Greedy Heuristic Resource Allocation Algorithm for Device-to-Device Aided Cellular Systems with System Level Simulations

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Abstract

Resource allocation in device-to-device (D2D) aided cellular systems, in which the proximity users are allowed to communicate directly with each other without relying on the intervention of base stations (BSs), is investigated in this paper. A new uplink resource allocation policy is proposed by exploiting the relationship between D2D-access probability and channel gain among variant devices, such as cellular user equipments (CUEs), D2D user equipments (DUEs) and BSs, etc., under the constraints of their minimum signal to interference-plus-noise ratio (SINR) requirements. Furthermore, the proposed resource-allocation problem can be formulated as the cost function of "maximizing the number of simultaneously activated D2D pairs subject to the SINR constraints at both CUEs and DUEs". Numerical results relying on system-level simulations show that the proposed scheme is capable of substantially improving both the D2D-access probability and the network throughput without sacrificing the performance of conventional CUEs.

Keywords: Device-to-Device (D2D); Signal to Interference-plus-Noise Ratio (SINR); D2D-Access Probability; Sum Throughput.

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1. Introduction

With the rapid development of wireless communication techniques as well as the rapid popularity of smart terminals (e.g. ipad and iphone), the existing cellular networks are becoming increasingly difficult to meet the customers' exponentially growing traffic demands [1]-[3].Therefore, both wireless spectrum efficiency and network capacity need to be substantially enhanced [4]–[6]. Meanwhile, the base stations (BSs) may often operate at an overloaded state due to the existing BS-centric architecture of wireless access networks (WANs), consequently resulting in a serious load imbalance over the whole network.

Device-to-Device (D2D) communication technology, which allows proximity users to exchange data directly without relying on the intervention of BSs [7], has been regarded as one of the effective ways for improving system performance [8]-[10] by addressing the above-mentioned issues mainly based on the following benefits. On the one hand, employing "proximity communication" is capable of offering a higher channel quality for proximity-communication peers, corresponding to attaining a higher channel capacity [11], [12] as well as a lower power consumption [13], [14]. On the other hand, a much lower delay than in conventional cellular communications can be guaranteed by enabling direct transmissions between proximity peers [15]. Furthermore, through reusing the licensed spectrum of conventional cellular user equipments (CUEs), the spectral efficiency of wireless networks can be substantially improved by activating D2D links [16]-[18].

However, activating the D2D links may impose a severe interference on the conventional CUEs, thus significantly eroding the performance of the latter [19]-[21]. To achieve a better overall system performance while guaranteeing the minimum Quality of Service (QoS) requirement of CUEs, an appropriate interference management technique (e.g., in terms of resource allocation, mode selection and power control, etc) must be implemented in the activated D2D user equipments (DUEs).

Up to now, interference-management technologies for D2D aided cellular systems have been widely studied in both academy and industry [22],[23]. To coordinate the interference among CUEs and DUEs, the authors in [24] derived the optimal power allocation for optimizing the sum data rate relying on power control schemes **for** different modes. Subject to a sum data rate constraint, a distributed power control algorithm relying on small-scale path losses has been proposed in [25] for minimizing the overall power consumption. Furthermore, a resource allocation scheme, in which the local awareness of the interference between CUEs and DUEs can be generated at the BSs, is proposed for minimizing the interference imposed on the CUEs [26]. In order to better exploit the advantages of both resource allocation and power control techniques, a joint resource allocation and power control scheme has been proposed in [27] for maximizing the energy-efficiency (EE) of D2D aided underlaying cellular networks. In addition, a scheme by jointly considering mode selection, channel assignment and power control simultaneously in D2D communications has been proposed in [28] for optimizing the overall system throughput while guaranteeing the minimum signal to interference-plus-noise ratio (SINR) of both CUEs and DUEs.

In this paper, resource allocation in D2D aided cellular systems is investigated. A heuristic resource allocation algorithm is proposed for maximizing the number of simultaneously activated D2D pairs. Unlike [29], in the proposed system model, we assume that there exists an interference limited area (ILA) either for BSs or for D2D receivers, inside which the licensed spectrum is prohibited to be reused by DUEs. Furthermore, we investigate the relationship between D2D-access ratio and channel gain among variant devices, such as CUEs, DUEs and BSs. Meanwhile, we use the singleton maximization model to analyze the global maximization under the constrains of both SINR and ILA.

The remainder of this paper is organized as follows. Section 2 gives out the system model. The proposed resource allocation strategy is discussed in Section 3, followed by evaluating the performance of the proposed algorithm using simulations in Section 4. Finally, Section 5 concludes this paper.

2. System Model

In this section, system model for the proposed D2D aided cellular networks is analyzed, followed by analyzing the SINR of wireless links. After that, a new framework for resource allocation in the proposed system is given out.

2.1 System Model for D2D Aided Cellular Networks

In this paper, without loss of generality, a single cell is considered, and licensed spectrum allocated to CUEs is allowed to be fully reused by D2D pairs, as illustrated in **Fig. 1.** Meanwhile, multiple D2D pairs are allowed to reuse the licensed spectrum of any individual CUE. However, an orthogonal spectrum is assumed to be allocated to an adjacent cell in order to avoid the inter-cell interference. Furthermore, uplink resource sharing is considered in the proposed system model, in which the D2D-induced interference is mainly imposed on BSs and the geographically close-by D2D receivers.

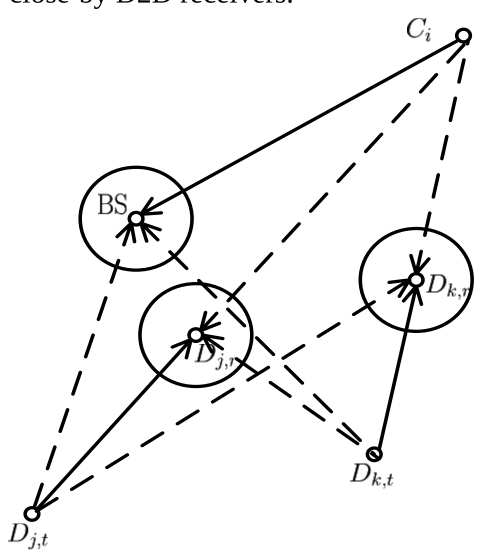

Fig. 1. System model for D2D aided cellular networks, in which multiple D2D pairs are permitted to reuse the licensed spectrum allocated to an individual CUE, where C_i and $D_{j,t}$ ($D_{k,t}$), $D_{j,r}$ ($D_{k,r}$), $i \in (1, N_c)$, $j \in (1, N_d)$, denote CUE and D2D transmitter, D2D receiver, respectively.

A fully-loaded spectrum allocation scenario is considered, in which all the spectrum resources are assumed to be allocated to the CUEs (i.e. there exists no spare spectrum). To mitigate the D2D-induced interference inside a given cellular coverage, a circle guard zone, namely the ILA, is pre-set for both BSs and D2D receivers, inside which area the licensed spectrum is prohibited to be reused by D2D transmitters. Before one D2D pair accessing the network, the BS must detect the distance between D2D transimitter and BS. After that, the BS will inform the D2D receivers the objective CUE's location, relying on which the D2D pair can decide whether to reuse the licensed resource or not. In the following, the radius of the ILA is denoted by d. Without loss of generality, all UEs are assumed to be uniformly distributed over the whole cellular coverage. Furthermore, similar to the CUEs, the DUEs also have their own minimum QoS requirements.

2.2 SINR Analysis for Cellular and D2D links

In this paper, without loss of generality, a typical Urban Micro (UMi) scenario is considered for modeling the proposed system. The performance erosion is assumed to be induced mainly by the impact of propagation and shadowing effects of wireless channels. Meanwhile, both the antenna gains of devices (i.e. including both BSs and CUEs/DUEs) and the feeder loss are taken into account. For convenience, we use $C=\{1,2,...,N_c\}$ and $D=\{1,2,...,N_d\}$ to denote the index sets of active CUEs and candidate D2D pairs, respectively, with N_c and N_d denoting the maximum number of CUEs and candidate D2D pairs, respectively. Furthermore, $\phi_i \subseteq D$ is used to denote the set of admitted D2D pairs (i.e. the activated DUE pairs), which will reuse the spectrum allocated to the i-th CUE. In addition, parameters C_i and D_j are used to denote the i-th CUE and j-th D2D pair, respectively.

The received SINR of the typical CUE-BS (i.e., C_i-BS) and D2D (i.e., D_j) links can be respectively represented as

$$\begin{cases} \gamma_i^c = \dfrac{P_0 g_{i,B}}{N_0 + \sum\limits_{j\in\phi_i} P_0 g_{j,B}}, \\ \gamma_j^d = \dfrac{P_0 g_j}{N_0 + \sum\limits_{k\in\phi_i \setminus j} P_0 g_{k,j} + P_0 g_{i,j}}, \end{cases} \tag{1}$$

where γ_i^c denotes the SINR of C_i-BS link, γ_j^d denotes the SINR of D2D link D_j, P_0 stand for the transmit power of users. Furthermore, $g_{i,B}$ denotes the channel gain between C_i and the corresponding BS, and $g_{j,B}$ denotes the channel gain between the j-th D2D transmitter and the associated BS. Thus, g_j can be used to denote the corresponding channel gain of D_j, with $g_{i,j}$ standing for the channel gain between C_i and the j-th D2D receiver. In addition, $\sum\limits_{j\in\phi_i} P_0 g_{j,B}$ is used to represent the interference power imposed on BS by D_j, and $\sum\limits_{k\in\phi_i \setminus j} P_0 g_{k,j} + P_0 g_{i,j}$ denotes the sum interference power imposed on D_j induced by C_i and other D2D pairs. Finally, N_0 is used to denote the power spectrum density of thermal noise. The sum throughput of the proposed D2D aided cellular systems can thus be expressed as

$$R_{sum} = \sum_{i \in C} \left(\log\left(1+\gamma_i^c\right) + \sum_{j \in \phi_i} \log\left(1+\gamma_j^d\right) \right). \quad (2)$$

2.3 Formulating the Proposed Resource Allocation Problem

It has been proven that the system performance in terms of sum throughput can be substantially improved by activating appropriate D2D links [23]. In the system model considering fully spectrum loaded scenario, the licensed spectrum allocated to any individual CUE is allowed to be reused by more than one D2D pair. For convenience of analysis, we can form a frequency reuse set comprising the objective CUE and its co-spectrum DUEs, provided that the minimum QoS (or in other words, minimum SINR) requirement of each user in this set can be guaranteed. Based on the above-mentioned principle, a resource-allocation framework can thus be formulated as:

$$P1: \max_{\phi_1, \phi_2, \ldots, \phi_{N_C}} \sum_{i \in C} \left|\phi_i\right| \quad (3)$$

$$s.t. \quad \gamma_i^c \geq \gamma_{\min}^c, \forall_i \in C, \quad (3a)$$

$$\gamma_j^d \geq \gamma_{\min}^d, \forall_j \in D, \quad (3b)$$

$$\phi_p \bigcap \phi_q = \varnothing, \forall_{p,q} \in C \;\&\; p \neq q, \quad (3c)$$

$$d_{j,B} > d, d_{t,j} > d, \forall_t \in C \,\|\, D \setminus j, \forall_j \in D, \quad (3d)$$

where ϕ_i represents the set of admitted D2D pairs reusing the spectrum of C_i, and $\gamma_{\min}^c$ and $\gamma_{\min}^d$ stand for the minimum SINR requirement of C_i and D_j, respectively. We also use $d_{j,B}$ to denote the distance between j-th D2D transmitter and BS, and use $d_{t,j}$ to denote the distance between interference transmitter (i.e. CUE or other D2D transmitter) and j-th D2D receiver. Furthermore, (3c) ensures that any D2D pair is permitted to reuse the spectrum of one and only one CUE. In addition, (3d) is used to limit the D2D-induced interference imposed on both BSs and D2D receivers (i.e. corresponding to formulating the function of ILA).

3. Resource Allocation Strategy For D2D Aided Cellular Systems

It is shown that the activated D2D links may impose a severe interference on the CUEs [23], and, the interference induced by either CUEs or the geographically close-by D2D transmitters may also significantly erode the quality of a given activated D2D link. To mitigate the D2D-induced interference, an appropriate resource allocation scheme, which is capable of balancing the probability of D2D access and the sum throughput of the whole system, should be implemented.

In this section, a resource allocation strategy aiming at maximizing the number of simultaneously activated D2D pairs while satisfying the minimum QoS requirements of all users (i.e. comprising both CUEs and DUEs) is proposed. According to (3a), and (3b), the maximum number of simultaneously activated D2D pairs can be expressed as

. *when* $\gamma_i^c \geq \gamma_{\min}^c, |\phi_i| \leq \frac{P_0 g_{i,B}}{\gamma_{\min}^c \bar{I}_i^c} - \frac{N_0}{\bar{I}_i^c},$

. *when* $\gamma_j^d \geq \gamma_{\min}^d, |\phi_i| \leq \frac{P_0 g_j}{\gamma_{\min}^d \bar{I}_j^d} - \frac{N_0}{\bar{I}_j^d},$

thus leading to

$$|\phi_i| \leq \min\left(\frac{P_0 g_{i,B}}{\gamma_{\min}^c \bar{I}_i^c} - \frac{N_0}{\bar{I}_i^c}, \frac{P_0 g_j}{\gamma_{\min}^d \bar{I}_j^d} - \frac{N_0}{\bar{I}_j^d} \right), \tag{4}$$

where $\bar{I}_i^c$ and $\bar{I}_j^d$ denote the average interference ($\bar{I}$) imposed on C_i and D_j receivers, respectively. In the following, we set $\Phi_1 = \frac{P_0 g_{i,B}}{\gamma_{\min}^c \bar{I}_i^c} - \frac{N_0}{\bar{I}_i^c}$ and $\Phi_2 = \frac{P_0 g_j}{\gamma_{\min}^d \bar{I}_j^d} - \frac{N_0}{\bar{I}_j^d}$, where $I_i^c = \sum_{j \in \phi_i} P_0 g_{j,B}$ and $I_j^d = \sum_{t \in C \| D \setminus j} P_0 g_{t,j}$, and Φ_1 is a monotonically decreasing function of $\bar{I}_i^c$. Likewise, Φ_2 is a monotonically decreasing function of $\bar{I}_j^d$, when both $\bar{I}_i^c > 0$ and $\bar{I}_j^d > 0$ are satisfied, we have $\bar{I}_i^c = \bar{I}_j^d = \bar{I}_{\max} = P_0 g_{\max}$ when $g_{j,B} = g_{t,j} = g_{\max}$ (i.e. the interfering transmitter is located at the boundary of the interference limitation area), on the other hand, we have $\Phi_1 \geq \Phi_{\min}^1 = \frac{P_0 g_{i,B} - \gamma_{\min}^c N_0}{\gamma_{\min}^c \bar{I}_{\max}}$ and $\Phi_2 \geq \Phi_{\min}^2 = \frac{P_0 g_j - \gamma_{\min}^d N_0}{\gamma_{\min}^d \bar{I}_{\max}}$. Meanwhile, $|\phi_i|$ should satisfy

$$|\phi_i| \leq \min\left(\Phi_{\min}^1, \Phi_{\min}^2\right), \tag{5}$$

Therefore, we can get the maximum-$|\phi_i|$ as

$$|\phi_{\max}^i| = \begin{cases} \Phi_{\min}^1, \frac{g_{i,B}}{g_j} \leq \frac{\gamma_{\min}^c}{\gamma_{\min}^d}, \\ \Phi_{\min}^2, \frac{g_{i,B}}{g_j} > \frac{\gamma_{\min}^c}{\gamma_{\min}^d}. \end{cases} \tag{6}$$

From (6), we can readily prove that $\frac{g_{i,B}}{g_j} \leq \frac{\gamma_{\min}^c}{\gamma_{\min}^d}$, showing that the maximum of simultaneously activated D2D pairs is $\Phi_{\min}^1 = \frac{P_0 g_{i,B} - \gamma_{\min}^c N_0}{\gamma_{\min}^c \bar{I}_{\max}}$. Note that the above-mentioned conclusion can be extended to arbitrary C_i, D_j and

$\Phi^1_{i,c} = \frac{P_0 g_{i,B} - \gamma^c_{\min} N_0}{\gamma^c_{\min} P_0 g_{j,B}}$. Thus, to maximize $\Phi^1_{i,c}$, we can take $g_{i,B} - \gamma^c_{\min} g_{j,B} > \frac{\gamma^c_{\min} N_0}{P_0}$ as a reuse constraint for selecting D_j . Similarly, if both $\frac{g_{i,B}}{g_j} > \frac{\gamma^c_{\min}}{\gamma^d_{\min}}$ and $\Phi^2_{i,c} = \frac{P_0 g_j - \gamma^d_{\min} N_0}{\gamma^d_{\min} P_0 g_{t,j}}$ are satisfied, we may take $g_j - \gamma^d_{\min} g_{t,j} > \frac{\gamma^d_{\min} N_0}{P_0}$ as a reuse constrain for selecting D_j. In summary, to maximize the D2D-access ratio, the reuse restrictions can be expressed as

$$\begin{cases} g_{i,B} - \gamma^c_{\min} g_{j,B} > \frac{\gamma^c_{\min} N_0}{P_0}, \quad when \quad \frac{g_{i,B}}{g_j} \le \frac{\gamma^c_{\min}}{\gamma^d_{\min}}, \\ g_j - \gamma^d_{\min} g_{t,j} > \frac{\gamma^d_{\min} N_0}{P_0}, \quad when \quad \frac{g_{i,B}}{g_j} > \frac{\gamma^c_{\min}}{\gamma^d_{\min}}. \end{cases} \tag{7}$$

From the above-mentioned analysis, the optimal constraints for improving the sum throughput of the proposed D2D aided cellular systems under the criteria (7) of maximizing the activated D2D pairs can be derived as follows.

Obviously, the sum throughput R_c in the traditional cellular network (i.e. without considering D2D communications) can be expressed as

$$R_c = \sum_{i \in C} \left[\log\left(1 + \xi^c_i\right) \right], \tag{8}$$

where

$$\xi^c_i = \frac{P^c_i g_{i,B}}{N_0}, \tag{9}$$

As compared to (8), the throughput gain brought about by employing D2D mode can be expressed as

$$R^G = R_{sum} - R_c = \sum_{i \in C} \left(\log\left(\frac{\left(1+\gamma^c_i\right) \prod_{j \in \phi_i} \left(1+\gamma^d_j\right)}{1+\xi^c_i} \right) \right), \tag{10}$$

and

$$\sum_{i \in C} \left(\log\left(\frac{1+\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j}{1+\xi^c_i} \right) \right) \le R^G \le \sum_{i \in C} \left(\log\left(\frac{\Upsilon}{1+\xi^c_i} \right) \right), \tag{11}$$

where

$$\begin{aligned} \Upsilon = & 1 + \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right) + \frac{C^1_{m-1}}{2} \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right)^2 \\ & + \ldots + \frac{C^n_{m-1}}{n+1} \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right)^{n+1} + \ldots + \frac{C^{m-1}_{m-1}}{m} \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right)^m , \end{aligned} \tag{12}$$

with m denoting the size of spectrum reuse set, as derived in Appendix. For conventional cellular systems, as a benchmark, it is easy to derive $R_{sum} = R_c$. However, for D2D aided cellular networks, it is shown that $R_{sum} > R_c$ can be met if $\gamma_i^c + \sum_{j\in\phi_i} \gamma_j^d > \xi_i^c$ is satisfied. Furthermore, the performance gain in terms of SINR can be expressed as

$$\begin{aligned}\gamma_{i,j}^G &= \gamma_i^c + \sum_{j\in\phi_i} \gamma_j^d - \xi_i^c \\ &= \sum_{j\in\phi_i} \frac{P_0 g_j}{N_0 + \sum_{t\in C\|D\backslash t} P_0 g_{t,j}} - \frac{\sum_{j\in\phi_i} P_0 g_{j,B}.P_0 g_{i,B}}{N_0\left(N_0 + \sum_{j\in\phi_i} P_0 g_{j,B}\right)},\end{aligned} \tag{13}$$

Let us set both $\Upsilon_1 = \sum_{j\in\phi_i} \frac{P_0 g_j}{N_0 + \sum_{t\in C\|D\backslash t} P_0 g_{t,j}}$ and $\Upsilon_2 = \frac{\sum_{j\in\phi_i} P_0 g_{j,B}.P_0 g_{i,B}}{N_0\left(N_0 + \sum_{j\in\phi_i} P_0 g_{j,B}\right)}$, where Υ_1 is a monotonically decreasing function of $g_{t,j}$ and Υ_2 is a monotonically decreasing function of $g_{j,B}$, when $g_{t,j} > 0$ and $g_{j,B} > 0$. Furthermore, let us set both $g_{t,j} = g_{\max}$ and $g_{j,B} = g_{\max}$, thus yielding

$$\begin{aligned}\gamma_{i,j}^G &\geq \frac{\sum_{j\in\phi_i} P_0 g_j}{N_0 + \sum P_0 g_{\max}} - \frac{\sum P_0 g_{\max}.P_0 g_{i,B}}{N_0\left(N_0 + \sum P_0 g_{\max}\right)}, \\ &\geq \frac{N_0 \sum_{j\in\phi_i} P_0 g_j - \sum P_0 g_{\max}.P_0 g_{i,B}}{N_0\left(N_0 + \sum P_0 g_{\max}\right)},\end{aligned} \tag{14}$$

To make $\gamma_{i,j}^G > 0$, we may take $N_0 \sum_{j\in\phi_i} P_0 g_j - \sum P_0 g_{\max}.P_0 g_{i,B} > 0$. Therefore

$$\frac{g_{i,B}}{g_j} < \frac{N_0}{P_0 g_{\max}} \tag{15}$$

Combine (7) and (15), the reuse restrictions can be expressed as

$$\begin{cases} g_{i,B} - \gamma_{\min}^c g_{j,B} > \dfrac{\gamma_{\min}^c N_0}{P_0}, \quad when \quad \dfrac{g_{i,B}}{g_j} \leq \min\left(\dfrac{\gamma_{\min}^c}{\gamma_{\min}^d}, \dfrac{N_0}{P_0 g_{\max}}\right), \\ g_j - \gamma_{\min}^d g_{t,j} > \dfrac{\gamma_{\min}^d N_0}{P_0}, \quad when \quad \dfrac{g_{i,B}}{g_j} \in \left(\dfrac{\gamma_{\min}^c}{\gamma_{\min}^d}, \dfrac{N_0}{P_0 g_{\max}}\right) \&\& \left(\dfrac{N_0}{P_0 g_{\max}} > \dfrac{\gamma_{\min}^c}{\gamma_{\min}^d}\right). \end{cases} \tag{16}$$

Note that the proposed resource-allocation problem can be readily formulated as a Maximum Independent Set Problem (MISP) for each CUE, where the D2D pairs (denoted by D) and the spectrum reuse relationship among different D2D pairs are denoted by the point set V and edge set E of an undirected graph $G=(V,E)$, respectively. Since ϕ_i denotes a complete graph, while ϕ_i represents the number of points belonging to the complete graph, our task becomes "finding the ϕ_i with max-ϕ_i value in G so as to maximize the number of simultaneously activated D2D pairs associated with each CUE (i.e. that reuse the licensed spectrum allocated to that CUE)". Therefore, (3) can be presented as

$$P2: \sum_{i\in C^N} \max|\phi_i| \tag{17}$$

$$s.t. \quad g_{i,B} > \gamma_{\min}^c\left(\frac{N_0}{P_0}+g_{j,B}\right), \quad when \quad \frac{g_{i,B}}{g_j} \le \min\left(\frac{\gamma_{\min}^c}{\gamma_{\min}^d}, \frac{N_0}{P_0 g_{\max}}\right), \tag{17a}$$

$$g_j > \gamma_{\min}^d\left(\frac{N_0}{P_0}+g_{t,j}\right), \quad when \quad \frac{g_{i,B}}{g_j} \in \left(\frac{\gamma_{\min}^c}{\gamma_{\min}^d}, \frac{N_0}{P_0 g_{\max}}\right) \&\& \left(\frac{N_0}{P_0 g_{\max}} > \frac{\gamma_{\min}^c}{\gamma_{\min}^d}\right), \tag{17b}$$

$$\phi_p \cap \phi_q = \varnothing, \forall_{p,q} \in C \;\&\; p \ne q, \tag{17c}$$

$$d_{j,B} > d, d_{t,j} > d, \forall_t \in C \,\|\, D \setminus j, \forall_j \in D, \tag{17d}$$

We use the following **Fig. 2** to represent the feasible domain, in which we can perform resource reuse. Note that the size between the points is uncertain, like $\min\left(\frac{\gamma_{\min}^c}{\gamma_{\min}^d}, \frac{N_0}{P_0 g_{\max}}\right) g_j$ and $\frac{\gamma_{\min}^c N_0}{P_0}$, we only list one of the possibilities to prove the existence of the solution where $g_{\min}$ denotes the minimum value under the constraint of cell radius. For arbitrary C_i, D_j, the equation (6) can be expressed as $|\phi_j^i| = \begin{cases} \frac{P_0 g_{i,B} - \gamma_{\min}^c N_0}{\gamma_{\min}^c P_0 g_{j,B}}, \frac{g_{i,B}}{g_j} \le \frac{\gamma_{\min}^c}{\gamma_{\min}^d}, \\ \frac{P_0 g_j - \gamma_{\min}^d N_0}{\gamma_{\min}^d P_0 g_{t,j}}, \frac{g_{i,B}}{g_j} > \frac{\gamma_{\min}^c}{\gamma_{\min}^d}. \end{cases}$, mathematically, the max-$|\phi_j^i|$ can be expressed as the maximum value of the slope between the point (x,y) and $\left(0, \frac{\gamma_{\min}^c N_0}{P_0}\right)$ (or $\left(0, \frac{\gamma_{\min}^d N_0}{P_0}\right)$) in feasible domain.

Relying on the formulated MISP, a greedy heuristic algorithm is also proposed for solving the proposed resource-allocation problem, as elaborated on in Algorithm 1, in which the complexity is $O(N_c N_d)$.

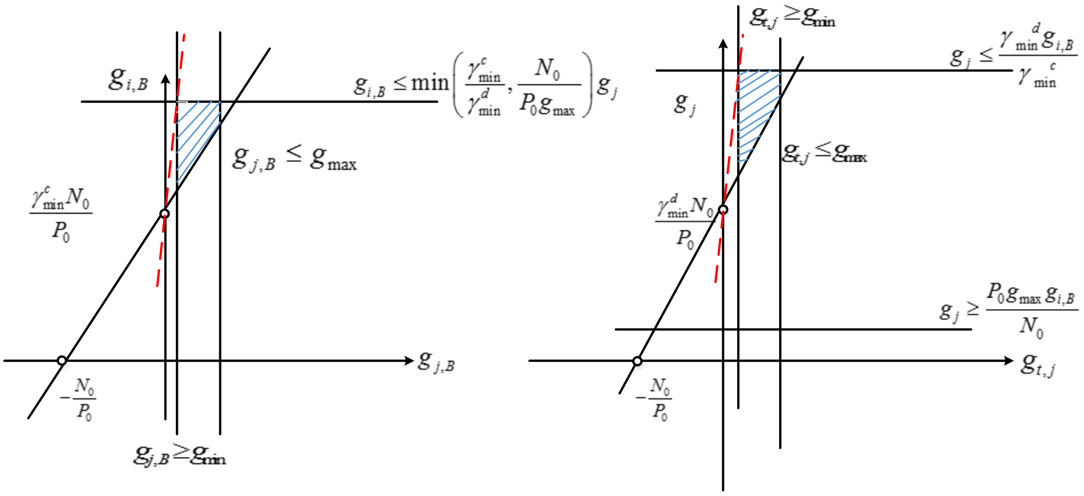

Fig. 2. the possible feasible domain of CUE and DUE

Algorithm 1: The Proposed Allocation Algorithm

C_N: The set of actives CUEs;
D_N: The set of candidate D2D pairs;
ϕ_i : The set of reuse D2D pairs;
$len(\phi_i)$: The size of ϕ_i;
for $D_j \in D_N$ **do**
  for $C_i \in C_N$ **do**
    if *C_i and D_j satisfy the equation of (17a)-(17d)* **then**
      if $len(\phi_i) == 0$ **then**
        $\phi_i = \{D_j\}$;
      end
      if $len(\phi_i) > 0$ **then**
        For any D2D pair in ϕ_i , calculate whether or not the threshold condition of SINR is met and the interferencing D2D transmitters are outside of ILA as the same time. If satisfied, $\phi_i = \phi_i + D_j$;
      end
    end
  end
end

Furthermore, the detailed reuse procedure between D2D pairs and CUE can be expressed as follows:

① D2D pairs want to aeccss the network.

② The BS chooses the D2D pair according to the session initiation time. If the time is consistent, BS selects the D2D pair according to the distance between D2D peers.

③ BS selects CUE according to the signal strength of CUE.

④ BS calculates whether D2D pair and CUE satisfy equations (17a)-(17d).

⑤ If equations (17a)-(17d) are satisfied, BS will send UL grant to D2D pair to start session, followed by picking other D2D pairs, and then repeat ①-⑤.

⑥ otherwise, repeat ①-⑤.

4. Numerical Analysis

In this section, numerical analysis relying on the proposed channel model is performed for exploring the attainable benefits brought about by employing the proposed algorithm. The objective functions of the proposed optimization is set to be the D2D access ratio (i.e. represented as the number of simultaneously activated D2D pairs to the total number of users), the sum throughput gain over the conventional cellular systems, and D2D link's average throughput parameterized by the increase of CUE-SINR threshold $\eta = \gamma_{\min}^{c}$ and ILA radius d.

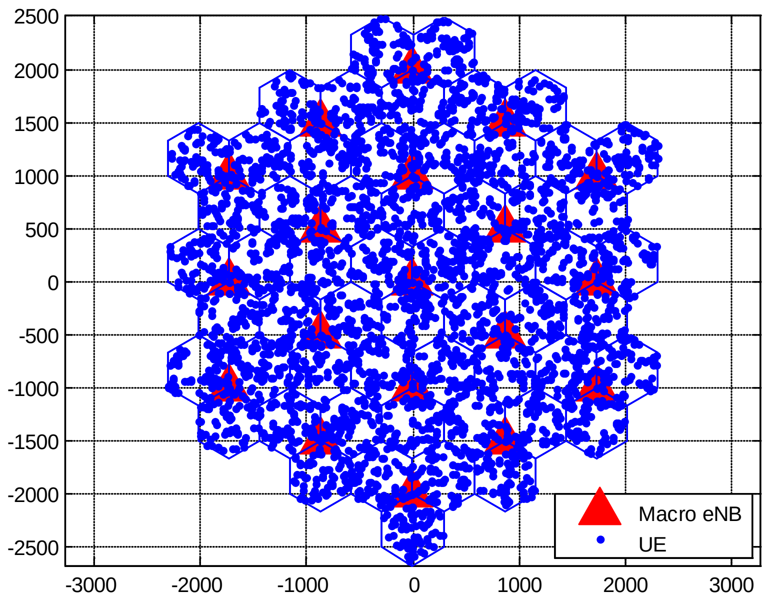

Fig. 3. The simulation is a wrap-around configuration of 19 sites, each comprising 3 cells, inside which the users are distributed uniformly over the whole area.

In the following, similar to [30], a wrap-around system configuration comprising 19 sites (i.e. each comprising 3 cells), with inter-site distance of 1000m, is considered, as depicted in **Fig. 3.** Without loss of generality, the minimum UE-to-BS distance is assumed to be 10m, and the maximum distance between a pair of D2D peers is 50m. Furthermore, orthogonal spectrum allocation among CUEs is performed. In addition, the transmit power of BS and CUEs assumed to be 42dBm and 24dBm, respectively. Finally, the noise power spectrum density is assumed to be $-174 dBm/Hz$. The detailed parameter settings, which come from the standard ITU-R M.2135[30], are elaborated on in **Table 1.**

Table 1. Parameter settings of the proposed system-level simulation.

Parameters	**Settings**
scenario environment	UMi
system bandwidth	10MHz (TDD)
carrier frequency	2.5 GHz
Inter-site distance (ISD)	1000m
the deployment of Macro BS	typical system layout of 19 sites, each comprising 3 cells with six resolvable angles
the min-distance of UE to BS	10m
Antenna model of Macro BS	$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_3}\right)^2, A_m\right]$ $A_e(\phi) = -\min(12\left(\frac{\phi-\phi_{tilt}}{\phi_3}\right)^2, A_m)$ $= -\min\left\{-\left(A(\theta)+A_\varepsilon(\phi)\right), A_m\right\}$ $A_m = 20dB,\ \ \theta_3 = 70,\ \ \phi_{tilt} = 15,$ $-180 \le \theta \le 180,\ \ -90 \le \phi \le 90$
Antenna model of UE	Omnidirectional
traffic pattern	full buffer
BS height	10m
UE height	1.5m
BS Noise Figure	5 dB
UE Noise Figure	7 dB
BS transmit power	42 dBm
UE transmit power	24 dBm
Power level of thermal noise	-174 dBm/Hz

4.1 Channel Model for System-Level Simulations

The Spatial Channel Model (SCM), which is a typical double directional geometry-based stochastic model [30], is adopted in this section. The path loss model of BS-to-UE links is given by ITU-R M.2135 standard, whereas the path loss model of UE-to-UE links has been defined in 3rd Generation Partnership Project (3GPP) specification 36.843-c01[31][32]. Furthermore, two propagation scenarios, including Line of Sight (LOS) and Non Line Of Sight (NLOS) for outdoor users in UMi, are considered. Note that the LOS probability can be parameterized as a function of distance l:

$$P_{LOS} = \min\left(\frac{18}{l}\right)\left(1-\exp\left(\frac{-l}{36}\right)\right)+\exp\left(\frac{-l}{36}\right). \tag{18}$$

Similarly, the UE-to-UE path loss can be expressed as

$$P_L = \max\left(P_{L,free}, P_{L,b}\right), \tag{19}$$

and

$$\begin{cases} P_{L,free} = 20.0\log(l) + 46.4 + 20.0\log(f_c), if \quad free-space, \\ P_{L,b} = 22.7\log(l) + 27.0 + 20.0\log(f_c), if \quad LOS \,\&\, \; l \in (10, 4.0h_{bs}h_{ms}f_c), \\ P_{L,b} = 40.0\log(l) + 7.56 - 17.3\log(h_{bs}) - 17.3\log(h_{ms}) + 2.7\log(fc), \\ if \quad LOS \,\&\, \; l \in ((0,10),(4.0h_{bs}h_{ms}f_c,\infty)), \\ P_{L,b} = (44.9 - 6.55\log(h_{BS}))\log(l) + 18.38 + 5.83\log(h_{BS}) + 23.0\log(f_c), \\ if \quad NLOS, \end{cases} \tag{20}$$

where l denotes the average distance between a pair of D2D peers, f_c stands for the center frequency, h_{BS} and h_{MS} represent the actual antenna height and the effective environmental height, respectively. Furthermore, we have $h_{bs} = h_{BS} - 1.0$ and $h_{ms} = h_{MS} - 1.0$.

Apart from it, shadowing effect is assumed to follow a log-normal distribution, as expressed as

$$\delta_{SF,n} = 10^{\frac{\gamma_n \delta_{SH}}{10}}, \tag{21}$$

where γ_n is a Gaussian random variable, and δ_{SH} denotes the shadow fading standard deviation in dB. Meanwhile, the antenna model is given by **Table 1**. The channel gain can thus be expressed as

$$g_{i,j} = \frac{1.0}{(P_L - S_F - A_i - A_j + feederloss)}, \tag{22}$$

where P_L denotes the path loss exponential, S_F represents the shadowing effect, A_i and A_j are the antenna gains of signal transmitter and signal receiver, respectively, and *feederloss* is set to be 20dB.

4.2 Simulation Results

In this subsection, the performance comparison between the greedy resource allocation algorithm (GRA) and without the greedy resource allocation algorithm in terms of D2D access probability is performed, where the throughput gain of the latter is evaluated subject to the SINR constraints of both CUEs and DUEs.

In **Fig. 4**, the performance of GRA and without GRA in terms of the maximum number of simultaneously activated D2D pairs is performed by considering variant η values, with a single CUE considered. It is shown that the number of simultaneously activated D2D pairs decreases as η increases, because the interference tolerance of CUE decreases as the SINR threshold increases, thus requiring fewer D2D pairs to be activated simultaneously so as to impose a lower interference on CUE (i.e. to guarantee the minimum SINR requirement of the CUE). Anyway, the proposed algorithm is shown to always outperform the without GRA in terms of the maximum number of simultaneously activated D2D pairs, because the former is capable of coordinating the interference between CUEs and D2D pairs and optimizing the spectrum reuse set adaptively according to the instantaneous channel condition.

In **Fig. 5**, the impacts of ILA radius and CUE-SINR threshold on the number of simultaneously activated D2D pairs in a single-cellular scenario is investigated. It is shown that the access probability of the proposed algorithm is a monotonically decreasing function of η, because the interference tolerance of DUEs decreases as η increases. Meanwhile, it is also shown that the performance of GRA increases first, and then decreases as d increases. We can explain this observation as follows: when ILA radius is small, the interference imposed on signal receiver from one interference transmitter is more intensive compared with signal receiver power when the distance of interference link is smaller than D2D links. But when ILA radius is beyond the distance of D2D links, the probability of candidate D2D pairs access to net-work declines with the increase of d, as a result, the number of admitted D2D pairs decreases.

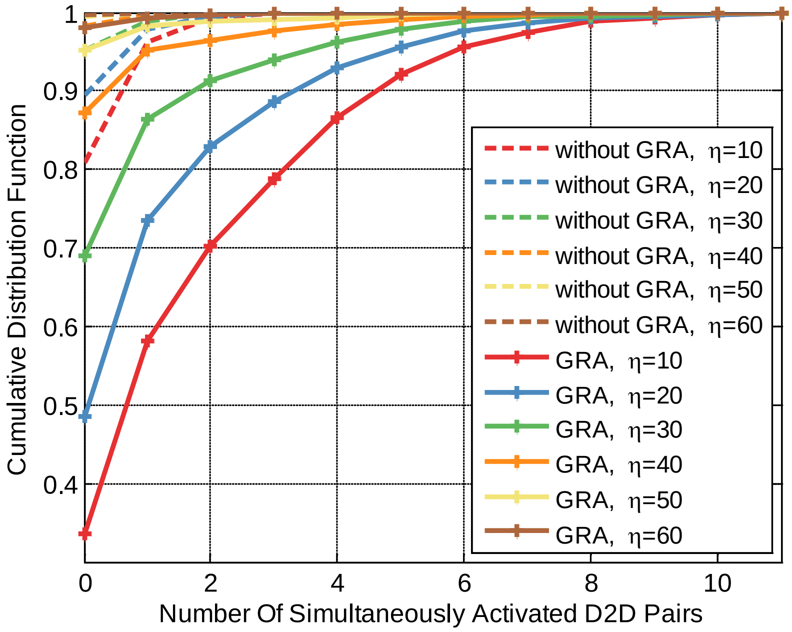

Fig. 4. Performance comparison of the greedy allocation algorithm and the without greedy allocation scheme in terms of the maximum number of simultaneously activated D2D pairs for variant SINR thresholds, with a single CUE considered, where $N_c = 50$, $N_d = 300$ and $d = 50$.

Fig. 6 demonstrates the impact of ILA on the throughput as a function of η. Evidently, the throughput is a monotonically decreasing function of η, because the number of simultaneously activated D2D pairs decreases as the SINR threshold increases. Meanwhile, the performance of the GRA is also shown to increase firstly, and then decreases as d increases. We can explain it as follows: Since the interference is much more intensive when $d < 50$ (i.e. the maximum allowable distance of D2D links) compared with receiver signal power, fewer D2D pairs can access the network under the requirement of “guaranteeing the required ILA radius, if it is beyond the distance of D2D links”. Consequently, the sum throughput decreases.

In **Fig. 7,** the impact of CUE-SINR threshold as a function of d on the D2D throughput is evaluated. It is shown that the performance is a concave function of d. We can explain this observation as follows: Increasing the ILA radius implies increasing the distance between the interference transmitters and signal receivers, and the interference imposed on D2D receivers by CUEs as well as that imposed on CUEs by D2D pairs will both decrease.

However, setting a larger inter-user distance will always reduce the access probability of DUEs. Consequently, as ILA radius increases, the relatively lower interference level will result in an increase in sum throughput in the fist place, and then the lower access probability of DUEs will lead to a reduction in the sum throughput. It is also shown that the performance of the proposed algorithm declines as η increases, making this degradation rate become slower as η becomes larger, because a higher SINR threshold corresponds to a lower interference tolerance.

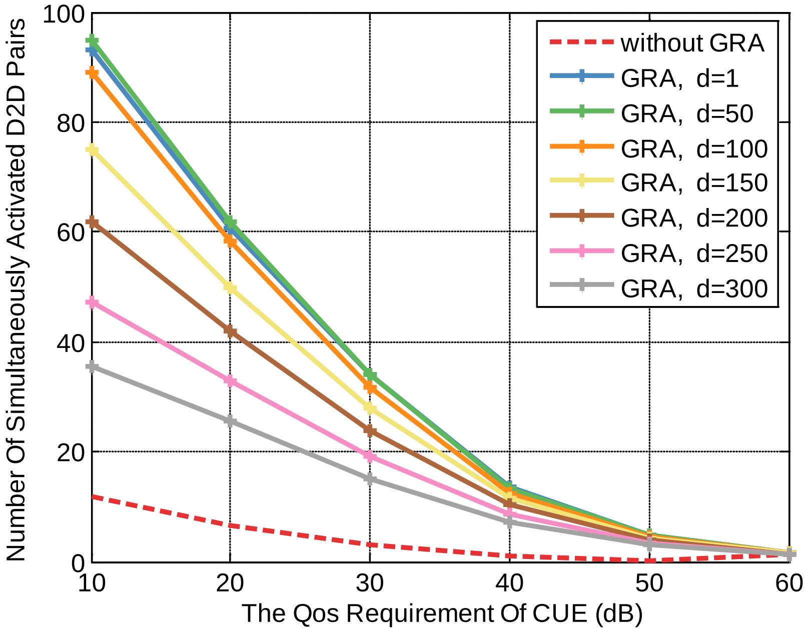

Fig. 5. The maximum number of simultaneously activated D2D pairs in the proposed greedy allocation algorithm system under different settings of SINR threshold, with a BS, where $N_c = 50$; $N_d = 300$.

5. Conclusion

In this paper, the problem of adaptive spectrum allocation was formulated as the maximization of the number of simultaneously activated D2D pairs in scenario of D2D reusing the uplink licensed spectrum, with a fully loaded cellular system considered. To maximize the number of simultaneously activated D2D pairs without eroding the SINRs of both CUEs and DUEs, a greedy heuristic algorithm was also implemented for finding the objective spectrum-reuse set. Numerical results showed that the proposed algorithm is capable of improving both the D2D-access probability and the sum throughput of the whole system. It was shown that the proposed greedy resource allocation algorithm is capable of improving the D2D-access probability by about 650% and the sum throughput by about 80% as compared to the without GRA when $\eta = 20dB$ and $d = 50m$.

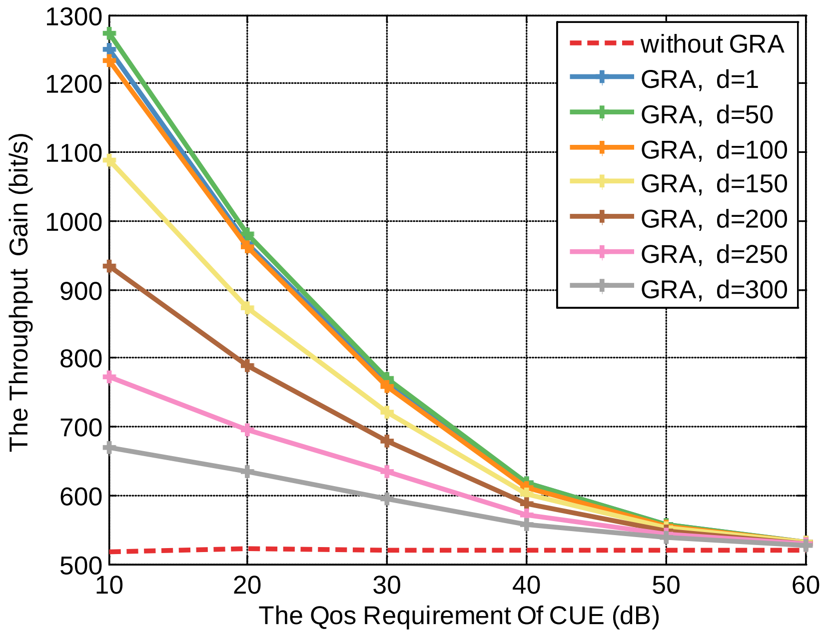

Fig. 6. Performance comparison of the greedy allocation algorithm and the without greedy allocation scheme in terms of the sum throughput gain for variant radius of ILA, where $N_c = 50$ and $N_d = 300$.

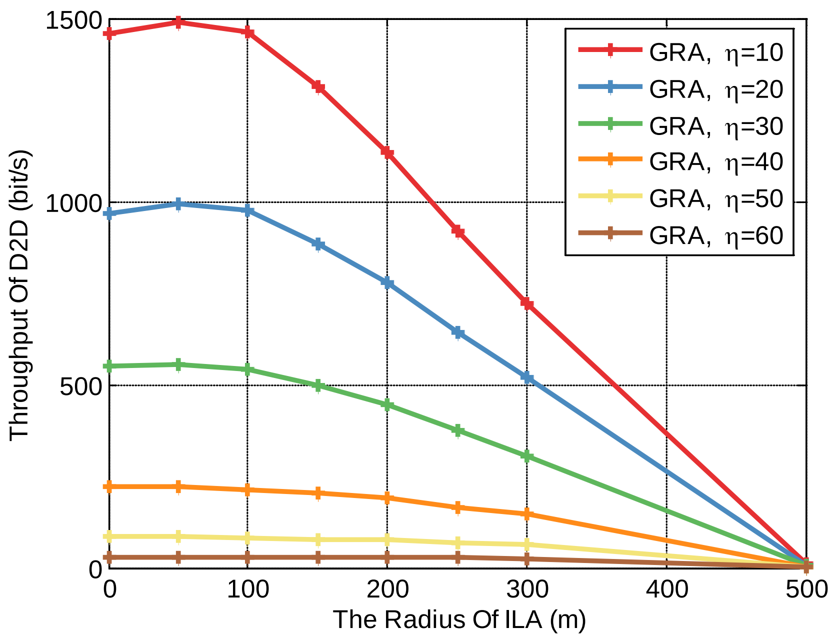

Fig. 7. Sum throughput of D2D links under variant settings of CUE-SINR threshold, where $N_c = 50$ and $N_d = 300$.

Appendix

The sum throughput of the proposed D2D aided cellular systems can be expressed as

$$\begin{aligned} R_{sum} &= \sum_{i\in C}\left(\log\left(1+\gamma_i^c\right)+\sum_{j\in\phi_i}\log\left(1+\gamma_j^d\right)\right) \\ &= \sum_{i\in C}\left(\log\left(\left(1+\gamma_i^c\right)\prod_{j\in\phi_i}\left(1+\gamma_j^d\right)\right)\right), \end{aligned} \tag{23}$$

where

$$\gamma_{i,j} = \left(1+\gamma_i^c\right)\prod_{j\in\phi_i}\left(1+\gamma_j^d\right), \tag{24}$$

By further analyzing (25), we have

$$\begin{aligned} \gamma_{i,j} &= 1+\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d+\sum_{j\in\phi_i}\gamma_i^c\gamma_j^d+\sum_{k\in\phi_i\setminus j}\sum_{j\in\phi_i}\gamma_k^d\gamma_j^d+\ldots+\gamma_i^c\prod_{j\in\phi_i}\gamma_j^d \\ &\geq 1+\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d \end{aligned} \tag{25}$$

And, we let m denote the size of reuse set,

when m=2, we can get

$$\begin{aligned} \gamma_{i,j} &= 1+\gamma_i^c+\gamma_j^d+\gamma_i^c\gamma_j^d \\ &\leq 1+\gamma_i^c+\gamma_j^d+\frac{1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_j^d\right)^2\right), \\ &\leq 1+\gamma_i^c+\gamma_j^d+\frac{1}{2}\left(\gamma_i^c+\gamma_j^d\right)^2, \end{aligned}$$

When m=3, we can get

$$\begin{aligned} \gamma_{i,j} &= 1+\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d+\gamma_i^c\gamma_{j_1}^d+\gamma_i^c\gamma_{j_2}^d+\gamma_{j_1}^d\gamma_{j_2}^d+\gamma_i^c\gamma_{j_1}^d\gamma_{j_2}^d \\ &\leq 1+\gamma_i^c+\sum_{k=1}^{2}\gamma_{j_k}^d+\frac{1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_1}^d\right)^2\right)+\frac{1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_2}^d\right)^2\right)+\frac{1}{2}\left(\left(\gamma_{j_1}^d\right)^2+\left(\gamma_{j_2}^d\right)^2\right) \\ &\quad +\frac{1}{3}\left(\left(\gamma_i^c\right)^3+\left(\gamma_{j_1}^d\right)^3+\left(\gamma_{j_2}^d\right)^3\right) \\ &\leq 1+\gamma_i^c+\sum_{k=1}^{2}\gamma_{j_k}^d+\frac{C_2^1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_1}^d\right)^2+\left(\gamma_{j_2}^d\right)^2\right)+\frac{C_2^2}{3}\left(\left(\gamma_i^c\right)^3+\left(\gamma_{j_1}^d\right)^3+\left(\gamma_{j_2}^d\right)^3\right) \\ &\leq 1+\gamma_i^c+\sum_{k=1}^{2}\gamma_{j_k}^d+\frac{C_2^1}{2}\left(\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d\right)^2+\frac{C_2^2}{3}\left(\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d\right)^3, \end{aligned}$$

when m=4, we can get

$$
\begin{aligned}
\gamma_{i,j} &= 1+\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d+\gamma_{j_3}^d+\gamma_i^c\gamma_{j_1}^d+\gamma_i^c\gamma_{j_2}^d+\gamma_{j_1}^d\gamma_{j_3}^d+\gamma_{j_1}^d\gamma_{j_2}^d+\gamma_{j_1}^d\gamma_{j_3}^d+\gamma_{j_2}^d\gamma_{j_3}^d \\
&\quad+\gamma_i^c\gamma_{j_1}^d\gamma_{j_2}^d+\gamma_i^c\gamma_{j_1}^d\gamma_{j_3}^d+\gamma_i^c\gamma_{j_2}^d\gamma_{j_3}^d+\gamma_{j_1}^d\gamma_{j_2}^d\gamma_{j_3}^d+\gamma_i^c\gamma_{j_1}^d\gamma_{j_2}^d\gamma_{j_3}^d \\
&\le 1+\gamma_i^c+\sum_{k=1}^{3}\gamma_{j_k}^d+\frac{1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_1}^d\right)^2\right)+\frac{1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_2}^d\right)^2\right) \\
&\quad+\frac{1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_3}^d\right)^2\right)+\frac{1}{2}\left(\left(\gamma_{j_1}^d\right)^2+\left(\gamma_{j_2}^d\right)^2\right)+\frac{1}{2}\left(\left(\gamma_{j_1}^d\right)^2+\left(\gamma_{j_3}^d\right)^2\right) \\
&\quad+\frac{1}{2}\left(\left(\gamma_{j_2}^d\right)^2+\left(\gamma_{j_3}^d\right)^2\right)+\frac{1}{3}\left(\left(\gamma_i^c\right)^3+\left(\gamma_{j_1}^d\right)^3+\left(\gamma_{j_2}^d\right)^3\right)+\frac{1}{3}\left(\left(\gamma_i^c\right)^3+\left(\gamma_{j_1}^d\right)^3+\left(\gamma_{j_3}^d\right)^3\right) \\
&\quad+\frac{1}{3}\left(\left(\gamma_i^c\right)^3+\left(\gamma_{j_2}^d\right)^3+\left(\gamma_{j_3}^d\right)^3\right)+\frac{1}{3}\left(\left(\gamma_{j_1}^d\right)^3+\left(\gamma_{j_2}^d\right)^3+\left(\gamma_{j_3}^d\right)^3\right) \\
&\quad+\frac{1}{4}\left(\left(\gamma_i^c\right)^4+\left(\gamma_{j_1}^d\right)^4+\left(\gamma_{j_2}^d\right)^4+\left(\gamma_{j_3}^d\right)^4\right) \\
&\le 1+\gamma_i^c+\sum_{k=1}^{3}\gamma_{j_k}^d+\frac{C_3^1}{2}\left(\left(\gamma_i^c\right)^2+\left(\gamma_{j_1}^d\right)^2+\left(\gamma_{j_2}^d\right)^2+\left(\gamma_{j_3}^d\right)^2\right) \\
&\quad+\frac{C_3^2}{3}\left(\left(\gamma_i^c\right)^3+\left(\gamma_{j_1}^d\right)^3+\left(\gamma_{j_2}^d\right)^3+\left(\gamma_{j_3}^d\right)^3\right)+\frac{C_3^3}{4}\left(\left(\gamma_i^c\right)^4+\left(\gamma_{j_1}^d\right)^4+\left(\gamma_{j_2}^d\right)^4+\left(\gamma_{j_3}^d\right)^4\right) \\
&\le 1+\gamma_i^c+\sum_{k=1}^{3}\gamma_{j_k}^d+\frac{C_3^1}{2}\left(\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d+\gamma_{j_3}^d\right)^2 \\
&\quad+\frac{C_3^2}{3}\left(\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d+\gamma_{j_3}^d\right)^3+\frac{C_3^3}{4}\left(\gamma_i^c+\gamma_{j_1}^d+\gamma_{j_2}^d+\gamma_{j_3}^d\right)^4,
\end{aligned}
$$

Thus, the generic formula can be expressed as

$$
\begin{aligned}
\gamma_{i,j} &= 1+\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d+\sum_{j\in\phi_i}\gamma_i^c\gamma_j^d+\sum_{k\in\phi_i\setminus j}\sum_{j\in\phi_i}\gamma_k^d\gamma_j^d \\
&\quad+\ldots+\gamma_i^c\underbrace{\sum_{n_1\in\phi\setminus n_{2\ldots n}}\sum_{n_2\in\phi\setminus n_{1.3..n}}\cdots\sum_{n_n\in\phi\setminus n_{1\ldots n-1}}}_{n}\gamma_{n_1}^d\gamma_{n_2}^d\ldots\gamma_{n_n}^d+\ldots+\gamma_i^c\prod_{j\in\phi_i}\gamma_j^d \\
&\le 1+\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d+\frac{C_{m-1}^{2-1}}{2}\left(\left(\gamma_i^c\right)^2+\sum_{j\in\phi_i}\left(\gamma_j^d\right)^2\right) \\
&\quad+\ldots+\frac{C_{m-1}^{n}}{n+1}\left(\left(\gamma_i^c\right)^{n+1}+\sum_{j\in\phi_i}\left(\gamma_j^d\right)^{n+1}\right)+\ldots+\frac{C_{m-1}^{m-1}}{m}\left(\left(\gamma_i^c\right)^{m}+\sum_{j\in\phi_i}\left(\gamma_j^d\right)^{m}\right) \\
&\le 1+\left(\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d\right)+\frac{C_{m-1}^{1}}{2}\left(\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d\right)^2+\ldots+\frac{C_{m-1}^{n}}{n+1}\left(\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d\right)^{n+1} \\
&\quad+\ldots+\frac{C_{m-1}^{m-1}}{m}\left(\gamma_i^c+\sum_{j\in\phi_i}\gamma_j^d\right)^{m},
\end{aligned}
\tag{26}
$$

thus proved (10) and (11).

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