System Capacity Optimization Algorithm for D2D Underlay Operation

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Abstract—Device-to-Device (D2D) communications is considered as one of the key technologies for 5G wireless communications system, since it offers several advantages compared with traditional cellular network, i.e. low end-to-end latency and high spectral efficiency. By allowing underlaying direct D2D communications, a D2D link which reuses the spectral resources of a cellular user causes increased interference to this cellular link. Further, the D2D link suffers from interference caused by the cellular user. In this paper, we propose a network controlled algorithm with low computation complexity to efficiently maximize the reuse of cellular network spectrum with the help of using channel information at base station. This algorithm can be used to select the transmission mode of potential D2D pairs. Besides, we also propose to use an auction algorithm for maximizing system capacity. The low complexity of these two algorithms reduces the setup delay of D2D links. Simulation results demonstrate improved system performance in terms of overall system capacity and number of established D2D links.

I. INTRODUCTION

Recently, network controlled device-to-device (D2D) communications has attracted a lot of attention in research, since it is able to efficiently complement cellular communications by taking advantage of physical proximity for improving coverage, spectral efficiency, data rates, and QoS [1]. Moreover some new services can also be enabled by D2D communications, such as direct multimedia transmission [2] [3]. The key functionality for D2D communications include [1]:

- Peer and Service Discovery
- Physical Layer Procedures (encoding, signaling, data transmission and reception, etc.),
- Radio Resource Management (RRM) (transmit power and resource allocation, data rates, etc.),
- Interference Management (e.g. intra-cell interference is no longer negligible due to use in LTE).

As one of the important issues in D2D communications, RRM covers the concepts of D2D transmit power control, mode selection and resource allocation. Power control is the mechanism of optimally selecting transmit powers in a communication system to achieve good performance and reduce interference [4] [5] [6]. Good performance in this context may be assessed using metrics, such as link data rates, network capacity, geographic coverage and range, etc. Transmit power determines the range over which the signal can be coherently received, and is therefore crucial for determining the performance of the network (e.g. with respect to throughput, delay, and energy consumption) [7]. In order to realize the proximity, reuse and hop gains, the available spectral resource need to be allocated for D2D communications in an efficient way. Presently, there are three modes of D2D operation that can be envisioned:

- Reuse Mode: D2D devices directly transmit the data by reusing some resources of the cellular network. The spectrum reuse can be either in uplink or downlink communications.
- Dedicated Mode: The cellular network dedicated a portion of resources for D2D devices for their direct communications.
- Cellular Mode: D2D traffic is relayed through eNBs in the traditional way.

Some solutions exclude the coexistence of the D2D and cellular communications using the same spectrum resource and therefore the dedicated mode is considered [1] [8] [9]. However, in order to improve the efficiency of valuable spectrum resources, the reuse mode for D2D is also investigated where the same spectrum resource is shared between D2D and cellular users [1] [9] [10] [11] [12]. The reuse mode becomes important when available frequency range is considered as precious and it is essential to reuse the same spectrum resource. In this paper, it is assumed that D2D communications operate in reuse mode. In Sect. II, the system model is introduced and the interference issues that are raised by D2D underlaying operation are illustrated. After, we construct an optimization problem in Sect. III which aims at enabling as many underlaying D2D links as possible. Further, a valid algorithm with a modest complexity is used to efficiently solve the optimization problem. In Sect. IV, the solution to a capacity optimization problem with the constraint that each D2D pair can maximally reuse only one resource block is presented. The numerical results shown in Sect. V demonstrate and compare system performance of different RRM algorithms. Finally, we draw a conclusion of our work in Sect. VI.

II. SYSTEM MODEL

We consider a scenario where mobile users are divided into two categories, cellular users and D2D users. Cellular users request communication service directly from a base station (BS). In comparison, two nearby D2D users form a D2D pair and perform a local communication service in order to exchange data with each other. Since in our scenario
D2D communication in reuse mode is assumed, there are no dedicated resources available for D2D communication. Hence a D2D pair can only reuse resource block of a cellular user. Further, it is assumed that each cellular user occupies one uplink resource block and one D2D pair can only reuse one uplink resource block of a cellular user. Therefore the scenario where multiple D2D pairs reuse the same resource block of a cellular user is not considered by the proposed algorithm. As shown in Fig. 1, totally \( N \) cellular users and \( M \) D2D pairs are deployed in a cell.

In Fig. 1, D2D communication is assumed to operate in the same uplink spectrum band as the cellular users and tries to reuse resource blocks that are already occupied by cellular links. With total awareness of channel information, the BS can assign one cellular resource block to a certain cellular link. With total awareness of channel information, BS can try to reuse resource blocks that are already occupied by the same uplink spectrum band as the cellular users and are deployed in a cell.

Now, the optimization problem can be constructed as follows:

\[
\text{maximize } \sum_{(m,n)} f(m, n),
\]

subject to

\[
 m \neq n \quad \text{if } m \neq m' \quad \text{for } (m, n) \quad \text{and } (m', n') \quad (7)
\]

\[
 m \neq m' \quad \text{if } n \neq n' \quad \text{for } (m, n) \quad \text{and } (m', n'). \quad (8)
\]

Eq. (6) is the objective function which tries to maximize the number of feasible D2D links. The constraints shown in Eq. (7) and Eq. (8) indicate the resource block of each cellular user can be maximally reused by one D2D pair and each D2D pair can only reuse resource block of one cellular user.

### III. Maximization of Feasible D2D Links

With total awareness of all channel gain, BS can make a decision on which resource block one D2D pair should reuse. In this section, we present the developed algorithm and consider the number of feasible D2D links as a key performance indicator (KPI).

#### A. Construction of Optimization Problem

In order to derive a RRM scheme which allows for establishing as many D2D links as possible, we firstly define a feasibility function as follows:

\[
f(m, n) = \begin{cases} 
1, & \text{if both Eq. (1) and Eq. (2) are fulfilled;} \\
0, & \text{else,}
\end{cases}
\]

This feasibility function indicates whether the \( m^{th} \) D2D pair can reuse the same resource block of \( n^{th} \) cellular user. We set the value of feasibility function to "1" when the reuse is feasible, which means this D2D link can be counted as one contribution to the number of feasible D2D links. When the value of feasibility function equals to "0", it means that no resource reuse is feasible and therefore the corresponding D2D pair can not be assigned the resource block of the \( n^{th} \) cellular user. Now, the optimization problem can be constructed as follows:

#### B. RRM Algorithm

The optimization problem defined above aims at enabling as many feasible D2D links as possible where both the SINR target values of D2D and cellular links are satisfied. In order to search for a global optimal solution, it is necessary to have the full channel gain information available, including channel gain between D2D Tx and Rx, cellular user and BS, all cellular users and D2D Rx, D2D Tx and BS. The first two

\[
P_{D2D}^T \quad \text{and } \quad P_{cell}^T \quad \text{denote the transmission powers of D2D and cellular transmitters, respectively.}
\]

\[
h_{m}^{D2D} \quad \text{represents the channel gain between transmitter and receiver of the } m^{th} \quad \text{D2D pair,}
\]

\[
h_{n}^{cell} \quad \text{the channel gain between the } n^{th} \quad \text{cellular UE and BS.}
\]

\[
h_{(m,n)} \quad \text{represents the channel gain from the } n^{th} \quad \text{cellular UE to } m^{th} \quad \text{D2D Rx,}
\]

\[
h_{(BS,m)} \quad \text{the channel gain from the } m^{th} \quad \text{D2D Tx to BS.}
\]
channel information are necessary to model the received signal strength for D2D and cellular links, and the last two to derive the potential interference power for D2D and cellular links correspondingly. It should be noticed that information about all potential interference coming from every cellular user to a specific D2D Rx is necessary at BS in order to achieve a global optimal resource allocation scheme. Even though once the resource allocation is done, one D2D Rx will only receive interference from one cellular user.

With total awareness of overall channel information, BS can scan all resource allocation option and find the optimal solution. However, this method requires a high computational complexity and meanwhile increases the time delay for network to set up a D2D link. In following, we introduce Alg. 1 that is able to solve the optimization problem, while exhibiting modest complexity.

The input to this algorithm is a feasibility matrix $F$, defined as:

$$F = \begin{pmatrix}
  f_{(1,1)} & \cdots & \cdots & \cdots & f_{(1,N)} \\
  \vdots & \ddots & \vdots & \vdots & \vdots \\
  \vdots & \vdots & f_{(m,n)} & \vdots & \vdots \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  f_{(M,1)} & \cdots & \cdots & \cdots & f_{(M,N)}
\end{pmatrix}, \quad (9)$$

which is an $M \times N$ binary matrix. Each element of $f_{(m,n)}$ in this matrix has a binary value of either "0" or "1" as defined in Eq. (5). This matrix is fed to the input of our algorithm.

The key idea of this algorithm is that we give a high priority to the set of users $\hat{m}$ which have least feasible option, in other words least "1"s on the $\hat{m}$th row in matrix $F$, by firstly considering to assign resource blocks to these users. The output of this algorithm are two vectors, D2DpairNum and CellularNum which indicate the decision of resource mapping. For instance, D2DpairNum(i) = $m$ and CellularNum(i) = $n$ demonstrate that our algorithm set the $m$th D2D pair to reuse the resource block of $n$th cellular user. Therefore, the length of one of these two vectors represents the number of feasible D2D links achieved by our RRM algorithm.

### Algorithm 1 Maximization of underlaying D2D links

**Input:**

- The feasibility matrix $F$.

**Output:**

- ID of the combined D2D pairs: D2DpairNum.
- ID of the combined cellular users: CellularNum.

1: if all elements in matrix $F$ equal to "0" then
2:  D2DpairNum=[]; CellularNum=[];
3:  end the algorithm without assigning any underlaying D2D pair.
4:  else
5:    i=1;
6:    if one column or one row vector in matrix $F$ has a unique "1" element at position $f_{(m,n)}$ then
7:      allocate the $m$th D2D pair with the resource block of $n$th cellular user: D2DpairNum(i) =$m$, CellularNum(i) =$n$;
8:      i=i+1;
9:    set all the elements in the $m$th row and $n$th column in matrix $F$ to "0";
10:   if all elements in matrix $F$ equal to "0" then
11:      end the algorithm;
12:    else
13:      return to step 6;
14:    end if
15:  else
16:    scan all the non zero columns and rows to find the column or row with the least number of "1"s, pick out the first position where $f_{(m,n)} = 1$ in this column or row.
17:    allocate the $\hat{m}$th D2D pair with the resource block of $\hat{n}$th cellular user: D2DpairNum(i) =$\hat{m}$, CellularNum(i) =$\hat{n}$;
18:    i=i+1;
19:    set all the elements in the $\hat{m}$th row and $\hat{n}$th column in matrix $F$ to "0";
20:   return to step 6;
21: end if
22: end if

C. Proof of Algorithm Validity

It should be noticed that Alg. 1 offers a sub-optimal solution. The sub-optimal originates from Step. 16 and Step. 17 where we combine the D2D pair and corresponding cellular user in a first-in-first-out manner. Therefore, in order to exploit this algorithm in reality, it is necessary to prove its validity. Without loss in generality, we assume the same amount of D2D pairs and cellular users deployed in a cell, as $M = N$. From mathematical point of view, we can construct a matrix $F$ which has the property that all resource blocks can be reused by D2D pairs and feed this matrix to the input of our algorithm. In this case, the theoretical optimal solution should enable D2D pairs to reuse all $M$ resource blocks. To construct such a matrix $F$, we firstly construct a diagonal matrix $F'$ with all diagonal elements having the value of "1" to make sure that every resource block can be reused. After the first step, the non diagonal elements of matrix $F'$ can be modeled by a random process which has a probability of $P$ to have value of "0" and a probability of $(1 - P)$ to have value of "1" at position $f_{(m,n)}$ where $m \neq n$. This step will not change the number of maximal reusable resource blocks, but only give more solution options for the RRM scheme. Finally the matrix will be randomly interleaved either in column-wise or row-wise manner to yield matrix $F$. In Sec. V, we show that our sub-optimal algorithm enables us to reuse almost all resource blocks which proves the efficiency of our algorithm.
IV. SYSTEM CAPACITY MAXIMIZATION

With the help of full channel gain information, we developed a resource allocation algorithm where the number of feasible D2D links is considered as KPI. This KPI is of importance since we want to support as many D2D users as possible with a certain number of resource blocks. However, there are other KPIs which should be under inspection, such as system capacity since nowadays network operators normally charge mobile users based on their consumed data volume. Therefore it is necessary to develop a RRM scheme which is able to maximize the system capacity.

From capacity point of view we can always assign a resource block to the D2D pair which offers better capacity performance. Therefore, the best solution is to check for each resource block which D2D pair/link yields maximum link capacity. Even though this method offers a straightforward solution which ensures the maximal capacity performance, it has several drawbacks. First of all, due to the distribution of D2D pairs, D2D pairs deployed near the base station have a low probability to be assigned resource blocks, since compared with the D2D pairs located near the cell edge they cause higher interference level and therefore lower capacity for cellular links. Thus, the D2D pairs near BS statistically have higher probability to not be assigned with any resource blocks, which is not fair in reality. Secondly, the D2D pairs that are assigned multiple resource blocks have to operate on multiple resource blocks which increases the hardware complexity of user device. In order to overcome these drawbacks, the capacity optimization problem is constructed as follows:

\[
\text{maximize } \sum_{(m,n)} C(m,n),
\]

subject to

\[
\begin{align*}
\quad \quad & n \neq n' \text{ if } m \neq m' \text{ for } (m,n) \text{ and } (m',n') \quad (11) \\
\quad \quad & m \neq m' \text{ if } n \neq n' \text{ for } (m,n) \text{ and } (m',n') \quad (12)
\end{align*}
\]

Eq. (10) is the objective function where \( C(m,n) \) represents the capacity if the \( m^{th} \) D2D pair reuse the resource block of \( n^{th} \) cellular UE. Eq. (11) and Eq. (12) state the same constraint as Eq. (7) and Eq. (8) which ensures that each D2D pair is assigned with one and only one resource block.

It should be noticed that the objective function in Eq. (10) can be used to maximize different capacity terms, e.g. capacity of overall cellular links, capacity of overall D2D links or the sum of both cellular and D2D links. Regarding above optimization problem, it can be considered as an auctioning problem. For resource block \( n \), \( C(m,n) \) can be considered as a benefit for assigning this resource block to the \( m^{th} \) D2D pair. Therefore, the auctioning algorithm presented in [13] has been used for solving the optimization problem.

V. SIMULATION ASSUMPTIONS AND NUMERICAL RESULTS

We firstly prove the validity of our resource allocation algorithm. In Fig. 2, we intentionally construct a diagonal matrix and then allocate binary values to non-main diagonal

<table>
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<td>Noise figure at D2D Rx</td>
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<tr>
<td>Target cellular SINR value</td>
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<tr>
<td>Target D2D SINR value</td>
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<td>Power level of thermal noise</td>
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Fig. 2: Provement of algorithm by mathematics

Fig. 3: Performance comparison on overall system capacity

Fig. 4: Performance comparison on number of established D2D links
elements \( \{ f_{(m,n)}, m \neq n \} \) with a statistic process, as stated in Sect. III-C. Further, it is assumed that each cellular user is assigned only one resource block, thus the number of resource blocks is identical to the number of cellular links. We feed this constructed matrix \( F \) to the input of our algorithm and the optimal allocation algorithm is able to reuse all resource blocks. The result in Fig. 2 shows that our algorithm enables to reuse all resource blocks without any noticeable loss. Besides, as can be seen from this figure, all five curves which represent different probabilities of zero matrix elements are overlapping together, which demonstrates the efficiency of our algorithm that it can achieve the optimal objective under different scenarios.

The applied simulation parameters are summarized in Tab. I. Besides, [14] and [15] are referred as baseline for channel models of D2D and cellular links. We also refer to [16] for the mapping from SINR value to capacity values for both D2D and cellular links. We also refer to [16] for the construction of a matrix which demonstrates the efficiency of our algorithm that it can achieve the optimal objective under different scenarios.

In Fig. 3, we show system performance of different algorithms from the perspective of overall system capacity. Five different algorithms are inspected here.

- Maximization of Overall Capacity: function \( C(m, n) \) in Eq. (10) represents the sum of D2D capacity and cellular capacity.
- Maximization of Cellular Capacity: function \( C(m, n) \) in Eq. (10) represents the cellular capacity.
- Maximization of D2D Capacity: function \( C(m, n) \) in Eq. (10) represents the D2D capacity.
- Maximization of Number of Feasible D2D Links: Alg. 1 is applied.
- Random Allocation: for each D2D pair, a resource block is randomly allocated.

As can be seen in Fig. 3, the three algorithms which maximize the three different capacity terms have a performance gain compared with the random allocation scheme. However, Alg. 1 has a worse performance compared with the random case. This is due to the fact that we give a high priority to the set of users which have less feasible option. These users are more vulnerable, since they experience low SINR values. Therefore, by offering resource block to these users, the corresponding capacity is lower than the average case which perfectly explains the scenario in Fig. 3.

In Fig. 4, number of established D2D links is considered as KPI for evaluating different algorithms. Since we give a high priority to vulnerable users by firstly assigning available resources to them, Alg. 1 outperforms the other algorithms with a significant gain. The three algorithms which maximize the three different capacity terms yield a slightly better performance compared with random allocation scheme.

VI. CONCLUSION

In this paper, we proposed two maximization algorithms with low computational complexity which allow for allocating resource blocks for underlying D2D communications and for efficiently achieving optimal solution regarding different KPIs. The low computational complexity enables base station to set up D2D links with a valid response and reduces the setup delay. Numerical result shows our resource allocation algorithms yield a better system performance in terms of overall system capacity and number of established D2D links.

VII. ACKNOWLEDGEMENT

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