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System Capacity Maximization With Efficient Resource Allocation Algorithms in D2D Communication

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ABSTRACT In a device to device (D2D) communication underlaying cellular network, total system sum rate (capacity) can be improved if cellular user equipment's (UEs) and D2D pairs share resource blocks (RBs). We consider an optimization problem where the objective is to maximize the total sum rate of the system by sharing RBs among cellular UEs and D2D pairs while maintaining the quality of service requirements. We consider three approaches depending on the degree of sharing i.e., *"One to One Sharing"*, *"One to Many Sharing"*, and *"Many to Many Sharing"*. Most of the existing algorithms consider that sharing of RBs can only improve the total system sum rate. However, sharing of RBs between a cellular UE and a D2D pair can also decrease the total system sum rate. Considering this observation, we propose an algorithm based on the weighted bipartite matching algorithm which avoids such sharing and maximize the total system sum rate for the *"One to One Sharing"* approach. Moreover, We propose resource allocation algorithms for *"One to Many Sharing"* and *"Many to Many Sharing"* with a target to maximize the system capacity and also provide the analysis of the proposed algorithms. Through simulations, we find that our proposed algorithms outperform the existing algorithms in terms of maximizing total system sum rate. Our proposed algorithms also perform better in terms of total interference introduced due to the sharing of RBs among cellular UEs and D2D pairs.

INDEX TERMS D2D communication, sum rate, interference, 5G, 5G+, LTE, Hungarian, bipartite matching.

I. INTRODUCTION

Device-to-Device (D2D) communication is rapidly becoming a familiar term in personal communications. As a technology, it is becoming popular for different types of inter device applications. Therefore, spectrum requirements for D2D communication is increasing day by day. Moreover, cellular user equipment (UEs) in close proximity need less amount of transmission power in direct communication rather than the conventional communication via E-UTRAN Node B, also known as Evolved Node B (eNodeB or eNB) [1], [2]. Instead of communicating in traditional manner, these cellular UEs can reuse the appropriate resource blocks (RBs) of the existing cellular network which generate minimal interference. Moreover, this technique increases spectral efficiency and system capacity of traditional cellular network, as well as reduces traffic load of the eNB and power consumption of the cellular UEs [3]. For better utilization of these advantages, D2D communication underlaying to cellular networks is introduced in fourth generation (4G) of wireless mobile telecommunications technology, Long Term Evolution (LTE) and continues to be one of the building blocks of fifth generation (5G) and beyond (5G+) to support the standard of media enrich high data rates [4]. However, choosing ill-fitting RBs ends up in catastrophic level of interference in the existing cellular network [5].

An efficient resource allocation technique which assigns suitable RBs to the D2D pairs can address the above mentioned issue. A number of resource allocation (RA) algorithms exist in the literature [6]–[10] aiming to increase the system sum rate while reducing the system interference level. However, there are rooms for improvements of the existing algorithms. Some of the approaches [6]–[8] do not allow a D2D pair to share the RBs of multiple cellular UEs, thus losing the opportunities to increase more system capacity.

Moreover, local search based resource allocation algorithm (**LORA**) [7] and Deferred Acceptance based algorithm for Resource Allocation (**DARA**) [8] algorithms allow reusing of RBs which return less amount of system sum rate than the system sum rate of traditional network (cellular network without any D2D pair reusing RBs). Furthermore, these approaches choose sub-optimal RBs, resulting less amount of improvement in system sum rate.

In addition, researchers are investigating the performance of WiFi Direct technology to offload the cellular traffic onto unlicensed radio spectrum [11]. To use this technology one of the devices need to act as the access point and other devices can connect to that access point. Researchers are also working on licensed shared access (LSA) technique which utilizes the available licensed band [12]. However, these are outside of the scope of this paper.

We propose resource allocation algorithms for D2D communication to maximize the system capacity in the existing cellular network. Our proposed algorithms maintain the minimum quality of service (QoS) constraint like Signal-to-Interference-plus-Noise-Ratio (SINR) for both D2D pairs and cellular UEs. The major contributions of this paper can be summarized as follow:

1) We propose three different approaches i.e., *"One to One Sharing"*, *"One to Many Sharing"*, *"Many to Many Sharing"* to solve the resource allocation problem in D2D communication. The definition of the sharing approaches is explained in section II.
2) Our proposed weighted bipartite matching algorithm for *"One to One Sharing"* approach returns the optimal solution.[1]
3) We propose two algorithms for *"One to Many Sharing"* approach i.e., general sharing and restricted sharing where the proposed algorithm for general sharing approach returns the optimal results in terms of system sum rate but admission rate of D2D pair is very low. However, the proposed algorithm for restricted sharing eradicates the problem of admission rate of D2D pairs in the system.
4) Our proposed algorithm for *"Many to Many Sharing"* approach is based on weighted graph coloring algorithm inspired by graph coloring based resource allocation algorithm (GOAL) proposed in [10] with a different weight calculation.
5) Simulation results confirm that our proposed algorithms for all of the three approaches outperform the state-of-the-art algorithms.

The rest of the paper is organized in the following manners. Section II canvasses the prior works related to our topic of interest. Section III discusses different aspects of system model and channel model. Section IV contains the problem formulation. Section V - VII present the detailed discussion on the working procedure of our proposed algorithms with different approaches including the performance evaluations. Finally, section VIII draws the conclusion.

[1] Initial version of *"One to One Sharing"* approach is appeared in [13]

II. BACKGROUND AND RELATED WORKS

A number of research works have been conducted on different aspects of D2D communication, focusing different research problems. Popular research problems include resource allocation, power control, protocol design, medium access technique etc. Furthermore the resource allocation problem is branched into different domains, focusing different objectives like maximization of system capacity [6]–[10], [14]–[18], minimization of interference [16], [19]–[28] etc. We discuss some of the research works, conforming with the research problem we are addressing.

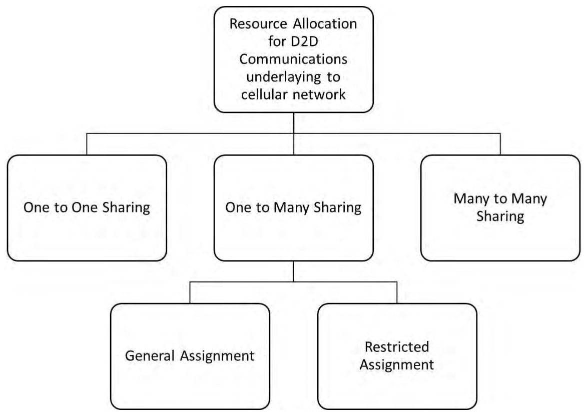


FIGURE 1. Taxonomy of different resource sharing approach.

The researcher works focusing on system capacity maximization in D2D communication underlaying cellular network, choose different mode of resource sharing among the cellular UEs and the D2D pairs. We classify the degree of resource(i.e. RBs) sharing into three approaches (depicted in figure 1).

i. *One to One Sharing* : *"One to One Sharing"* implies that, one D2D pair can share the RBs of only one cellular UE provided that no other D2D pairs share the RBs of that cellular UE yet.
ii. *One to Many Sharing* : *"One to Many Sharing"* implies that, one D2D pair can share the RBs of multiple cellular UEs but multiple D2D pairs cannot share the RBs of a single cellular UE.
iii. *Many to Many Sharing* : *"Many to Many Sharing"* implies that, one D2D pair can share the RBs of multiple cellular UEs as well as multiple D2D pairs can share the RBs of a single cellular UE.

For better understanding we categorize the related works on system throughput maximization based on the modes of resource sharing and present them in the following subsections. Moreover, a summary of all notable resource allocation algorithms for system sum rate maximization is presented in table 1.

TABLE 1. **Summary of existing resource allocation algorithms to maximize the system capacity for D2D communication.**

One to One sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
Greedy Heuristic [14]	Uplink / Downlink	• Greedy approach. • Use CQI (Channel Quality Identifier) as evaluation weight. • QoS is maintained.	• Might not terminate in some cases. • Resources are allocated only based on QoS constraints .	$O(n^2)$ for each phase
LORA [7]	Downlink	• Local search technique. • Use [14] as the initial feasible solution. • QoS is considered.	• Performance depends on the initial feasible solution. • Might be stuck in local optima.	$O(n^2S)$, S is total system sum rate and n is the number of total cellular UEs
DARA [8]	Downlink	• Stable matching algorithm. • Use proximity for preference calculation.	• Proximity is not an appropriate choice of preference for the application. • Ultimate result differs from theory. • QoS is not considered	$O(n^2)$, n is the number of cellular UEs.
Graph-Based [17]	Downlink	• Maximum weight matching algorithm. • Use sum rate as evaluation weight.	QoS is not considered	$O(mn)$, m is the number of D2D pairs and n is the number of cellular UEs.
One to Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
CORAL [9]	Downlink	• Allows one D2D pair to use radio resources of multiple cellular UEs. • Restricts a D2D pair to share the radio resource of any cellular UEs present inside the CORE region of that D2D pair.	• Selects cellular UEs for sharing RBs depending on the channel gain but system capacity does not depend on the channel gain solely. • It is a greedy approach and might be stuck in local optima.	$O(mn^2)$, m is the number of D2D pairs and n is the number of cellular UEs.
Many to Many sharing				
Algorithm	**Resource**	**Approach**	**Flaws**	**Complexity**
GOAL [10]	Downlink	• Graph coloring based approach.	Produces low sum rate in critical scenario	$O(nm^2)$, m is the number of D2D pairs and n is the number of cellular UEs..

A. ONE TO ONE SHARING APPROACH

A greedy heuristic resource allocation algorithm is discussed in [14] where the cellular UEs are sorted in decreasing order depending on the Channel Quality Indicator (CQI). A D2D pair with the lowest channel gain which is not yet assigned is selected for a cellular UE which has higher CQI provided that QoS constraints are maintained. However, the algorithm may not terminate in some cases. A cellular UE with higher CQI coupled with a D2D pair with the lowest channel gain can maximize the SINR of the cellular UEs. However, it is not the optimal choice for maximizing the total system capacity. Some of the D2D pairs might be missed out to be allocated or some of the D2D pairs are selected for earlier cellular UE which might give better system sum rate to the cellular UEs chosen later on.

A simple local search based resource allocation algorithm (LORA) is designed in [7] to solve the similar research problem (maximizing system sum rate while maintaining some QoS) we are considering. The result of the greedy heuristic [14] is considered as the initial feasible solution of this algorithm. After that, the algorithm checks whether any improvement can be found if a D2D pair chooses a new cellular UE. If there is an improvement and it also satisfies the minimum SINR constraints then sharing is swapped. However, the final result of the heuristic might miss out some of the D2D pairs for assignments considered in the optimal solution. These D2D pairs can also be missed out in the final assignments returned by this local search algorithm and in practice the local optima of this algorithm can be far away from the global solution. Moreover, as local search is an iterative improvement technique, it might take much more time to reach the solution and cannot be very useful in LTE networks.

A deferred acceptance based resource allocation algorithm (DARA) is proposed in [8] to solve the similar resource allocation problem which is based on the stable matching algorithm [29]. Preferences for both cellular UEs and D2D pairs are calculated depending on the location of D2D pairs and cellular UEs. On the basis of given preferences, a cellular UE is selected to be coupled with a D2D pair to share the RBs. Typically a stable matching algorithm [29]gives an optimal result to the initiator, which does not necessarily provide the optimal results to the overall system. In this algorithm, preference is calculated on the basis of distance between a D2D pair and a cellular UE only. However distance is not the only factor behind better system sum rate. There are other factors like transmission power, RBs allocated to a cellular UE etc. It is assumed that a lower distance is preferred over a higher distance. However, a cellular UE experiences more interference from an assigned D2D pair and we encounter such observations in our simulations. Based on Gale-Shapley [29] algorithm, GaSaBa scheme is proposed in [30] where D2D pairs are prioritized during resource sharing operation. In GaSaBa Scheme, preference of each cellular UE depends on the ratio between the channel gain between transmitting and receiving ends of a D2D pair and channel gain between the cellular UE and the D2D pair.

A graph based algorithm is proposed in [17], to solve a resource allocation problem which is similar to the problem we are addressing. However, their proposed algorithm does not consider QoS requirements. The proposed algorithm assigns the RBs of multiple cellular UEs to a D2D pair whenever possible. On the other hand, a three phase technique based on bipartite graph is discussed in [6]. In the first phase of this algorithm it formulates an estimation process of required power for both of the D2D pair and the cellular UE. In the second phase, the admissibility of a D2D pair is calculated based on the transmission range of the D2D pairs and the cellular UEs. Finally in the third phase, it adopts the maximum weighted bipartite matching algorithm to calculate the feasible solution. However, in this approach some of the D2D pairs can be considered in the admissible set which reduces the system capacity.

An algorithm is proposed in [15], that works on the model where a single D2D pair cannot share the RBs of multiple cellular UEs but multiple D2D pairs can share the RBs of a single cellular UE. The authors argue that conventional graph based resource allocation technique is unable to model the interference from multiple cellular UEs which makes those conventional approaches perform bad. They model the problem with the help of hypergraph theory and use the hypergraph coloring technique to solve it. It is noteworthy that, hypergraph algorithm prioritize both D2D pairs and cellular UEs equally. Because of treating both D2D pairs and cellular UEs similarly, hypergraph algorithm might allocate RBs to some D2D pairs instead of some other cellular UEs to attain a higher system sum rate. However, all of the cellular UEs of the system should be allocated some RBs (if possible) as they are the primary consumers of the cellular network. In [31], Gupta *et al.* formulate a non-convex problem of joint resource block and power allocation for sum rate maximization in D2D communication, and transform it into an optimization problem.

Apart from the above works, authors in [22]–[24], [34] deal with the resource allocation problem where the objective is to minimize the total system interference while maintaining a predefined level of system capacity. A knapsack based interference aware resource allocation algorithm is proposed in [23] whereas two phase auction based fair resource allocation algorithm is proposed in [22]. However, they cannot always give the assurance of returning results while algorithms in [24], [34] guarantee the result if present. Moreover, it assures the result to be optimal or near to optimal.

B. ONE TO MANY SHARING APPROACH

Cai *et al*. [9] works on a model where a D2D pair can share radio resources of multiple cellular UEs, however multiple D2D pairs cannot share the RBs of a single cellular UE. They formulate an equation which represents the restricted region of a D2D pair termed as capacity oriented restricted (CORE) region. If a cellular UE is present inside the CORE region of a D2D pair then that D2D pair cannot share the radio resources of the cellular UE. Meanwhile, Chang *et al*. [32] propose a fairness-and-safety capacity oriented resource allocation, FAST CORAL scheme where CORE region is incorporated into traditional stackelberg game [33] approach. Moreover, CORAL sub-algorithm [9] is applied to boost up the D2D pair's capacity.

C. MANY TO MANY SHARING APPROACH

Cai *et al.* [10], model the resource allocation problem in such a way that, each D2D pair can share radio resources of multiple cellular UEs as well as resources of one cellular UE can be shared by multiple D2D pairs. They propose graph coloring based resource allocation (GOAL) algorithm. In this algorithm, the cellular UE in the system is assumed as colors and the D2D pairs are assumed as vertices. GOAL algorithm assigns color to the vertices following a defined set of rules which is discussed in details in section VII.

III. SYSTEM MODEL AND CHANNEL MODEL

In the following subsections we present the system model and the channel model we consider for our research problem.

A. SYSTEM MODEL

We consider a cell area consisting of a single eNB, a number of D2D pairs and a number of cellular UEs. To keep the model simple, we assume that all devices are equipped with omni-directional antenna. The eNB is in charge of allocating RBs and determining the allowed maximum transmission power for both cellular UEs and D2D pairs to avoid unwanted interference and higher gain in system capacity. In normal scenario, the number of cellular UEs is much higher than the number of D2D pairs. We consider the similar scenario that is considered in [7], [8], and [14] with n cellular UEs and m D2D pairs, where $n >> m$. The set of cellular UEs is represented as $C = \{c_1, c_2, c_3, \ldots, c_n\}$, whereas the set of D2D pairs is represented as $D = \{d_1, d_2, d_3, \ldots, d_m\}$. A D2D pair $d_i \in D$ contains a receiving device d_r and a transmitting device d_t.

B. CHANNEL MODEL

LTE network consists of both uplink (UL) and downlink (DL) resources. Figure 2 illustrates the system model of downlink resources. In our work, we consider the sharing of DL resources which uses Orthogonal Frequency Division Multiple Access technique [1]. In case of OFDMA, inter-cell interference can be reduced with the help of power control and resource scheduling [35].

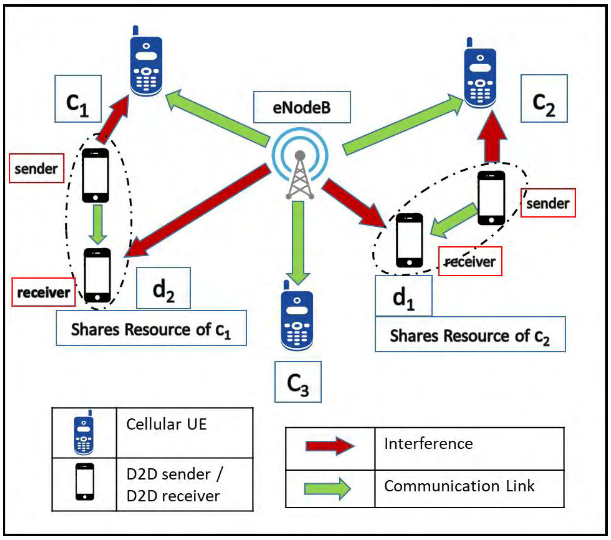


FIGURE 2. An illustration of system model using downlink RBs.

We consider the intra-cell interference only. As the eNB transmits signal to the cellular UEs using DL resources, cellular UEs only experience interference from their shared D2D transmitters whereas D2D receivers encounter interference from the eNB.

We consider an urban micro system, which follows the Rayleigh fading path loss model [7], [8], [14]. The path loss (PL) (dB unit) equation is

$$PL = 36.7 \log_{10}(dist) + 22.7 + 26 \log_{10}(f_c), \tag{1}$$

where $dist$ (in meter) is the distance between the transmitter and the receiver of the radio signal and f_c (in GHz) is the carrier frequency. Now, the channel gain ($G^{x,y}$)between these two devices is

$$G^{x,y} = 10^{-PL^{x,y}/10}, \tag{2}$$

where x and y are the two devices i.e., transmitter and receiver and $PL^{x,y}$ is the distance dependent path loss between x and y.

IV. PROBLEM FORMULATION

The SINR of a receiver is the ratio between the received signal power and interference with noise power. In a downlink interference model, the SINR value of a cellular UE depends on the transmitting power of the eNB, channel gain between a eNB and a cellular UE as well as the intra channel interference. Let us consider the individual transmitting powers of an eNB, a cellular UE and a D2D transmitter are P^{eNB}, P^c and P^d, respectively. It should be noted that proposed algorithms will not control the transmission power of the devices. The transmission power can be calculated using techniques discussed in [6]. Thermal noise which is also known as the energy of Additive White Gaussian Noise (AWGN) introduced at the receiving end is denoted by T. As only intra-channel interference needs to be considered, interference occurs at a cellular UE whenever one or more D2D pairs share the RBs of that cellular UE. So, the SINR of a cellular UE $c \in C$ in DL phase [14] can be represented as

$$SINR_c^{DL} = \frac{P^{eNB} G^{eNB,c}}{T + \sum_d x_d^c P^d G^{d_t,c}}. \tag{3}$$

where a binary variable x_d^c indicates whether the D2D pair $d \in D$ shares the RBs of the cellular UE c or not. $G^{d_t,c}$ implies the channel gain between the D2D transmitter d_t and the cellular UE c. In the denominator of equation (3), summation refers to the total interferences to the cellular UE c introduced by all D2D pairs, sharing the RBs of c.

Similarly, the SINR at the D2D receiver [14] is

$$SINR_d^{DL} = \frac{\sum_c x_d^c P^d G^{d_t,d_r}}{T + P^{eNB} G^{eNB,d_r} + \sum\limits_{c \epsilon C} \sum\limits_{\substack{d' \epsilon D, \\ d' \neq d}} x_d^c x_{d'}^c P^d G^{d'_t,d_r}}, \tag{4}$$

where, G^{d_t,d_r} denotes the channel gain between a D2D transmitter d_t and a D2D receiver d_r. The summation in the numerator of the equation (4) indicates the total signals incurred from a D2D pair d for different cellular UE sharing the RBs of d. Third term in the denominator indicates the total interference from other D2D devices $d' \epsilon D$ which are using the same RBs as the D2D pair d.

The aim of this paper is to maximize the total system sum rate contribution of all individual cellular UEs and D2D pairs. According to Shannon's Capacity formula, the sum rate for a given receiver r can be presented as

$$R = B \log_2(1 + SINR_r), \tag{5}$$

where B is the channel bandwidth and $SINR_r$ is the SINR at the receiver r.

Suppose the sum rate contribution of an individual cellular UE and a D2D pair are R_c^{DL} and R_d^{DL} (using one RB) respectively. Then the objective function satisfying the QoS requirements can be formulated as

$$\max \left(\sum_c^C R_c^{DL} N_c + \sum_c^C \sum_d^D x_d^c R_d^{DL} N_c \right) \tag{6}$$

$$\text{subject to,}\ \frac{P^{eNB}G^{eNB,c}}{T+\sum_d x_d^c P^d G^{d_t,c}} \geqslant SINR_{c,min}^{DL}, \quad \forall\, c \in C \tag{7}$$

$$\frac{\sum_c x_d^c P^d G^{d_t,d_r}}{T+P^{eNB}G^{eNB,d_t}} \geqslant SINR_{d,min}^{DL}, \quad \forall\, d \in D \tag{8}$$

$$x_d^c = \{0,1\}, \quad \forall\, c \in C \text{ and } \forall\, d \in D, \tag{9}$$

where, N_c denotes the number of RBs allocated to a cellular UE c; C and D denotes the set of cellular UEs and D2D pairs respectively. A D2D pair might share RBs with multiple cellular UEs.

Several constraints need to be satisfied while sharing the RBs to maintain QoS requirements. Each device requires a target SINR for maintaining normal transmission rate and equations (7), (8) and (9) represent different constraints. $SINR_{c,min}^{DL}$ and $SINR_{d,min}^{DL}$ in (7) and (8) are the minimum SINR value for a cellular UE c and a D2D pair d, respectively. Equation (9) represents the orthogonality of sharing.

So the objective function needs to satisfy the following two new constraints for this category.

$$\sum_d^D x_d^c \leqslant 1, \quad \forall\, c \in C \tag{10}$$

$$\sum_c^C x_d^c \leqslant 1, \quad \forall\, d \in D. \tag{11}$$

"One to Many Sharing" implies that, one D2D pair can share the RBs of multiple cellular UEs provided that no other D2D pairs share the RBs of those cellular UEs. In this case the objective function needs to satisfy constraint (10) but constraint (11) is relaxed as follows (n is the number of cellular UE in the system)

$$n \geqslant \sum_c^C x_d^c \geqslant 0, \quad \forall\, d \in D. \tag{12}$$

So the solution of *"One to Many Sharing"* approach needs to satisfy the constraints (7), (8), (9), (10)and (12). We classified *"One to Many Sharing"* approach into two categories as followed:

1) General Sharing
2) Restricted Sharing

Details about these approaches will be discussed in section VI.

"Many to Many Sharing" implies that, D2D pairs can share the RBs of multiple cellular UEs and different D2D pairs can share RBs of same cellular UE. In this case the objective function needs to satisfy constraint (12) instead of constraint (11) and constraint (10) is relaxed as follows (m is the number of D2D pair in the system)

$$m \geqslant \sum_d^D x_d^c \geqslant 0, \quad \forall\, c \in C \tag{13}$$

So the solution of *"Many to Many Sharing"* approach needs to satisfy the constraints (7), (8), (9), (12) and (13).

Our proposed Algorithms for all of these approaches are discussed in following sections. Comparison with the existing algorithms are also included in the respective sections for the better understanding. It should be noted that, the network operators will choose one of the three approaches based on their necessity.

V. PROPOSED ALGORITHM FOR ONE TO ONE SHARING APPROACH

The resource allocation problem for *"One to One sharing"* approach is translated into a maximum weighted bipartite matching problem where each D2D pair needs to be assigned to only one cellular UE. This solution approach needs to satisfy necessary constraints (7), (8), (9), (10) and (11) discussed in section IV. The goal of the assignment scheme is to attain the maximum system capacity. The working procedure for this approach is discussed in between subsections V-A and V-D. Simulation environment and performance evaluation are presented in subsection V-E and V-F respectively.

A. CANDIDATE SELECTION

Sharing of RBs might decrease the system capacity in some cases due to greater interference in the system. Such kind of sharing needs to be avoided to maximize the objective function (6). So our proposed algorithms allow sharing of RBs when shared sum rate is greater than non-shared sum rate. Shared sum rate implies total sum rate attain by the D2D pair and the cellular UE when they share the RBs. Whereas non-shared sum rate means the sum rate attain by the cellular UE provided that no D2D pair is sharing the RBs of the cellular UE. So a candidate cellular UE c for a D2D pair d needs to satisfy the following constraint

$$R_c + R_d > R_{c_0}, \tag{14}$$

where R_{c_0} denotes the sum rate attained by the cellular UE c alone (no D2D pair shares the RBs), R_c denotes the sum rate attained by the cellular UE c (D2D pair d shares the RBs of c) and R_d denotes the sum rate attained by the D2D pair d (sharing the RBs of c).

Thus a cellular UE cannot be a candidate for a D2D pair to share RBs in following cases.

i) After sharing RBs, if either the D2D pair or the cellular UE does not satisfy the constraints (7) and (8).
ii) If sharing of RBs of the cellular UE by the D2D pair does not increase the sum rate (constraint (14)).

So candidate set of cellular UEs for a D2D pair d is $Q_d = \{c|c$ and d can share RBs satisfying eqs. (7), (8) and (14) $\}$

B. FORMATION OF THE BIPARTITE GRAPH

The bipartite graph is constructed of two disjoint sets i) set of the existing cellular UEs C and ii) set of all D2D pairs D^{new}. In second set there are $n - m$ dummy D2D pairs which is required for matching algorithm discussed in subsection V-D. So $D^{new} = D \cup D^{dummy}$ where D is the set of existing D2D pairs and D^{dummy} is the set of all dummy D2D pairs needed. The dummy D2D pairs are not present in the real system. Rather they are only introduced to make the set of cellular UEs and set of D2D pairs equal. So a dummy D2D pair sharing a cellular UE actually means that no D2D pair is sharing the cellular UE.

C. WEIGHT CALCULATION

In our proposed algorithm the weight of the edges represent the sum rate contribution of that D2D pair and cellular UE when they shares RBs. Edges of the constructed graph can be categorized into the following three groups.

i) Edges between D2D pair $d \in D$ and cellular UE $c \in Q_d$ defined in section V-A.
ii) Edges between D2D pair $d \in D$ and cellular UE $c \in Q'_d$, where $Q'_d = C - Q_d$ and C is the set of all cellular UEs in the system.
iii) Edges between D2D pair $d \in D_{dummy}$ and cellular UE $c \in C$.

Any D2D pair d sharing RBs of a cellular UE $c \in Q_d$ increases the system sum rate. So the weight of the edges in the first group is $R_c + R_d$ as it is their contribution to the system sum rate. On the other hand, any D2D pair d sharing RBs of a cellular UE $c \in Q'_d$ decreases the system sum rate (constraint (14)) or fails to satisfy the constraints (7) and (8) should be avoided. So the weight of the edges of second group is R_{c_0}. Edges between a dummy D2D pair $d \in D_{dummy}$ and a cellular UE $c \in C$ represent that the cellular UE c is not sharing RBs. So the edges of third group has a weight of R_{c_0} too.

D. MATCHING ALGORITHM

For the optimal bipartite matching algorithm, we use the Hungarian algorithm [36] for the maximization of the total system sum rate. Hungarian algorithm is optimal depending on the weight matrix with polynomial time complexity. Though classical Hungarian algorithm is intended for minimization, but with simple modification this can be used for maximization also. Hungarian algorithm works on square weight matrix, where elements of the matrix depict the weight of the associated row and column which is a non-negative value. As we have $n >> m$, we make the matrix square by adding $n - m$ dummy D2D pairs at the time of constructing bipartite graph in V-B. The pseudo code of our proposed algorithm is described in Algorithm 1.

Algorithm 1 Resource Allocation Algorithm (OneToOne)

1: **procedure** OneToOneSharingRA($D(d_1, d_2, \dots, d_m)$, $C(c_1, c_2, \dots, c_n)$) ▷ An allocation from C(cellular UEs) to D(D2D pairs)
2: Let $S[1 \dots n][1 \dots n]$ be a new Matrix ▷ $S_{i,j}$ is the weight of the edge between d_i and c_j
3: Assign weight in S, as described in section V-C
4: Let $M[1 \dots n][1 \dots n]$ be a new matrix ▷ A boolean matrix, a true value in i, j index depicts, d_i is assigned to c_j
5: M = Hungarian(S) ▷ Optimal bipartite matching algorithm which will return a boolean matrix
6: **for** $i = 1$ to m and $j = 1$ to n **do**
7: **if** $M_{i,j} = TRUE$ and $c_j \in Q_{d_i}$ **then**
8: Assign RBs of c_j to d_i

We introduce an $n \times n$ matrix S in line 2 of Algorithm 1 as the weight matrix. The rows represent D2D pairs and the columns represent cellular UEs. The matrix is populated as discussed in subsection V-C. In line 5, the weight matrix is passed to the Hungarian algorithm for the maximum weighted bipartite matching. This algorithm returns a boolean matrix ($M_{i,j}$) containing the assignments between the cellular UEs and the D2D pairs depending on the weight matrix. In line 7, if $M_{i,j}$ is true and c_j is a candidate cellular UE of d_i then D2D pair d_i is assigned the RBs of cellular UE c_j. The reason of this check is that Hungarian algorithm takes decision from the weight matrix and has no idea about the candidacy of a D2D pair. Thus before assigning, we should check the validity of that assignment. It is to be noted that only m rows of M is checked because the rest of the rows of M are for dummy D2D pairs.

Hungarian algorithm dominates the other parts of the algorithm 1 in terms of the running time which is $O(n^3)$ [36]. So the total running time of our proposed algorithm is also $O(n^3)$ where n is the number cellular UEs.

We can derive the following theorem from algorithm 1.

Theorem 1: Our proposed algorithm gives the optimal solution.

Proof: If R_{ij} is the sum rate contribution of a D2D pair d_i and a cellular UE c_j when they share RBs and R_j is the sum rate of a cellular user c_j without sharing of RBs, then in an optimal solution, c_j and d_i cannot share RBs *iff* $R_j > R_{ij}$.

If an algorithm gives an optimal solution for a weighted bipartite matching problem then it will also give the optimal solution of the problem that we consider in this paper. Hence, the problem can be solved in polynomial time.

Above statements are suffice to prove theorem 1, that our proposed algorithm returns the optimal solution.

E. SIMULATION ENVIRONMENT

We simulate different scenarios to evaluate the efficiency of our proposed algorithm. We use NS3 (network simulator) [37] that supports D2D communication underlaying the LTE system. We use the same simulation parameters used in [6]–[8], [14] (Table 2) as well as we tune some of the parameters to check the variability of our results and we find that performance of our algorithms is consistent. A single cell network is considered in our simulations where we consider two distributions of cellular UEs and D2D pairs; i) Cellular UEs and D2D pairs are uniformly distributed in the cell area and ii) Cluster distribution model of D2D pairs discussed in [6] where the D2D pairs are uniformly distributed in a random cluster with a maximum radius of 15 meter. Each of the

TABLE 2. Simulation parameters.

Parameter	Value
Cell Radius	1000 meters
D2D pairs	10 to 250 (increments of 10)
Maximum D2D pair distance	15 meters
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
eNB transmit power	46 dBm
Noise power (AWGN)	-174 dBm
Carrier Frequency	1.7 GHz for LTE
$SINR_{c,min}^{DL}$	Random in the range of $(0 \sim 20)$ db
$SINR_{d,min}^{DL}$	Random in the range of $(0 \sim 20)$ db

simulation results presented is an average of 20 different runs for a particular scenario. In the next subsection, the description and the performance of different other resource allocation (RA) algorithms compared to our proposed algorithm is explained. To measure the performance we assume three metrics: system sum rate, total interference introduced and total SINR in the system.

F. PERFORMANCE EVALUATION

To evaluate the performance of our proposed algorithm for *"One to One Sharing"* approach, we compare it with some of the existing algorithms that address the same research problem. Some of the selected algorithms are discussed briefly in the followings

1) GREEDY HEURISTIC RESOURCE ALLOCATION ALGORITHM (GREEDY)

A greedy heuristic resource allocation algorithm is discussed in [14] where the cellular UEs are sorted in decreasing order depending on the Channel Quality Identifier (CQI). A D2D pair with the lowest channel gain not yet assigned is selected for a cellular UE which has higher CQI provided that QoS constraints are satisfied. However, the algorithm may not terminate in some cases. We modify that portion of the algorithm without altering the main theme for our comparison study. A cellular UE with higher CQI coupled with a D2D pair with the lowest channel gain can maximize the $SINR_c^{DL}$ (3). However, it might not be an optimal choice. Some of the D2D pairs might be missed out to be allocated or some of the D2D pairs are selected earlier for some cellular UEs might give better sum rate coupled with some other cellular UEs chosen later on.

2) DEFERRED ACCEPTANCE BASED ALGORITHM FOR RESOURCE ALLOCATION (DARA)

DARA [8] follows the stable matching algorithm presented in [29]. Preferences for both cellular UEs and D2D pairs are calculated depending on the location of D2D pairs and cellular UEs. For example, for each cellular UE the nearer D2D pair is preferred over other D2D pairs. Depending on the given preference, a D2D pair selects a cellular UE to share RBs following stable matching algorithm. If the preference is calculated correctly, there will be no pair of assignment which can be swapped to get more system sum rate. In this algorithm, preference is calculated on the basis of distance between a D2D pair and a cellular UE only. But distance is not the only factor behind better sum rate. Here a lower distance is preferred over a higher distance. However, a cellular UE experiences more interference from a nearby assigned D2D pair and we encounter such observations in our simulations. Moreover, in some cases, a cellular UE and a D2D pair can be matched even though QoS are not satisfied.

3) LOCAL SEARCH BASED RESOURCE ALLOCATION ALGORITHM (LORA)

LORA [7] uses the allocation given by the greedy algorithm [14] as the initial feasible solution. Then it swaps assignment between a pair of D2D pairs, and cellular UEs only if the swapping improves the objective function and the constraints (7) and (8) are satisfied. LORA can also face the similar problem encountered in the greedy algorithm [14]. So, a particular D2D pair can be unassigned at the end of the local search algorithm. It is very easy to find an example, where such a D2D pair can be assigned in the optimal solution.

4) WEIGHTED BIPARTITE MATCHING ALGORITHM

Algorithms based on the weighted bipartite matching, are used in [17]and [6] for similar resource allocation problem in D2D communications. A weight matrix is calculated based on the sum rate contribution of cellular UEs and D2D pairs. After that bipartite matching algorithm is applied based on the weight matrix. However they did not consider the condition where sharing RBs with a D2D pair might decrease the sum rate. In our simulation and performance evaluation, we also consider a similar algorithm [36].

5) RESULT COMPARISONS AND EXPLANATION

In case of *"One to One Sharing"* approach we compare our proposed algorithm with greedy [14], LORA [7], DARA [8] and normal bipartite matching [17]. Figures 3 and 5 represent the total system sum rate returned by RA algorithms. To get a comparative view, we normalize all results with respect to the system sum rate of our proposed algorithm. Figure 3 shows the comparison result for the scenario where D2D pairs are distributed uniformly while Figure 5 represents the comparison result for the cluster distribution as discussed in [6].

Simulation results show that our proposed algorithm outperforms other algorithms in terms of the system sum rate and the differences get significant with the increased number of D2D pairs for a fixed number of cellular UEs. LORA always performs better than the greedy approach as it uses the result of the greedy heuristic as the initial feasible solution and then tries to improve result. On the other hand, bipartite matching performs better than LORA. However, all of the three algorithms do not consider the possibility of reduced system capacity due to the assignment of D2D pair to a cellular UE.

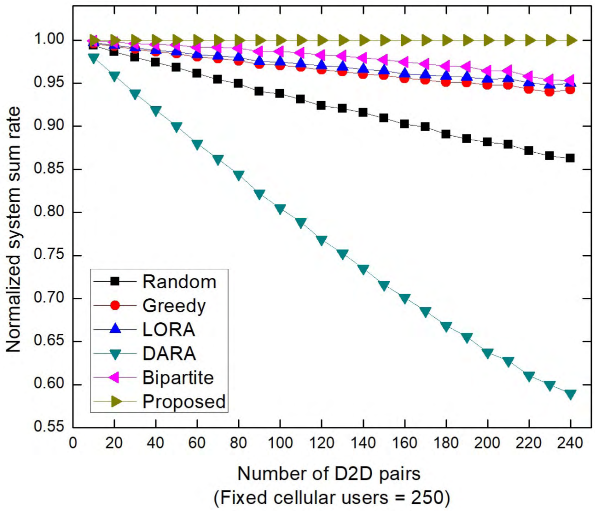


FIGURE 3. Comparison of system sum rate (normalized with respect to the proposed algorithm) of different RA algorithms (uniform distribution).

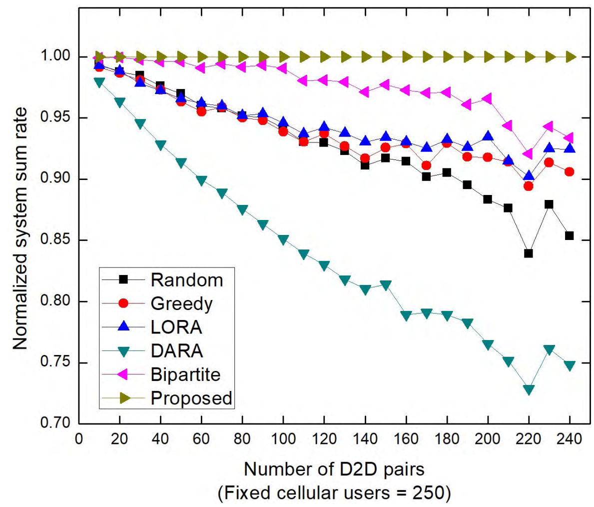


FIGURE 5. Comparison of system sum rate (normalized with respect to the proposed algorithm) of different RA algorithms (cluster distribution).

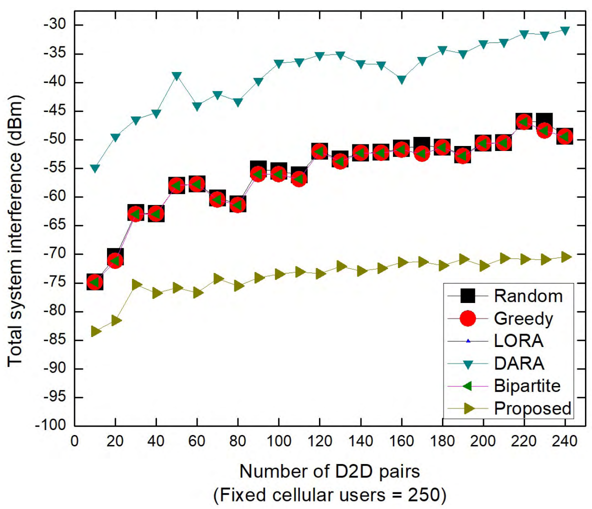


FIGURE 4. Comparison of system interference of different RA algorithms (uniform distribution) (Data points of Random, greedy, LORA, Bipartite Matching are very close and the symbols overlap in the figure).

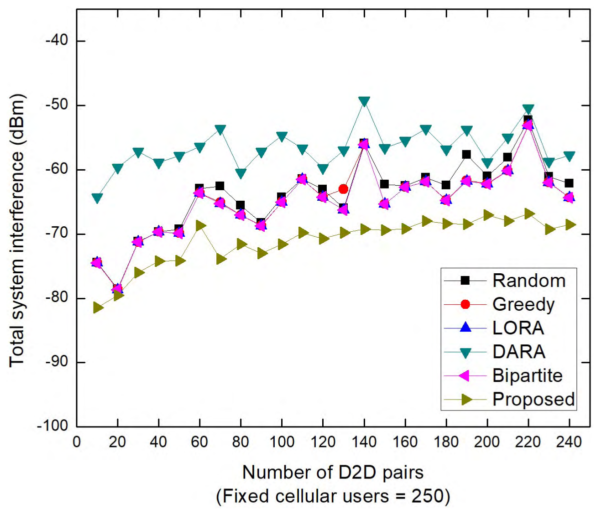


FIGURE 6. Comparison of system interference of different RA algorithms (cluster distribution).

So, if we ignore this possibility then the weighted bipartite matching always outperforms other algorithms as our results confirm. The weighted bipartite matching algorithm always returns the optimal assignment for a given weight. However, the algorithm should not select such assignments which produce negative sum rate contribution. We consider this scenario in our proposed algorithm in the process of candidate selection described in V-A and then we use the weighted bipartite matching algorithm. We also find that DARA performs the worst among all of the algorithms as it uses the increasing order of proximity for calculating the preferences for both the cellular UEs and the D2D pairs which causes a lot of the interference and the system sum rate gets affected.

Figures 4 and 6 represent the comparisons of different algorithms in terms of the total interference introduced in the system due to sharing of the RBs. Figure 4 is for a system where the D2D pairs are distributed uniformly where figure 6 is for a system where D2D pairs are distributed in a cluster form. The data points of Random, Greedy, LORA, Bipartite Matching are very close in figure 4, so readers might miss that there are actually four lines in the middle overlapping to one another. From the figures we can see that, our proposed algorithm introduces the minimum interference among all of the algorithms whereas DARA performs worst and all other algorithms (LORA, greedy and bipartite) introduce similar interference.

We also find that our proposed algorithm returns the best total SINR for both shared and non-shared cellular device after the assignments. On the other hand, all of the other algorithms produce similar total SINR at a D2D pair. From equation (4), it is certain that interference is introduced at a

D2D pair only by the eNB and signal strength is dependent on the distance between the transmitter and the receiver of a D2D pair. Thus, SINR at the D2D pairs should be similar (small differences are there due to the fact that the number of assigned D2D pairs can be different in these algorithms) if the number of assigned D2D is same.

Our proposed algorithm assigns fewer number of D2D pairs compared to other algorithms as assigning those D2D pairs can degrade of the system sum rate. According to the original problem definition [7], [8], [14] our goal is to maximize the total system sum rate by adding as many D2D pairs as possible. So, we should not add those D2D pairs which cannot find any cellular UE with whom it can share the RBs and the sharing results in an improved system sum rate. If any network provider wants to maximize the number of assigned D2D pairs even compromising the system sum rate then it becomes a different optimization problem and the solution of that problem can be investigated differently which is not in the scope of this paper.

VI. PROPOSED ALGORITHMS FOR ONE TO MANY SHARING APPROACH

In this approach, one D2D pair can share the RBs of multiple cellular UEs but multiple D2D pairs cannot share the RBs of a single cellular UE. For this mode of sharing sum rate increases drastically as a D2D pair can reuse more RBs.

This mode of sharing can be addressed using two approaches based on the assignment strategies. They are:

i. General Assignment
ii. Restricted Assignment.

We discuss both of the approaches in the following subsections. For better understanding we use an example scenario presented in figure 7. There are two D2D pairs d_1 and d_2 and three cellular UEs c_1, c_2 and c_3 where d_1 is nearer to cellular UEs c_1, c_2 and c_3 than d_2. Assume that if d_2 shares the RBs of

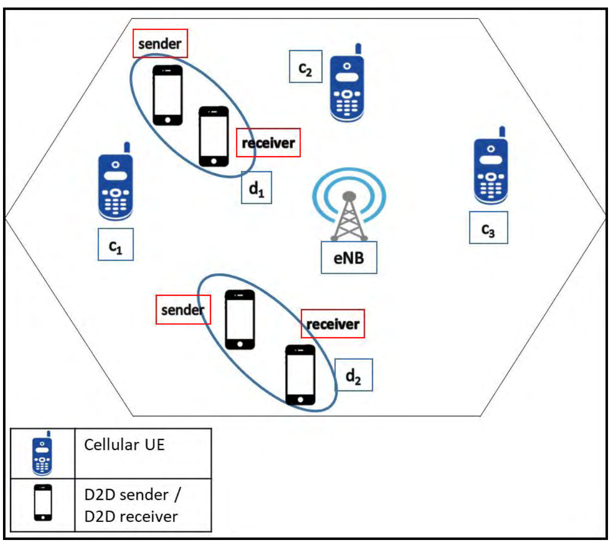


FIGURE 7. An illustration of *"One to Many Sharing"* approach.

any cellular UE it will increase the system capacity more than if d_1 shares. Thus for *"One to Many Sharing"*, if d_2 shares the RBs of all of the cellular UEs, the system sum rate will be the maximum possible. However, it will deprive d_1 from communication.

General assignment ensures that, all D2D pairs are going to be allocated some RBs provided that the D2D pairs have non empty candidate set. On the other hand, if an RA algorithm does not depend on this criteria then we term this as restricted assignment. Solutions for both of the approaches use the candidate selection method and the weight calculation for the edges discussed in section V.

A. GENERAL ASSIGNMENT

In this approach, as a single D2D pair can share the RBs of multiple cellular UEs, the highest weight needs to be selected for sharing each time. If the RBs of a cellular UE is shared then that cellular UE is removed from the candidate sets of all other D2D pairs.

Algorithm 2 is the proposed algorithm for the *"One to Many Sharing"* (general assignment) approach. At first the candidate sets of all of the D2D pairs are calculated in line 2. A candidate set represents the feasible cellular UEs, a D2D pair might share the RBs with. In the same line weight of all of the edges are calculated for this sharing. As the General Assignment approach does not care about the number of D2D pair assigned in the medium, to maximize the system capacity highest weight is selected for every cellular UE in line 5. To maintain the constraint (10), assigned cellular UE is removed from the candidate sets of all other D2D pairs (line 7).

Algorithm 2 Resource Allocation Algorithm (OneToMany - General Assignment)

1: **procedure** OneToManyGenSharingRA($D(d_1, d_2, \ldots, d_m)$, $C(c_1, c_2, \ldots, c_n)$, $TYPE$)
 ▷ An allocation from C (cellular UEs) to D (D2D pairs)
2: Create candidate set of all $d_i \in D$, form bipartite graph and calculate the weight of all edges
 ▷ Using the same method from V
3: **for** $j = 1$ to n **do**
4: **if** c_j is not yet shared by any D2D pair **then**
5: Find d_i such that the edge between d_i and c_j has the highest weight
6: Assign RBs of c_j to d_i
7: Remove cellular UE c_j from the candidate sets of all D2D pairs candidate set

The run time of the algorithm 2 is $O(mn)$ for general assignment, where m is the total number of D2D pairs and n is the total number of cellular UEs in the system.

B. RESTRICTED ASSIGNMENT

For the restricted assignment approach, all of the D2D pairs with non-empty candidate set must be assigned with the

RBs of at least one cellular UE. To ensure this we use the OneToOneSharingRA(D,C) method from algorithm 1. Using Hungarian algorithm we choose the optimal one to one correspondence and then we adopt the greedy approach to maximize the system capacity as discussed in subsection VI-A.

As a part of algorithm 3, algorithm 1 is executed in line 3 to get the optimal *"one to one sharing"*. It ensures that each D2D pair with non-empty candidate set is assigned with the RBs. In line 4 the assigned cellular UEs are removed from the candidate sets of all D2D pairs to maintain the constraint (10). Then the greedy approach, discussed in VI-A, is executed to distribute the RBs of remaining cellular UEs among the D2D pairs.

Algorithm 3 Resource Allocation Algorithm (OneToMany - Restricted Assignment)

1: **procedure** OneToManySharingResRA($D(d_1, d_2, \ldots, d_m)$, $C(c_1, c_2, \ldots, c_n)$)
 ▷ An allocation from C (cellular UEs) to D (D2D pairs)
2: Create candidate set of all $d_i \in D$, form graph and calculate the weight of all edges
 ▷ Using the same method from V
3: OneToOneSharingRA(D,C)
 ▷ Using Hungarian Algorithm minimum constraint of restricted assignment is satisfied
4: Remove all the assigned cellular UE from candidate sets
5: **for** $j = 1$ to n **do**
6: **if** c_j is not yet shared by any D2D pair **then**
7: Find d_i such that the edge between d_i and c_j has the highest weight
8: Assign RBs of c_j to d_i
9: Remove cellular UE c_j from the candidate set of all D2D pairs

Restricted assignment approach executes the Hungarian algorithm (line 3) and it dominates in term of running time. So the run time complexity of the algorithm 3 is $O(n^3)$.

C. PERFORMANCE EVALUATION

We evaluate the proposed algorithms with CORAL algorithm and two variants of DARA algorithms. We discuss the key points of CORAL algorithm and two variant of DARA algorithm in the next subsection. Then we discuss how our proposed algorithm performs better than the existing algorithm with the simulation result. We use the same simulation environment discussed in section V-E.

1) CAPACITY ORIENTED RESOURCE ALLOCATION ALGORITHM (CORAL)

CORAL [16] introduces the concept of Capacity Oriented Restricted Region (CORE) where sharing of RBs results in negative system capacity gain. This CORE region is used to calculate the candidate set of a D2D pair. CORAL algorithm has two phases. First phase finds out the highest ratio of the channel gain of a cellular UE with the base station to the channel gain of a D2D pair with that cellular UE and assigns that D2D pair with the RBs of the cellular UE. After assigning all of the D2D pairs second phase starts where remaining unshared cellular UEs are distributed among the D2D pairs for further capacity gain. It selects the lowest channel gain of a D2D pair with a cellular UE and assigns the RBs of that cellular UE to the D2D pair.

CORAL algorithm selects the cellular UEs for sharing RBs depending on the channel gain. However system capacity does not depend on the channel gain solely. It also depends on the transmission power and position of the receiver with respect to the other transmitters using the same RBs. In the first phase CORAL selects the optimal cellular UEs for each of the D2D pairs and similarly in second phase it chooses the optimal D2D pairs for the remaining unshared cellular UEs. So it is observable that CORAL does not return overall optimal or best result rather it is a greedy approach which might be stuck in a local optima.

2) RESULT COMPARISONS AND EXPLANATION

In case of *"One to Many Sharing"* approach we compare our proposed algorithm with CORAL [9]. In addition we modified some existing *"One to One Sharing"* algorithms (i.e., running the *"One to One Sharing"* algorithm multiple times). The modification is to. After each run the assigned cellular UE is removed from the list and the new list is passed to the next run as input. We use variants of DARA [8] by taking different factors into account e.g., distance and CORAL weight. In the case of modified DARA One to Many (CORAL), the preference matrix is populated based on the weight described in CORAL [9], which is R_{c_0}(sum rate of cellular UE c when no D2D pair shares the RBs of c) if the D2D pair is inside the CORAL region, $R_c + R_d$ otherwise.

Figures 8 and 9 represent the total system sum rate returned by the RA algorithms in *"One to Many Sharing"* approach. To get a comparative view, we normalize the results with respect to our proposed *"Restricted One to Many Sharing"* algorithm (Algorithm 3). Figure 8 shows comparison results for the uniform distribution of the D2D pairs whereas figure 9 represents the comparison result for the cluster distribution. Both of the figures suggest that *"Restricted One to Many Sharing"* algorithm produces the highest system sum rate as discussed in VI-A. However the admission rate of D2D pairs might be very low. We run DARA multiple times with higher distance as the higher preference. We use the similar weight discussed in CORAL to make the preference matrix and it performs better than the distance based preference matrix. The reason is that in case of CORAL weight we only assign the RBs whenever the cellular UE is in the candidate set of the D2D pair as discussed in V-A.

3) ADMISSION RATE OF D2D PAIRS

The term admission rate is introduced to represent the number of assigned D2D pairs in the system, in other words, number of D2D pairs getting resource blocks for communication.

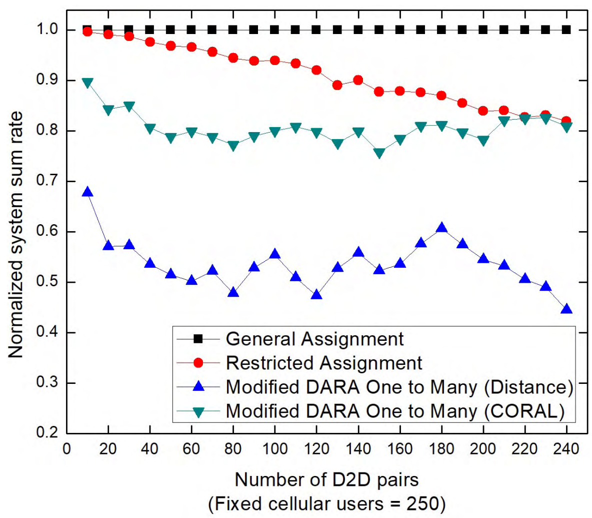


FIGURE 8. **Comparison of system sum rate (normalized with respect to the General assignment *"One to Many Sharing"* algorithm) of different RA algorithms following *"One to Many Sharing"* approach (uniform distribution).**

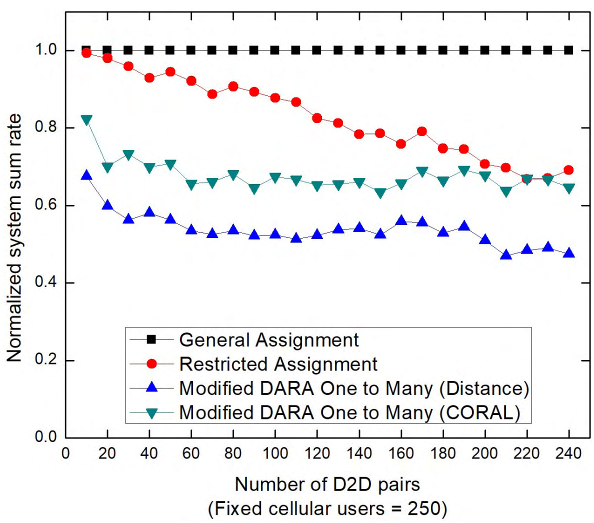


FIGURE 9. **Comparison of system sum rate (normalized with respect to the General assignment *"One to Many Sharing"* algorithm) of different RA algorithms following *"One to Many Sharing"* approach (cluster distribution).**

Figure 10 depicts the admission rate of the D2D pairs in the system where we can find that the admission rate of the general allocation is higher than the restricted allocation and the difference gets significant with the increasing number of D2D pairs. It is to be noted that general assignment does not allocate all the D2D pairs in the system rather it allocates all possible D2D pairs which increase the system sum rate.

VII. PROPOSED ALGORITHM FOR MANY TO MANY SHARING APPROACH

In *"Many to Many Sharing"* approach, This section mainly discusses an improved version of Graph Coloring Based Resource Allocation Algorithm (GOAL) discussed in [10]

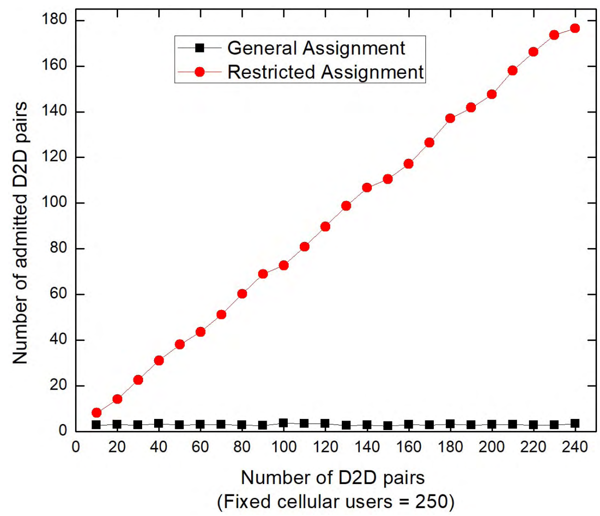


FIGURE 10. **Comparison of admission rate of D2D pairs by proposed RA algorithms following *"One to Many Sharing"* approach.**

which addresses the same problem. We use the same setup and graph formulation of GOAL algorithm. The graph formulation, neighbor construction, weight calculation and revised algorithm are discussed in the following subsections. A critical scenario is discussed after that where the revised algorithm improves the solution. The revised algorithm is named as Multiple Allocation D2D (MAD) in the rest of the paper.

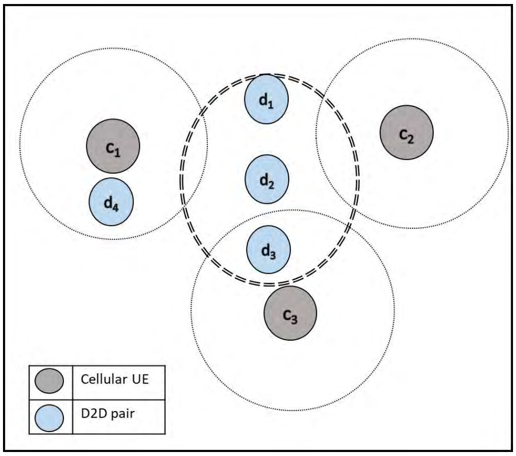
A. GRAPH FORMULATION

MAD (Algorithm 4) algorithm is devised on the basis of graph coloring approach. In this approach, a vertex of the graph represents a D2D pair and an edge of the graph represents that the connecting vertices are neighbor to each other. There might be significant amount of interference among the neighbors if they use the same RBs. So the neighboring D2D pairs should not share the RBs of same cellular UE. Hence the cellular UEs are assumed to have different colors. D2D pairs in close proximity of a cellular UE should not share the RBs as it creates huge interference to that cellular UE. Thus, each vertex has its own candidate color set based on the distance between the cellular UEs with respect to the D2D pair representing the vertex.

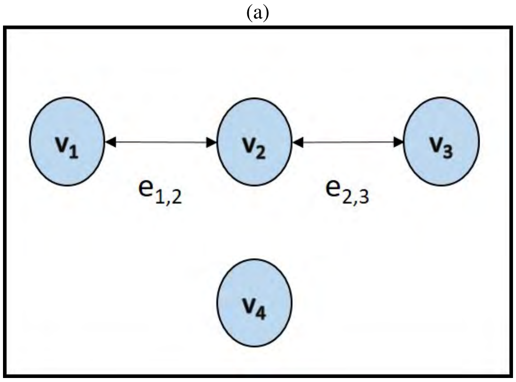
A vertex can choose a color from its candidate color set. After assigning the color, all of the neighbors of that vertex remove the color from their candidate color set if available. To achieve the maximum system sum rate, MAD aims to assign all of the colors to the vertices until candidate color sets of all of the D2D pairs are empty.

In figure 11, an example of "Many to Many Sharing" approach is presented, where figure 11a is the system model and figure 11b is the graph representation of the presented system model. D2D pair is represented by d_i and cellular UE is represented by c_j in the figure 11a. If any D2D pair, residing inside the circular (single dotted line) region around any cellular UE c_j, share RBs with one another then the cellular

UE will face higher interference from the D2D pair. Thus from the figure 11a d_4 should not share the RBs of cellular UE c_1. Similarly if any D2D pair, residing inside the circular (double dashed line) region around any D2D pair d_i, should not share same RBs. Thus from the figure 11a d_2 and d_1 as well as d_2 and d_3 should not share the same RBs.



(a)



(b)

FIGURE 11. **An illustration of *"Many to Many Sharing"* approach. (a) Relative position of cellular UEs and D2D pairs. (b) Graph formulation of scenario presented in figure 11a.**

Figure 11b represents a graph $G = (V, E)$, where $v_i \in V$ represents a D2D pair d_i and $e_{m,n} \in E$ implies v_m and v_n are neighbor to each other and they cannot share the same RBs. Edge $e_{1,2}$ implies that v_1 and v_2 cannot share same RBs and similarly $e_{2,3}$ means v_2 and v_3 cannot share same RBs whereas c_1, c_2, c_3 represent colors available to the system. It is noteworthy that neighbors cannot have same color. From figure 11 we can see that v_1 and v_2 has c_1, c_2 and c_3 in their candidate color set. Similarly v_3 has c_1 and c_2 in its candidate color set and so on.

B. NEIGHBOR CONSTRUCTION

GOAL algorithm introduces a term interference negligible distance (INS) which dictates the neighbors of a D2D. If two or more D2D transmitters using the same RBs are very close to one of the receiver then that D2D receiver will face huge interference from those transmitters which lowers the SINR at that D2D pair and results in lower system sum rate. If the distance is above the INS then it is assumed that those D2D pairs can share the same RBs without causing high interference to each other. There is an edge between two D2D pairs if their distance is smaller than the INS. The INS is assumed to be fixed value in GOAL algorithm and MAD algorithm also considers this approach.

C. CANDIDATE COLOR SET FORMATION

SINR limited area (SLA) is introduced in GOAL algorithm to form the candidate color set of each of the D2D pairs. If a D2D pair in close proximity of a cellular UE shares the RBs then the cellular UE might face severe interference. To avoid this kind of sharing the SLA is coined so that a D2D pair does not have a cellular UE in its candidate color set even if it resides in the SLA of the cellular UE. An SLA for a cellular UE c_j is an area where the $SINR$ at c_j is smaller than a minimum acceptable $SINR$. GOAL algorithm defines the SLA by the following equation

$$SINR_j = \frac{P^{eNB} G^{eNB,c_j}}{P^d G^{d_t,c_j}} \leq SINR_{min} \tag{15}$$

The denominator represents the interference introduced by a D2D transmitter d_t at a cellular UE c_j. From equation (15) it is evident that GOAL algorithm does not consider the interference from multiple D2D pairs. It is possible to select multiple D2D pairs residing just outside of the SLA, which might reduce the $SINR$ at the cellular UE cumulatively. MAD algorithm also follows this approach but checks the constraints prior to the assignment to satisfy the constraints.

D. WEIGHT CALCULATION

GOAL algorithm puts a label to each of the vertices for each of the colors. It uses correlation degree in calculating the label. Correlation degree of a vertex i for color j is the number of neighboring vertices having the same color in their candidate set. Label L_{ij} is calculated using the following equation

$$L_{ij} = \frac{\log_2(1 + SINR_i) + \log_2(1 + SINR_j)}{\rho_{ij} + 1}, \tag{16}$$

where $SINR_i$ indicates the $SINR$ at D2D pair d_i, $SINR_j$ indicates the $SINR$ at cellular UE c_j and ρ_{ij} is the correlation degree. However MAD algorithm does not use this label directly. Rather a revised label $L^r_{ij}evised$ of the vertex i for color j is defined by the following equations

$$W_{i,j} = R^{DL}_{c_i} + R^{DL}_{d_j} \tag{17}$$

$$L^{revised}_{i,j} = \sum_{h}^{X^j} W_{i,h} - W_{i,j}, \tag{18}$$

where R_{d_i} and R_{c_j} represent the individual sum rate contribution of d_i and c_j respectively calculated using the equation (5). X^i is the set of neighboring D2D pairs of d_i.

From equation (16) (which is used by GOAL algorithm) we can observe that, numerator represents the total sum rate of cellular c_j and D2D pair d_i though bandwidth B is missing which can be assumed as a constant value for all. In denominator correlation number is incremented by 1 (to avoid divide by zero error in case a correlation number is zero). So we can say that L_{ij} is the average sum rate contribution of the vertices.

It should be noted that, if color j is assigned to vertex i then color j cannot be assigned to the neighbors of vertex i. The label $L_{i,j}^{revised}$ in equation (18), represents the amount of sum rate loss if color j is assigned to vertex i. MAD tries to minimize this loss.

E. MAD ALGORITHM

MAD algorithm uses the same idea of neighbor construction and candidate color set formation of GOAL algorithm. The key differences are in weight calculation and color assignment to the vertices.

Algorithm 4 Multiple Allocation D2D (MAD)

1: **procedure** MAD($D(d_1, d_2, \ldots, d_m)$, $C(c_1, c_2, \ldots, c_n)$) ▷ An allocation from C (cellular UEs) to D (D2D pairs)
2: Create candidate color set for every D2D pair in the system ▷ It follows the procedure from VII-C
3: Create neighboring set of each D2D pair ▷ It follows the procedure from VII-B
4: **for** each $c_j \in C$ **do**
5: Let $N(n_1, n_2, \ldots, n_k) \in D$ containing c_j as candidate color set
6: Let $W[1..k]$, $S[1..k]$ and $M[1..k]$ be three new matrices
7: **for** each $n_i \in N$ **do**
8: $M_i = L_{i,j}^{revised}$ ▷ Label is calculated using equation (18)
9: **while** N is not empty **do**
10: Let M_q is the lowest value ▷ Choosing the lowest loss from the labels
11: **if** D2D pair d_q shares RBs of cellular UE c_j does not break the constraint (7) and (8) **then**
12: Assign color j to vertex q ▷ Assigning RBs of c_j to d_q for sharing
13: Remove color j from the vertex q and all the vertex neighbor of q
14: **else**
15: Remove color j from the vertex q

In MAD algorithm, at first candidate color set for all of the D2D pairs are calculated in line 2 (algorithm 4) and the neighbors of all of the D2D pairs are calculated in line 3 (algorithm 4). The neighbor set of a D2D pair is fixed throughout the algorithm, but the candidate color set of a D2D pair is updated in each cycle.

In line 4-15 (algorithm 4) a color is assigned to a suitable vertex. In line 8 (algorithm 4) label for each vertex M_i is calculated depending on the equation (18). In line 10 (algorithm 4), the lowest label is selected for assignment but before assigning, constraint checking is done in line 11 (algorithm 4). The reason behind this checking is that, SLA and INS area could not give certainty about these constraints, because SLA region does not consider multiple allocation in equation (15), and INS region is a fixed value set by the system administrator manually which can also break the constraints. If the constraints are satisfied, the color is assigned to the vertex (line 12 of algorithm 4) and the assigned color is removed from all of the neighboring vertices (line 13 of algorithm 4). However if the constraints are not satisfied then it is removed only from the selected assigned vertices.

F. CRITICAL SCENARIO

We present a critical scenario in figure 12 where MAD algorithm performs better than GOAL algorithm. Let us consider, a cellular UE $c_j \in C$ has three candidate D2D pairs d_1, d_2 and d_3 where d_1 has d_2 as neighbor, d_2 has both d_1 and d_3 as neighbor and d_3 has d_2 as neighbor. For c_j, weights of d_1, d_2 and d_3 are a, $\frac{19a}{14}$ and b respectively and assume that $a + b < \frac{19a}{14}$. GOAL algorithm chooses d_1 at the very beginning as it gives the maximum value according to their equation. Later it chooses d_3 and total weight gain is $a + b$. However in the case of MAD, it chooses d_2 at first as it gives the lowest in M and weight gain is $\frac{19a}{14}$ which is greater than $a + b$.

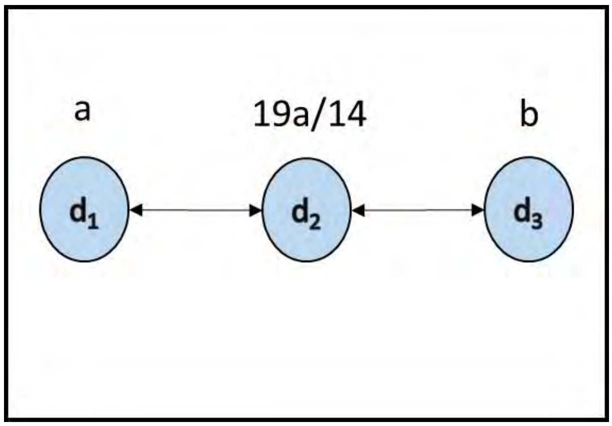


FIGURE 12. A critical scenario in *"Many to Many Sharing"* approach where GOAL algorithm fails (For easy calculation assume that a = 14 and b = 1).

G. PERFORMANCE EVALUATION

We evaluate MAD algorithm by comparing with the GOAL algorithm. In normal scenario both of the algorithms give same result but GOAL algorithm could break the constraints or give lower sum rate in some cases as discussed in subsection VII-F. This is evident in figure 13 where MAD algorithm gives better result than the GOAL algorithm in few cases.

In subsection VII-A, VII-B, VII-C and VII-D we have discussed the key points of the GOAL algorithm. GOAL algorithm differs from MAD at the time of selecting D2D

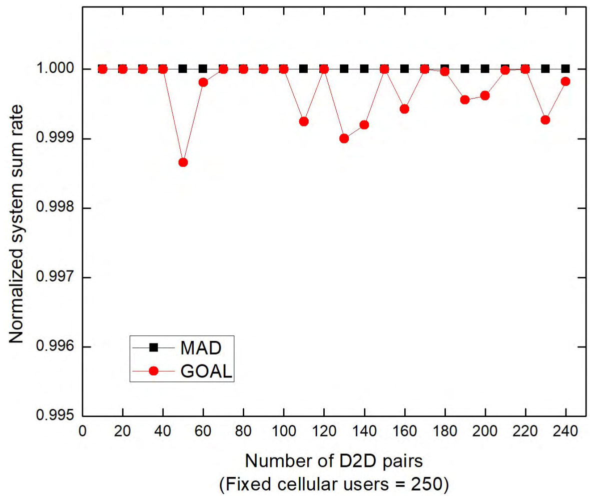


FIGURE 13. **Comparison of system sum rate (normalized with respect to the MAD algorithm) of MAD and GOAL algorithm (*"Many to Many Sharing"* approach).**

pairs for a color when it calculates the label (equation 16) and choose the highest label for an assignment. However it does not check any constraints before this assignment.

As discussed earlier, MAD algorithm rectifies some issues of GOAL algorithm. MAD algorithm performs better in some critical scenario showed earlier with explanation. However an error-nous allocation in *"Many to Many Sharing"* approach, might produce a large interference in the cellular network, as multiple D2D pairs use the RBs of a particular cellular UE. Thus we discourage to follow the *"Many to Many Sharing"* approach to maximize the system sum rate.

VIII. CONCLUSION

Resource allocation in D2D communication underlaying cellular network is an important research problem. Reusing the appropriate RBs of the cellular UEs in the system increase the system sum rate manifold. We propose algorithms for three different approaches (i.e., *"One to One Sharing"* approach, *"One to Many Sharing"* approach and *"Many to Many Sharing"* approach) depending on the degree of sharing, maintaining SINR requirements of the cellular UEs and the D2D pairs. In case of *"One to One Sharing"* approach, our proposed algorithm removes the nonviable (which decrease the system sum rate) D2D pairs by using the optimal weighted bipartite matching on that D2D pairs set. Our algorithm returns the maximum system sum rate, and introduces the minimum interference in the network while satisfying all constraints. Allowing multiple assignment increases the total system sum rate. We show two variants of multiple assignment (*"One to Many Sharing"* approach), in one case admission rate of D2D pair is totally ignored and in another, keeping the admission rate moderate, maximization of sum rate is performed. We also offer an algorithm for *"One to Many Sharing"* approach which returns higher result than the existing algorithm. Our proposed algorithms for *"One to One sharing"* approach and *"One to Many Sharing"* Approach (both variation) gives optimal solution in polynomial time. We also propose a better algorithm for *"Many to Many sharing"* approach. It should be noted that proposed resource allocation algorithms are offline algorithm (i.e., after any changes in the system, the algorithm needs to calculated from the beginning). In future we will work on online resource allocation algorithm for D2D communication underlaying cellular networks where after any change (e.g., entry of a D2D pair, cellular UE into the system or exit of D2D pair, cellular UE from the system) in the system, preserving the previous assignment, the resource allocation algorithm will try to calculate the assignment only for the changes.

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