Coalition Formation Game Based Relay Selection and Frequency Sharing for Cooperative Relay Assisted Wireless D2D Networks with QoS Constraints

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Abstract

With device-to-device (D2D) communications, an inactive user terminal can be utilized as a relay node to support multi-hop communication so that connective experience of the cell-edge user as well as the capacity of the whole system can be significantly improved. In this paper, we investigate the spectrum sharing for a cooperative relay assisted D2D communication underlying a cellular network. We formulate a joint relay selection and channel assignment problem to maximize the throughput of the system while guaranteeing the quality of service (QoS) requirements of cellular users (CUs) and D2D users (DUs). By exploiting coalition formation game theory, we propose two algorithms to solve the problem. The first algorithm is designed based on merge and split rules while the second one is developed based on single user's movement. Both of them are proved to be stable and convergent. Simulation results are presented to show the effectiveness of the proposed algorithms.

Keywords: D2D networks, relay selection, resource allocation, coalition formation game, QoS constraints

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1. Introduction

With device-to-device (D2D) communications, proximity users in a cellular network can establish a direct link without going through the base station. They can significantly improve the spectrum efficiency and energy efficiency of the network, therefore are considered as one of the promising technologies in 5G wireless networks [1]-[7].

In a D2D-enabled system, D2D users (DUs) and cellular users (CUs) typically operate in common spectrum to effectively utilize scarce resources. Since DUs are randomly distributed within the network, they may generate severe interference to the transmission of existing CUs if not designed properly. Therefore, resource allocation is one of the most important issues in D2D-enabled networks. In [9] [10] [15], game theory based resource allocation algorithms were proposed to optimize the overall system throughput. In [11], the authors proposed a distributed algorithm to maximize the throughput of DUs while guaranteeing the minimum rate requirements of the CUs. The authors in [1] developed three-step method to maximize the overall throughput of the system while considering the QoS requirements of both DUs and CUs. However, the aforementioned work only considered single-hop D2D communications, without exploring the potential of utilizing relay node to improve the transmission rate of D2D communications.

By exploiting idle user terminals as relays, multi-hop D2D communications are established so that the performance of deeply faded DUs can be significantly improved due to the shorter transmission distance. However, integrating multi-hop D2D communications into cellular network also brings in major design challenges in resource allocation. Compared with traditional single-hop D2D communications, it requires perfect coordination for the transmission in the first and second hops to avoid severe interference to CUs. In addition, proper relay selection schemes should also be considered for D2D communications, which increases the dimension of the optimization problem. Therefore, resource allocation for multi-hop D2D communications is worth further exploring. In [26], a bargaining game based method is proposed to deal with the relay selection problem in a D2D-enabled cellular network. While in [5], a distanced based relay selection and power allocation algorithm was developed to maximize the energy efficiency of the uplink transmission in a D2D-enabled heterogeneous networks. Both the above works assumed that D2D communications operated in dedicated spectrum resources without consideration of the spectrum sharing issue with CUs. Spectrum sharing problems were investigated in [13] [14] [23] [25] for multi-hop D2D communications. Specially, the authors in [14] pre-assigned the relay nodes for DUs and allocated the transmission resource using game theory based method. In [25], the authors allocated the transmission frequency and relay nodes for DUs in a greedy searching way. But the works in [14] [25] did not consider the QoS requirements of either CUs or DUs. In [23], the authors proposed a cluster–based method to optimize the system throughput and relay assignment scehme of a D2D-aided network coding system while guaranteeing the minimum data requirements of the DUs. In [13], a 3-dimensional matching-based method was developed to maximize the downlink throughput of the sytem while guaranteeing the QoS requirements of both CUs and DUs via joint optimization of spectrum sharing and relay selection. However, the algorithms in [13] [23] only focused on the partial spectrum sharing, where CUs were inactive for some transmission slots of multi-hop D2D communications, but ignoring the full spectrum sharing between CUs and DUs.

Motivated by the above works, in this paper, we investigate the fully sharing problem for multi-hop D2D communications underlying a cellular network via joint relay selection and channel assignment. By exploiting coalition formation game theory, we propose two algorithms to maximize the system throughput while guaranteeing the QoS requirements of both CUs and DUs. The first algorithm is designed based on merge and split rules while the second one is developed based on single user's movement. Both algorithms are proved to be stable and convergent.

The main contributions are summarized as follows.

1) Different from the previous work which only considers partial spectrum or ignores the QoS requirements of users, we consider the joint relay selection and channel assignment problem to maximize the uplink throughput while guaranteeing the minimum rate requirements of both CUs and DUs. Although we consider multi-hop D2D communications of DUs in this paper, the work can be straightforwardly extend to the system with D2D-assisted multi-hop transmission of CUs.
2) Unlike previous work on collation formation game based D2D networks, which only adopts comparison orders of system performance, such as utilitarian order (cumulative users' transmission rate) [12] [24], Pareto order (Pareto criterion) [15] or Max order (maximum users' transmission rate) [21], in this paper, we devise a new comparison order named "QoS order" which considers both the QoS constraint of users and the system throughput. Moreover, we also have proved the transitivity and monotonicity of the proposed "QoS order".
3) Based on the new defined comparison order, we have proposed two resource allocation algorithms in relay-assisted D2D networks. The first algorithm is designed based on merge and split rules. Although these rules are widely used in coalition formation game, here we reuse them by the newly designed order, which has not been mentioned in literature. The second algorithm is developed based on single user's movement, which can further improve the system performance. In addition, we have proved the complexity and stability of both algorithms analytically.
4) Numerical results show that the two proposed algorithms are able to achieve near optimal performance. In addition, we also compare the convergence performance of the two algorithms, and observe that the single user's movement based method can always achieve better system throughput with a slower convergence speed.

The rest of this paper is organized as follows. In Section 2, we present the system model and formulate the relay selection and channel assignment problem. To solve the problem, we propose the two coalition formation game based algorithms in Section 3. Then we present the simulation results in Section 4. Finally, we draw conclusion in Section 5.

2. System Model

2.1 Scenario Description

We investigate uplink spectrum sharing for D2D communication underlying a cellular network, where L D2D pairs coexist with Q CUs. The transmission of each D2D pair can be established either by direct transmission or with the help of idle users. Specially, there are M idle users and each of them supports AF cooperative transmission for D2D pairs. For analysis simplicity, we consider a fully loaded scenario as in [15], where Q active CUs occupy Q orthogonal channels and there are no spare channels. In addition, one CU can share the transmission resource with multiple D2D links, but only one D2D link is active during each time slot [14] [16] [17]. As shown in **Fig. 1**, $\mathbf{CU}_1$ shares the uplink resource with D2D pair $(\mathbf{s}_1, \mathbf{ds}_1)$ which uses direct transmission mode, and $\mathbf{CU}_2$ shares the transmission resource with $(\mathbf{s}_2, \mathbf{ds}_2)$ which uses cooperative relay transmission mode with the help of idle user $\mathbf{r}_2$. $\mathbf{CU}_3$ uses the transmission resource alone. Two nodes $\mathbf{r}_*$ are idle users. During the transmission period, $\mathbf{CU}_1$ transmits signal to the BS suffering the interference from D2D source node $\mathbf{s}_1$, and $\mathbf{CU}_2$ suffers the interference from $\mathbf{s}_2$ and $\mathbf{r}_2$. Also, the transmission of $\mathbf{CU}_1$ and $\mathbf{CU}_2$ cause interference to $\mathbf{ds}_1$, $\mathbf{ds}_2$ and $\mathbf{r}_2$ respectively.

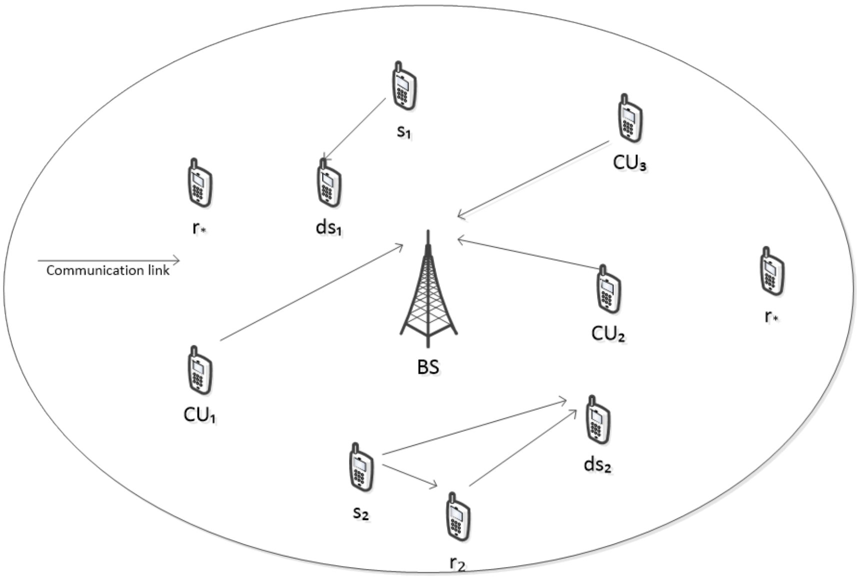

Fig. 1. System model of CUs sharing uplink resources with D2D pairs and relay nodes

Note that a D2D link ℓ can be a pair of $(\mathbf{s,r})$, $(\mathbf{r,ds})$ or $(\mathbf{s,ds})$ link. With the interference imposed from D2D link ℓ, the received signal at the BS from $\mathbf{CU}_k$ can be expressed as

$$y_k = \sqrt{P_k g_{kB}}\, x_k + z_B + \sqrt{P_\ell g_{\ell B}}\, x_\ell \tag{1}$$

where P_k, P_ℓ are the transmission powers of $\mathbf{CU}_k$ and the source node of D2D link ℓ, respectively. Here we assume that the link ℓ in (1) is one of the D2D links using the same uplink resource with $\mathbf{CU}_k$ which causes the most interference to $\mathbf{CU}_k$. x_k, x_ℓ are the transmitted signal of $\mathbf{CU}_k$ and D2D link ℓ with unit power. z_B is the additive white Gaussian noise (AWGN) at the BS with one-sided power spectral density N_0. $g_{kB} = d_{kB}^{-\alpha} \cdot |h_0|^2$ [9] [15], where d_{kB} is the distance between $\mathbf{CU}_k$ and the BS, α is the path-loss exponent, and h_0 is the complex Gaussian channel coefficient which obeys the distribution $\mathcal{CN}(0,1)$. $g_{\ell B}$ is the channel gain between the source node of ℓ and the Base station.

For D2D pair ℓ, if it uses the transmission resource of $\mathbf{CU}_k$ through direct mode, the received signal at the destination node can be expressed as

$$y_\ell^k = \sqrt{P_\ell g_\ell}\, x_\ell + z_\ell + \sqrt{P_k g_{k\ell}}\, x_k \tag{2}$$

where P_ℓ is the transmission power of ℓ's source node, x_ℓ is the transmitted signal of ℓ, g_ℓ is the channel gain between the source and destination node of ℓ. $g_{k\ell}$ is the channel gain between $\mathbf{CU}_k$ and the destination node of ℓ.

If ℓ uses cooperative relay transmission mode with the help of relay node r, for the first time slot, the received signal at the destination node of ℓ and r can be expressed respectively as

$$y_{\ell}^{k}=\sqrt{P_{\ell}g_{\ell}}x_{\ell}+z_{\ell}+\sqrt{P_{k}g_{k\ell}}x_{k} \tag{3}$$

$$y_{\ell r}^{k}=\sqrt{P_{\ell}g_{\ell r}}x_{\ell}+z_{r}+\sqrt{P_{k}g_{kr}}x_{k} \tag{4}$$

For the second time slot, the received signal at the destination node of ℓ is

$$y_{r\ell}^{k}=\sqrt{P_{r}g_{r\ell}}x_{r}+z_{\ell}+\sqrt{P_{k}g_{k\ell}}x_{k} \tag{5}$$

where x_r is the relayed signal for ℓ's source node with normalized unit power. Here, $g_{\ell r}$ and $g_{r\ell}$ respectively represent the channel gain of the D2D link $(\ell\text{'s source node}, r)$ and $(r, \ell\text{'s destination node})$.

Assume that the noises in different channel have the same variance σ^2. For the D2D pair ℓ that uses transmission relay mode, ℓ's destination node combines the two received signal using MRC technique with the SNR [18] as

$$\Gamma_{\ell r}=\gamma_{\ell}+\gamma_{\ell r} \tag{6}$$

$$\gamma_{\ell}=\frac{P_{\ell}g_{\ell}}{\sigma^{2}+P_{k}g_{k\ell}} \tag{7}$$

$$\gamma_{\ell r}=\frac{\dfrac{P_{\ell}g_{\ell r}}{\sigma^{2}+P_{k}g_{kr}}\cdot\dfrac{P_{r}g_{r\ell}}{\sigma^{2}+P_{k}g_{k\ell}}}{\dfrac{P_{\ell}g_{\ell r}}{\sigma^{2}+P_{k}g_{kr}}+\dfrac{P_{r}g_{r\ell}}{\sigma^{2}+P_{k}g_{k\ell}}+1} \tag{8}$$

The transmission rate of CU_k, D2D pair ℓ under direct transmission mode, and ℓ under cooperative relay mode with the help of r can be expressed respectively as

$$R_{k}=\log_{2}(1+\frac{P_{k}\cdot g_{kB}}{\sigma^{2}+P_{\ell}\cdot g_{\ell B}}) \tag{9}$$

$$R_{\ell,0}^{k}=\frac{1}{L_{k}}\log_{2}(1+\frac{P_{\ell}\cdot g_{\ell}}{\sigma^{2}+P_{k}\cdot g_{k\ell}}) \tag{10}$$

$$R_{\ell,r}^{k}=\frac{1}{L_{k}}\log_{2}(1+\Gamma_{\ell,r}) \tag{11}$$

where L_k represents the accumulated number of time slots that all the D2D pairs which use the same transmission resource with CU_k complete sending signal for one time. Note that the D2D pairs which use cooperative relay transmission mode spend two consecutive time slots to complete one transmission process.

2.2 Problem Formulation

Considering CUs and DUs always have their transmission rate demands to guarantee the QoS, we need to determine the optimal resource allocation scheme under the rate constraint while maximizing the network throughput. Combining the above analysis, the resource allocation problem can be formulated as the following optimization problem:

$$\max \sum_{\ell,r,k} x_{\ell,r}^{k} R_{\ell,r}^{k} + \sum_{k} R_{k} \tag{12}$$

subject to

$$R_k \geq R_{\text{th}} \tag{13}$$

$$R_{\ell,r}^{k} \geq R_{\text{th}} \tag{14}$$

$$\sum_{\ell} \sum_{k} x_{\ell,r}^{k} \leq 1 \quad \forall r \neq 0 \tag{15}$$

$$\sum_{r} \sum_{k} x_{\ell,r}^{k} \leq 1 \quad \forall \ell \tag{16}$$

$$x_{\ell,r}^{k} \in \{0,1\} \quad \forall r \neq 0 \tag{17}$$

The objective function (12) represents that the allocation scheme should maximize the overall network throughput. Constraints (13) and (14) are the QoS requirements of CUs and D2D pairs. (17) is the resource allocation coefficients, where $x_{\ell,r}^{k} = 1$ indicates that D2D pair ℓ uses the transmission resource of CU_k with the help of relay node r, $r = 0$ represents ℓ uses direct transmission mode. (15) is the relay constraint that one relay node can serve at most one D2D pair. (16) represents that one D2D pair can only use one CU's frequency resource and one transmission mode.

Compared with the NP-hard problem (9) in the work [15] which is only a frequency sharing problem, the above problem includes both transmission resource sharing and relay allocation with rate constraints, so the problem (12)-(17) is also a NP-hard problem. In the next section, we introduce the two coalition formation game based approaches to obtain a near optimal solution.

3. Coalition Formation Game based Algorithms

In this section, we propose two coalition formation game based algorithms to solve the above optimization problem. First, we formulate the problem as a Transferable Utility (TU) game with a newly defined "QoS order". Then, the two proposed algorithms are introduced and the corresponding properties are proved.

3.1 Coalition Formation Game Formulation

Solving the problem (12) with the constraints (13)-(17) is actually a selection process of the optimal resource allocation scheme: each DU chooses a transmission frequency, an appropriate transmission mode and a relay node to maximize the network throughput with guaranteed QoS of all users. Thus, the users with the same transmission frequency can be seen as a coalition, and the resource allocation problem in (12) is actually a coalition formation problem. So, the coalition game can be depicted as follows.

Definition 1 (grand coalition, coalition, collection, partition) : $\mathbb{N} := \{1, 2, ..., Q + L + M\}$ is called the grand coalition where Q, L, M are defined in subsection 2.1. Non-empty subsets of $\mathbb{N}$ are called coalitions. A collection $\mathcal{C}$ is the set which is consisted of mutually disjoint coalitions. The k_{th} coalition in $\mathcal{C}$ is represented as $\mathbb{C}_k$. The collection which contains all the elements of $\mathbb{N}$ is called a partition $\mathcal{P}$ of $\mathbb{N}$.

Definition 2 (TU-game): A coalitional TU-game is a pair $(\mathbb{N}, v)$, where $\mathbb{N}$ is the grand coalition and v is a function that obtains all users' transmission rates in a coalition or collection. For coalition $\mathbb{C}_k$ in collection $\mathcal{C}$, $v(\mathbb{C}_k) \triangleq [v(i)]_{i\in\mathbb{C}_k}$. For collection $\mathcal{C}$, $v(\mathcal{C}) \triangleq [v(i)]_{i\in\bigcup\mathbb{C}_k,\, \mathbb{C}_k\in\mathcal{C}}$.

In this paper, users' transmission rates in one coalition are discussed through the following three situations:

- If no CU exists in this coalition, the users' rates are all zero.
- If more than one CU exists, the users' rates are set to a non-zero minimum value.
- If only one CU exists, the users' rates are calculated using (9)-(11).
- The rates of relay nodes are zero.

Different from existing work where v is usually defined as the sum rate of one collection, the definition of v in this paper is to obtain the rate vector of a collection, which is convenient for checking whether a single user's transmission rate reaches the threshold.

For two collections $\mathcal{A}$ and $\mathcal{B}$ where $\bigcup\mathcal{A} = \bigcup\mathcal{B}$, let $\mathbf{r}_{\mathcal{A}}$ and $\mathbf{r}_{\mathcal{B}}$ denote the relay nodes set in $\mathcal{A}$ and $\mathcal{B}$. $\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}}$ represents the collection that $\mathcal{A}$ removes the relay nodes in $\mathbf{r}_{\mathcal{A}}$. $\mathcal{A} \rhd \mathcal{B}$ means that the collection $\mathcal{A}$ is preferred to $\mathcal{B}$. R_{th} is the rate threshold of CUs and DUs. The definition of QoS order, which is a comparison realition between two collections in the scenario of this paper, can be depicted as:

Definition 3 (QoS order):

(C1) If $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\} < R_{\text{th}}$ and $\min\{v(\mathcal{B} \setminus \mathbf{r}_{\mathcal{B}})\} < R_{\text{th}}$

(C1.1) If the number of nodes whose rates are smaller than R_{th} in $\mathcal{A}$ equals that in $\mathcal{B}$, then,

$$\mathcal{A} \rhd \mathcal{B} \;\; \textit{iff} \;\; \sum v(\mathcal{A}) > \sum v(\mathcal{B});$$

(C1.2) If the number of nodes whose rates are smaller than R_{th} in $\mathcal{A}$ is less than that in $\mathcal{B}$, then,

$$\mathcal{A} \rhd \mathcal{B};$$

(C2) If $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\} \geq R_{\text{th}}$ and $\min\{v(\mathcal{B} \setminus \mathbf{r}_{\mathcal{B}})\} \geq R_{\text{th}}$, then,

$$\mathcal{A} \rhd \mathcal{B} \;\; \textit{iff} \;\; \sum v(\mathcal{A}) > \sum v(\mathcal{B});$$

(C3) If $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\} \geq R_{\text{th}}$ and $\min\{v(\mathcal{B} \setminus \mathbf{r}_{\mathcal{B}})\} < R_{\text{th}}$, then,

$$\mathcal{A} \rhd \mathcal{B}.$$

This definition puts both the system sum rate and the users' QoS into consideration. For two collections $\mathcal{A}$ and $\mathcal{B}$ with the same elements, users' rates are firstly calculated in these collections respectively. Then based on $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\}$, $\min\{v(\mathcal{B} \setminus \mathbf{r}_{\mathcal{B}})\}$ and $\sum v(\mathcal{A})$, $\sum v(\mathcal{B})$, the preferred collection can be determined.

According to the definition of QoS order, the partition which guarantees the users' transmission rates and provides higher network sum rate is always preferred. In coalition formation theory, a comparison relation should satisfy the conditions of transitivity and monotonicity. Now, we show that the QoS order is a transitive and monotonic comparison relation.

Proposition 1: The QoS order is transitive and monotonic.

Proof: The proof is shown in the Appendix.

3.2 Merge and Split Rules based Algorithm

Based on the QoS order defined in the previous subsection, we propose a coalition formation algorithm using two rules which transform the partition of the grand coalition: merge and split rules [19].

Definition 4 (Merge and Split Rules): For the coalitions $\mathbb{C}_1, \mathbb{C}_2, ..., \mathbb{C}_n$,

- Merge Rule: $\{\mathbb{C}_1, \mathbb{C}_2, ..., \mathbb{C}_n\} \to \{\bigcup_{j=1}^{n} \mathbb{C}_j\}$, when $\{\bigcup_{j=1}^{n} \mathbb{C}_j\} \triangleright \{\mathbb{C}_1, \mathbb{C}_2, ..., \mathbb{C}_n\}$.
- Split Rule: $\{\bigcup_{j=1}^{n} \mathbb{C}_j\} \to \{\mathbb{C}_1, \mathbb{C}_2, ..., \mathbb{C}_n\}$, when $\{\mathbb{C}_1, \mathbb{C}_2, ..., \mathbb{C}_n\} \triangleright \{\bigcup_{j=1}^{n} \mathbb{C}_j\}$.

Note that before the partition is transformed via these two rules, we should recalculate the nodes' rates, and compare these two different partition using QoS order. So the merge and split rules based algorithm can be depicted as the following Algorithm 1.

Proposition 2: Given the rate threshold R_{th}, Algorithm 1 converges to a final state in which all DUs obtain a transmission resource.

Proof: Every iteration of merge and split operations produces different partitions $\mathcal{P}_1$, $\mathcal{P}_2$ $\cdots$ with $\mathcal{P}_{i+1} \triangleright \mathcal{P}_i$ for $i \geq 1$. But the number of different partitions is finite. So the algorithm converges to a final state. Assume that there are some users whose transmission rates are zero in the final state. According to condition (C3) in the definition of QoS order, these users must be combined with the coalition with a CU via the merge rule.

Note that the value of R_{th} is an important factor for the final partition. Selecting a large value of R_{th} may result in a final state that some DUs cannot obtain a transmission resource, because if joining one coalition, the users' rates in that coalition would decrease to a value that is lower than R_{th}. Therefore, R_{th} in Proposition 2 is set to a small value. The situation of high rate threshold is considered in the simulation section.

Proposition 3: Algorithm 1 converges to a $\mathbb{D}_{hp}$–stable state.

Proof: Assume that $\mathcal{P} = \{\mathbb{C}_1, \mathbb{C}_2, \ldots, \mathbb{C}_Q, \mathbb{C}_{Q+1}, \mathbb{C}_{Q+2} \ldots \mathbb{C}_{Q+J}\}$ with $J \leq M$ is the final partition of the merge and split iterations. According to Proposition 2, the first Q coalitions in $\mathcal{P}$ are consisted of one CU with some D2D pairs and relay nodes, and the remaining J coalitions are the relay nodes which are not allocated. For any $i \in \{1, \ldots, Q+J\}$ and any partition $\{\mathbb{Z}_1, \ldots, \mathbb{Z}_N\}$ of $\mathbb{C}_i$, if $\{\mathbb{Z}_1, \ldots, \mathbb{Z}_N\} \triangleright \mathbb{C}_i$, the partition $\mathcal{N}$ can still be transformed to another preferred partition through split rules, which contradicts Proposition 2 that the Algorithm 1 converges to a final state. For partition $\mathcal{P}$ and $T \subseteq \{1, \ldots, Q+J\}$, if $\bigcup_{i \in T} \mathbb{C}_i \triangleright \mathcal{C}_T$ ($\mathcal{C}_T$ is the collection which is consisted of $\{\mathbb{C}_i\}_{i \in T}$), $\mathcal{P}$ can be transformed through merge rules, which also contradicts Proposition 2. So, $\mathcal{P}$ meets the two conditions of a $\mathbb{D}_{hp}$-stable state [19].

In coalition formation game theory, there exist two kinds of stable states which have better performance than $\mathbb{D}_{hp}$-stable, namely $\mathbb{D}_c$-stable and $\mathbb{D}_p$-stable. A $\mathbb{D}_c$-stable state should satisfy the two conditions in Theorem 4.5 of [19]. However, if some D2D pair leaves the coalition with a CU to form a coalition separately, the transmission rate would be zero. So, for the $\mathbb{C}$-incompatible coalition like this, the second condition cannot be satisfied. In addition, according to the definition of $\mathbb{D}_p$-stable state, a $\mathbb{D}_p$-stable state is the optimal solution of the problem in Section 2.2 which is proved to be a NP-hard problem. So $\mathbb{D}_p$-stable state cannot be reached in polynomial time.

In Algorithm 1, one coalition may contain multiple D2D pairs and relay nodes. The relay allocation in one coalition is a local optimization problem. The relay nodes first help the D2D pairs whose rates are lower than the rate threshold, then help the D2D pairs that provide the highest sum rate.

Algorithm 1: The merge and split rules based algorithm

```
Initial Phase:
  Each CU forms a coalition, and the D2D pairs are randomly distributed into these coalitions. Each relay node forms a coalition. The whole network is partitioned as $\mathcal{P} = \{\mathbb{C}_1, ..., \mathbb{C}_Q, \mathbb{C}_{Q+1}, ...\mathbb{C}_{Q+M}\}$.
Coalition Formation Phase:
  In this phase, coalition transformation using the merge and split rules occurs.
      repeat
        Randomly select two coalitions $\mathbb{C}_i$, $\mathbb{C}_j$ in $\mathcal{P}$;
        Temporarily merge $\mathbb{C}_i$, $\mathbb{C}_j$ into one coalition $\mathbb{C}_k$;
        Recalculate users' transmission rates in $\mathbb{C}_k$;
        Compare $\mathbb{C}_k$ with the collection $\{\mathbb{C}_i, \mathbb{C}_j\}$ according to the QoS order;
        if $\mathbb{C}_k \triangleright \{\mathbb{C}_i, \mathbb{C}_j\}$
            Merge $\mathbb{C}_i$, $\mathbb{C}_j$ into $\mathbb{C}_k$, and generate another partition $\mathcal{P}'$;
        else
            $\mathcal{P}' = \mathcal{P}$;
        end
        Randomly select one coalition $\mathbb{C}_{k'}$ in $\mathcal{P}'$;
        Temporarily split $\mathbb{C}_{k'}$ into two coalitions $\mathbb{C}_{i'}$, $\mathbb{C}_{j'}$ in any manner;
        Recalculate users' transmission rates in $\mathbb{C}_{i'}$, $\mathbb{C}_{j'}$;
        Compare the collection $\{\mathbb{C}_{i'}, \mathbb{C}_{j'}\}$ with $\mathbb{C}_{k'}$ according to the QoS order;
        if $\{\mathbb{C}_{i'}, \mathbb{C}_{j'}\} \triangleright \mathbb{C}_{k'}$
            Split $\mathbb{C}_{k'}$ into $\mathbb{C}_{i'}, \mathbb{C}_{j'}$, and generate another partition $\mathcal{P}$;
        else
            $\mathcal{P} = \mathcal{P}'$;
        endif
      until: Merge and Split operations terminate.
```

Next, we analyze the complexity of the above algorithm. According to Algorithm 1, different initial states will lead to different number of merge and split operations, and thus the Algorithm 1 has different computational complexity. After each merge and split operation, D2D pairs' transmission rates and relay allocation scheme should be re-determined. For the most extreme case when all D2D pairs and relay nodes are in the same coalition with one CU, the calculation complexity is $O[(M+L)!/(M!\cdot L!)+Q]$. So the complexity of the proposed Algorithm 1 can be estimated as $O\{N\cdot[(M+L)!/(M!\cdot L!)+Q]\}$, where N is the total number of merge and split operations, which is also the number of partition variations. However in pratice, the number of these two operations can be significantly reduced, because the QoS comparison order prevents the situation that too many D2D pairs exist in one coalition, and thus reduces the number of merge operations. In addition, not all users are suitable for split operations. The split process only occurs if there exists some D2D pairs whose transmission rates are smaller than the threshold according to the QoS order. So, the complexity of the proposed algorithm can be futher lowered. Compared with the exhaustive method, the complexity is significantly reduced.

3.3 The Single User's Movement based Algorithm

Before converging to the final partition, Algorithm 1 keep iterating the merge and split operations. However, the final state may be a local optimum which still has a large room for improvement. That is, starting from the partition obtained by Algorithm 1, one can improve the system's sum rate by moving one D2D pair to another coalition without breaking the QoS constraint. But this operation cannot be realized using merge and split rules through QoS order. To improve the network performance, another algorithm based on single user's moving process is proposed.

Assume that the coalition where CU_k is located is $\mathbb{C}_k$. Let $\mathbb{C}_k \succ_i \mathbb{C}_{k'}$ denotes that D2D pair i (or relay node) prefers moving from the coalition $\mathbb{C}_k$ to $\mathbb{C}_{k'}$ according to the QoS order. Note that this moving process does not affect the other coalitions. So, a new transfer rule is defined as follows:

$$\mathbb{C}_k \succ_i \mathbb{C}_{k'} \ \mathit{iff}\ \{\mathbb{C}_k \cup i, \mathbb{C}_{k'} \setminus i\} \rhd \{\mathbb{C}_k, \mathbb{C}_{k'}\} \tag{18}$$

This definition implies that D2D pair i (or relay node i) prefers being a member of $\mathbb{C}_k$ over $\mathbb{C}_{k'}$ if the new collection is better according to the QoS order. Using this transforming rule, we propose the improved algorithm as in Algorithm 2.

Proposition 4: Every combination result of the merge and split rules can be obtained through (18).

Proof: If one coalition merges into another coalition, it must be the coalition with no CU in it merge into the coalition with CU. Other merge process disobeys the definition of QoS order. So according to the definition of QoS order and (9)-(11), the merge process can be decomposed to separate steps. In each step, one D2D pair or relay node leaves from its coalition, and move to another coalition with a CU. Similarly, every split operation can be decomposed through (18).

Proposition 5: The final state of Algorithm 2 satisfies Proposition 2 and Proposition 3, that is: Algorithm 2 converges to a final $\mathbb{D}_{hp}$-stable state in which all DUs obtain a transmission resource under an appropriate R_{th}.

Proof: Using the same method of the proving process of Proposition 2, we can prove that Algorithm 2 converges to a final state and all DUs obtain a transmission resource.

According to Proposition 4, every merge or split operation can be obtained through (18). In the final state of Algorithm 2, the partition cannot be transformed through (18), which also implies that the final partition is steady no matter how to merge or split it. So, Algorithm 2 converges to a $\mathbb{D}_{hp}$-stable state.

The complexity analysis of Algorithm 2 is similar with Algorithm 1 in the extreme case, except the total number of partition variations N. Similarly in practice, the complexity can be significantly reduced, because the situation that all D2D pairs and relay nodes exist in the same coalition is almost impossible under random initial state. The partition always transforms in a monotonic way according to the QoS order (which has been proved in Proposition 1). In the next section, we will show the difference of convergence speed between the proposed two algorithms.

Algorithm 2: The single user's movement based algorithm

```
Initial Phase:
  Each CU forms a coalition, and the D2D pairs are randomly distributed into these
  coalitions. Each relay node forms a coalition. The whole network is partitioned as
  $\mathcal{P} = \{\mathbb{C}_1,...,\mathbb{C}_Q,\mathbb{C}_{Q+1},...\mathbb{C}_{Q+M}\}$.
Coalition Formation Phase:
  In this phase, coalition is transformed according to (18).
    repeat
      Randomly choose one D2D pair or relay node $i$, and denote its coalition as $\mathbb{C}_{k'}$;
      Randomly choose another coalition which contains a CU, and denote it as $\mathbb{C}_k$;
      Temporarily remove $i$ from $\mathbb{C}_{k'}$ and put it into $\mathbb{C}_k$;
      Recalculate the users' transmission rates in $\mathbb{C}_k$ and $\mathbb{C}_{k'}$;
      if $\mathbb{C}_k \succ_i \mathbb{C}_{k'}$
          $i$ leaves $\mathbb{C}_{k'}$ and joins $\mathbb{C}_k$;
          Renew the partition $\mathcal{P}$;
      endif
    until: the partition converges to the final state.
```

4. Performance Evaluation

In this section, we provide the simulation results to evaluate the performance of the two proposed algorithms. The simulations are executed in a single cell of D2D cellular networks with radius of 200 m. The CUs, D2D pairs, and relay nodes are uniform randomly distributed in the cell. Other parameters used in the simulation are summarized in **Table 1**.

Table 1. Simulation Parameters

Parameter	Value
Uplink bandwidth	15 MHz
Noise power density	-174 dBm/Hz
Max D2D communication distance	50 m
CU Tx power	20 mW
D2D Tx power	10 mW
Relay Tx power	10 mW
Path loss exponent	4

In order to show the efficiency of the proposed two algorithms, the following schemes are compared:

(1) Optimal Solution: As shown in the above section, the optimal solution of the resource allocation problem is NP-hard, we only find the solution in a small network scenario through exhaustive search.

(2) Greedy Approach: Greedily search resource allocation solution for each D2D pair and relay node. Consider all the situations for each D2D pair that each relay node (include the direct mode) and CU are matched with this D2D pair, and find the best solution.

(3) Random Allocation: The D2D pairs and relay nodes are randomly allocated into the coalitions of CU.

As discussed in the section 3.2, for a large value of R_{th}, an optimal solution of the resource allocation problem may not exist because some CUs or D2D pairs may obtain a transmission rate that is smaller than R_{th}. So, in this section, two metrics are considered to evaluate the algorithm performance: (1) system's sum rate, (2) the number of users that cannot meet the QoS threshold. Due to the randomness of the produced network, the simulation is repeated for 100 times and the average value is obtained.

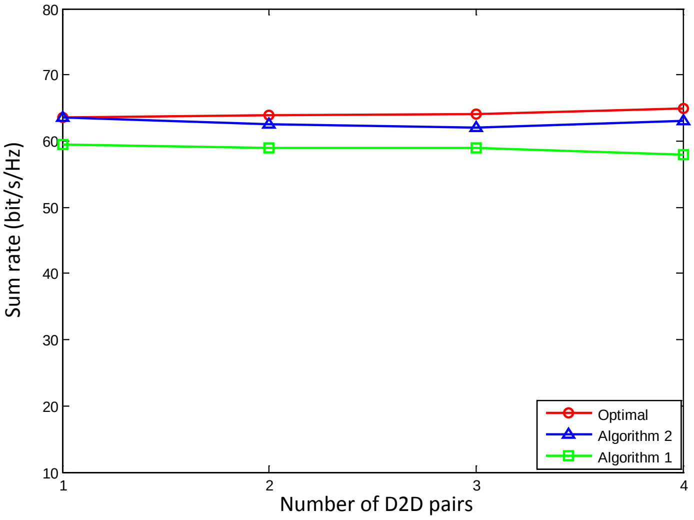

Fig. 2. Performance of network sum rate with different number of D2D pairs

Fig. 2 illustrates the throughput of proposed algorithms for different number of DUs when $Q=3$ and $M=4$. We set $R_{\text{th}} = 0.01$ bit/s/Hz to guarantee that R_{th} can be achieved by each user. Since the transmission power of each user is fixed and only one D2D pair is active in one timeslot, the overall throughput of the system is insenstive to the change of the number of DUs. It can be seen from the figure that the performance of Algorithm 2 always performs better than that of Algorithm 1. This is because that the single user movement rule utitlized in Algorithm 2 can transform the partition formed by Algorithm 1, which can further improve the sytem performance. In addition, we can also observe that the performance of Algorithm 1 and 2 are close to that of the optimal one. Considering the much lower complexity of Algorithm 1 and 2 as shown in Section 3.2 and 3.3, we can obtain that the proposed algorithms can achive a good tradeoff between the performance and complexity.

Fig. 3 (a) illustrates the sum rate of the whole system for different number of CUs when $R_{\text{th}} = 1$ bit/s/Hz, L=5, and M=5. From the figure, we can observe that the sum rate increases with the number of CUs. This is because more spectrum resource is avaiable for DUs to use as the number of CUs increases. The random approach gets the worst network sum rate since the channel diversity has not been approprately exploited. Algorithm 2 achieves the highest sum rate since it takes the sum rate of the whole system into the definition of QoS order and improves the local optima case in Algorithm 1. The greedy approach "seems" performing better than the proposed Algorithm 1 on the performance of the network sum rate. However, **Fig. 3 (b)** shows that on the performance of the average number of users whose rates are smaller than R_{th}, the proposed algorithms perform better than both the greedy and random approachs. The reason is that both the system's sum rate and the QoS requirement have been put into consideration in the QoS order. This also explains the reason that the greedy approach performs better than Algorithm1 in **Fig. 3 (a)**: the greedy scheme obtains higher sum rate at the cost of violating the QoS requirements of some users. Taking **Fig. 3 (a)** and **Fig. 3 (b)** together, the proposed Algorithm 2 performs best due to the single user's movement according to the QoS order.

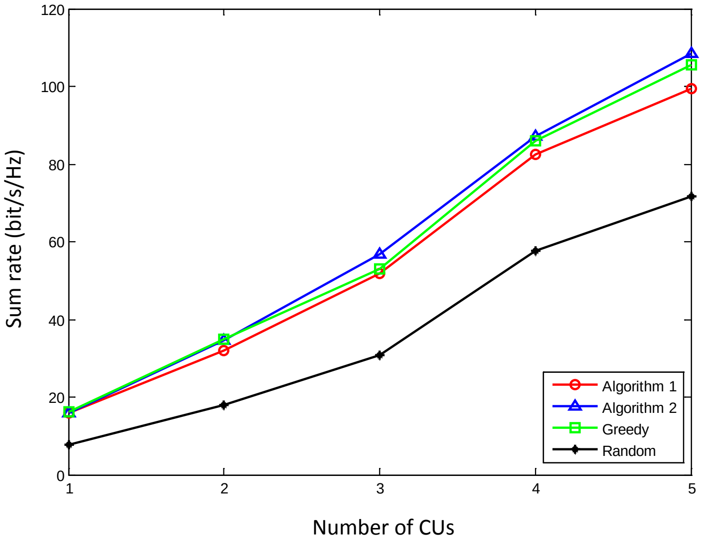

Fig. 3(a). Performance of network sum rate with different number of CUs

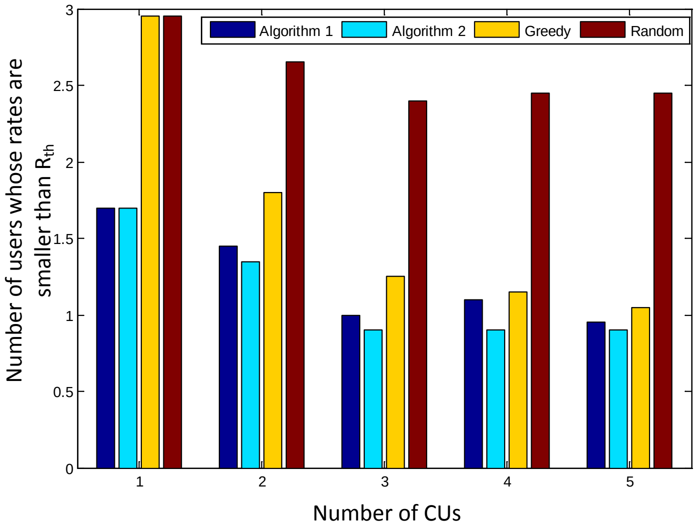

Fig. 3(b). Performance of the number of users whose rate are smaller than R_{th} with different number of CUs

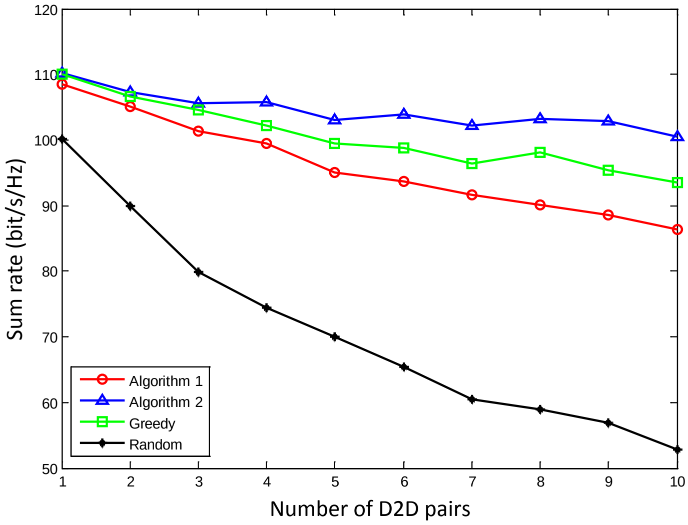

Fig. 4(a). Performance of network sum rate with different number of D2D pairs

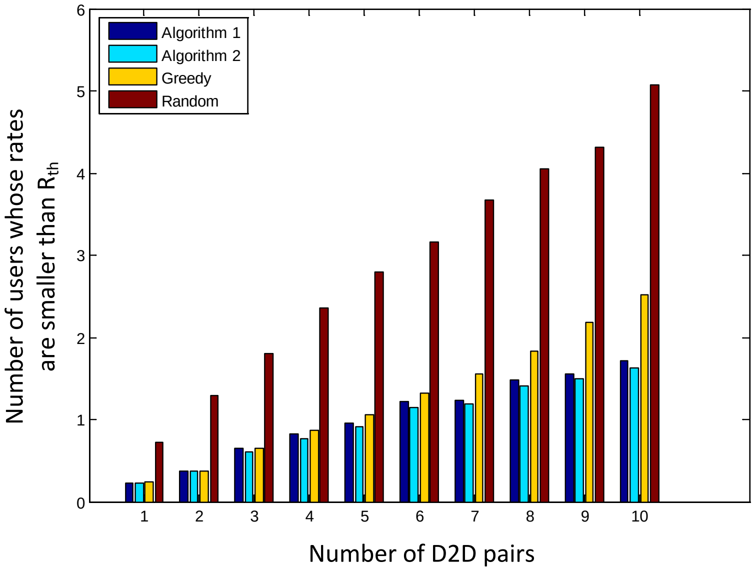

Fig. 4(b). Performance of the number of users whose rate are smaller than R_{th} with different number of D2D pairs

Fig. 4 (a) and **Fig. 4 (b)** depict the system performance for different number of D2D pairs when $R_{\text{th}} = 1$ bit/s/Hz, $Q = 5$, and $M = 10$. From **Fig. 4 (a)**, the sum rate decreases with the increase of D2D pairs. Since the spectrum resource of the system is fixed, more DUs may render intensive competitions for the transmission chances. To satsify the minimum rate requirement of each DU, the system may sacrifice a little performance of network's sum rate to guarantee the QoS constraint. It can also be seen from **Fig. 4 (a)** and **Fig. 4 (b)** that Algorithm 2 can always achieve a better performance than other algorithms either in the sum rate or QoS constraints, which is consistent with the results of **Fig. 3 (a)** and **Fig. 3 (b)**.

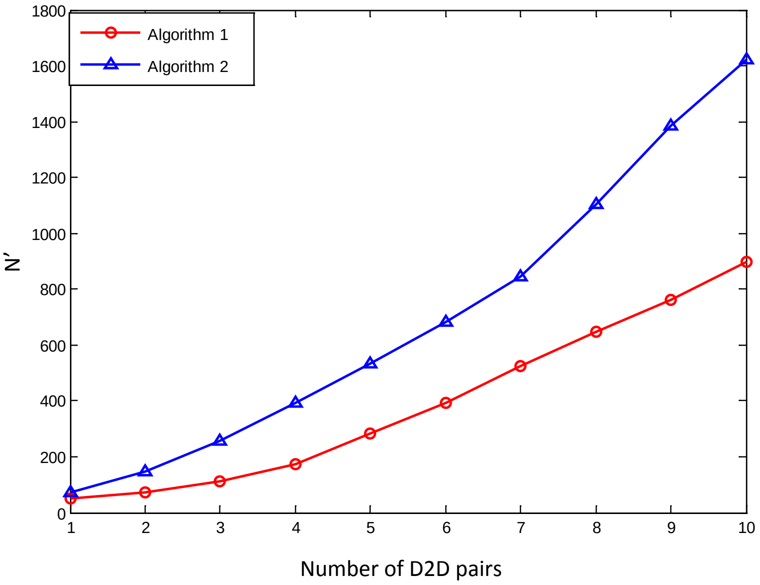

Fig. 5. Performance of the convergence speed with different number of D2D pairs

Fig. 5 depicts the convergence speed of the two algorithms with $Q = 5$, $M = 10$, and $R_{\text{th}} = 1$ bit/s/Hz. The convergence speed N' is defined as the number that the partition tries to change before it converges to the final steady state. Note that this is different from the number of partition changes N because N' additionally contains the number that the partition dosen't change before the steady state. From the figure, we can see that N' increases with the number of D2D pairs, because more partition transformations are needed until the final steady state. It can also been seen that Algorithm 1 always has better convergence property than Algorithm 2. This is because the operational objective of Algorithm 1 is coalition, which may contain more elements. Algorithm 2 operates on single user's movement, which is a smaller granularity to form coalition than that in Algorihtm 1 and thus leads to the increasement of N' and low convergence speed.

5. Conclusion

In this paper, we have investigated the relay selection and frequency sharing problem in cooperative relay based D2D networks under a QoS constraint. Two algorithms which are based on the coalition formation game theory with a newly defined “QoS order” are proposed to solve the NP-hard resource allocation problem. Simulation results show the effectiveness of the proposed algorithms compared to the optimal solution, greedy search and random allocation approaches. The transmission power adjustment, rate threshold selection, and multi-cell scenario would be addressed in future work.

Appendix

Proof of Proposition 1

First, we prove the transitivity of QoS order. The condition of a relation’s transitivity is defined in the “(tr) of Ref [19]”. For all collections $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$ with $\bigcup\mathcal{A} = \bigcup\mathcal{B} = \bigcup\mathcal{C}$, assume that $\mathcal{A} \rhd \mathcal{B}$ satisfies condition (C2), and $\mathcal{B} \rhd \mathcal{C}$ satisfies the condition (C1.1). Then for $\mathcal{A}$ and $\mathcal{C}$, we have $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\} \geq R_{\text{th}}$ and $\min\{v(\mathcal{C} \setminus \mathbf{r}_{\mathcal{C}})\} < R_{\text{th}}$. According to condition (C3), $\mathcal{A} \rhd \mathcal{C}$. If $\mathcal{A} \rhd \mathcal{B}$ satisfies condition (C3), and $\mathcal{B} \rhd \mathcal{C}$ satisfies the condition (C1.2), we have $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\} \geq R_{\text{th}}$, $\min\{v(\mathcal{B} \setminus \mathbf{r}_{\mathcal{B}})\} < R_{\text{th}}$, and $\min\{v(\mathcal{C} \setminus \mathbf{r}_{\mathcal{C}})\} < R_{\text{th}}$. According to condition (C3), $\mathcal{A} \rhd \mathcal{C}$. Other situations of collections $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$ can be proved through the same method as above. So, the QoS order is transitive.

Next, we prove the monotonicity of QoS order. The condition of a relation's monotonicity is defined in the "(m1) and (m2) of Ref [19]". For all collections $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$ with $\bigcup\mathcal{A} = \bigcup\mathcal{B}$, $\bigcup\mathcal{C} = \bigcup\mathcal{D}$, and $(\bigcup\mathcal{A}) \bigcap (\bigcup\mathcal{C}) = \varnothing$, assume that $\mathcal{A} \rhd \mathcal{B}$ satisfies (C3), $\mathcal{C} \rhd \mathcal{D}$ satisfies (C1.2). Then for the collections $\mathcal{A} \bigcup \mathcal{C}$ and $\mathcal{B} \bigcup \mathcal{D}$, we have $\min\{v((\mathcal{A} \bigcup \mathcal{C}) \setminus (\mathbf{r}_{\mathcal{A}} \bigcup \mathbf{r}_{\mathcal{C}})\} < R_{\text{th}}$ and $\min\{v((\mathcal{B} \bigcup \mathcal{D}) \setminus (\mathbf{r}_{\mathcal{B}} \bigcup \mathbf{r}_{\mathcal{D}})\} < R_{\text{th}}$. Since the number of nodes whose rates are lower than R_{th} in $\mathcal{C}$ is less than that in $\mathcal{D}$, and $\min\{v(\mathcal{A} \setminus \mathbf{r}_{\mathcal{A}})\} \geq R_{\text{th}}$, $\min\{v(\mathcal{B} \setminus \mathbf{r}_{\mathcal{B}})\} < R_{\text{th}}$, the collections $\mathcal{A} \bigcup \mathcal{C}$ and $\mathcal{B} \bigcup \mathcal{D}$ satisfy (C1.2). So, $\mathcal{A} \bigcup \mathcal{C} \rhd \mathcal{B} \bigcup \mathcal{D}$. If $\mathcal{A} \rhd \mathcal{B}$ satisfies (C2), $\mathcal{C} \rhd \mathcal{D}$ satisfies (C1.1), for the collections $\mathcal{A} \bigcup \mathcal{C}$ and $\mathcal{B} \bigcup \mathcal{D}$, we have $\min\{v((\mathcal{A} \bigcup \mathcal{C}) \setminus (\mathbf{r}_{\mathcal{A}} \bigcup \mathbf{r}_{\mathcal{C}})\} < R_{\text{th}}$ and $\min\{v((\mathcal{B} \bigcup \mathcal{D}) \setminus (\mathbf{r}_{\mathcal{B}} \bigcup \mathbf{r}_{\mathcal{D}})\} < R_{\text{th}}$. However, $\sum v(\mathcal{A} \bigcup \mathcal{C}) > \sum v(\mathcal{B} \bigcup \mathcal{D})$. Then according to (C1.1), we have $\mathcal{A} \bigcup \mathcal{C} \rhd \mathcal{B} \bigcup \mathcal{D}$. Other situations can be proved through the same method. The condition (m1) in Ref [19] is satisfied.

For all collections $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$ with $\bigcup\mathcal{A} = \bigcup\mathcal{B}$ and $\bigcup\mathcal{A} \bigcap \bigcup\mathcal{C} = \varnothing$, assume that $\mathcal{A} \rhd \mathcal{B}$ satisfies the condition (C2) and $\min\{v(\mathcal{C} \setminus \mathbf{r}_{\mathcal{C}})\} < R_{\text{th}}$. The collections $\mathcal{A} \bigcup \mathcal{C}$ and $\mathcal{B} \bigcup \mathcal{C}$ satisfy the condition (C1.1). So $\mathcal{A} \bigcup \mathcal{C} \rhd \mathcal{B} \bigcup \mathcal{C}$. If $\mathcal{A} \rhd \mathcal{B}$ satisfies the condition (C3) and $\min\{v(\mathcal{C} \setminus \mathbf{r}_{\mathcal{C}})\} > R_{\text{th}}$, we have $\min\{v(\mathcal{A} \bigcup \mathcal{C} \setminus \mathbf{r}_{\mathcal{A}} \bigcup \mathbf{r}_{\mathcal{C}})\} > R_{\text{th}}$ and $\min\{v(\mathcal{B} \bigcup \mathcal{C} \setminus \mathbf{r}_{\mathcal{B}} \bigcup \mathbf{r}_{\mathcal{C}})\} < R_{\text{th}}$. Then according to the condition (C3), we have $\mathcal{A} \bigcup \mathcal{C} \rhd \mathcal{B} \bigcup \mathcal{C}$. Other situations can be proved through the same method. The condition (m2) in Ref [19] is satisfied.

So the QoS order is monotonic.

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