# Joint User Association and Resource Allocation of Device-to-Device Communication in Small Cell Networks

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## Abstract

With the recent popularity of smart terminals, the demand for high-data-rate transmission is growing rapidly, which brings a new challenge for the traditional cellular networks. Both device-to-device (D2D) communication and small cells are effective to improve the transmission efficiency of local communication. In this paper, we apply D2D communication into a small cell network system (SNets) and study about the optimization problem of resource allocation for D2D communication. The optimization problem includes system scheduling and resource allocation, which is exponentially complex and the optimal solution is infeasible to achieve. Therefore, in this paper, the optimization problem is decomposed into several smaller problems and a hierarchical scheme is proposed to obtain the solution. The proposed hierarchical scheme consists of three steps: D2D communication groups formation, the estimation of sub-channels needed by each D2D communication group and specific resource allocation. From numerical simulation results, we find that the proposed resource allocation scheme is effective in improving the spectral efficiency and reducing the outage probability of D2D communication.

***Keywords:*** D2D communication, small cell network, resource allocation, multicast

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## 1. Introduction

With the increasing demand for high-data-rate services, local communication has attracted the widespread attention. As an essential way of local communication, device-to-device (D2D) communication has become a research hotspot in recent years [1, 2, 3, 4]. Different from the traditional cellular communication, user equipments (UEs) can communicate to each other directly without the relay of base station (BS) via D2D communication, which can reduce the traffic load of the core network. D2D communication has many advantages, such as increasing data rate, reducing energy cost, reducing transmission delays, and extending coverage area. As an underlay to cellular communication, D2D communication may generate harmful interference to cellular user equipments when they share the same frequency resources. D2D communication was introduced systematically in [4]. The main problems of D2D communication like mode selection, power control, resource allocation and handover were discussed therein. The resource sharing ways between D2D and cellular communications are generally classified into two categories: orthogonal mode and reuse mode [5]. In orthogonal mode, D2D communication gets part of the resources and leaves the remaining part to cellular UEs, which can avoid the interference between D2D and cellular communications effectively. In reuse mode, D2D and cellular communications reuse the same frequency resources. Although orthogonal mode does not need to consider the interference between D2D and cellular communications, reuse mode has been widely adopted since it can achieve better spectral efficiency. Most of the researches about D2D communication have been carried out on mode selection, interference cancelation, power control and resource allocation [3, 5, 6, 7].

To fulfill the increasing customer demands, recently proposed small cell network (SNet) has gained widely concern [8]. SNet is an useful way to increase the spectral and energy efficiency of wireless networks and reduce traffic load from the macrocell network. Some researches about SNet have been done in recent years [9, 10]. In [9], a joint sub-channel and power allocation scheme was proposed in indoor dense environments. An enhanced small cell grouping based inter-cell interference control scheme was proposed in [10]. Both SNet and D2D communication are effective to improve the spectral efficiency and reduce the traffic load of the central network. However, so far, there is hardly no research has been done for combining D2D communication and SNets.

Based on the above analysis, in this paper, we endeavors to apply D2D communication into SNets to achieve better performance of the hybrid system. Firstly, we build the system model and formulate the optimization problem. Since the optimization problem includes system scheduling and resource allocation, it is exponentially complex and the optimal solution is infeasible to obtain. Therefore, a hierarchical resource allocation scheme is proposed to obtain the sub-optimal solution. The proposed hierarchical scheme consists of three parts: D2D communication groups formation, the estimation of the number of sub-channels needed by each D2D communication group, and resource allocation. The contributions of our work are: 1) D2D communication is applied into small cell network system, by which the interference from one small cell base station (SBS) to UEs in neighboring small cells could be avoided to some extent. 2) We decompose the complex optimization problem into three smaller problems: D2D communication groups formation, sub-channels demands estimation, and resource allocation. 3) Both D2D unicast communication and D2D multicast communication could be adopted in this paper.

The rest of this paper is organized as follows. System model and the optimization problem are introduced in Section 2. In Section 3, we give a detailed introduction to the proposed hierarchical scheme step by step. Numerical simulation results and analysis of results are given in Section 4, which demonstrate better performance of our proposed scheme in comparison with some existed resource allocation schemes. Finally, Section 5 concludes the paper and highlights our findings.

## 2. Related work

Allocating the resource properly is essential to keep the interference within a reasonable range. Many literatures have studied the resource allocation of D2D communication underlying cellular network [3, 5, 6, 7]. In [3], to mitigate the interference from cellular transmission to the D2D link, a distance-constrained resource sharing criterion was proposed to select the cellular UE for a given D2D link to share its frequency resource. Yu et al. analyzed the resource allocation in non-orthogonal mode, orthogonal sharing mode and cellular mode respectively in [5]. They also analyzed two optimization cases: greedy sum-rate maximization and sum-rate maximization subject to rate constraints.

The optimization problems for resource allocation of D2D communication can be roughly classified into the following five cases.

1) Maximizing the overall throughput/ sum data rate of both cellular communication and D2D communication while guaranteeing the quality of services (QoS) of both cellular users and D2D users [11]. Feng et al. formulated the optimization problem of maximizing the overall throughput and proposed a three-step solution in [11]: QoS-aware admission control for D2D pairs; optimal power control for the D2D pair and its reuse partner; maximum weighted matching to find the optimal reuse partner for each admissible D2D pair.
2) Maximizing the throughput of D2D communication while guaranteeing QoS of cellular communication [6, 12]. Jointly optimizing the transmit power of the cellular and D2D UEs, an optimal resource sharing strategy was characterized by a closed-form solution in [6] to maximize the D2D communication throughput with guaranteed the QoS for cellular users. Further, one suboptimal design with cellular users using fixed power was designed to only optimize the transmit power of the D2D UEs.
3) Maximizing the minimum rate for all D2D links [13]. In [13], considering the fair resource allocation problem for D2D communication in cellular networks, a cognitive based approach to develop two-phase resource allocation algorithm for both cellular and D2D users was adopted.
4) Minimizing the interference from D2D transmission to cellular communication [3, 14]. Xu *et al.* showed an admission control process to reject the D2D pairs which cause strong interference to the cellular communication and a heuristic algorithm was proposed in [14].
5) Maximizing the energy efficiency of communication [15]. The energy efficiency has become an increasingly important issue in wireless communications because of the increasing energy cost and concern over the environmental issues [16]. [15] showed the energy efficiency in three resource sharing modes for D2D communication underlying cellular networks and the energy efficient power allocation schemes with the maximum transmission power constraint were discussed.

Since D2D multicast technology is involved and the data rate of a D2D multicast group is limited with the minimum rate of all links in this D2D multicast group, the optimization problem in this paper is modeled as maximizing the minimum value of normalized rate of each

D2D link. Formulating the problem by maximizing the minimum normalized rate of each D2D link not only ensures the quality of D2D multicast communication, but also maintains the fairness among all D2D UEs.

## 3. System Model and Problem Formulation

In this section, we give a brief introduction to the system model of D2D communication in SNets and illustrate the optimization problem of resource allocation.

### 3.1 System Model

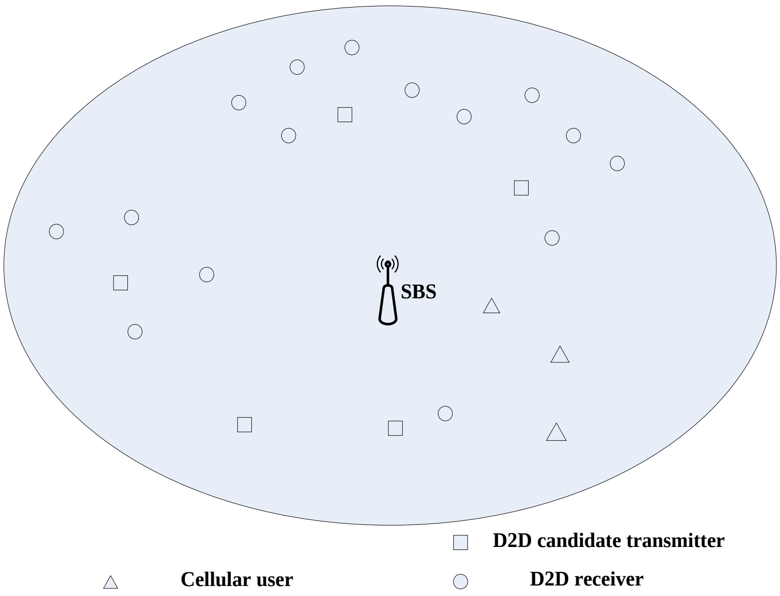


**Fig. 1.** System model of user equipments in a small cell

**Fig. 1** illustrates the system model of a small cell with some UEs. As shown in the figure, the SBS is located in the center of small cell. In this paper, the independent homogeneous Poisson point process (PPP) is used for the location of UEs. The Poisson point process is the simplest and most important model for random point pattern.The distribution of PPP satisfies strong independent conditions [17, 18]. There are two types of D2D user equipments (DUEs): D2D candidate transmitters (DCTs) and D2D receivers (DRs). DCTs are the DUEs that have received signals correctly and willing to act as a header of D2D communication group to transmit the signals to DRs. DRs are the DUEs that waits for receiving data transmitted by DCTs. There are $N$ DRs and $M'$ DCTs in this small cell. We consider an orthogonal frequency-division multiple access (OFDMA) system as in the Long Term Evolution (LTE) standard with $K$ effective sub-channels for D2D communication. Each sub-channel is a physical resource block (PRB) with a bandwidth of $B$. The channels between DCTs and DRs are modeled as Rayleigh fading with average power determined by distance attenuation and large scale fading statistics. We assume that the frequency used by macro base station (MBS) is orthogonal to the frequency used by the small cell.

Due to limited coverage, the signals from the SBS of a small cell inevitably bring interference to UEs of neighboring cells. Therefore, if there are enough DCTs in a small cell, D2D communication is a much better choice than cellular communication. In this paper, the D2D communication patterns can be multicast communications, not just unicast communications. If more than one DR selects the same one DCT as their transmitter of D2D communication group, a D2D multicast group will be formed. While if just one DR selects one DCT as the transmitter of D2D communication, a D2D transmission pair will be formed. As a valid way to improve the transmission efficiency, D2D multicast technology has been studied in recent years [12, 19]. Like the traditional multicast communication, the data rate of a D2D multicast group is also limited with the minimum rate of all the links in this D2D multicast group.

### 3.2 Problem Formulation

Considering that D2D multicast communication is involved and the data rate of a multicast group is limited with the minimum rate of all the links in the group, we formulate the resource allocation problem to maximize the minimum rate of D2D communication. The channels between UEs are modeled as frequency selective Rayleigh fading with average power determined by distance attenuation and large scale fading statistics. The rate achieved on a specific channel is assumed to be given by its Shannon capacity. The optimization problem is modeled as maximizing the minimum value of normalized rate of each DR, which is given by:

$$
\begin{aligned}
&\max_{\{p_{m,n}^{(k)}\},\{S_m\}} (\min_n \frac{1}{R_n}(\sum_{k=1}^{K} B\log_2(1+\frac{p_{m,n}^{(k)}h_{m,n}^{(k)}}{I_{nC}^{(k)}+I_{nD}^{(k)}+P_{N_0}}))),\\
&s.t. \sum_{k=1}^{K} B\log_2(1+\frac{p_{m,n}^{(k)}h_{m,n}^{(k)}}{I_{nC}^{(k)}+I_{nD}^{(k)}+P_{N_0}}) \ge R_n,\\
&\sum_{k=1}^{K}\sum_{n} p_{m,n}^{(k)} \le P,\\
&p_{m,n}^{(k)} \ge 0,\\
&S_i \cap S_j = \varnothing,
\end{aligned}
\tag{1}
$$

where $R_n$ denotes the required rate of the $n_{th}$ DR, and $B$ is the bandwidth of each PRB. $p_{m,n}^{(k)}$ and $h_{m,n}^{(k)}$ are the transmit power and the channel gain from the $m_{th}$ DCT to the $n_{th}$ DR on the $k_{th}$ sub-channel, respectively. $I_{nC}^{(k)}$ and $I_{nD}^{(k)}$ are the interference from the cellular communication and D2D communication to the $n_{th}$ DR which reuse the same frequency of the $k_{th}$ sub-channel . $P_{N_0}$ is the noise power per PRB. $S_i$ is the set of the DRs served by the $i_{th}$ DCT. The first constraint in equation (1) ensures that the transmission rate of the each DR must satisfy its rate demand. $S_i \cap S_j = \varnothing$ means that each DR is served by only one DCT.

The optimal solution to (1) is infeasible to achieve because system scheduling and resource allocation are included in the optimization problem. Furthermore, it would be impractical to gain the channel conditions of all links from DRs to DCT, which would result in a huge overhead to the central controller. Therefore, we propose a hierarchical scheme to achieve a suboptimal solution.

## 4. Joint User Association and Resource Allocation Scheme

The sub-optimization problem is divided into three sub-problems in this paper:

1) D2D communication group formation: each DR selects the most appropriate DCT as its D2D transmitter, and D2D communication groups are established accordingly;
2) Sub-channels demands estimation: based on the demand of data transmission rate by each DR in that group, the minimum sub-channels requirement of each D2D communication group is estimated by the transmitter in each D2D communication group;
3) Resource allocation: specific PRBs and power are allocated to each D2D communication group.

### 4.1 Steps of Joint User Association and Resource Allocation Scheme

### A. D2D communication group formation

To satisfy the data rate requirement, selecting the most appropriate DCT as D2D transmitter is important to each DR. We assume that all users are in the coverage area and a handover is not in need. DR measures the power received from all the DCTs and selects the DCT that offers the highest long time average received power, which ensures that the D2D communication group formation procedure does not need to know the instantaneous channel gain and reduces the overhead. In this process, we just take the distance attenuation into consideration, so the D2D communication group formation is based on the distance relationship of DUEs. Specifically, one DR selects the nearest DCT as the corresponding D2D transmitter. When all DRs have finished the selection processes, D2D groups (or pairs) were established. The implementation process of D2D communication group formation is shown specifically in **Table 1.**

**Table 1.** The pseudo-code of D2D communication group formation algorithm

| Algorithm 1 : The D2D communication group formation algorithm (DGFA) |
|---|
| Input: $N, M'$ , $D' = [d'_{ij}]_{N\times M'}$ ( $d'_{ij}$ denotes the distance between the $i_{th}$ DR to the $j_{th}$ DCT ) |
| Output: $z$ (The number of DRs served by each DT) |
| DGFA.1 $i=1, c=0_{N\times M'}$ |
| DGFA.2 $j^* = \arg_j \min_{1\le j\le M'} (d'_{ij}), c(i, j^*)=1$ |
| DGFA.3 if $i<N$ |
| $i=i+1$,and go to DGFA.2 |
| end if |
| DGFA.4 $j=1$ |
| DGFA.5 $I = find\left(c(:, j) \sim= 0\right);\ z(j)=length\left(I\right)$ |
| DGFA.6 if $j<M'$ |
| $j=j+1$,and go to DGFA.5 |
| end if |
| DGFA.7 end |

After the procedure of D2D communication groups formation, the system model with D2D communication groups is shown in **Fig. 2**. We assume that there are $M (M \le M')$ D2D communication groups formed in this small cell. The transmitter in each D2D communication group is referred as DT in the remainder of this article.

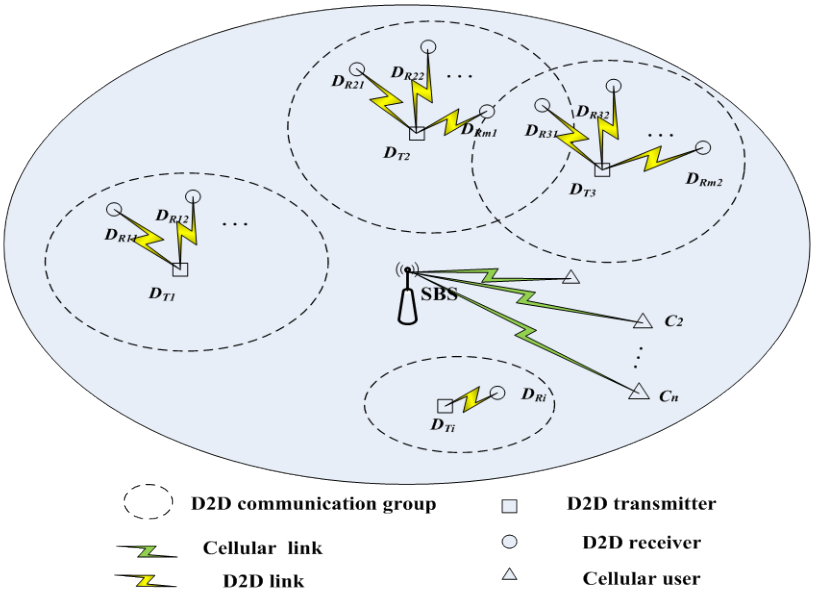


**Fig. 2.** D2D communication groups in small cell

### B. Sub-channels demands estimation

The adaptation in spectrum allocation enables D2D communication to achieve better performance. Since the channels are frequency selective faded and DT does not know which PRBs it will be allocated, each DT estimates its sub-channels demand by using only the average channel gains. Due to limited frequency resources, the goal for sub-channels demands estimation is to minimize the PRBs cost for each D2D communication group while satisfying the rate demands of DRs. So, the problem can be formulated as:

$$\begin{aligned} &\min \ N_m, \\ &s.t. \ N_m B \log_2 (1 + \min_{n \in S_m} (\frac{P_m H_{mn}}{I_C + I_D + N_m P_{N0}})) \geq \max_{n \in S_m} (R_n), \\ &\quad 0 \leq P_m \leq P, \\ &\quad N_m \geq 0, \end{aligned} \tag{2}$$

where $N_m$ denotes the minimum number of sub-channels required to the $m_{th}$ D2D communication group. $S_m$ is the set of DRs served by the $m_{th}$ DT. $P_m$ is the sum power allocated to the $m_{th}$ D2D communication group. $H_{mn}$ is the average channel power seen by the $n_{th}$ DR in the $m_{th}$ D2D communication group. $I_C$ and $I_D$ are the interference from the cellular communication and D2D communication to the $n_{th}$ DR which reuse the same frequency. $P$ is the maximum allowable value of power can be allocated to a DT. The first constraint in (2) ensures that the transmission rate of the $m_{th}$ D2D communication group must satisfy the rate demands of all DRs in this group.

In this paper, we assume that the resource allocated to cellular communication is orthogonal to D2D communication. Considering the intractability of the problem, we derive the cumulative distribution function (CDF) for a special case where the interference among D2D groups is ignored since it could be kept within a reasonable range by resource allocation. In addition, we set $P_m = N_m p_0$, where $p_0$ is the average value of power allocated to each sub-channel. The equation (2) can be rewritten as follow:

$$\begin{aligned} &\min \ N_m, \\ &s.t. \ N_m B \log_2(1+\min_{n\in S_m}(\frac{N_m p_0 H_{mn}}{N_m P_{N0}})) \geq \max_{n\in S_m}(R_n), \\ &0 \leq p_0 \leq P/N_m, \\ &N_m \geq 0. \end{aligned} \tag{3}$$

From the first constraint in (3), $N_m$ can be expressed as:

$$N_m \geq \frac{\max_{n\in S_m}(R_n)}{B\log_2(1+\min_{n\in S_m}(\frac{p_0 H_{mn}}{P_{N0}}))} \tag{4}$$

Then, we can get the minimum number of sub-channels required to the $m_{th}$ D2D communication group:

$$N_m{}^* = \frac{\max_{n\in S_m}(R_n)}{B\log_2(1+\min_{n\in S_m}(\frac{p_0 H_{mn}}{P_{N0}}))}. \tag{5}$$

*Proposition*: The CDF of $N_m$ is given by:

$$F_{N_m}(n_m) = (F_D((\frac{P_{N0}(2^{\frac{\max_{n\in S_m}(R_n)}{n_m B}}-1)}{p_0 L})^{-1/\alpha}))^{z(m)}, \tag{6}$$

where $z(m)$ is the number of DRs served in the $m_{th}$ D2D group. $n_m$ is the number of PRBs allocated to the $m_{th}$ D2D group. $L$ and $\alpha$ denote the path loss coefficient and exponent respectively. $F_D(d)$ is the CDF of the distance between DT and DR.

DTs' locations are modeled by a homogeneous PPP with density $\lambda_{DT}$, so the CDF of the distance from DT to DR can be written as:

$$F_D(d) = P(D < d) = 1 - P(n(\pi d^2) = 0) = 1 - \exp(-\lambda_{DT}\pi d^2). \tag{7}$$

The $P(n(\pi d^2)=0)$ in (7) means the probability of no DT is in the area of $\pi d^2$.

*Proof*: The (6) is derived as follow:

$$F_{N_m}(n_m) = P(N_m < n_m). \tag{8}$$

Substitute (5) into (8), we can get

$$F_{N_m}(n_m) = P(\frac{\max_{n\in S_m}(R_n)}{B\log_2(1+\min_{n\in S_m}(\frac{p_0 H_{mn}}{P_{N0}}))} < n_m), \tag{9}$$

where $H_{mn} = Ld_{mn}{}^{-\alpha}$, $d_{mn}$ is the distance between the $m_{th}$ DT to the DR in the $n_{th}$ D2D communication group. So, (9) can be written as:

$$
\begin{aligned}
F_{N_m}(n_m) &= P(\min_{n\in S_m}(\frac{p_0 Ld_{mn}{}^{-\alpha}}{P_{N0}}) > 2^{\frac{\max_{n\in S_m}(R_n)}{n_m B}} - 1) \\
&= P(\min_{n\in S_m}(d_{mn}{}^{-\alpha}) > \frac{P_{N0}(2^{\frac{\max_{n\in S_m}(R_n)}{n_m B}} - 1)}{p_0 L}) \\
&= \bigcup_{\substack{n=1 \\ n\in S_m}}^{z(m)} P((d_{mn}) < (\frac{P_{N0}(2^{\frac{\max_{n\in S_m}(R_n)}{n_m B}} - 1)}{p_0 L})^{-1/\alpha}) \\
&= (F_D((\frac{P_{N0}(2^{\frac{\max_{n\in S_m}(R_n)}{n_m B}} - 1)}{p_0 L})^{-1/\alpha}))^{z(m)}.
\end{aligned} \tag{10}
$$

The proof of (6) is completed.

## C. Resource allocation

After finishing the processes of D2D communication groups formation and the sub-channels demands estimation, the procedure of resource allocation can be performed. If two nearest D2D communication groups reuse the same PRBs, both of them will seriously interfere with each other. To reduce the interference between D2D communication groups, we set a principle that two closest D2D communication groups cannot reuse the same frequency resource. According to this principle, a distance-based resource allocation algorithm is proposed. The location information of each DUE can be obtained by the global positioning system (GPS) [20] or through cooperative localization [21]. The idea behind the algorithm is that one D2D communication group use different frequency resource with the nearest D2D communication group.

This resource allocation algorithm consists of two parts. 1) Confirming the order of D2D communication groups for resource allocation: Selecting which D2D communication group as the first one been assigned resource will determine the order of sub-channels allocation. Once the first D2D multicast group to be assigned resource is selected, the allocated order can be determined with the principle of choosing the nearest one to allocate other sub-channels. The total distance of the route of allocating order can be determined as well. For two D2D communication groups which reuse the same resource, the longer the distance between them is, the smaller interference they get. To mitigate the interference from near D2D communication groups, we choose the resource allocation order with the maximum sum distance. 2) Specific resource allocation: After confirming the allocation order, system needs to find the most appropriate PRBs allocate to each D2D communication group and allocate appropriate power to each PRB. The problem is transformed into maximizing the minimum rate of the DRs in each D2D communication group. The scheduling problem is formulated as:

$$
(p_{m,n}^{(k)*}, S_{PRB_m}^{*}) = \underset{\{p_{m,n}^{(k)}\},\{S_{PRB_m}\}}{\arg} \max(\min_{n\in S_m, k\in S_{PRB}} (\log_2(1 + \frac{\sum_{k=1}^{N_m} p_{m,n}^{(k)} h_{m,n}^{(k)}}{N_m P_{N_0}}))), \tag{11}
$$

where $S_{PRB_m}$ is the set of PRBs allocated to the $m_{th}$ D2D communication group.

The procedure of distance-based sub-channels allocation scheme is shown specifically in **Table 2.**

**Table 2.** The pseudo-code of distance-based resource allocation algorithm (DRAA)

```
Algorithm 2 : The distance-based resource allocation algorithm (DRAA)
Input: N, M, n_PRB, D = (d_ij)_{M×M} (d_ij denotes the distance between the i_th and j_th DT),
        S_PRB = {1, 2, ···, K} (S_PRB is the set of all available PRBs.)
Output: Reuse matrix (r_{m,n})_{M×M}, r_{m,n} denotes the number of PRBs reused by the m_th and n_th D2D
        communication group
DRAA.1 k = 1
DRAA.2 i = k, u = 1, Q_k(u) = i, sum_d_k = 0.
DRAA.3 j* = arg_j min_{1≤j≤M, j∉Q_k} (d_ij), u = u + 1, Q_k(u) = j*, sum_d_k = sum_d_k + d_ij*
DRAA.4 if u < M
            i = j*, and go to DRAA.3
         else
            go to DRAA.5
         end if
DRAA.5 k = k + 1
DRAA.6 if k < M
          go to DRAA.2
       else
          go to DRAA.7
       end if
DRAA.7 k* = arg_k max_{1≤k≤M} (sum_d_k), Q* = Q_k*
DRAA.8 m = 1
DRAA.9 i_m = Q*(m),
DRAA.10 According to (11), find the most appropriate n_{i_m} PRBs allocate to the D2D communication
         group i_m and allocate power to corresponding PRBs.
DRAA.11 S_PRB = S_PRB \ S*_{PRB_m}.
DRAA.12 m = m + 1,
DRAA.13 if m < M
          if length(S_PRB) ≥ n_{i_m}
             go to DRAA.9
          else
             S_PRB = {1, 2, ···, K} \ S*_{PRB_{m-1}}, go to DRAA.9
          end if
        end if
DRAA.14 r_{m,n} = length(S*_{PRB_m} ∩ S*_{PRB_n}), for m=1,2,…,M; n=1,2,…,M.
DRAA.15 end
```

### 4.2 Analysis of the Proposed Resource Allocation Scheme

The proposed scheme is partially-distributed. The D2D communication group formation, sub-channels demands estimation and allocation order confirmation are carried out locally and concurrently at each DT, since only local information is required. The resource allocation is carried out at the SBS.

### A. Spectral efficiency analysis

In this paper, the spectral efficiency of D2D communication $sp_{d2d}$ is defined as the ratio between the throughput of D2D communication ($Thr_{d2d}$) and the bandwidth occupied by D2D communication ($Bandwidth_{d2d}$).

$$sp_{d2d} = \frac{Thr_{d2d}}{Bandwidth_{d2d}}. \tag{12}$$

The throughput of D2D communication can be calculated by :

$$Thr_{d2d} = \sum_{m=1}^{M} z(m) N_m^* B \log_2(1 + \min_{n \in S_m}(\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \neq m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}})), \tag{13}$$

where $z(m)$ is the number of DRs in the $m_{th}$ D2D group. $N_m^*$ denotes the number of PRBs allocated to the $m_{th}$ D2D communication group. The interference from other D2D groups that reuse the same frequency with the $m_{th}$ D2D group equals to $\sum_{i=1, i \neq m}^{M} r_{i,m} p_i^* H_{in}$ . $r_{i,m}$ denotes the number of PRBs reused by the $i_{th}$ and $m_{th}$ D2D communication group.

The bandwidth occupied by D2D communication is given by:

$$Bandwidth_{d2d} = KB, \tag{14}$$

where $K$ denotes the number of PRBs available to D2D communication in this small cell.

Inserting (13) and (14) in (12), the spectral efficiency of D2D communication $sp_{d2d}$ is given by:

$$sp_{d2d} = \frac{\sum_{m=1}^{M} z(m) N_m^* \log_2(1 + \min_{n \in S_m}(\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \neq m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}}))}{K}. \tag{15}$$

### B. Outage analysis

The outage probability is defined as the probability that the instantaneous data rate falls below a predetermined protection ratio, which can be given by:

$$P_{out} = \Pr[r \le r_{th}] = 1 - \prod_{n \in S_m} \Pr[\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \ne m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}} > 2^{\frac{r_{th}}{N_m^* B}} - 1], \tag{16}$$

where $r_{th}$ is the threshold data rate to ensure the reliable D2D communication.

*Proof of equation (16):*

$$\begin{aligned} P_{out} &= \Pr[r \le r_{th}] = \Pr[N_m^* B \log_2(1 + \min_{n \in S_m}(\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \ne m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}})) \le r_{th}] \\ &= \Pr[\min_{n \in S_m}(\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \ne m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}}) \le 2^{\frac{r_{th}}{N_m^* B}} - 1] \\ &= 1 - \Pr[\min_{n \in S_m}(\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \ne m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}} > 2^{\frac{r_{th}}{N_m^* B}} - 1] \\ &= 1 - \prod_{n \in S_m} \Pr[\frac{\sum_{k=1, k \in S_{PRB}^*}^{N_m^*} p_{m,n}^{(k)*} h_{m,n}^{(k)}}{\sum_{i=1, i \ne m}^{M} r_{i,m} p_i^* H_{in} + N_m^* P_{N_0}} > 2^{\frac{r_{th}}{N_m^* B}} - 1]. \end{aligned} \tag{17}$$

The proof is complete.

## C. Complexity analysis

1) D2D communication group formation: Each DR connects to the DT with the highest average received power. Finding the DT with the maximum received power requires $M$ comparisons at each DR. Hence, the complexity of this procedure is of the order $O(M)$ for each of $N$ DRs.
2) Sub-channels demands estimation: To obtain $N_m^*$, DT needs to find the highest data rate demand and the minimum value of signal to noise ratio for DRs among the $m_{th}$ D2D communication group. Therefore, the computational complexity of the estimation process is $O(z(m))$ for each D2D communication group, where $z(m)$ is the number of DRs connected to the $m_{th}$ DT.
3) Resource allocation: The resource allocation algorithm consists of two parts. The resource allocation order confirmation procedure (DRAA. 1 – DRAA. 7) has complexity of $O(M^2)$, where $M$ denotes the number of D2D communication groups in the small cell. The

complexity of procedure of specific resource allocation (DRAA. 8 –DRAA. 14) is $O(N_m^* M)$ for the $m_{th}$ D2D communication group.

## 5. Numerical Results and Discussion

In this section, we evaluate the performance of the proposed sub-channels allocation scheme for D2D communication in SNets. We consider a small cell network, where UEs are randomly distributed in the small cell. The downlink transmission scheme for an LTE system is based on OFDMA where the available spectrum is divided into multiple subcarriers each with a bandwidth of 15kHz. Resources are allocated to users in blocks of 12 subcarriers referred to as physical resource blocks (PRB). Hence, the bandwidth of each PRB is 180kHz. The noise power spectral density is set to -174dBm/Hz.

The basic parameters are summarized in **Table 3.**

**Table 3.** BASIC SIMULATION PARAMETERS

| PARAMETER | VALUE |
|---|---|
| Maximum D2D pair distance | 25 m |
| Available bandwidth for D2D communication | 10 MHz |
| SNets Cell radius | 50 m (Except for Fig.6- Fig.7) |
| The number of available PRBs for D2D communication | 35 (Except for Fig.4- Fig.5) |
| The data rate demand for D2D communication | 2Mbps (Except for Fig.8- Fig.9) |
| SBS Tx power | 20 dBm |
| D2D Tx maximize power | 17 dBm |
| Noise spectral density | -174 dBm/Hz |
| Pass loss model for D2D link | 148+40log10(d[km]) |
| The number of DTs in each small cell | 40 |
| $\lambda_{DT}$ | $40/(250\pi)$ |
| The number of DRs in each small cell | 100 |
| $\lambda_{DR}$ | $100/(250\pi)$ |

The performances of the proposed scheme is compared with that of other three resource allocation schemes: the fixed resource allocation (FRA) scheme, the graph-coloring based resource allocation (GCRA) scheme proposed in [22] and the efficient resource allocation (ERA) scheme proposed in [23]. In FRA, a fixed number ( $N_f$ ) of PRBs are assigned to each D2D communication group. In GCRA scheme, the number of PRBs assigned to each D2D group is proportional to the number of DRs served by each DT. The vertices of the graph represent DTs. An edge connects two vertices if the distance between them is larger than a prescribed value (30 meters in our simulation). The degree of a vertex is the number of the edges connected with this vertex. When allocating sub-channels, the DT with bigger degree will be allocated PRBs earlier. In the simulation, to better evaluate the performance of the proposed hierarchical scheme, the user association and sub-channels demands estimation for other three schemes are as follow: each DR randomly selects one DCT as the transmitter if it is in the coverage range of the DCT. The number of sub-channels allocated to each D2D communication group is proportional to the number of DRs served in this D2D communication group.

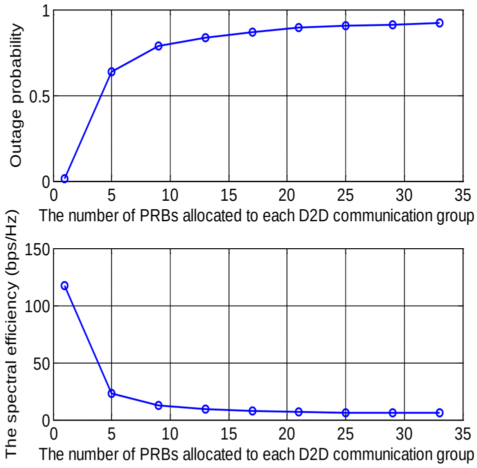


**Fig. 3.** Outage probability and throughput of D2D communication with FRA scheme

Firstly, we consider the performance of the FRA scheme. In a network with fixed resource allocation, the number of PRBs assigned to each D2D communication group ( $N_f$ ) affects the performance of D2D communication. **Fig. 3** shows the spectral efficiency and the outage probability of D2D communication with FRA scheme. It can be seen from this figure that the spectral efficiency of D2D communication decreases with the increment of number of PRBs assigned to each D2D communication group. Besides, the outage probability of D2D communication rises with the increasing of $N_f$ . That is because that the more available PRBs system has, the less PRBs reused by different D2D communication groups and the less interference they get. In this example, $N_f$ =1 gives the best performance for the given D2D communication group. In subsequent simulation, we use a fixed value of $N_f$ =1, which means the number of PRBs assigned to each D2D communication group is one. This allows for a comparison of the proposed scheme to the best-case scenario for the FRA scheme.

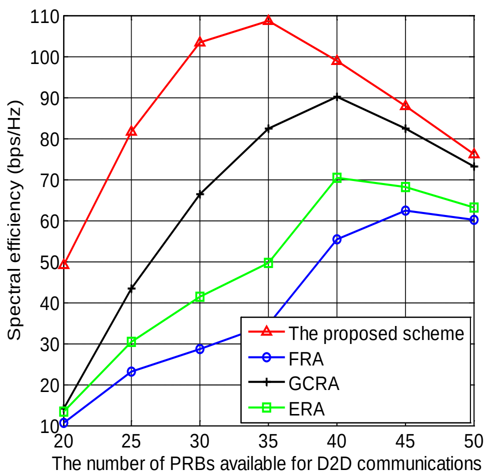


**Fig. 4.** The spectral efficiency vs. the number of PRBs for D2D communication

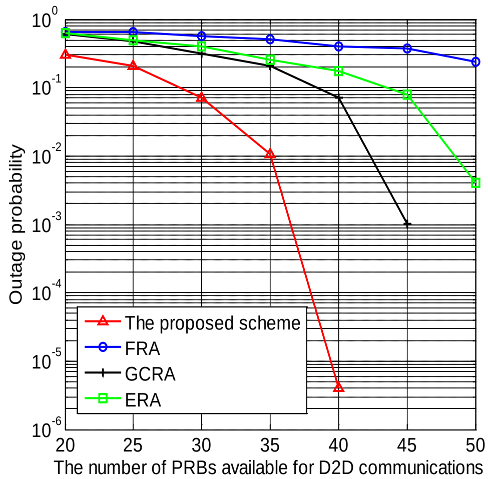


**Fig. 5.** The outage probability vs. the number of PRBs for D2D communication

**Fig. 4** shows the spectral efficiency of D2D communication in the small cell with different resource allocation schemes. From this figure, we have the following observations. Firstly, the spectral efficiency of D2D communication in the system with the proposed resource allocation scheme is always the highest one. The spectral efficiency of D2D communication in the system with GCRA is inferior and that of the system with FRA is the worst. The highest spectral efficiency of our proposed scheme attributes to the adaptive sub-channels allocation. The spectral efficiency of D2D communication can be improved by allocating power and PRBs appropriately. Secondly, the spectral efficiency of D2D communication with all these schemes first increase and then decrease with the increasing number of available PRBs for D2D communication. That is because that the more available PRBs system has, the less PRBs reused by different D2D communication groups and the less interference they get. At first, the interference reduction is the main influence factor on the spectral efficiency. When the number of available PRBs reaches a certain point, the PRBs consumption becomes the main influence factor on the spectral efficiency.

The outage probability of D2D communication for different schemes versus the number of available PRBs for D2D communication is shown in **Fig. 5**. It can be seen that the number of DUEs in outage decreases with the increment of the number of PRBs for D2D communication. The outage probability for DUEs with the proposed scheme decreases rapidly with the increment of the PRBs for D2D communication. That is because that the more available PRBs system has, the less PRBs reused by different D2D communication groups and the less interference they get. From (16), there is a positive relationship between outage probability of D2D communication and the interference among D2D links. So, the less interference they get, the small outage probability is. Additionally, with same number of available PRBs, the number of DUEs in outage with the proposed scheme is lowest. This illustrates that D2D user equipments in outage can be mitigated by allocating power and PRBs appropriately.

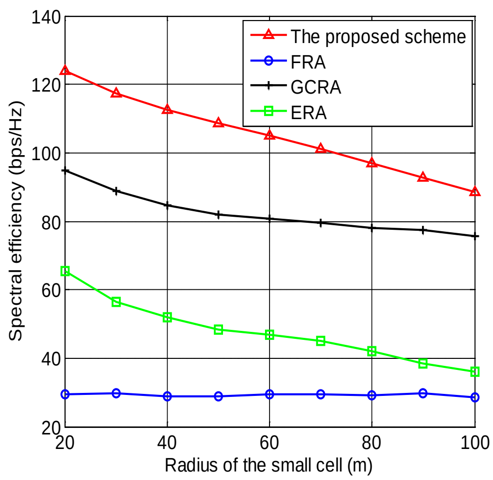


**Fig. 6.** The spectral efficiency vs. the radius of the small cell

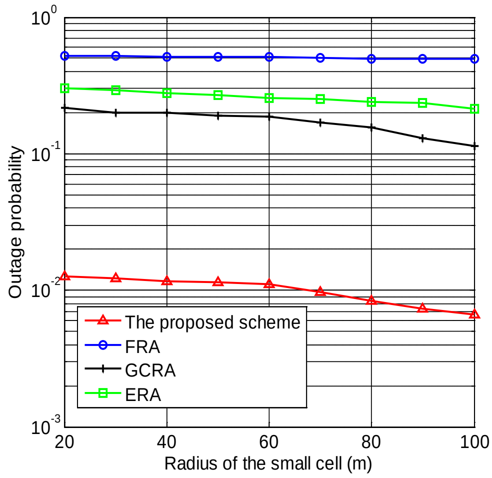


**Fig. 7.** The outage probability of D2D communication vs. the radius of the small cell

**Fig. 6** illustrates the spectral efficiency of D2D communication with different resource allocation schemes. It can be observed that the proposed scheme achieves the highest average spectral efficiency. For example, the spectral efficiency with the proposed scheme is between 90 bps/Hz and 125 bps/Hz, while that of FRA, GCRA and ERA schemes are about 80 bps/Hz, 50 bps/Hz and 30 bps/Hz, respectively. The higher spectral efficiency of the proposed scheme is due to it allocating frequency and power properly to mitigating the interference between

D2D multicast groups. In addition, except for the FRA scheme, the spectral efficiency with other three schemes are decreasing with the increment of the radius of small cell. That is because the distances between DRs and DCTs increase as the radius of small cell increases, then the number of DRs served in one D2D multicast group decreases, which leads to lower efficiency of multicast communications.

To evaluate the relationship between outage probability of D2D communication and radius of small cell, we compare the outage probability of D2D communication with different schemes versus radius of small cell and the result is shown in **Fig. 7**. From this figure we can see that by implementing the proposed scheme, the outage probability of D2D links decreases obviously. For example, the outage probabilities of D2D communication are almost always lower than $10^{-2}$ by using the proposed hierarchical scheme. While the outage probabilities of D2D communication with other three schemes are bigger than $10^{-1}$. This illustrates the proposed scheme can improve the outage performance of D2D communication.

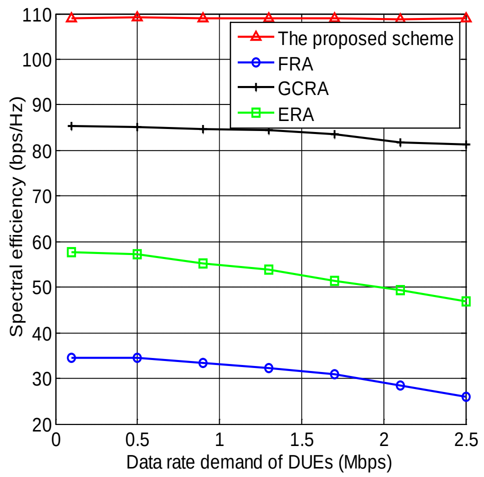


**Fig. 8.** The spectral efficiency vs. the rate demand for DRs

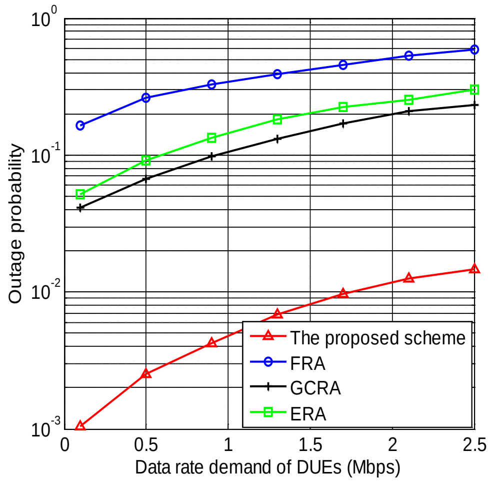


**Fig. 9.** The outage probability of D2D communication vs. the rate demand for DRs

**Fig. 8** shows the spectral efficiency versus the rate demand of DUEs. It is obvious that the proposed scheme outperforms the conventional schemes. The reason for our proposed scheme can obtain the highest spectral efficiency is that it adjusts power and the number of PRBs allocated to each D2D communication group adaptively according to different data rate demands of DUEs. In addition, the changes of DUEs' data rate demand only seem to be affecting the spectral efficiency of system with FRA, GCRA and ERA, and with little affect on the spectral efficiency of system with the proposed scheme. That is due to the adaptive PRBs allocation in our proposed scheme. As the rate demand of DUEs increases, the number of PRBs allocated to each D2D communication group also increases. From the perspective of the whole system, the overall throughput of D2D communication with our proposed scheme is essentially unchanged.

**Fig. 9** illustrates the average outage probability of the D2D links against rate demand of DUEs. It reveals that by applying the proposed scheme, the outage probability of the D2D links is reduced. For example, when the rate demand equals to 0.5Mbps, the average outage probability of D2D links with the proposed scheme is around $1.5\times10^{-3}$, while that of the other three schemes are higher than $5\times10^{-1}$. As the rate demand of DUEs increases, the outage probabilities of the four schemes also increases. The reason can be obtained from equation

(16): the bigger $r_{th}$ is, the more D2D user equipments are in outage.

## 6 Conclusions

A hierarchical resource allocation scheme for D2D communication in SNets is proposed in this article. We divided the optimal problem into three sub-problems, which includes D2D communication groups formation, sub-channels demands estimation, and resource allocation. The main advantage of the proposed hierarchical scheme is decomposing a complex optimization problem into several smaller problems with smaller sets of optimization variables. To make better use of the frequency resource while satisfying the data rate demand of each D2D receiver, a distance-based resource allocation algorithm is proposed to allocate the sub-channels to D2D communication groups. The proposed scheme ensures that the system select the best allocation order and allocate the available sub-channels to D2D communication groups successfully. The simulation results demonstrate that our proposed hierarchical scheme not only improves the spectral efficiency of D2D communication greatly, but also decreases the outage probability of the D2D links.

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