Spatial Reuse Based Resource Allocation in Device-to-Device Communications

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Abstract. Device-to-Device (D2D) communications have attracted more concern recently, since it provides a supplemental paradigm of short range communications for the current cellular networks. In D2D communications information bits are directly transmitted between devices without traversing base station (BS). As a result, D2D communications can potentially facilitate the improvement of the network capacity, extension of the network coverage, enhancement of the spectrum efficiency, and the energy efficiency as well. It also works well for couple of new applications, such as information exchange between devices in Internet of Things (IoT) and low delay video content sharing. From the perspective of resource allocation in D2D communications, multiple D2D users (DUs) may reuse the same resource of cellular users (CUs). Thus, we put our focus on the spatial reuse resource allocation in this paper. We formulate the spatial reuse problem which aims to maximize the system throughput while maintaining the desirable signal-noise-interference-ratio (SINR) at receivers. Accordingly, a greedy based user set selection algorithm is proposed to filter the candidate DU set to further reduce the computation complexity. Simulation results show that the cellular network can achieve a higher throughput by using our proposed scheme.

Keywords: Device-to-device communications · Resource allocation · Spatial reuse

1 Introduction

With the development of mobile Internet and the continuous improvement of terminal functions, many new technologies have emerged with demanding, such as the Internet of things, IoT. These service providers are offering a variety of applications, and thus frequently changing users' demands, which has been challenging the current wireless communications technologies. In the previous cellular network, communications between the users have to go through the BS. However, nowadays the communications between the equipments are frequently

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carried out in a relatively close range in many scenes, for example, in the Internet of things, many adjacent devices need to connect with others to share information. Device-to-Device communications, as a supplement to cellular networks, which can meet user communications needs, reduce the burden of the network, and improve the overall throughput of the network at the same time [1].

D2D communications enable the users in the cellular network to communicate with the users in his neighborhood through direct link rather than circumvent the BS as the traffic relay. D2D communications can share the wireless resource of cellular networks unlike Bluetooth and WiFi technologies. D2D communications can be easily implemented without making too much changes to the infrastructure of the cellular network while improving the system capacity, lowering the energy consumption of users' handhold devices, enhancing the spectral efficiency, reducing communications delay, and reducing the load of the BS. Owing to the above advantages, D2D communications have attracted a lot of attention.

There are many research topics in the D2D communications technology, such as proximity discovery, connection establishment, access control, mode selection, resource allocation, e.g. [2–4]. The Social-Dependent Chinese Restaurant Process D2D user clustering scheme in [5] used both social information and physical distance information to cluster. Aiming at the problem of resource matching, [6] proposed a fast pairing strategy which can improve the matching speed compared with the previous scheme. [7] provided the clustering scheme based on access strategy after analyzing the important factors like interests, hobbies, location and equipment abilities which affected the behavior of users. Authors discussed applications of D2D communications in heterogeneous networks [8]. In addition, D2D communications were also applied to enhance the conventional multicast scheme for delivering video content in 4G networks [9–11].

A lot researchers have already done some work about spatial reuse in ad-hoc networks and wireless mesh networks, e.g. [12,13]. As the network structure and the attribute of nodes in the ad-hoc networks are different from those in the cellular network, those research findings cannot be used directly to analyze the spatial reuse in cellular networks. However, there are also researches on spatial reuse in D2D communications in cellular networks recently from different perspectives. Authors in [14] proposed the semi-distributed resource allocation scheme to maximize the spatial reuse of radio resource in the D2D communications which is in the overlay mode. To exploit spatial reuse and maintain fairness among D2D pairs, a resource scheduling algorithm was also studied in [15]. A two-stage resource management scheme was proposed in [16], which aims to maximize the resource efficiency in a hybrid mode of underlay and overlay. Researchers in [17] demonstrated the spatial reuse gain through joint mode selection and resource allocation. Graph coloring theory was applied to analyze the spatial reuse cellular resource in [18,19]. A location dependent resource allocation scheme in [20] considered the mobility of D2D communications. Although the spatial reuse in D2D communications has been studied from different perspectives, few people study the problem that how to choose appropriate D2D pairs when one CU's resource can be reused by multiple D2D pairs. We study the problem and give the solution.

In this paper, we first formulate the problem of resource allocation based on spatial reuse with the objective of maximizing the throughput of cellular network by allowing the simultaneous transmission of D2D users (DUs) on the same resource while ensuring the SINR demand at receivers. Then the problem becomes to select a group of appropriate DUs to reuse the resource of each CU and guarantee the communications quality of each DU and CU at the same time. A greedy algorithm is proposed to solve the problem, based on which we can obtain the results of resource allocation for D2D communications. Simulation results confirm that a higher system throughput can be obtained by using the proposed spatial reuse based scheme compared to the benchmark.

The remaining part of this paper is organized as follows: we describe the system model and analyze the interference at D2D receivers and the BS in Sect. 2. In Sect. 3, we formulate the resource allocation problem and Sect. 4 propose a greedy based user set selection algorithm to solve it. Section 5 present the simulation result and Sect. 6 gives the conclusion of this paper.

2 System Model

In this section, we describe the system model and analyze the interference between CU and D2D pair, D2D pair and D2D pair using the same resource in the scenario.

We investigate spectrum sharing for D2D communications underlay in cellular networks as depicted in Fig. 1. Assume the eNB is in the center of the cell, the users are divided into two types, CUs and DUs. CUs and DUs are randomly located

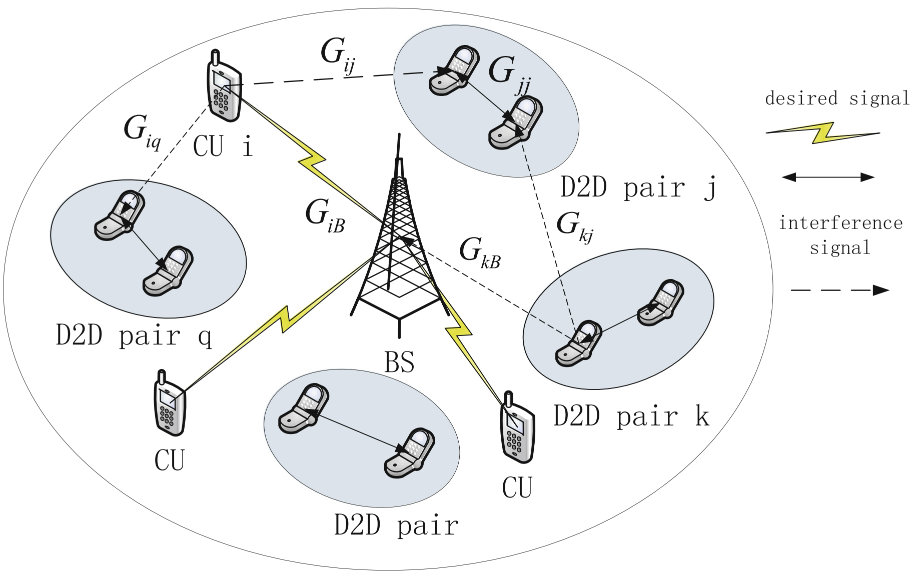

Fig. 1. System model.

around the center. There are M CUs represented by $C = \{1, 2, ..., i, ..., M\}$, and J D2D pairs denoted by $D = \{1, 2, ..., j, ...J\}$. Every D2D pair consists of a transmitter D^t and a receiver D^r. The distance between the D2D transmitter and the D2D terminal of the same D2D pair should be less than the maximum distance constraint of D2D communications, thus ensuring the QoS for D2D communications.

In particular, uplink resource reusing is adopted in this paper, since uplink spectrum is under-utilized compared to that of the downlink in the frequency division duplexing (FDD) based cellular systems [21]. A resource block (RB) is the basic unit for the radio resource allocation which represents one subchannel of the uplink band. The BS is responsible for allocating RBs for CUs based on their requests. DUs then can reuse the uplink resource of these CUs. Different from previous studies where each DU can only reuse the resource of one CU, we assume that each DU can reuse the uplink resource of a plurality of CUs and the uplink resource of each CU can be multiplexed by multiple DUs as well in this model.

We assume a fully loaded cellular network scenario like [22,23]. For the CUs, the system assign them the same number of RBs, that is the orthogonal frequency bands. CU i uses the assigned RBs to communicate with the BS. And then in order to benefit from spatial reuse, we define a set of D2D pairs K_i ($K_i \subset D$), which means that only the D2D pairs in K_i can reuse the RBs of CU i for D2D communications.

We assume that the BS can obtain accurate channel state information of all the links in the network by nodes reporting. The large scale path loss model based on physical distance is considered for the channel fading.

Next, we analyze the only problem of the interference in cellular networks after D2D communications are adopted. Since a D2D pair reuse the uplink resource of CUs, the interference from the D2D transmitter to the cellular uplink is mainly the interference to the BS. For one of the D2D pairs j, the channel power gain between the DU transmitter D_j^t and the base station is G_{jB}. The interference caused by spatial reuse of cellular user's allocated RBs, to the BS can be expressed as $\sum_{j \in K_i} P_d G_{jB}$. Therefore, the received SINR at the BS is:

$$\gamma_i^c = \frac{P_c G_{iB}}{\sum_{j \in K_i} P_d G_{jB} + \sigma^2}. \tag{1}$$

P_c is the transmit power of CU i, G_{iB} denotes the channel power gain between the CU and the BS, P_d represents the transmit power of D2D transmitter D_j^t, the channel power gain between the D2D transmitter and the BS is represented by G_{jB}, and σ^2 is the power of noises. For receiver of any D2D pair in K_i, the interference comes from the corresponding CU i who share its RBs with it and other D2D transmitters in K_i. For D2D pair j, the interference to the DU receiver D_j^r is $\sum_{k \neq j, k \in K_i} (P_d G_{kj} + P_c G_{ij})$, where G_{ij} is the channel power gain between CU and D_j^r, G_j the channel gain between D_j^t and D_j^r and G_{kj} the channel gain between D_k^t and D_j^r. Then, the SINR at D_j^r can be expressed as:

$$\gamma_{ji}^d = \frac{P_d G_j}{\sum_{k \neq j, k \in K_i} (P_d G_{kj} + P_c G_{ij} + \sigma^2)}. \tag{2}$$

In order to guarantee the communications quality, the SINR at BS and D2D receivers are required to satisfy the desired SINR demand when they reuse the same RBs which can be constrained by $\gamma_{\mathrm{i}}^{c} \geq \gamma_{\min}^{c}$ and $\gamma_{j}^{d} \geq \gamma_{\min}^{d}$, respectively. $\gamma_{\min}^{c}$ is the desired SINR demand for cellular and $\gamma_{\min}^{d}$ for D2D.

3 Resource Sharing Between CUs and D2D Pairs

Based on the above mathematical model, this paper presents a resource allocation scheme. Next, we describe the scheme in detail.

3.1 Problem Formulation

Recall the description above, since each CU uses orthogonal frequency band resource that has been assigned by the system, there is no interference between users when they communicate in different frequency bands, and D2D pairs can use different resource to communicate, i.e., one D2D pair can be assigned the resource of multiple CUs in the resource allocation for D2D communications. Therefore, the problem above can be divided into M subproblems, namely, finding out the set of D2D pairs which can reuse resource of each CU to maximize the sum rate of the combination R_i. This can make the network system throughput to reach the maximum. CU i and D2D pair set K_i share the same frequency band resource, which causes interference with each other in the communications as analyzed before. The co-channel interference are different to the set of D2D pair set K_i and CU i as a whole when different D2D pair is added to K_i. We need to consider the D2D pair selection process in this case: which D2D pair group can reuse the resource of CU i that can maximize the sum rate of the CU i and D2D pairs while guaranteeing the communications quality of both CU and D2D pairs, that is $\gamma_{\mathrm{i}}^{c} \geq \gamma_{\min}^{c}$ for CU i and $\gamma_{j}^{d} \geq \gamma_{\min}^{d}$ for any D2D pairs in K_i. Therefore, the problem is converted to the problem of selecting appropriate D2D pairs to obtain the maximum sum rate of CUs and D2D pairs.

3.2 Problem Derivation

Resource of every CU can be reused by multiple D2D pairs, while each D2D pair can also reuse resource of multiple CUs. We have assume that all the DUs are capable of reusing the resource of CU i as a set K_i ($K_i \subset D$). The transmission rate of each uplink cellular link can be represented as:

$$R_i^c = \log_2\left(1 + \frac{P_c G_{iB}}{\sum\limits_{j=1}^{J} l_{ji} P_d G_{jB} + \sigma^2}\right), \tag{3}$$

where $l_{ji} \in \{0,1\}$ with $l_{ji} = 1$ means that the D2D pair j is in set K_i, and $l_{ji} = 0$ the opposite. On the other hand, the transmission rate of each D2D pair obtained by reusing resource of CU i is:

$$R_{ji}^{d} = l_{ji} \log_2 \left(1 + \frac{P_d G_j}{\sum\limits_{\substack{k=1 \\ k \neq j}}^{J} l_{ki} P_d G_{jk} + P_c G_{ij} + \sigma^2} \right). \tag{4}$$

The sum rate of CU i and D2D pairs which reuse its resource is:

$$R_i = R_i^c + \sum_{j=1}^{J} R_{ji}^{d}. \tag{5}$$

We have assumed that each CU will be assigned resource by the system, as mentioned before, and DUs can reuse resource of more than one CU. The total system throughput can be expressed as:

$$R = \sum_{i=1}^{M} R_i = \sum_{i=1}^{M} R_i^c + \sum_{i=1}^{M} \sum_{j=1}^{J} R_{ji}^{d}. \tag{6}$$

Note that, although we have assumed a fully loaded cellular network scenario before, the scheme can also be used for other scenarios. We can formulate the resource allocation problem as below:

$$(l_{11}, l_{12} \ldots l_{ji} \ldots l_{JM}) = \text{ argmax } R \tag{7}$$

Subject to

$$\gamma_{\mathrm{i}}^{c} \geq \gamma_{\min}^{c} \qquad \forall i \in C, \tag{8}$$

$$\gamma_{j}^{d} \geq \gamma_{\min}^{d} \qquad \forall j \in K_{\mathrm{i}}, \tag{9}$$

$$l_{ji} \in \{0,1\} \qquad \forall j \in D. \tag{10}$$

Our goal is to calculate appropriate l_{ij} values to leverage the system throughput. The expression $\gamma_{\mathrm{i}}^{c} \geq \gamma_{\min}^{c}$ means that when the CU communicates with the BS, the received SINR need to be greater than $\gamma_{\min}^{d}$. Similarly, $\gamma_{j}^{d} \geq \gamma_{\min}^{d}$ indicates that when the D2D pairs communicate with each other, the SINR at the receiver should be greater than $\gamma_{\min}^{d}$, otherwise the D2D pair cannot reuse the resource.

4 The Matching Problem Between CU and D2D Pairs

In this section, we describe the problem and introduce the greedy based user set selection algorithm and give an example to illustrate it.

4.1 Problem Description

According to the description of the previous paragraph. The problems we are facing can be described in this way. Resource of CU can be reused by multiple D2D pairs, the reuse of resource improves the system throughput. But, Due to the use of same channel, users interfere with each other. The more D2D pairs join to reuse, the more serious the interference will be. In order to ensure the quality of communications, only part of the D2D pairs can be able to reuse resource. Therefore, in order to improve the throughput of the system and guarantee the user's communications quality, appropriate D2D pairs which can reuse resource need to be choosen by calculation.

4.2 Greedy Based User Set Selection Algorithm

It is very difficult to find the optimal solution of the problem above directly. Now, we present a greedy algorithm for solving the proposed problem. A greedy based user set selection algorithm (GUS-algorithm) is an algorithm that follows the problem solving heuristic of making the locally optimal choice at each stage with the hope of finding a global optimum. In many problems, the greedy strategy can not produce an optimal solution in general, but it is still a greedy heuristic that may produce a locally optimal solution in a reasonable time to approximate the global optimal solution. As presented in Algorithm 1, this algorithm starts with setting up an empty set K_i, which represents the set of D2D pairs who will reuse the resource of CU i, and then set a set $D = \{1, 2...j...J\}$ which is the candidate D2D pair set. At first step, the D2D pairs in D will be sorted according to the channel gain information G_{jB} on the basis of descending order. Then the D2D pairs with smaller G_{jB} values will be in the front, and each step will be carried out in accordance with this order in the next calculation process. Calculate the sum rate of CU i and all the D2D pairs in K_i in case of one D2D pair j joins K_i for every D2D pair j in D. Then we have the results of every D2D pairs in D. Since our goal is to leverage the sum rate of the CUs and D2D pairs, we choose the only one DU j^* which can maximize the sum rate at each step. On the other hand, we still need to verify that the DU j^* we have chosen can meet the needs of communications quality for CU i, D2D pairs in set K_i and itself. If the SINR value of anyone mentioned above is below the desire SINR demand, the chosen D2D pair j^* cannot join K_i, and it will be removed from D, and otherwise it can stay in K_i and we still remove it from D. After the set K_i and D are updated, and the same process will continue until the set D is empty. Then set $l_{ji} = 1$ for the D2D pair j^* successfully joining in K_i, and otherwise $l_{ji} = 0$.

4.3 Algorithm Example

In order to illustrate this scheme more clearly, let us give a simple example to illustrate the algorithm. Assume that there are 10 CUs and 10 D2D pairs in a cellular network cell, the CUs are assigned the same amount of the resource. CUs uses the orthogonal frequency band, and each D2D pair can reuse resource

Algorithm 1. Greedy based user set selection algorithm

$K_i \Leftarrow \emptyset$
$D \Leftarrow \{1, 2...j \cdots J\}$
for all $j \in D$ **do**
  sort D2D pair in D according to G_{jB}
end for
return *sorted* D
while $D \neq \emptyset$ **do**
  $j^* \Leftarrow \arg\max_{j \in D} R_i$
  $K_i \Leftarrow K_i \cup \{j^*\}$
  if $\gamma_i^c \geq \gamma_{\min}^c$ **then**
    if $\gamma_j^d \geq \gamma_{\min}^d$ for all $j \in K_i$ **then**
      $l_{j^*i} = 1$
    else
      $l_{j^*i} = 0$, $K_i \Leftarrow K_i - \{j^*\}$
    end if
  else
    $l_{j^*i} = 0$
    $K_i \Leftarrow K_i - \{j^*\}$
  end if
  $D \Leftarrow D - \{j^*\}$
end while
return l_{1i},l_{2i}...l_{Ji}

of multiple CUs. So, the resource allocation for D2D can be converted to choose the optimal D2D pairs to reuse resource of each CU. That is to say, the same selection process is needed to be carried out for each CU. For CU 1, there are 10 D2D pairs who may reuse the resource. So we set up a set $D = \{1, 2...j...10\}$ which means the candidate D2D pairs, and set an empty set $K_1 = \{\}$ which will be added the feasible D2D pairs. First, we sort the 10 D2D pairs in D according to the channel gain G_{jB} in descending order, then we get an ordered list of D2D pairs, for example, $D = \{2, 4, 1, 5, 3, 6, 7, 9, 8, 10\}$. The next calculation carried out in this order. We assume that D2D pair 2 in the set D is reusing the resource of the CU 1, and use the formula (5) mentioned above to calculate the sum rate of CU and DUs. In the same way, we assume other D2D pairs 4,1...10 to reuse the resource of CU 1 respectively. By comparing these ten rate results, we choose the D2D pair which has the maximum value. Next, suppose D2D pair 2 is selected, it needs to verify that the SINR of CU 1 and D2D pair 2 satisfy the conditions. If the conditions are fulfilled, then D2D pair 2 is added to set K_1, else, it is ruled out to reuse the resource.

After several calculations, assume that there has been three D2D pairs in K_1, as $K_1 = \{2, 4, 5\}$ and $D = \{6, 7, 9\}$. To continue to execute the algorithm, we calculate the sum rate of CU 1 and D2D pair 2, 4, 5, 6 supposing D2D pair 6 to join to reuse the resource. Similarly, we also do this for D2D pair 7 and 9. Then choose D2D pair 6 which has the max sum rate and verify the SINR demands of CU 1 and D2D pair 6, 2, 4, 5 are met. If the conditions are satisfied, 6 joins K_1, else it should be removed. Continue to repeat the calculation process mentioned above until the set D is empty.

Iterate the algorithm for each CU in C, and the D2D pair set which can reuse its resource is determined, and thus we complete resource allocation for D2D users.

5 Numerical Simulation and Performance Analysis

In this part we set up the simulation to verify the performance of the proposed scheme. The simulation scenario is set up in a cellular network whose radius is 500 m, where users are randomly distributed within this range. The BS is located in the center of the circle. The spectral density of the noise is set to −174 dBm/Hz. At simulation initialization, D2D links are randomly generated with the constraint that the distance between the transmitter and the receiver of each D2D pair is less than 40 m. According to the large scale path-loss model, all link channel gains are related to the distance. Assume the large scale path-loss exponent between the BS and CU to be $\alpha = 3.5$ and that of D2D pair is $\alpha = 4$. The channel power gain between the cellular users and the BS is $G_{cB} = {d_{cB}}^{-\alpha}$, where d_{cB} is the distance between them. Similarly, $G_{cd} = {d_{cd}}^{-\alpha}$ stands for the channel power gain between CUs and the D2D receiver, where the distance between them is d_{cd}. The channel power gain between D2D pairs is denoted as $G_{dd} = {d_{dd}}^{-\alpha}$, where d_{dd} represents the distance between them. The uplink resource are assigned to CUs for cellular network communications according to the round robin scheduling, and based on the proposed scheme, these resource are reused by D2D pairs. We assume that the transmit power of CUs and D2D transmitters are, respectively, 200 mw and 10 mw. The desired SINR demand of cellular link and D2D links are 10 dB and 5 dB, respectively. The benchmark scheme is a simple resource allocation scheme without considering the optimization of spatial reuse. In this scheme, the system chooses the D2D pairs to reuse the resource of CUs randomly, which also need to ensure the communications quality requirements of the CUs and the D2D pairs at the same time. Our simulation is averaged over 1000 random trials.

Figure 2 shows the system throughput performance varying with different number of CUs. With the increase of the number of CUs, the overall throughput gradually increases, because the available wireless resource for D2D communications are increasing. As shown in the figure, the blue line with triangular pattern is the spatial reuse resource allocation scheme which uses the GUS-algorithm and the red line with square pattern is the benchmark scheme which choose the D2D pair to reuse in a random fashion. With the increase of M, the growth rate of the two schemes is similar, which is mainly because the number of D2D pairs remains unchanged, and thus the interference level between the two scheme is the same, and the number of reusable resource is increasing. The number of D2D pairs which can reuse the resource is subject to the desired SINR demand of CUs and D2D pairs, so the composition of set K_i is important to the system throughput. In the proposed scheme, the D2D pairs which can reuse the resource

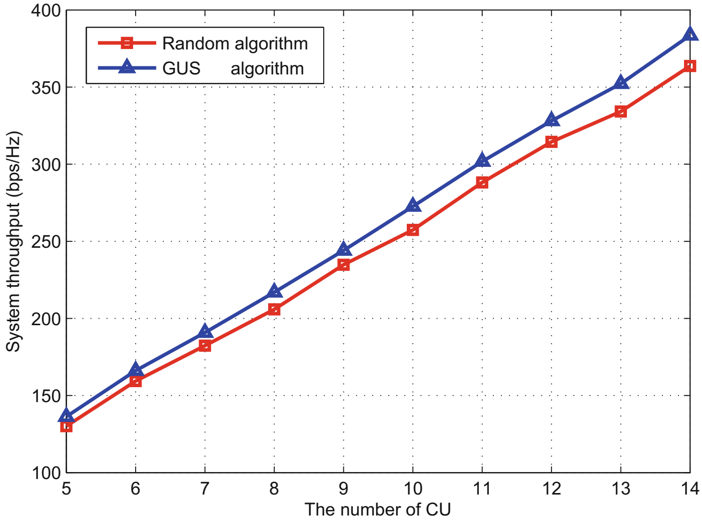

Fig. 2. System throughput versus number of CUs. (Color figure online)

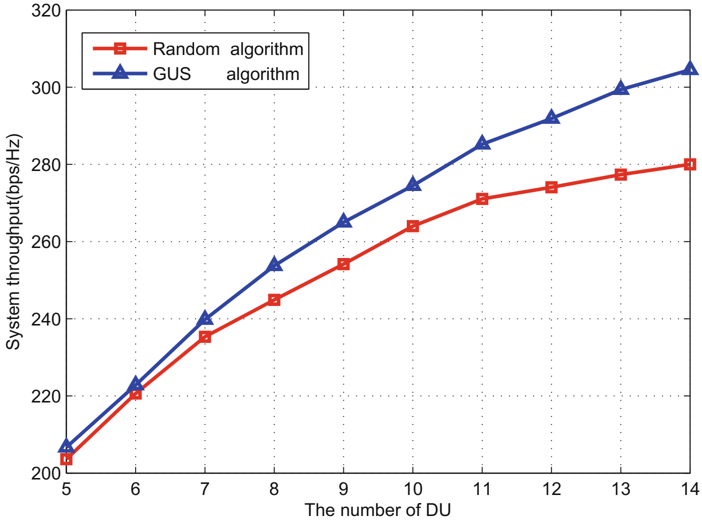

Fig. 3. System throughput versus number of DUs.

of CU are selected by the algorithm which aims to maximize the sum rate. We can see that the overall performance of the proposed scheme is better than the benchmark one.

Figure 3 indicates the relationship between the system throughput and the number of D2D pairs when the number of CUs is fixed at $M = 10$. As can be seen from the graph, the overall throughput of the network is increasing when the number of D2D pairs increases. This is because the increase in the overall number of D2D pairs lead to an increase number of D2D pairs that can reuse the RBs of CUs. However, with the growth of D2D pairs, the interference the CUs also increase. The system throughput may not grow rapidly considering the SINR demand of the CUs and D2D pairs. In the proposed scheme, D2D pairs are selected to reuse the RBs of CUs which can make the sum rate to reach the maximum at each iteration of D2D resource allocation algorithm. On the other hand, the benchmark scheme did not consider choosing the best D2D pair to reuse resource. The performance of the proposed scheme is better than the benchmark one, especially with the increasing number of D2D pairs.

6 Conclusions

In this paper, we proposed a spatial reuse resource allocation scheme for D2D communications in cellular networks. We presented a greedy based user set selection algorithm to select appropriate D2D pairs to reuse the resource of CUs so as to maximize the throughput. More specifically, the basic communications quality is also guaranteed to satisfy the minimum required SINR for both CUs and D2D pairs. The results of the simulation show that the cellular network can obtain a better network throughput by using the proposed scheme.

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