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Resource Allocation for Device-to-Device Communications Reusing Uplink in Cellular Networks

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ABSTRACT

Efficient spectrum sharing is an important issue in Device-to-Device (D2D) communications underlaying cellular networks as it can mitigate the interference to cellular users and improve the performance of the systems. In this paper, we formulate the radio resource allocation in D2D communications as a mixed nonlinear integer programing. We show the formulated problem is NP-hard and thus a polynomial time algorithm to solve is not possible. Since such a problem is very hard to obtain the optimal solution within a short running time, we instead propose a fast heuristic suboptimal algorithm to mitigate the interference caused to cellular users and improve the performance of the systems. Simulation results are provided to evaluate the performance of the proposed algorithm.

Key words: Resource Allocation, D2D Communications, Cellular Networks, Spectrum Sharing, Nonlinear Integer Programing.

1. INTRODUCTION

With the explosive growing of mobile data traffic because of the emergence of fourth-generation (4G) mobile networks [1], Device-to-Device (D2D) communication has been considered as an effective feature for next generation cellular networks in order to cope with this situation [2]. D2D communication allows two physical nearby located users to transmit data directly without relaying the signal through the Base Station (BS). Therefore, D2D communication can enhance the system throughput, reduce the end-to-end delay and obtain better resource utilization [2]. In cellular networks with D2D enabled, the radio resources can be either allocated orthogonally to Cellular Users (CUs) and D2D pair, or shared between them [3]. The former can simplify the interference management, however the resource utilization is very poor and not flexible. To improve the resource utilization, we consider D2D communications underlaying cellular networks, i.e., D2D pairs share the same radio resources with CUs.

In general, the downlink often becomes the bottle-neck and the uplink is usually under-utilized, hence the resource utilization can be improved if the uplink is reused [4]. In addition, if the uplink is reused, the victim of the interference brought by D2D transmissions is the BS, which is typically more capable of dealing with co-channel interference than user equipments. Therefore, we focus on the scenario when CUs and D2D pairs share the same uplink spectrum.

Since the CUs and D2D pairs share the same radio resources, any resource allocation scheme must guarantee: (1) the Quality-of-Service (QoS) of CUs, and (2) improving the performance of the system. In this paper, we propose a simple yet effi-

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cient spectrum sharing to fulfil those tasks. We formulate the problem of allocating resources for D2D communication as a mixed integer nonlinear programing. Such an optimization problem is very hard to obtain the optimal solution within a fast transmission interval of practical networks such as LTE, WiMAX. We instead propose a fast yet efficient heuristic suboptimal algorithm to mitigate the interference caused to cellular users and improve the performance of the systems. The proposed algorithm does not require any modification to the scheduling of the primary cellular networks. The contributions of the paper can be summarized as follows.

- We model the system and formulate the problem of resource allocation as a mixed integer nonlinear programing, we then show its NP hardness and thus a polynomial time algorithm to solve is not possible.
- We propose a fast yet efficient heuristic suboptimal algorithm to mitigate the interference caused to cellular users and improve the performance of the systems.
- We evaluate the proposed algorithm with numerical analysis.

The remainder of this paper is organized as follows. We present related works in section II. In section III, we describe our system model, the problem formulation. Section IV presents our proposed algorithm. Section V gives the evaluation of the proposed algorithm and section VI eventually concludes the paper.

2. RELATED WORKS

Resource allocation for D2D communications in cellular networks can be found in [5]-[9]. [5] suggests that the network throughput can be significantly improved when users make use of unoccupied uplink resources. The authors in [6] propose an algorithm based on the statistics of the signal to interference plus noise ratio (SINR) of all users, however the SINR behavior is formulated based on the position of the D2D pair while in practice such an location information is not easy to obtained. In [7], the authors investigate D2D communications in Wi-Fi ad hoc mode in the unlicensed band, however the cellular operators are more likely to use licensed band for the easy of signal controlling. In [8], an other algorithm is derived under the framework of game theory for cognitive radio networks (we note that D2D communications is a kind of cognitive radio networks), however the obtained solution is inefficient duo to the selfness of each transmitter. In addition, cognitive users have to sense the surrounding environment to detect the temporal and spatial "holes" in the spectrum and thereby avoid interference with the primary users, however the sensing ability demands high level of complexity to detect the weak signal of primary users. In [9], a simple resource allocation scheme is proposed for D2D communications in underlaying LTE networks, the algorithm is simple and easy to implement in practice, however this algorithm place concentration on the data rate of cellular users, hence the throughput of the whole network including cellular and D2D users is not significantly improved.

3. SYSTEM MODEL AND PROBLEM FORMULATION

3.1 System model

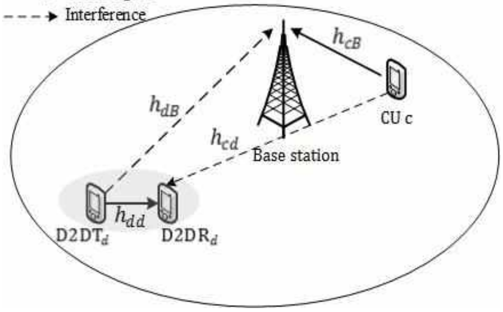

Fig. 1. Single cell with assisted D2D communications.

In this paper, we consider a single cell system as depicted in Fig. 1. Let $\varPhi$ and $\varOmega$ are the set of CUs and D2D pairs respectively, $|\varPhi| = C$ and $|\varOmega| = D$ where $|.|$ denotes the cardinality of a set. We assume an infinite backlogged model where network users always have data in their queues to transmit, in addition, all channel gains are fixed during the time of interest (e.g., in slow mobility scenario). There are N orthogonal channels in the system and each CU is exclusively assigned one channel for transmission. Let $\mathrm{CU_c}$ is CU c, $\mathrm{D2D_d}$ is D2D d, $\mathrm{D2DT_d}$ and $\mathrm{D2DR_d}$ are the transmitter and receiver of D2D pair d respectively. Let x_d^c be the indicator variable which the value is specified as follow

$$x_d^c = \begin{cases} 1 \text{ if } \mathrm{D2D_d} \text{ reuses resource of CU c} \\ 0 \text{ otherwise} \end{cases}.$$

The signal to interference plus noise ratio (SINR) of $\mathrm{CU_c}$ at the BS is given as

$$\gamma_c = \frac{p_c h_{cB}}{N_0^c + \sum_{d=1}^{D} x_d^c p_d h_{dB}^c}, \tag{1}$$

where p_c and p_d are the transmit powers of CU c and $\mathrm{D2D_d}$ respectively, h_{cB} is the channel gains from $\mathrm{CU_c}$ to the BS and h_{dB}^c is the channel gains from and $\mathrm{D2DT_d}$ to the BS on the radio resource of $\mathrm{CU_c}$, N_0^c is the noise at $\mathrm{CU_c}$. The SINR of $\mathrm{D2D_d}$ is given as

$$\gamma_d = \frac{\sum_{c=1}^{C} x_d^c p_d h_{dd}^c}{N_o^d + \sum_{c=1}^{C} x_d^c p_c h_{cd}}, \tag{2}$$

where h_{dd}^c is the channel gains between $\mathrm{D2DT_d}$ to $\mathrm{D2DR_d}$ on the radio resource of $\mathrm{CU_c}$, h_{cd} is the channel gain of $\mathrm{CU_c}$ to $\mathrm{D2DR_d}$. The throughput of $\mathrm{CU_c}$ and $\mathrm{D2D_d}$ are given according to Shannon capacity model, i.e.,

$$\begin{aligned} R_c &= \log_2(1+\gamma_c), \\ R_d &= \log_2(1+\gamma_d). \end{aligned} \tag{3}$$

3.2 Problem formulation

The problem here is: how to allocate the radio resources of CUs for D2D pairs and what is the corresponding transmit power to maximize the system throughput while guarantee the QoS of CUs. Mathematically, we have to solve the following optimization problem

$$\begin{aligned} &\max_{x_d^c \geq 0, p_d \geq 0} \sum_{c=1}^{C} R_c + \sum_{d=1}^{D} R_d \\ &s.t. R_c \geq R_{c,\min}, c = 1, \ldots, C, \\ &\quad \sum_{c=1}^{C} x_d^c \leq 1, c = 1, \ldots, C, \\ &\quad \sum_{d=1}^{D} x_d^c \leq 1, d = 1, \ldots, D. \end{aligned} \tag{4}$$

Where $R_{c,\min}$ is the minimum data rate requirement of $\mathrm{CU_c}$ for $c = 1, \ldots, C$. The second constraint is to guarantee that each CU is allowed to share the radio resource with at most one D2D pair while the third constraint guarantees that each D2D pair is allowed to reuse only one resource of CU.

Remark: Problem (4) is a mixed integer nonliner programming. From the proof of Theorem 1 in [10], it can be seen that even with binary power control for a given radio resource scheme is NP-hard. Therefore, we conclude that problem (4) with integer variable x_d^c and continuous transmit power p_d is also NP-hard. As a result, a polynomial time algorithm to determine that optimal solution is not possible. Although that problem can be solved via exhaustive search approach. However such approach requires to collect all channel gains between all transmitters and receivers, as well as evaluate all possible spectrum sharing schemes and power allocation, which results in hugh signalling overhead and computational complexity. Therefore, in the next section, we propose a suboptimal yet fast and efficient algorithm to solve this problem.

4. D2D RESOURCE ALLOCATION (D2DRA)

We first make some observations from the derivation of the data rate of CUs and D2D pairs, i.e., equation (1), (2) and (3). It should be noticed that on one hand, D2D pair d should reuse the radio resource of $\mathrm{CU_c}$ which has the largest channel gain h^c_{dd} so $\mathrm{D2D_d}$ will have the best SINR. On the other hand, $\mathrm{CU_c}$ should allow D2D pair who has the smallest channel gain h_{dB} to reuse its radio resource so the SINR of $\mathrm{CU_c}$ at the base station is maximized. However, since in practice, the distance between the transmitter and receiver of any D2D pair is much smaller than the distance between CU and BS, which means that the data rate of each D2D pair generally grater than that of each CU. Therefore we concentrate on the date rate of D2D pairs rather than that of each CU. With this intuition, each $\mathrm{D2D_d}$ should be matched with $\mathrm{CU_c}$ using the following rule:

$$x^c_d = \begin{cases} 1 \text{ if } c = \arg\max_c h^c_{dd} \\ 0 \text{ otherwise} \end{cases}.$$

This matching rule simply means that $\mathrm{D2D_d}$ should reuse the radio resource of $\mathrm{CU_c}$ if it has the best data rate on that resource. Now we have to specify the transmit power of $\mathrm{D2D_d}$ so that the QoS constraint of $\mathrm{CU_c}$ who shares the same resource with $\mathrm{D2D_d}$ is not violated. From (1) and (3) we have that

$$\begin{aligned} & R_{c,\min} \le R_c \\ & \Leftrightarrow R_{c,\min} \le \log_2(1+\gamma_c) \\ & \Leftrightarrow R_{c,\min} \le \log_2\left(1+\frac{p_c h_{cB}}{N^c_0 + p_d h_{dB}}\right), c = \arg\max_c h^c_{dd} \\ & \Leftrightarrow p_d \le \frac{1}{h_{dB}}\left(\frac{p_c h_{cB}}{2^{R_{c,\min}}-1} - N^c_0\right) = P_{d,\max}. \end{aligned} \tag{5}$$

From the analysis above, the QoS of $\mathrm{CU_c}$ is not violated as long as the transmit power of D2D pair d lies in the interval $[0, P_{d,\max}]$, since the data rate of $\mathrm{D2D_d}$ is an increasing function in p_d, then it is easy to verify that the optimal transmit power of $\mathrm{D2D_d}$ is given by

$$p^*_d = P_{d,\max}, P_{d,\max} = \frac{1}{h_{dB}}\left(\frac{p_c h_{cB}}{2^{R_{c,\min}}-1} - N^c_0\right).$$

Note that if $P_{d,\max} \le 0$, then $p^*_d = 0$, in other words, we have

$$p^*_d = \max(0, P_{d,\max}).$$

The D2DRA is given by the following algorithm.

Table 1. The D2DRA algorithm

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Collecting the channel gains
    $h^c_{cd}, h_{cB}, h^c_{dd}, h^c_{dB}, R_{c,\min}$ for $c=1,...,C, d=1,...,D$.
Sort the channel gain $h^c_{dd}$ in decreasing order.
Begin $d=1$
While $d<D$
    Match the resource of $\mathrm{CU_c}$ with D2D pair $d$ using
        the rule $x^c_d = \begin{cases} 1 \text{ if } c=\arg\min_c h^c_{dd} \\ 0 \text{ otherwise} \end{cases}$.
    Calculate the transmit power of $\mathrm{D2D_d}$ by using
        $p^*_d = \max(0, P_{d,\max}), P_{d,\max} = \frac{1}{h_{dB}}\left(\frac{p_c h_{cB}}{2^{R_{c,\min}}-1} - N^c_0\right)$.
    set $d=d+1$.
    Set $\Phi = \Phi - \{c\}$.
end
end
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Remark: In order to perform this algorithm, the BS which is the controller has to collect the channel gains $h^c_{cd}, h_{cB}, h^c_{dd}, h_{dB}, R_{c,\min}$ for $c=1,...,C, d=1,...,D$.

These channel gains can be obtained by having each receiver measure the channel condition and feed back to the controller. The complexity of this algorithm can be evaluated as follows. First, we have to sort the channel gains $h_{dd}, d=1,...,D$ in decreasing order, using the sorting algorithm in [11], the complexity of the sorting process is $O(DC\log DC)$. Performing the calculation of the transmit power in (5) needs $O(D)$ calculations. Collecting the following information $h^c_{cd}, h_{cB}, h^c_{dd}, h^c_{dB}, R_{c,\min}$ for $c=1,...,C$ and $d=1,...,D$ requires $O(3CD+2C)$. Therefore, the overall computational complexity of the D2DRA is $O(DC\log DC + 3CD + 2C)$ which is polynomial in time.

5. NUMERICAL ANALYSIS

In this section, we evaluate the performance of the proposed D2DRA using simulation using Matlab.

We set up a single cell system with the cell radius is 500 m. Cellular users and D2D pair are randomly distributed in an area in which the minimum distance to the base station is 150 m. The distance between the transmitter and receiver of any D2D pair is randomly distributed between 15 and 30 m. Fig. 2 depicts a snapshot of the topology used for simulation. The path loss is modeled as $33+33\log(y)$ where y (meters) is the distance from the transmitter to the receiver, the shadowing is modeled as log-normal random number with zero mean and standard deviation 4 dB [12]. The noise variance is assumed as -120 dBm. The number of resources (radio channels) are equal to the number of CUs C, these resources are allocated to CUs using a Round-Robin scheme, i.e., in the first round, the channel is assigned to the CU who has the best channel gain, then this CU is excluded and the second round is repeated to allocate the channel to the next CU. This process is repeated until all CUs are assigned radio resources. Finally the maximum transmit powers of BS and D2DTs are normalized as 1, i.e., $P_{d,\max}=P_{bs,\max}=1$.

In Fig. 3, we plot the data rate of three CUs obtained by the proposed algorithm with $R_{c,\min}=2.6$ Bits/s/Hz. It can be observed that, in the first time (i.e., $t=1$) the data rates of CUs are obtained without D2D transmissions. After this time, the D2D transmissions are started, causing co-channel interference to the CU receivers, thus the data rates of CUs decrease dramatically and some fall bellow the minimum data rate requirement. At this point, the transmit powers of D2DTs which cause excessive interference to those CUs need to be adjusted as in (5), and the data rates of CUs monotonically increase and satisfy the minimum data rate requirement.

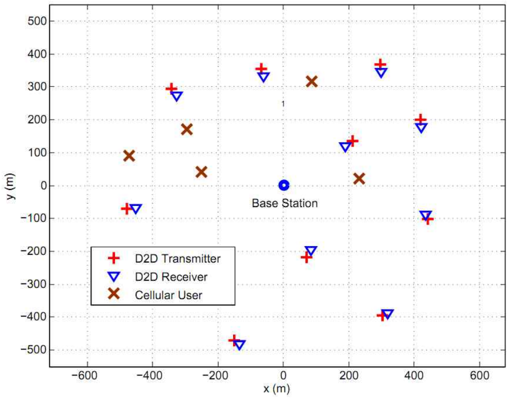

Fig. 2. An example of topology.

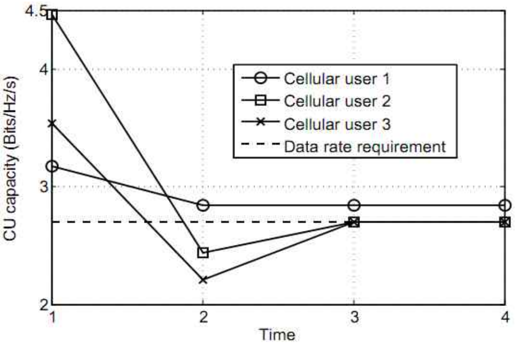

Fig. 3. Data rate of CUs.

In Fig. 4, 5 and 6, we plot the sum capacity of D2D pairs, CUs and the total capacity of the system respectively. Each plot is average over 200 independent channel realizations, in each realization, the location of CUs and D2D pairs are kept fixed while the shadowing is average over 25 times. We compare the sum capacity obtained by the proposed D2DRA with the Heuristic strategy in [9] and the cellular mode (i.e., when the transmitter

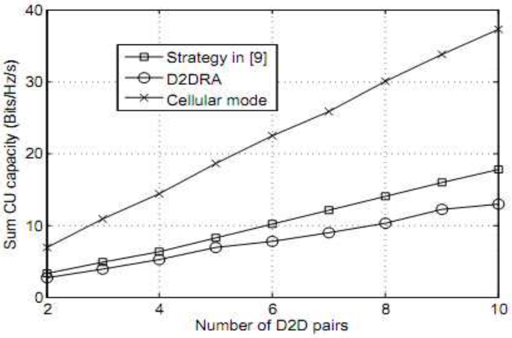

Fig. 4. Sum D2D capacity versus the number of D2D pairs.

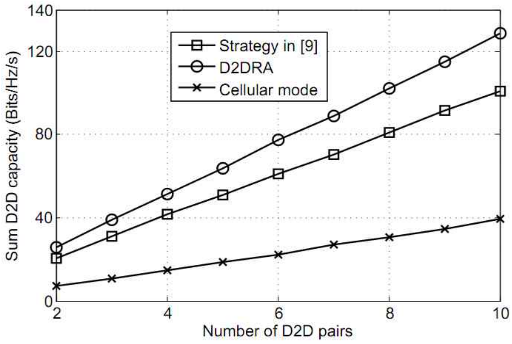

Fig. 5. Sum CU capacity versus the number of D2D pairs.

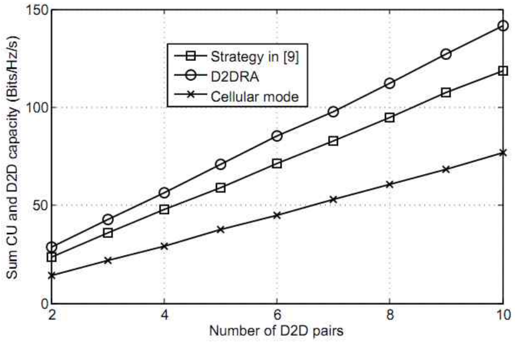

Fig. 6. Total system capacity versus the number of D2D pairs.

and receiver of a D2D pair communicates with each other via the base station). The reason we compare with the algorithm in [9] is that it does not require any modification to the scheduling of CUs and complex computations, which is also one of our goal, also for running, the DDRA needs to collect the same amount of information as in [9]. We observe that the D2DRA outperform the strategy in [9] and the cellular mode in term of sum D2D capacity (Fig. 4). Note that in the D2DRA, the channel of CU is assigned to the D2D pair which has the best channel gain (i.e., $x_d^c = 1 \text{ if } c = \arg\max_c h_{dd}^c$) while in [9] the resource of CU is assigned to the D2D pair which has the smallest channel gain to the CU (i.e., $x_d^c = 1 \text{ if } c = \arg\min_c h_{dB}^c$). The results are tow folds, first the CU sum capacity obtained by the strategy in [9] is higher than the D2DRA (Fig. 5) because the D2DT is chosen such that it cause less interference to the CU. However, the D2D sum capacity obtained by the D2DRA is much higher than the one obtained by the scheme in [9] since the channel gain h_{dd}^c is much stronger than h_{dB}^c due to short distance between the transmitter and receiver of one D2D pair.

In the cellular mode, since there is no interference between CUs, hence the CU sum capacity is highest among three schemes. However due to the far distances between the CUs and the BS, the total capacity of the system in lowest. With the highest gain in the D2D sum capacity, the D2DRA obtains the highest system capacity (Fig. 6).

V. CONCLUSION

In this paper, we propose an resource allocation algorithm for D2D communications in cellular systems. We formulate the problem of radio resource matching between CUs-D2D pairs and the transmit power allocation as a mixed integer non-linear programming. We show its NP-hardness, hence a polynomial time algorithm to obtain the optimal solution is not possible. We then propose a sub-optimal polynomial time algorithm to match CU-D2D pair for resource sharing and derive the corresponding transmit powers for D2D transmitters. The proposed algorithm guarantees the QoS of cellular users.

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