Maximum cellular transmission power P_{max}^{C}(dBm)	20
Maximum D2D transmission power P_{max}^{D}(dBm)	20 (if fixed)
SINR requirements of cellular links γ_{min}^{C} (dB)	10 (if fixed)
SINR requirements of D2D links γ_{min}^{D} (dB)	15
Noise power σ^2 (dB)	-110
Pathloss exponent for D2DT-Relay-D2DS links $\alpha1$	3
Pathloss exponent for other communications $\alpha2$	4

We define our joint optimization as the *Proposed Scheme*. For the sake of comparison, the following schemes are taken into account.

Scheme in [8]: Authors solve the joint mode selection and resource allocation problem for D2D underlaid cellular communication systems without considering the relay selection.

Scheme in [4]: Authors consider the power and channel allocation for D2D underlaid cellular communication systems on DM without considering the mode and relay selection.

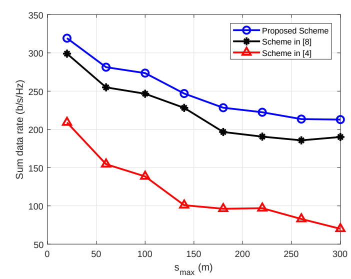

Fig. 2. The system sum rate under varying s_{max}.

Fig. 2 shows the overall system sum rate under varying maximum distance between D2D pair in three different schemes. From Fig. 2, we can see that with the increase of s_{max} the system sum rate decrease moderately for *Proposed Scheme* and *Scheme in [8]* and decrease dramatically for *Scheme in [4]*. The reason what why the system sum rate deceases with the increasing of s_{max} is that the path loss of D2D links become larger, which will result in the reduction of D2D links data rate. However, with the relay nodes assistance, the D2D links have more tolerate when s_{max} is larger. Thus, the system sum data rate decrease moderately in *Proposed Scheme* and *Scheme in [8]*, as shown in Fig. 2.

Fig. 3 shows the system sum rate under varying the minimum SINR requirement of cellular link. We can see that the system sum data rate decreases moderately as the increasing of γ_{min}^{C} in three schemes. As the increase of γ_{min}^{C}, the cellular links tend to increase their transmission power, but D2D links (include relay nodes) tend to decrease their transmission power to maintain the QoS of cellular communications. It means the D2D links transmit lower power level, and suffer more interference from the cellular links. This will results in the decreasing of the system sum data rate.

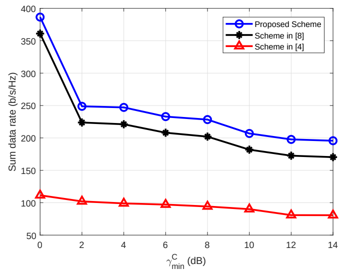

Fig. 3. The sum rate of system network under varying γ_{min}^{C}.

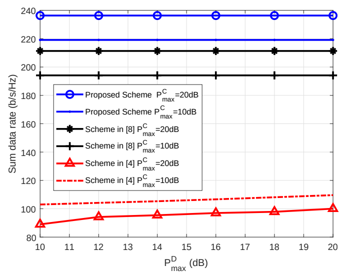

Fig. 4. The sum rate of system network under varying P_{max}^{C}.

Fig. 4 shows the system sum rate under varying the maximum D2D transmission power P_{max}^{D} for different schemes with different maximum cellular transmission power P_{max}^{C}. From Fig. 4 we can see that the performance in *Proposed Scheme* and *Scheme in [8]* keep stable and increases slightly in *Scheme in [4]* with the increase of P_{max}^{D}. It reveals that both D2D transmitter and relay node do not need to transmit their maximum power to maximize the system performance in *Proposed Scheme* and *Scheme in [8]*. Moreover, larger P_{max}^{C} leads better system performance in this two schemes. According to the OPA-II algorithm in [4], we believe that only considering *Case 1* is enough for us to get the optimal system performance, and this will dramatically reduce the power allocation computational complexity.

However, either increase of P_{max}^{D} or decrease of P_{max}^{C} will result better performance for *Scheme in [4]* as shown in Fig. 4. This is because, both strategies can improve the performance of D2D links.

All the above results show that our proposed scheme has the better performance than other schemes.

VI. Conclusion

In this paper, we have formulated the joint mode selection, resource allocation and relay selection problem as a MINLP, which is NP-hard. We then proposed the algorithms to optimally solve our optimization problems. More specifically, we allocate the transmission powers for all reuse possibilities between D2D and cellular links for both DM and RM. Based on power allocation, we then linearise the channel allocation into the ILP by adding auxiliary variables. After that, channel allocation can be solved effectively by standard INP method. The simulation results show that our proposed scheme significantly outperforms the exist schemes.

In our future work, a more realistic optimization on joint cellular and D2D channel allocation in relay-assisted D2D communication will be researched. An effective algorithm for the joint channel allocation will also be proposed.

References

[1] P. Mach, Z. Becvar, and T. Vanek, "In-band device-to-device communication in OFDMA cellular networks: A survey and challenges," *IEEE Commun. Surveys Tut*, vol. 17, no. 4, pp.1885-1922, Fourth Quarter 2015.

[2] P. Phunchongharn, E. Hossain, and D. I. Kim, "Resource allocation for device-to-device communications underlaying LTE-advanced networks," *IEEE Wireless Commun. Mag.*, vol. 20, no. 4, pp. 91-100, Aug. 2013.

[3] K. Doppler, C.-H. Yu, C. B. Sibeiro, and P. Janis, "Mode selection for device-to-device communication underlaying an LTE-advanced network," *Proc. IEEE WCNC*, pp. 1-6, 2010.

[4] D. Feng et al., "Device-to-device communications underlaying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541-3551, Aug. 2013.

[5] C. Gao et al., "Joint mode selection channel allocation and power assignment for green device-to-device communications," *Proc. IEEE ICC*, pp. 178-183, Jun. 2014.

[6] L. Wei, S. Q. Hu, Y. Qian, and G. Wu,"Energy-efficiency of multi-hop device-to-device communications underlaying cellular networks," *IEEE Trans. Veh. Tech.*, to appear, 2015.

[7] R. Ma, N. Xia, H. Chen, C. Chiu, and C. Yang, "Mode Selection, Radio Resource Allocation, and Power Coordination in D2D Communications," *IEEE Wireless Commun.*, no. 99, pp. 2-11, Feb. 2017.

[8] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Joint mode selection and resource allocation for relay-based D2D communications," *IEEE Commun. Lett.*, vol. 21, no. 2, pp. 398-401, Feb. 2017.

[9] M. Liu, and L. Zhang, "Joint Power and Channel Allocation for Relay-Assisted Device-to-Device Communications," in *Proc. 15th IEEE ISWCS,* 2018.

[10] S. Ma, Y. J. Chang, H. H. Chen, and C. Y. Chiu, "On Relay Selection Schemes for Relay-Assisted D2D Communications in LTE-A Systems," *IEEE Transactions on Vehicular Technology*, 2017.

[11] T. Kim, M. Dong, "An iterative hungarian method to joint relay selection and resource allocation for D2D communications," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 625-628, Dec. 2014.

[12] C. Vlachos et al., "Bio-inspired resource allocation for relay-aided device-to-device communications," *Proc. 84th Veh. Technol. Conf.*, pp. 1-6, 2016.

[13] L. C. Coelho. *Linearization of the product of two variables* [Online]. Available: https://www.leandro-coelho.com/linearization-product-variables/, 2013.

[14] S. K. Arora, Optimization: Algorithms and Applications, CSC Press, pp. 264-277, 2015.