Multi-Sharing Resource Allocation for Device-to-Device Communication Underlaying 5G Mobile Networks

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***Abstract*—Device-to-device (D2D) communication can improve system spectrum efficiency in mobile networks; however, existing D2D resource allocation techniques may not work well in 5G mobile networks with many simultaneously connected devices. To address this problem, we study the multi-sharing resource allocation problem, which allows any cellular user equipment to share its radio resource with *multiple* D2D devices. We formulate the multi-sharing resource allocation problem and prove its NP hardness. Besides, we develop the Greedy Throughput Maximization Plus (GTM+) algorithm. Simulation results show that GTM+ is fast and outperforms existing algorithms in throughput and the number of permitted D2D pairs.**

***Index Terms*—D2D communication, mobile network, resource allocation.**

I. Introduction

The increasing demand for high data rate applications has been leading to the ongoing research of fifth-generation (5G) mobile networks. Compared with 4G systems, 5G mobile networks are expected to achieve higher system spectrum efficiency and support much higher numbers of devices. It is forecast in [1] that there will be 25 billion of interconnected devices by 2020. To achieve these goals, device-to-device (D2D) communication is a promising component because of its two inherent advantages—traffic offloading and radio resource reusing: Pairs of D2D user equipments (DUEs), which reuse radio resource allocated to cellular user equipments (CUEs), communicate directly with the other ends without adding communication load on the base station (BS).

In general, D2D communication [2], [3] can have several modes to operate in—it can underlay or overlay the cellular network, utilize dedicate or shared radio resource, and if shared, reuse the uplink or downlink resource of CUEs. Dopper et al. [4] in 2010 studied mode selection that maximizes user rate. Xu et al. [5] in 2012 investigated the resource sharing mode in the downlink direction. They developed an auction-based resource allocation method—the bidder who places the highest bid gets the resource but pays the price bid by the second-highest bidder.

Rather than downlink resource sharing, the recent focus of D2D communication is more on uplink resource sharing. The major reason is because Internet traffic is heavier in the download direction and the uplink spectrum is often underutilized. This asymmetric traffic phenomenon is likely to remain true by 2019 or later because as forecast by Cisco in [6], video (which is mainly transmitted in the downlink direction) accounts for 2/3 of mobile data traffic in 2014-2019. For uplink resource sharing, Han et al. [7] in 2012 developed an optimal algorithm and a fast heuristic that ensures maximum permitted DUE pairs as well as minimum total interference under prerequisite of the maximum number of permitted DUE pairs. The max-DUE-min-interference problem Han et al. studied in [7] is essentially the assignment problem and the optimal algorithm they proposed is essentially a Hungarian method. Feng et al. [8] also studied uplink resource sharing but aimed to maximize the system throughput instead. They developed the Optimal Resource Allocation (ORA) algorithm, which consists of admission control, transmit power allocation, and DUEs-to-CUEs maximum weight matching. The third step of ORA is essentially the assignment problem, in which the Hungarian algorithm is used.

The aforementioned papers only consider the *single-sharing* scenario, in which any resource block (RB) allocated to a CUE can be reused by at most one DUE pair. Indeed the *multi-sharing* scenario, in which any RB can be reused by multiple DUE pairs, is more flexible and beneficial in 5G mobile networks. For the multi-sharing scenario, Sun et al. [9] aimed to maximize the number of permitted DUE pairs. They developed the Greedy Resource Allocation (GRA) algorithm, which first forms a conflict graph for each CUE and then chooses proper DUEs in the order of smallest degree first. Xu et al. [10] jointly dealt with uplink resource allocation and power control by the iterative and auction-based algorithm called I-CAs. I-CAs considers the multi-sharing scenario in the sense that pre-dispatched "packages" of DUE pairs, rather than individual DUE pairs, reuse the RBs of CUEs. These multi-sharing schemes aforementioned have a common assumption—a CUE can share its RBs with multiple DUE pairs, but a DUE pair can simultaneously reuse the RBs of up to one CUE.

None of the above algorithms is designed for a 5G mobile network with a vast quantity of DUEs. The algorithms designed for the single-sharing scenario severely restrict the number of simultaneously connected DUEs. As to the existing multi-sharing schemes, GRA does not perform well in system throughput; I-CAs relies on pre-dispatch of DUE pairs to packages, but how to obtain an optimal pre-dispatch is unclear since it is a combinatorial problem. This motivates our study in the

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multi-sharing resource allocation problem and in developing a new scheme that improves system throughput while being fast enough to support many DUEs in 5G mobile networks.

In this paper, we formulate the multi-sharing resource allocation problem and prove its NP hardness. We jointly consider (real) CUEs and idle RBs that can be scheduled for transmission. In addition, we propose the Greedy Throughput Maximization Plus (GTM+) algorithm which gives a fast yet efficient solution for the multi-sharing resource allocation problem. GTM+ exploits conflict graph and maximal weight independent set to improve system throughput while ensuring the minimum SINR requirements of CUEs and DUEs. Simulation results show that the algorithm outperforms existing schemes.

The remaining part of this paper is organized as follows: Section II describes the system model. We formulate the multi-sharing resource allocation and show its NP hardness in Section III. Section IV presents the algorithm we propose. The performance evaluation and comparison are shown in Section V. We present some concluding remarks in Section VI.

II. System Model

As shown in Fig. 1, we consider a cell[1], in which there are N DUEs, $M - K$ real CUEs, and K idle RBs scheduled for transmission during a transmission interval. Each idle RB, which is not used by any real CUEs, can be regarded as a virtual CUE with zero transmit power and no SINR requirement. M is the total number of CUEs, including real CUEs and virtual CUEs. The CUEs and DUEs are denoted by $C_1, C_2, \ldots, C_M$ and $D_1, D_2, \ldots, D_N$, respectively. For simplicity of exposition, when there is no ambiguity, m and n are also used to denote C_m and D_n, respectively. We denote the sender side of the DUE pair n by $D_{n,\mathrm{Tx}}$ and the receiver side by $D_{n,\mathrm{Rx}}$.

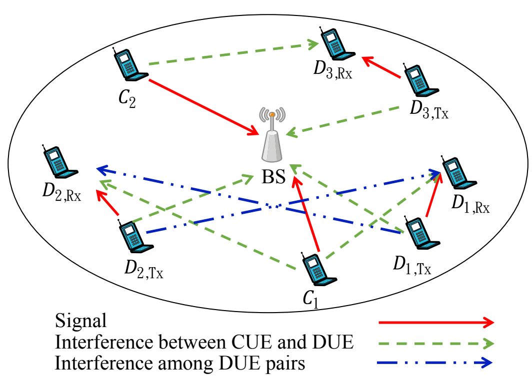

Fig. 1. CUEs share RBs with DUEs (C_1 shares with D_1 and D_2; C_2 shares with D_3 in this figure), causing mutual interference.

Each CUE is pre-assigned a set of *uplink* RBs before sharing the RBs to DUEs. The sets are disjoint; their sizes can be either identical or different. The allocated bandwidth is proportional to the number of allocated RBs. For any certain CUE, say m, we denote its allocated bandwidth by W_m, its transmit power by P_{C_m} or P_m, and the noise power by σ_m^2. CUE m's bandwidth, W_m, is proportional to the number of RBs allocated to CUE m. To make the system model as general as possible for the need of future 5G mobile networks, different CUEs are allowed to have different bandwidth (or equivalently, different numbers of allocated RBs), transmit power, and/or noise power.

Whereas many existing papers study the case when $N \leq M$ or restrict each CUE to share its RBs with at most one DUE pair (or one DUE package), this paper studies multi-sharing resource allocation by which each CUE is allowed to share its RBs with multiple DUE pairs in order to support as many simultaneously connected DUE pairs as possible. This multi-sharing scenario matches the reality of 5G mobile networks, which are expected to have a large number of DUEs.

To specify CUE-DUE relationship, Θ_n is defined as the set of CUEs that shares RBs with DUE pair n; Δ_m is defined as the set of the DUE pairs that reuse the RBs allocated to CUE m.[2] All $\Delta_1, \Delta_2, \ldots, \Delta_M$ are subsets of $\{1, 2, \ldots, N\}$. For the DUE pair n, we denote the transmit power at the sender by P_{D_n} or P_n, and the noise power at the receiver by σ_n^2.

All CUEs have minimum SINR requirements. A set of DUEs can reuse CUE m's uplink RBs only if the imposed interference on m's transmission does not violate m's SINR requirement. Within a cell, RBs are allocated disjointly/orthogonally among CUEs. So, for any CUE $m \in \{1, 2, \ldots, M\}$, the received SINR must exceed the threshold:

$$\frac{P_m G_{mB}}{\sigma_m^2 + \sum_{n \in \Delta_m} P_n G_{nB}} \geq \gamma_m \tag{1}$$

where G_{mB} is the channel gain between CUE m and the serving base station, G_{nB} is the channel gain between the sender of the DUE pair n and the base station, and γ_m (or γ_{C_m}) is the SINR threshold CUE m requires.

Similarly, DUE pairs also have their minimum SINR requirements. For any DUE pair n, n reuses certain RBs only if the received SINR exceed the SINR threshold:

$$\frac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn} + \sum_{n' \in \Delta_m - \{n\}} P_{n'} G_{n'n}} \geq \gamma_n, \forall m \in \Theta_n \tag{2}$$

where γ_n (or γ_{D_n}) is the SINR threshold of DUE pair n, G_{nn} is the channel gain between the two ends of DUE pair n, G_{mn} is the channel gain from CUE m to DUE pair n, and $G_{n'n}$ is the channel gain from $D_{n',\mathrm{Tx}}$ to $D_{n,\mathrm{Rx}}$.

III. Problem Formulation and NP Hardness

A. Problem Formulation

Same as many cited papers, it is assumed that the serving BS gets the channel state information (CSI) for all the links and knows the SINR threshold of all users. So the BS knows the values of G_{mB}, G_{nB}, G_{nn}, G_{mn}, $G_{n'n}$, W_m, P_m, P_n, σ_m^2,

[1] Inter-cell interference is not considered because according to [5] it can be managed efficiently with power control or resource scheduling mechanisms.

[2] For notation consistency, we define $\Theta_n = \emptyset$ if no CUE shares its RBs with DUE pair n. $\Delta_\emptyset$ is defined as the set of all DUE pairs which is $\{1, 2, \ldots, N\}$.

σ_n^2, γ_m, and γ_n. The objective of the multi-sharing resource allocation problem is to determine how CUEs share RBs with DUEs (more specifically, to determine $\Delta_1, \Delta_2, \ldots, \Delta_M$) such that system throughput (denoted by T) is maximized, where system throughput is calculated by the sum of all CUEs' and DUEs' Shannon capacities. Mathematically, the multi-sharing resource allocation problem can be formulated as follows:

$$T = \max_{\Delta_1,\Delta_2,\ldots,\Delta_M} \sum_{m=1}^{M} \Big\{ W_m \log_2(1+\tfrac{P_m G_{mB}}{\sigma_m^2 + \sum\limits_{n\in\Delta_m} P_n G_{nB}}) + \sum_{n\in\Delta_m} W_m \log_2(1+\tfrac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn} + \sum\limits_{n'\in\Delta_m-\{n\}} P_{n'} G_{n'n}}) \Big\} \quad (3)$$

subject to

$$\sum_{n\in\Delta_m} P_n G_{nB} \le \tfrac{P_m G_{mB}}{\gamma_m} - \sigma_m^2,\ \forall m\in\{1,2,...,M-K\} \quad (4)$$

$$P_m G_{mn} + \sum_{n'\in\Delta_m-\{n\}} P_{n'} G_{n'n} \le \tfrac{P_n G_{nn}}{\gamma_n} - \sigma_n^2, \quad \forall n \in \{1,2,...,N\},\ \forall m \in \Theta_n \quad (5)$$

$$n \in \Delta_m,\ \forall n \in \{1,2,\ldots,N\},\ \forall m \in \Theta_n \quad (6)$$

The constraint (4) comes from (1) after applying simple arithmetic manipulation; it means that the imposed interference on CUE m's transmission from DUE pairs that reuse m's uplink RBs, which is $\sum_{n\in\Delta_m} P_n G_{nB}$, cannot exceed the *maximum tolerable interference* on m's transmission

$$I_m = \frac{P_m G_{mB}}{\gamma_m} - \sigma_m^2 \quad (7)$$

Similarly, The constraint (5) which stems from (2) means that the imposed interference on DUE pair n's transmission from CUE and DUEs cannot exceed the *maximum tolerable interference* on n's transmission

$$I_n = \frac{P_n G_{nn}}{\gamma_n} - \sigma_n^2 \quad (8)$$

B. NP Hardness

The below theorem states NP-hardness of the multi-sharing resource allocation problem formulated above.

Theorem 1. *The multi-sharing resource allocation problem, which determines how DUE pairs reuse CUEs' RBs with the objective function shown in* (3) *under the constraints* (4)–(6)*, is NP-hard.*

Proof. We prove NP hardness of the multi-sharing resource allocation problem by showing that a special case of it is NP-hard. Consider the special case that satisfies the following conditions:

- $M = 1$ and $K = 0$. That is, in this special case, there is only one CUE and no idle RB. For exposition purpose, the CUE is denoted by CUE m.
- $G_{n'n} = 0, \forall n', n \in \{1, 2, \ldots, N\} : n' \neq n$. That is, all DUE pairs in this special case do not interfere each other.
- $\frac{P_m G_{mB}}{\sigma_m^2} \ll \frac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn}}$ for all n. That is, the received SNR of CUE's communication is much weaker than than the received SINR of any D2D communication.
- $\gamma_n = 0, \forall n \in \{1, 2, \ldots, N\}$. That is, all DUE pairs do not have any SINR requirement.

By the second and third conditions in the above, we know that in the special case, the received SINR of the CUE's communication is much weaker than that of any D2D communication because:

$$\frac{P_m G_{mB}}{\sigma_m^2 + \sum_{n\in\Delta_m} P_n G_{nB}} \le \frac{P_m G_{mB}}{\sigma_m^2} \ll \frac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn}} = \frac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn} + \sum_{n'\in\Delta_m-\{n\}} P_{n'} G_{n'n}}$$

Due to the enormous SINR difference shown above, the Shannon capacity of the CUE's communication is negligible in the special case, compared to the Shannon capacity of any D2D communication. Therefore, in this special case, the multi-sharing resource allocation problem previously formulated in the last subsection degenerates to:

$$T = \max_{\Delta_m} \sum_{n\in\Delta_m} W_m \log_2(1 + \tfrac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn}})$$

subject to

$$\textstyle\sum_{n\in\Delta_m} P_n G_{nB} \le \frac{P_m G_{mB}}{\gamma_m} - \sigma_m^2$$

since there is only one CUE in the cell (i.e., $M = 1$).

Now, image that any DUE pair, say DUE pair n, is an item with a weight equal to $P_n G_{nB}$ kilograms and a value equal to $W_m \log_2(1 + \frac{P_n G_{nn}}{\sigma_n^2 + P_m G_{mn}})$ dollars. And image that CUE m has a knapsack that can bear up to $\frac{P_m G_{mB}}{\gamma_m} - \sigma_m^2$ kilograms. For the special case, finding out the optimal set of DUE pairs that maximizes system throughput is exactly equivalent to putting the optimal set of items that can fit in the knapsack (without exceeding the weight limit) such that the total value is maximized. Therefore, the multi-sharing resource allocation problem in the special case is equivalent to the 0-1 knapsack problem and thus is NP-hard.

Since such a special case is NP-hard, we have proved NP hardness of the multi-sharing resource allocation problem. □

IV. The GTM+ Algorithm

Because the multi-sharing resource allocation problem is NP-hard, we develop the Greedy Throughput Maximization Plus (GTM+) algorithm to find an efficient yet fast solution.

As shown in the pseudocode, GTM+ is an iterative algorithm. GTM+ starts with random pre-allotment of idle RBs. If there are any idle RBs, one DUE pair is randomly chosen for each idle RB—any chosen DUE pair is pretended and treated as a CUE that is willing to share its RB. After that, GTM+ takes a number of iterations to decide how to reuse RBs of all CUEs.

Before the beginnings of all iterations, every unallocated DUE pair joins the unmarked group that maximizes its own *utility*. (By DUE pair n joining group m, we mean that DUE pair n requests to reuse the RBs of CUE m. The set of DUE pairs that join group m is denoted by Γ_m.) Then the largest unmarked group m' finds out, among its group members, a set of DUE pairs that aggregately maximize the total utility while not causing high mutual interference. This is done by taking the maximum weight independent set of the conflict graph corresponding to group m'. Such DUE pairs are *candidates* for reusing the RBs of CUE m'. In order to ensure the SINR requirements of CUE m' and the candidates themselves, one candidate is removed at a time until the SINR requirements are satisfied. After doing this, $\Delta_{m'}$ (which is the set of DUE pairs that will reuse RBs of CUE m') ends up being the remaining candidates and group m' is marked done, which ends an iteration. If there are unmarked groups left, the algorithm goes to the next iteration; otherwise, it completes.

What follows gives additional details about the utility function, the conflict graph for a group, the candidates found with the help of a conflict graph, and the complexity of the GTM+ algorithm. First, the utility of D_n joining C_m is defined as

$$u_n(m) = W_m \log_2(1+\frac{P_m G_{mB}}{\sigma_m^2+P_n G_{nB}})+W_m \log_2(1+\frac{P_n G_{nn}}{\sigma_n^2+P_m G_{mn}})$$

The utility $u_n(m)$ can be interpreted as the system throughput pretending that D_n reuses C_m's RBs and pretending that there exists neither other CUE nor other DUE pair in the cell.

The conflict graph $G_{m'}$ for a group m' is formed as follows: The vertices in the conflict graph correspond to the DUE pairs in group m'. Each vertex is assigned a weight whose value is set to the utility of the corresponding DUE pair joining group m'. For any two vertices, an edge is added to the conflict graph if the mutual interference exceeds a threshold. An edge connecting two vertices implies that the two corresponding DUE pairs should not reuse the same RBs simultaneously.

The candidates are determined as follows, with the help of the conflict graph $G_{m'}$ whose vertices represent DUE pairs. We aim to remove DUE pairs that cannot coexist due to too large mutual interference and to keep the DUE pairs that aggregately maximize system throughput. To this end, the candidates are set to be the maximum weight independent set (MWIS) of the conflict graph $G_{m'}$. This makes sense because in the conflict graph, an edge connecting two vertices implies too large mutual interference and a vertex weight represents a potential increment in system throughput. Because the MWIS problem is NP-hard, we use the heuristic algorithm in [11] to obtain a maximal weight independent set instead. The heuristic is of time complexity $O(n^3)$.

The worst-case complexity of GTM+ is $O(n^4)$. This is because the complexity of the heuristic used to solve the MWIS problem is $O(n^3)$ and in each iteration, at least one DUE pair is granted to reuse the RBs. Nevertheless, our simulation results show that on average, GTM+ is more than 10X faster than a Hungarian method of time complexity $O(n^3)$.

Algorithm 1: GTM+

Algorithm *GTM+*
- **Input**: N DUE pairs, $M-K$ real CUEs, and K idle RBs.
- **Output**: RB allocation results $\Delta_1, \Delta_2, \dots, \Delta_M$.
- // Pre-allotment of idle RBs.
- Randomly pick K DUE pairs, say $D_{\delta_1}, D_{\delta_2}, \dots, D_{\delta_K}$, one for each idle RB. Pretend and treat these DUE pairs as K CUEs which are numerated as CUEs $M-K+1, M-K+2, \dots, M$.
- // Initialization.
- $U \leftarrow \{1, 2, \dots, M\}$. // U is the set of unmarked groups/CUEs.
- Set $\Gamma_1, \Gamma_2, \dots, \Gamma_M$ to be empty sets. // Γ_m is the set of DUEs that joins group m.
- **foreach** $n \in \{1, 2, \dots, N\} - \{\delta_1, \delta_2, \dots, \delta_K\}$ **do**
  - $m^* \leftarrow$ WhoGivesMaxUtility(n, U).
  - $\Gamma_{m^*} \leftarrow \Gamma_{m^*} \cup \{n\}$. // That is, D_n joins group m^*.
- // The main body (consisting of iterations) starts here.
- **while** $U \neq \emptyset$ **do**
  - Form the conflict graph $G_{m'}$ for the largest group $\Gamma_{m'}$ in U. // $m' \leftarrow \arg\max_{m \in U} |\Gamma_m|$.
  - $\Delta_{m'} \leftarrow$ the maximum weight independent set of $G_{m'}$.
  - **foreach** $n' \in \Delta_{m'}$ **do**
    - // Check if DUE pair n' does not meet its SINR requirement.
    - **if** $P_{m'} G_{m'n'} + \sum_{n \in \Delta_{m'} - \{n'\}} P_n G_{nn'} > I_{n'}$ **then**
      - Remove n' from $\Delta_{m'}$.
  - Sort elements/DUEs in $\Delta_{m'}$ by their interference on $C_{m'}$ in descending order.
  - // Remove one DUE from $\Delta_{m'}$ at a time until the superposed interference is below maximum tolerable interference $I_{m'}$.
  - **while** $\sum_{n \in \Delta_{m'}} P_n G_{nB} > I_{m'}$ **do**
    - Remove the first element from $\Delta_{m'}$.
  - **foreach** $n \in \Gamma_{m'} - \Delta_{m'}$ **do**
    - $m^* \leftarrow$ WhoGivesMaxUtility(n, $U - \{m'\}$).
    - $\Gamma_{m^*} \leftarrow \Gamma_{m^*} \cup \{n\}$. // D_n joins group m^*.
  - $U \leftarrow U - \{m'\}$. // Make group m' marked.

Function *WhoGivesMaxUtility(n, C)*
- // Return $m^* = \arg\max_{m \in C} \{u_n(m) : P_n G_{nB} \leq I_m\}$.
- MaxUtility $\leftarrow$ 0.
- $m^* \leftarrow 0$.
- **foreach** $m \in C$ **do**
  - **if** $P_n G_{nB} \leq I_m$ **then**
    - **if** $u_n(m) >$ *MaxUtility* **then**
      - MaxUtility $\leftarrow u_n(m)$.
      - $m^* \leftarrow m$.
- Return m^*.

V. Performance Evaluation

We evaluate the performance of our proposed GTM+ algorithm by simulation and compare its performance with two existing algorithms—GRA [9] and ORA [8]. GTM+ and GRA are designed for the multi-sharing scenario, whereas ORA works only in the single-sharing scenario. GRA is a heuristic aiming to permit as many DUE pairs as possible to reuse CUEs' radio resource. In the single-sharing scenario, ORA is optimal in terms of system throughput.

The simulation is set as follows. M is set to 110, which is the number of RBs a 20 MHz LTE/LTE-A systems can have in theory. The number of real CUEs varies between 40 and 110. The ratio of DUE pairs to real CUEs is set to four. For comparison with the the existing algorithms, all CUEs are set to have the same SINR threshold, transmission power, and noise spectral density. (Otherwise, some algorithms cannot be applied.) CUEs and DUEs are randomly distributed in a single cell with the BS at the center. All DUE pairs are set to have equal SINR threshold. Most parameters are set according to [9]; some of them are listed in Table I. All results are averaged over 1000 instances. Important performance metrics

TABLE I
SIMULATION PARAMETERS.

Parameters	Value
CUE transmission power	23 dBm
DUE transmission power	10 dBm
Radius of BS coverage	500 m
Noise spectral density	-174 dBm/Hz
Path loss model for CUE and DUE	$128.1 + 37.6 \log_{10}(d\text{ [km]})$
Path loss model for DUE pairs	$148 + 40 \log_{10}(d\text{ [km]})$
SINR requirement of each CUE	7 dB
SINR requirement of each DUE pair	4.7 dB
The distance between each DUE pair	15 m
Bandwidth per RB	12 * 15kHz = 180 kHz

include the percentage of permitted DUE pairs and system throughput (which is normalized to have a unit of bit/s/Hz). We also evaluate the running time each algorithm takes.

As observed in Fig. 2, GTM+ permits more DUE pairs to reuse RBs than the other two algorithms do. GTM+ permits more than 89% of DUE pairs to reuse CUEs' RBs under the SINR requirements listed in Table I. In the same situation, GRA only permits 75% to 80% of DUE pairs and ORA performs even worse. ORA does not perform well because ORA is not designed for the multi-sharing scenario.

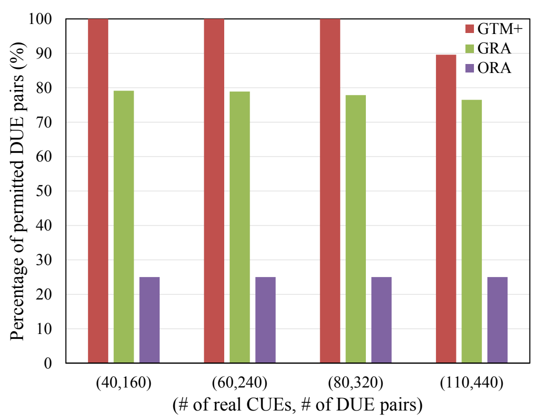

Fig. 2. The percentage of permitted DUE pairs.

In terms of system throughput, GTM+ performs best, GRA is the second place, and ORA performs worst, as seen in Fig. 3. The histograms of individual throughput in Fig. 4 help to explain the ranking. GTM+ excels GRA in system throughput because *i)* GTM+ permits more DUE pairs than GRA does and *ii)* the DUE pairs permitted by GTM+ often get higher throughput than the DUE pairs permitted by GRA get. ORA performs worst because it really permits too few DUE pairs.

In addition to the performance measures aforementioned, we present in Fig. 5 the running time each algorithm takes. Although the worst-case time complexity $O(n^4)$ of GTM+ seems largest, GTM+ takes least time on average. GTM+ is roughly 2 times faster than GRA and is more than 10 times faster than ORA of time complexity $O(n^3)$. Note that the running time results are obtained from executing Matlab code; in real systems, the GTM+ algorithm can easily complete in

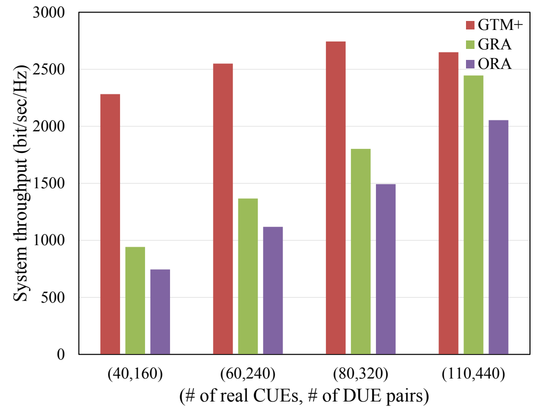

Fig. 3. System throughput.

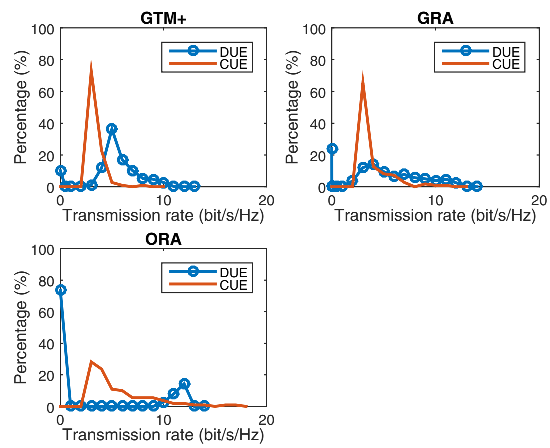

Fig. 4. Histograms of the individual throughputs of real CUEs and DUEs when there are 110 real CUEs and 440 DUEs.

a much shorter time than what Fig. 5 shows, for example, by implementing GTM+ in C/C++. Note that GTM+ can run faster in a software-defined radio access network (RAN) architecture or in a cloud RAN architecture with stronger computational power.

Based on the above simulation results, we notice that GTM+ has many advantages: Among the three algorithms, GTM+ performs best in both system throughput and the percentage of DUE pairs permitted to reuse CUEs' RBs. At the mean time, GTM+ is fastest at run time.

VI. CONCLUSION

In this paper, we have addressed the multi-sharing resource allocation problem for D2D communication underlaying 5G mobile networks, in which each CUE can share its uplink RBs with multiple DUE pairs. We have formulated the problem and proven its NP-hardness. We have proposed the GTM+ algorithm. Extensive simulation results show that compared to existing algorithms, GTM+ has superior performance in terms of system throughput, the percentage of permitted DUE pairs, and running time.

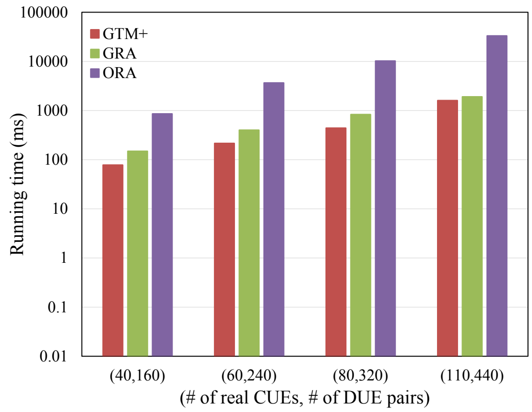

Fig. 5. The running time each algorithm takes.

ACKNOWLEDGMENT

This work was supported in part by the Ministry of Science and Technology (MOST), Taiwan, under grants no. MOST 103-2221-E-007-041-MY3, MOST 103-2218-E-007-022, and MOST 104-2218-E-007-013.

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