

Resource Allocation for Cooperative Relay based Wireless D2D Networks with Selfish Users

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Abstract

This paper considers a scenario that more D2D users exist in the cell, they compete for cellular resources to increase their own data rates, which may cause transmission interference to cellular users (CU) and the unfairness of resource allocation. We design a resource allocation scheme for selfish D2D users assisted by cooperative relay technique which is used to further enhance the users' transmission rates, meanwhile guarantee the QoS requirement of the CUs. Two transmission modes are considered for D2D users: direct transmission mode and cooperative relay transmission mode, both of which reuses the cellular uplink frequency resources. To ensure the fairness of resource distribution, Nash bargaining theory is used to determine the transmission mode and solve the bandwidth allocation problem for D2D users choosing cooperative relay transmission mode, and coalition formation game theory is used to solve the uplink frequency sharing problem between D2D users and CUs through a new defined "Selfish order". Through theoretical analysis, we obtain the closed Nash bargaining solution under CUs' rate constraints, and prove the stability of the formatted coalition. Simulation results show that the proposed resource allocation approach achieves better performance on resource allocation fairness, with only little sacrifice on the system sum rates.

Keywords: D2D networks, selfish users, cooperative relay, resource allocation, fairness

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1. Introduction

With the drastic growth of intelligent mobile device applications such as video streaming and file downloading, users have much higher requirements on transmission data rates than before. Device-to-Device (D2D) communication, which was defined as direct communication between two users without traversing the Base Station or core network [1], has brought much attention in recent years for its good properties on improving spectral efficiency and energy efficiency, increasing cellular network capacity, and D2D communication technology appears to be a promising technology in 5G cellular networks [2]. However, the interference management becomes more complicated due to the transmission resource sharing between traditional CUs and D2D users.

The majority of researches use the in-band underlay sharing method [1] in D2D systems, where cellular resources are allocated for both cellular and D2D communication, for improving the systems' sum rate using some optimization algorithms[3-7]. The work in [3] proposed an interference graph based resource allocation algorithm to obtain a network sum rate that approaches the optimal system sum rate. In [4-6], researchers utilized coalition formation game theory to increase the system achievable sum rate. The work in [4] modeled the joint mode selection and spectrum sharing problem as a coalition game. In [5], D2D users cooperated with each other to form a coalition to win the preferred spectrum resources. The work in [6] proposed a coalition game based algorithm to achieve sub-optimal system sum rate. In [7], an iterative combinatorial auction game based allocation mechanism was introduced to optimize the network sum rate.

Due to the resource sharing mechanism, prior works also considered some sharing methods under the situation that selfish D2D users compete for the CUs' frequency resources. In [5], each D2D pair intended to maximize its own utility through the cooperation with other pairs to form a user group using coalition game. In [8], the cellular users which viewed as leaders charged some fee for the D2D users viewed as followers, and a Stackelberg game based resource allocation scheme was proposed to group one CU and one D2D pair to form a leader-follower pair. In [9], each CU was assigned a resource block, selfish D2D users bid for every resource block with a bidding value consisted of achievable throughput, and a sequential second price auction based allocation approach was proposed to improve system sum rate. In [10], researchers proposed a detection approach for selfish attack in cognitive radio ad-hoc networks. However, in D2D cellular networks, the cellular users share the transmission frequency resources with several D2D pairs, which is different from cognitive radio networks.

In D2D cellular networks, the scarcity of spectrum resources becomes more serious as users in one cell grow rapidly, more D2D users will choose to use the transmission resources of CUs which causes severe deterioration to CUs' QoS. In addition, users in cellular networks always hope to obtain higher transmission rates to meet the application requirements such as videos or games. Selfish D2D users prefer to select the transmission frequency with which they can get higher rates. Consequently, the resource allocation efficiency and fairness become worse if more D2D users choose one same transmission frequency, which causes severe impact to users' QoS and the overall networks performance. Thus, the sharing scheme must be carefully designed for D2D cellular networks, especially in large scale scenarios.

In this paper, we propose a joint resource allocation and uplink frequency sharing approach with CUs' data rates constraint in dense D2D networks. To further increase network

throughput, D2D source node can communicate with its destination under the help of a relay node, which is also a D2D user. So the cooperative relay transmission mode is allowed for D2D users if they can get higher transmission rates. Considering the selfishness of D2D users, Nash bargaining theory is used to determine the transmission mode for D2D pairs between cooperative relay mode and direct transmission mode, and solve the fair resource allocation problem for the D2D pairs which have selected cooperative relay transmission mode. This mode selection scheme we proposed can be simply extended to the scenarios which contain other transmission modes such as cellular mode or dedicated mode [11]. Then the coalition formation game is used for selfish D2D users to choose a cellular uplink frequency resource with which they can increase their data rates. User coalition is defined as a cellular user and several D2D pairs which have the same transmission frequency. We propose a new defined “selfish order” to effectively model the process of selfish D2D pairs selecting a preferred coalition. The selfish order allows the D2D pairs select a coalition in which they can get higher rates, without decreases the system sum rate. Finally, the efficiency of the joint resource allocation and coalition selection algorithm is verified through simulations.

The rest of the paper is organized as follows. In Section 2, we describe the cooperative transmission model, and formulate the resource allocation and mode selection problem under CU’s rate constraint in one coalition scenario. In Section 3, multiple coalitions scenario is proposed, where we describe the coalition selection process of the D2D pairs. Simulation results are presented in Section 4 to describe the performance of the proposed approach. Finally, Section 5 concludes the paper.

2. One Coalition Case

2.1 Scenario Description

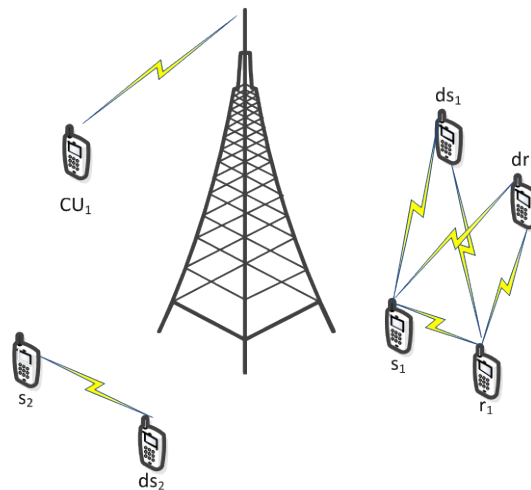


Fig. 1. System model of D2D communications sharing uplink frequency resource of CU

We consider a single cell scenario where the CUs share the uplink frequency resource with D2D links via underlay scheme. As depicted in Fig. 1, there are one cellular user \mathbf{CU}_1 , one D2D pair (s_2, ds_2) and one relay D2D pair $(s_1, ds_1; r_1, dr_1)$ which share the uplink frequency resource of \mathbf{CU}_1 . The relay D2D pair consists of two D2D pairs. All D2D links, (including

the link (s_1, ds_1) , (r_1, dr_1) , (s_1, r_1) , (s_1, dr_1) , (r_1, ds_1) and (s_2, ds_2) , satisfy a maximum distance constraint. User coalition is defined as the union of one CU and several D2D pairs sharing the same radio frequency. In one coalition, if one D2D pair is using the cellular uplink frequency resource, other D2D pairs in the same coalition should keep in silent state [8, 12]. During the uplink period of the cellular network, CU_1 transmits data to the base station which suffers the interference from s_1 or s_2 or r_1 . Also, D2D destination node ds_1 or ds_2 or dr_1 is exposed to interference from CU_1 . For the D2D pair, s_2 directly transmits signal to ds_2 . For the relay D2D pair, s_1 and r_1 can either use direct transmission to communicate with ds_1 and dr_1 , or use cooperative relay transmission with each other's help. Here we assume that source and relay node are fixed to each other according to some relay selection algorithm. The dynamic relay selection scenario will be considered for extended research.

2.2 Cooperative transmission model

In this paper, we adopt the cooperative relay transmission policy and the frame structure proposed in [13], which uses AF protocol in two consecutive frames. Each frame consists of N time slots and is assigned to one node. Without loss of generality, we use s and r to represent the D2D source nodes and their relays. The frame structure is depicted in Fig. 2. Node s takes out n_s time slots to relay its partners' messages with relay power P_s' . So s transmits its own messages in the first $N - n_s$ time slots with power P_s . The first n_r time slots of messages are relayed by the partner through cooperative relay mode, the following $N - n_s - n_r$ time slots of messages are transmitted to the destination through direct transmission mode. Note that this time slots allocation scheme is under the situation that node s is the source node and r is the relay node. The same time slots allocation method is also applied to the situation that r is the source node and s is the relay node. Node s and r play the same role.

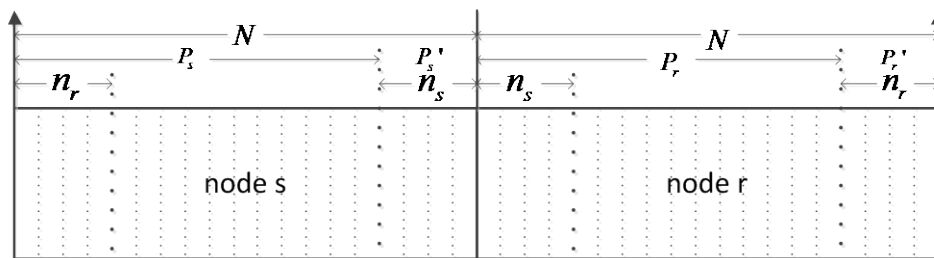


Fig. 2. Frame structure of D2D cooperative relay mode [13]

For the first n_r slots of node s , the received signal of node ds and r can be represented as

$$y_{s,r} = \sqrt{P_s g_{s,r}} x_s + z_{s,r} + \sqrt{P_c g_{c,r}} x_c \tag{1}$$

$$y_{s,ds} = \sqrt{P_s g_{s,ds}} x_s + z_{s,ds} + \sqrt{P_c g_{c,ds}} x_c \tag{2}$$

where x_s , x_c represents the transmitted signal of the D2D user node s and the CU with unit power; P_c is the transmission power of the CU; $g_{i,j}$ is the channel gain between node i and j ; $z_{i,j}$ is the additive noise of link (i, j) . $g_{i,j} = d_{i,j}^{-\alpha} \cdot |h_0|^2$, where $d_{i,j}$ is the distance of link (i, j) , α is the path loss exponent, and h_0 is the complex Gaussian channel coefficient that obeys the distribution of $\mathbf{CN}(0,1)$.

For the last n_r slots of node r , it relays the message received in the first n_r slot of s to ds . The received signal of node ds for these slots is

$$y_{r,ds} = \sqrt{P_r} g_{r,ds} x_r + z_{r,ds} + \sqrt{P_c} g_{c,ds} x_c \quad (3)$$

where x_r is the transmitted relay signal for node s with normalized unit power. In addition, we assume the noise of different links have the same variance σ^2 . After the two transmitted frames, node ds combines the two received signal using maximum ratio combining technology with the SNR as [13, 14]

$$\Gamma_{s,ds} = \gamma_{s,ds} + \gamma_{s,r,ds} \quad (4)$$

$$\gamma_{s,ds} = \frac{P_s g_{s,ds}}{\sigma^2 + P_c g_{c,ds}} \quad (5) \quad \gamma_{s,r,ds} = \frac{\frac{P_s g_{s,r}}{\sigma^2 + P_c g_{c,r}} \cdot \frac{P_r g_{r,ds}}{\sigma^2 + P_c g_{c,ds}}}{\frac{P_s g_{s,r}}{\sigma^2 + P_c g_{c,r}} + \frac{P_r g_{r,ds}}{\sigma^2 + P_c g_{c,ds}} + 1} \quad (6)$$

For node r , the corresponding received signal and the SNR at dr can be obtained through the same method as above.

The transmission data rates for D2D users s and r under cooperative relay mode can be written as

$$R_s^c = \frac{1}{LN} \left[n_r \log_2(1 + \Gamma_{s,ds}) + (N - n_s - n_r) \log_2(1 + \gamma_{s,ds}) \right] \quad (7)$$

$$R_r^c = \frac{1}{LN} \left[n_s \log_2(1 + \Gamma_{r,dr}) + (N - n_r - n_s) \log_2(1 + \gamma_{r,dr}) \right] \quad (8)$$

The transmission data rates of s and r under direct transmission mode are

$$R_s^d = \frac{1}{L} \log_2 \left(1 + \frac{P_s g_{s,ds}}{\sigma^2 + P_c g_{c,ds}} \right) \quad (9)$$

$$R_r^d = \frac{1}{L} \log_2 \left(1 + \frac{P_r g_{r,dr}}{\sigma^2 + P_c g_{c,dr}} \right) \quad (10)$$

where L is the number of D2D pairs in the coalition.

2.3 Problem Formulation

In one coalition scenario, D2D users should select a transmission mode where they choose from direct transmission mode and cooperative relay mode for higher transmission rates. If the cooperative relay mode is chosen by a relay D2D pair, the allocation of n_s and n_r directly affects the transmission rate of node s and node r . The selfishness of D2D users requires that both of the two nodes can increase their data rates through the allocation of n_s and n_r in a fair manner. So, this process can be seen as a two users' bargaining game. In addition, the interference caused by D2D users should not decrease the CU's transmission rate. Thus, Nash bargaining game (the solution of which provides a Pareto optimal payoff distribution [13]) under CU's QoS constraint is adopted to solve this problem, and the utility function is expressed as follows:

$$\max_{n_s, n_r, P_s, P_r, P_s', P_r'} \prod_{i=s,r} (R_i^c - R_i^d) \quad (11)$$

subject to

$$R_i^c \geq R_i^d \quad (12)$$

$$\log_2 \left(1 + \frac{P_C g_{CB}}{\sigma_C^2 + P_s g_{sB}} \right) \geq R_{th} \quad (13)$$

$$\log_2 \left(1 + \frac{P_C g_{CB}}{\sigma_C^2 + P_s' g_{sB}} \right) \geq R_{th} \quad (14)$$

$$\log_2 \left(1 + \frac{P_C g_{CB}}{\sigma_C^2 + P_r g_{rB}} \right) \geq R_{th} \quad (15)$$

$$\log_2 \left(1 + \frac{P_C g_{CB}}{\sigma_C^2 + P_r' g_{rB}} \right) \geq R_{th} \quad (16)$$

where R_{th} is the CU's data rate requirement. R_i^c or R_i^d in the game can be considered as the solution if the bargaining process is successful or failed. (11) is the standard utility function of the Nash bargaining game, which maximizes the players' benefits through the bargaining process, and the solution of (11) is the Nash bargaining solution which is fair and Pareto optimal [13, 22]. Constraint (12) ensures that the data rate of D2D pairs which have selected cooperative relay mode is higher than that under direct transmission mode. Constraints (13) – (16) are to protect CU from the interference of the D2D source and relay nodes in all time slots. Note that R_i^d represents the direct transmission mode rate of D2D users in this one coalition scenario, but it can be extended to other transmission mode rate such as cellular mode or dedicated mode [11].

2.4 Resource Allocation in One Coalition

From (9) (10), we can see that if the number of D2D pairs L is given, D2D pair's data rate under direct transmission mode R_i^d is only related to the transmission power. If direct transmission mode is selected, D2D users would like to use the maximum power to increase their own data rates. And the maximum transmission power of D2D user in each time slot can be obtained through (12) – (16) for both of the two transmission mode. So R_i^d in (11) can be seemed as a constant value, and the maximum value of (11) can be obtained if and only if R_i^c can reach the maximum value, which can be acquired by maximizing P_s , P_s' , P_r and P_r' according to (4) – (8) and (12) – (16). As in [13], assume $A = \log_2(1 + \gamma_{s,ds})$, $B = \log_2(1 + \Gamma_{s,ds})$, $C = \log_2(1 + \gamma_{r,dr})$, $D = \log_2(1 + \Gamma_{r,dr})$, $G = B - A$, $H = D - C$. So, (11) can be translated into

$$\max_{n_s, n_r} \prod_{i=s,r} (R_i^c - R_i^d) \quad (17)$$

subject to

$$R_i^c \geq R_i^d$$

So we can obtain the transmission mode selection and resource allocation scheme by solving (17).

Proposition 1: In one coalition scenario, if $GH > AC$ and

$$\max \left\{ \frac{(D-C)(R_s^d \cdot LN - NA) + A(R_r^d \cdot LN - NC)}{[GH - AC]}, \frac{C(R_s^d \cdot LN - NA) + (B-A)(R_r^d \cdot LN - NC)}{[GH - AC]} \right\} \leq N,$$

D2D pairs select the cooperative relay transmission mode, and

$$n_s = \left\lfloor \frac{N \left(\frac{C}{D} + \frac{G}{B} \right) + \frac{N (LR_s^d - A)(BC - DG)}{2 B(GH - AC)} + \frac{N (LR_r^d - C)(DG - BC)}{2 B(GH - AC)}}{1} \right\rfloor$$

$$n_r = \left\lfloor \frac{N \left(\frac{H}{D} + \frac{A}{B} \right) + \frac{N (LR_s^d - A)(BH - DA)}{2 B(GH - AC)} + \frac{N (LR_r^d - C)(DA - BH)}{2 B(GH - AC)}}{1} \right\rfloor;$$

If $GH \leq AC$, or $\frac{(D-C)(R_s^d \cdot LN - NA) + A(R_r^d \cdot LN - NC)}{(GH - AC)} > N$, or

$\frac{C(R_s^d \cdot LN - NA) + (B-A)(R_r^d \cdot LN - NC)}{(GH - AC)} > N$, D2D pairs select direct transmission mode.

Proof: The proof is shown in the Appendix.

3. Multiple Coalitions Case

In multiple coalitions scenario, more than one CU exist in the cell, each of which forms a user coalition with some D2D pairs or relay D2D pairs. Besides the selection of transmission mode, D2D users have to choose a user coalition to obtain transmission frequency resource. Due to the selfishness of D2D users, they prefer the transmission frequency with which they can get higher data rates. So, the coalition which permits higher transmission power according (13) – (16) is always preferred by D2D users. However, if more D2D users choose one same coalition, the data rates of all these users would decrease, which severely affects the performance of the whole network. In this section, we use coalition formation game to solve this problem.

3.1 Coalition Formation Game Formulation

We consider the scenario that the amount of uplink frequency resource in the cell is the same as the number of CUs. However, the proposed approach can be easily extended to the scenario that the frequency resource is enough for the CUs to allow other transmission mode. As mentioned in Section 1, user coalition is defined as the union of one CU and several D2D pairs or relay D2D pairs which use the same transmission frequency. According to (13) – (16), different maximum transmission powers of D2D users are allowed by different CUs. Generally, for a required transmission rate, the CUs which are closer to the base station can endure more interference, so D2D users prefer to join such coalition because they can transmit with higher power to increase their data rates. However, due to the user selfishness, D2D users may join the same coalition, which will decrease the rate gain. In this section, coalition formation game [15-18] with transferable utility [6, 16] is used to propose a selfish approach for D2D users to select a transmission frequency.

Definition 1 (Coalition Formation Game for D2D Frequency Resource Sharing): The coalition formation game is denoted by a two-element vector (Players, Coalition Value) [16] which is defined as follows:

- **Players:** The game players are the set of D2D pairs (note that one relay D2D pair can be considered as two D2D pairs).
- **Coalition Value:** \mathbf{C}_m is defined as the coalition where cellular user m exists. $R(\mathbf{C}_m)$ is the coalition value, which is the sum rate of all the D2D pairs in \mathbf{C}_m . It can be viewed as a transferable utility considering each D2D pairs' transmission rate as the assigned payoff [6].

3.2 Coalition Formation Algorithm

In [15, 16, 18], two transformation rules “merge and split” are adopted in coalition formation game to form a coalition structure that meets certain requirements. In this paper, no more than K coalitions are formed if there're K cellular users in the cell, but ordinary “merge and split” rules may form a collection (Please refer to [15] for the meanings) that the coalition number is more than K , which causes some D2D pairs having no chance to get transmission frequency. In addition, selfish D2D users only care about their own rate gain through coalition selection. Pareto order, which bases the preference on individual payoffs of the players rather than the coalition value [15, 16], is always used to assess a coalition structure and provide a guideline for transformation rules. Based on Pareto order, one player can move to other coalitions to improve its payoff without hurting other players' payoffs. However, in multiple D2D coalitions case, one D2D pair's coalition variation must decrease the D2D pairs' rates in the

new coalition if all coalitions are not empty. For example, consider a scenario where $K - 1$ coalitions contain only one D2D pair and the remaining coalition contains other D2D pairs. This coalition structure can be treated as a collection that is achieved by Pareto order, because any D2D pair's coalition change will decrease some D2D pairs' rates. But apparently, this resource allocation scheme is unfair and not rational for D2D users.

Based on the above discussion, we introduce the concept of "selfish order" \succ_i for each D2D pair i as follows:

Definition 2 (Selfish Order): $\mathbf{C}_{new} \succ_i \mathbf{C}_{old} \Leftrightarrow R_i(\mathbf{C}_{new}) > R_i(\mathbf{C}_{old}) \& \sum_i R_i \geq \sum_i R_i(\mathbf{C}_{old})$

where \mathbf{C}_{new} and \mathbf{C}_{old} denotes the examined new coalition and the original coalition of D2D pair i . $R_i(\mathbf{C}_{new})$ and $R_i(\mathbf{C}_{old})$ are the transmission rates of D2D pair i in \mathbf{C}_{new} and \mathbf{C}_{old} respectively. R_i represents the transmission rate of D2D pair i after the coalition and the transmission mode is determined. $\mathbf{C}_{new} \succ_i \mathbf{C}_{old}$ represents that D2D pair i would like to leave \mathbf{C}_{old} and join \mathbf{C}_{new} .

In the above definition, $R_i(\mathbf{C}_{new}) > R_i(\mathbf{C}_{old})$ means that D2D pair i selfishly choose a coalition to increase its own data rate; $\sum_k R_k \geq \sum_k R_k(\mathbf{C}_{old})$ means the coalition variation of D2D pair i should not decrease the overall D2D network data rates, which increases the overall D2D network throughput and prevents that one or multiple D2D pairs' coalition variations unfairly occupy better transmission resource, and it can be used as a common constraint for all D2D pairs, which also guarantees the convergence of coalition variation process. So the definition implies that D2D pair i prefers being a member of \mathbf{C}_{new} over \mathbf{C}_{old} , if it can get a higher data rate without decreasing the overall network rates. D2D users can follow the newly defined "selfish order" to select new coalitions.

Based on the above mentioned "selfish order", we describe the joint transmission mode and coalition selection algorithm in the following Algorithm 1.

In Algorithm 1, Step 1 is to construct an initial coalition partition in a random manner. Step 2 – 13 are to calculate the transmission rate of D2D pairs in the initial coalition partition. Step 14 – 28 are the coalition variation process. Considering cooperative relay transmission mode is allowed, we first investigate whether the relay D2D pair which contains the chosen D2D pair could join in the new coalition in Step 17 – Step 20. If not, Step 22 – 26 investigate whether the chosen D2D pair could join in the new coalition. Then, repeat the whole process of Step 15 – 27, until the partition converges to the final state, where no change in coalition can be made.

Algorithm 1: The Joint Transmission Mode and Coalition Selection Algorithm for D2D Pairs

- 1: Randomly distribute all the D2D pairs to the coalitions in the cell to form an initial coalition partition;
- 2: **for** each relay D2D pair
- 3: **if** (s, ds) and (r, dr) are in the same coalition
- 4: Calculate the transmission mode and data rate according to Proposition 1;
- 5: **if** the cooperative relay mode is selected

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6:      Calculate  $n_s, n_r$ , and  $R_i^c = R_i = R_i(\mathbf{C}_{old}), i \in \{s, r\}$ ;
7:      else
8:      Set  $n_s = n_r = 0$ , and  $R_i^d = R_i = R_i(\mathbf{C}_{old}), i \in \{s, r\}$ ;
9:      endif
10: else
11: Calculate the transmission rate for  $(s, ds)$  and  $(r, dr)$  respectively under direct
    transmission mode, and  $R_i^d = R_i = R_i(\mathbf{C}_{old}), i \in \{s, r\}$ ;
12: endif
13: endfor
14: repeat
15: Randomly choose one D2D pair  $(s, ds)$ , and denote the assigned relay node by  $r$ ;
16: Randomly choose a new coalition  $\mathbf{C}_{new}$  for  $(s, ds)$ ;
17: Calculate the rate of D2D pair  $(s, ds)$  and  $(r, dr)$  in  $\mathbf{C}_{new}$  using Proposition 1,
    denoted as  $R_s(\mathbf{C}_{new}), R_r(\mathbf{C}_{new})$ ;
18: Set  $R_s = R_s(\mathbf{C}_{new}), R_r = R_r(\mathbf{C}_{new})$ . Update other D2D pairs' rates  $R_i, i \notin \{s, r\}$ ;
19: if  $\mathbf{C}_{new} \succ_s \mathbf{C}_{old}$  and  $\mathbf{C}_{new} \succ_r \mathbf{C}_{old}$ 
20: Let D2D pairs  $(s, ds)$  and  $(r, dr)$  join  $\mathbf{C}_{new}$ ;
21: else
22: Set  $R_i = R_i(\mathbf{C}_{old})$  for all D2D pairs;
23: Calculate  $R_s^d(\mathbf{C}_{new})$  for  $(s, ds)$ . Update other D2D pairs' rates  $R_i, i \neq s$ ;
24: if  $\mathbf{C}_{new} \succ_s \mathbf{C}_{old}$ 
25: Let D2D pair  $(s, ds)$  join  $\mathbf{C}_{new}$ ;
26: endif
27: endif
28: until the partition converges to the final state

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In the following, we prove that Algorithm 1 converges to a final stable state.

Definition 3 (\mathbf{D}_{hp} -stable): If no player in the partition is interested in leaving it through merge and split rules to form other partitions, then the partition is \mathbf{D}_{hp} -stable [18, 20].

Theorem 1 [18]: A partition $\mathbf{C} = \{\mathbf{C}_1, \dots, \mathbf{C}_K\}$ is \mathbf{D}_{hp} -stable if and only if the following two conditions are satisfied:

(i) For each $i \in \{1, \dots, K\}$ and each partition $\{\mathbf{P}_1, \dots, \mathbf{P}_l\}$ of $\mathbf{C}_i \in \mathbf{C}$,

$$R(\mathbf{C}_i) \geq \sum_{j=1}^l R(\mathbf{P}_j),$$

(ii) For each $T \subseteq \{1, \dots, K\}$,

$$\sum_{i \in T} R(\mathbf{C}_i) \geq R(\cup_{i \in T} \mathbf{C}_i),$$

Proposition 2: Starting from any initial coalition partition, the proposed algorithm converges to a \mathbf{D}_{hp} -stable state.

Proof: A partition is \mathbf{D}_{hp} -stable if and only if the two conditions of Theorem 1 are satisfied. Suppose that there're K CUs in the cell, the maximum coalition number is K . So the number of partitions K is the Bell number [16], thus the random switch operations will terminate with probability 1 [6], and the proposed algorithm converges to a final state. If all the coalitions in the final state are not empty, any split operation will make some D2D pairs having no transmission resource, which is not practical. Assume that the rates of these D2D pairs are

$-\infty$, so the sum coalition value is also $-\infty$, which is less than the sum coalition value without split operation. So the first condition of Theorem 1 is satisfied. Due to the time division mechanism, if any two coalitions are merged together, the transmission rate of D2D pairs in these two coalitions must be decreased. So the second condition of Theorem 1 is satisfied. Thus, we have proved that the proposed algorithm converges to a \mathbf{D}_{hp} -stable state.

Definition 4 (Nash-stable) [6]: A coalition structure $\mathbf{C} = \{\mathbf{C}_1, \dots, \mathbf{C}_K\}$ is Nash-stable if for any D2D pair $i \in \mathbf{C}_m \in \mathbf{C}$, $\mathbf{C}_m \succ_i \mathbf{C}_{m'} \cup \{i\}$ for all $\mathbf{C}_{m'} \in \mathbf{C} \setminus \mathbf{C}_m \cup \{\emptyset\}$.

Proposition 3: The final partition is Nash-stable.

Proof: We prove it by contradiction as in [6]. If the final partition is not Nash-stable, then there exists a D2D pair i that wants to join in another coalition which meets the ‘‘selfish order’’ in Definition 2. According to the proposed algorithm and Proposition 2, D2D pair i can perform a coalition moving with probability 1, which contradicts the fact that partition is the converged final state. Thus, the final partition is Nash-stable.

4. Performance Evaluation

In this section, we use Matlab R2012a to evaluate the performance evaluation of Algorithm 1 in an isolated cell of D2D cellular networks with a radius of 500 m, where the cellular users and relay D2D pairs are distributed randomly. All D2D links are within the maximum allowed distance, including (s, ds) , (r, dr) , (s, dr) and (r, ds) . As mentioned in section 2, assume that the source and relay node pairs are fixed to each other according to some relay selection algorithm. Other parameters used in the simulation are summarized in **Table 1**.

Table 1. Simulation Parameters

Parameter	Value
Cell radius	500 m
Uplink bandwidth	15 MHz
Noise power density	-174 dBm/Hz
Max D2D communication distance	100 m
CU Tx power	200 mW
Time slots in one frame	500
Pathloss exponent	3
CU rate constraint	7 bits/s/Hz

Two metrics are considered to evaluate the algorithm performance: (1) the sum rate of all D2D pairs; (2) the Jain’s fairness index [21], which is widely used to measure the fairness of system resource allocation among D2D pairs. Since randomness is involved in Algorithm 1, the simulation is repeated for 100 times and the average value is obtained. To demonstrate the efficiency of Algorithm 1, we compare the proposed algorithm (denoted as pCG in all figures) with the following schemes:

(1) Random Coalition Selection (RC): D2D pairs join coalitions randomly. For relay D2D pairs, if the source node and relay node are in the same coalition, they select a transmission mode according to Proposition 1; Otherwise, D2D pairs use the direct transmission mode.

(2) All Direct Transmission Mode (AD): All D2D pairs choose direct transmission mode to select coalition using ‘‘Selfish Order’’ defined in Definition 2.

(3) Coalition Game based scheme in [6] (CG): this algorithm is to optimize the sum rate of all users including all D2D pairs and CUs using coalition formation game. We use this algorithm in the scenario where CUs' transmission rates should be guaranteed and cooperative relay transmission mode is permitted in the system.

The simulation results of the above three schemes and Algorithm 1 are obtained from two kinds of scenarios: (1) the number of CU is fixed to 20, and the number of relay D2D pairs varies from 1 to 20; (2) the number of relay D2D pairs is fixed to 20, and the number of CU varies from 1 to 20. As mentioned in Section 2, each relay D2D pair contains two D2D pairs.

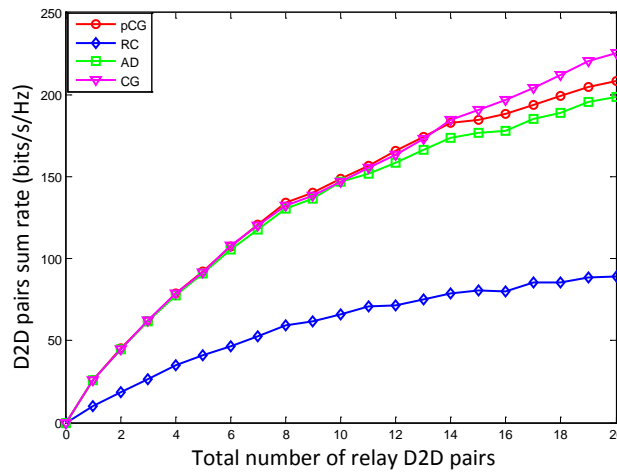


Fig. 3. The sum rate of D2D pairs with different relay D2D pairs and 20 CUs

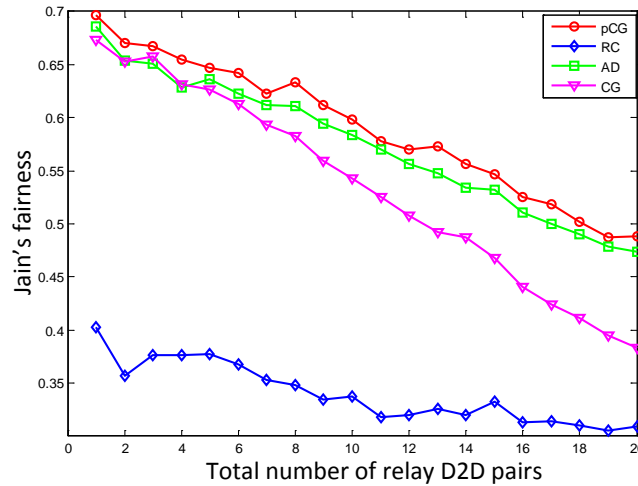


Fig. 4. The Jain's fairness of D2D pairs with different relay D2D pairs and 20 CUs

Fig. 3 depicts the sum rate of all D2D pairs with 20 CUs in the cell. The sum rate of D2D pairs increases as the number of relay D2D pairs increases. Because the CUs share uplink resources with D2D pairs, more D2D pairs give better utilization of the resource. When the number of D2D pairs is small, pCG, AD and CG have similar performance on the sum rate, while RC has the worst performance. As each D2D pair occupies one CU's uplink frequency

resource, and RC selects D2D pairs randomly in coalitions, multiple D2D pairs may exist in one coalition.

When the number of D2D pairs grows, pCG outperforms RC, because D2D pairs select coalition using “selfish order”, which increases the transmission rate. pCG outperforms AD as D2D pair would select cooperative relay transmission mode to increase data rate. However, the sum rate obtained by pCG is a little lower than CG. In pCG, D2D pairs follow the “selfish order” rule to select coalitions, which increases individual transmission rate and converges to a local maximal sum rate.

Fig. 4 depicts the Jain’s fairness of D2D pairs in the above scenario. Since D2D pairs have no chance to join a preferred coalition in RC, it has the worst performance. The fairness index of pCG, AD and CG decrease as the number of D2D pairs grows. In these algorithms, some D2D pairs contribute a significant portion of the sum rate. For other D2D pairs, although they can move into another coalition to increase their own rates, their contributions to the sum rate are quite limited. However, pCG still outperforms other schemes thanks to the “selfish order” rule and the Nash bargaining game based cooperative relay transmission mode for D2D pairs.

Fig. 5 and **Fig. 6** depict the sum rate and Jain’s fairness of D2D pairs with 20 relay D2D pairs and different number of CUs. As the number of CUs grows, the sum rate of D2D pairs increases since more CUs’ uplink frequency resources can be used for D2D pairs. Similar to Fig. 3, the performance of pCG is lower than CG and better than the other two schemes.

However, on the Jain’s fairness performance, pCG outperforms all other schemes. Compared with AD, pCG allows cooperative relay transmission mode which uses Nash bargaining game to increase the data rate and guarantee the resource allocation fairness. The goal of CG is to optimize the sum rate of all D2D pairs and CUs. In order to achieve the maximum sum rate, D2D pairs are willing to move into a new coalition even if the transmission rate of this D2D pair decreases. The fairness performance of CG is lower than pCG, as D2D pairs using pCG follow “selfish order” to select a coalition where the transmission rate must increase.

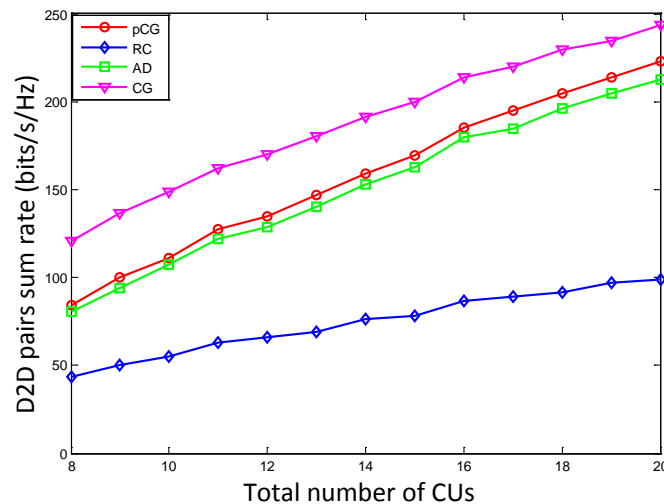


Fig. 5. The sum rate of D2D pairs with different CU number and 20 relay D2D pairs

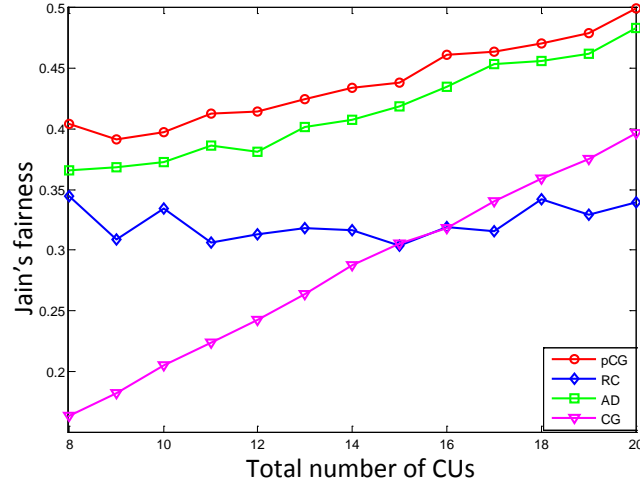


Fig. 6. The Jain's fairness of D2D pairs with different CU number and 20 relay D2D pairs

Fig. 7 depicts the number of iterations of pCG and CG until these two algorithms achieve the final state in the scenario with 20 CUs and different relay D2D pairs. The iterations number to the final stable state grows as the number of relay D2D pairs increases. pCG outperforms CG in iterations number, because when CG gets to the local optimal value, it has to calculate a new probability to move out this value and re-run the whole algorithm. However, pCG does not require additional operations to move out of the local maxima, which shortens the convergence process and reduces the iterations number.

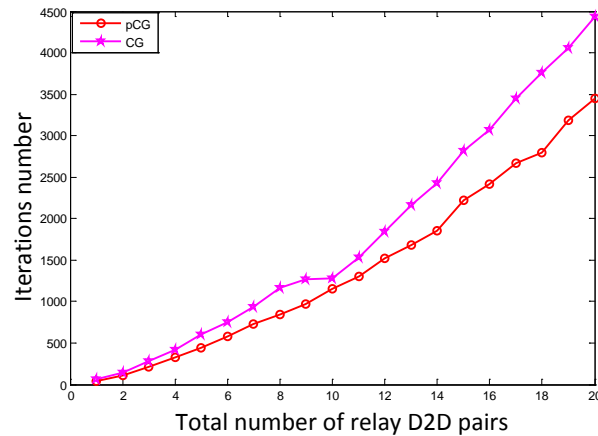


Fig. 7. Iteration numbers of different relay D2D pairs with 20 CUs

5. Conclusion

In this paper, we have investigated the resource allocation problem in wireless D2D networks with selfish users. Cooperative relay transmission mode is allowed for D2D pairs to increase their data rates. The Nash bargaining theory and coalition formation game are adopted for D2D pairs to fairly select the transmission modes and uplink frequency resource. Theoretical analysis and simulation results show that the proposed algorithm has a better performance on the fairness of resource allocation and fast convergence speed with only a little loss on the sum

rate of D2D pairs. Dynamic relay node selection method, and other transmission modes, such as cellular mode and dedicated mode, would be addressed in future work.

Appendix

Proof of Proposition 1

$$\begin{aligned}
& \max_{n_s, n_r} \prod_{i=s,r} (R_i^c - R_i^d) \\
&= \max_{n_s, n_r} (R_s^c - R_s^d)(R_r^c - R_r^d) \\
&= \left(\frac{1}{LN}\right)^2 [n_r B + (N - n_r - n_s)A - LNR_s^d][n_s D + (N - n_r - n_s)C - LNR_r^d] \\
&= \left(\frac{1}{LN}\right)^2 [n_r(B - A) - n_s A + NA - LNR_s^d][n_s(D - C) - n_r C + NC - LNR_r^d]
\end{aligned}$$

Through (13) – (16), we can get P_s , P_s' , P_r , P_r' . According to (9) (10), R_s^d and R_r^d can be seemed as a constant value. So the problem can be depicted as following:

$$\max [n_r(B - A) - n_s A + NA - LNR_s^d][n_s(D - C) - n_r C + NC - LNR_r^d] \quad (18)$$

subject to

$$\frac{1}{LN}[n_r B + (N - n_s - n_r)A] \geq R_s^d \quad (19)$$

$$\frac{1}{LN}[n_s D + (N - n_r - n_s)C] \geq R_r^d \quad (20)$$

Assume that $G = B - A$, $H = D - C$. Combing (19) (20), we can get that if $GH > AC$, we have

$$n_r \geq \frac{H(R_s^d \cdot LN - NA) + A(R_r^d \cdot LN - NC)}{GH - AC} = J \quad (21)$$

$$n_s \geq \frac{C(R_s^{NC} \cdot LN - NA) + G(R_r^d \cdot LN - NC)}{GH - AC} = K \quad (22)$$

If $GH < AC$, $n_s < 0$, $n_r < 0$, which is not practical. Considering (21) (22), so if $GH < AC$ or $J > N$ or $K > N$, direct transmission mode is selected.

If $GH > AC$ and $J \leq N$ and $K \leq N$, we assume that

$$\alpha = n_r(B - A) - n_s A + NA - LNR_s^d \quad (23)$$

$$\beta = n_s(D - C) - n_r C + NC - LNR_r^d \quad (24)$$

Combing (23) (24), we can get

$$n_s = \frac{\alpha C + \beta G - NCA + 2LCR_s^D - NCG + LNGR_r^D}{GH - AC} \quad (25)$$

$$n_r = \frac{\alpha H + \beta A - NAH + LNGR_s^D - NAC + LNAR_r^D}{GH - AC} \quad (26)$$

Note that n_s and n_r should be smaller than N . So we have

$$J \leq n_r \leq N \quad (27)$$

$$K \leq n_s \leq N \quad (28)$$

$$0 \leq n_s + n_r \leq N \quad (29)$$

So, $J + K \leq n_s + n_r \leq N$. Using (21) (22) (25) (26), we can get

$$D(R_s^D \cdot LN - NA) + B(R_r^D \cdot LN - NC) + \alpha D + \beta B \leq N(GH - AC) \quad (30)$$

From (30), we observe that when (30) holds with equality, (18) achieves the maximum value. So we can get

$$\beta = \frac{N(GH - AC) - D(R_s^D \cdot LN - NA) - B(R_r^D \cdot LN - NC) - \alpha D}{B} \quad (31)$$

Substituting (25) (26) (31) into (18), we can obtain a function which is only related to α . Then, we make the first order derivation of this function to α and make it to zero, so as to obtain the optimal α^* . Put α^* into (31), we can obtain optimal β^* .

Using α^* and β^* , and put them into (25) (26), we can get

$$n_s = \left[\frac{N \left(\frac{C}{D} + \frac{G}{B} \right)}{2} + \frac{N (LR_s^D - A)(BC - DG)}{2B(GH - AC)} + \frac{N (LR_r^D - C)(DG - BC)}{2B(GH - AC)} \right]$$

$$n_r = \left[\frac{N \left(\frac{H}{D} + \frac{A}{B} \right)}{2} + \frac{N (LR_s^D - A)(BH - DA)}{2B(GH - AC)} + \frac{N (LR_r^D - C)(DA - BH)}{2B(GH - AC)} \right]$$

So we have proved Proposition 1.

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