Received: 25 August 2017 | Accepted: 20 January 2018
DOI: 10.1002/dac.3555

RESEARCH ARTICLE

WILEY

Relax online resource allocation algorithms for D2D communication

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Summary

Maximizing the system sumrate by sharing the resource blocks among the cellular user equipments and the D2D (device to device) pairs while maintaining the quality of service is an important research question in a D2D communication underlaying cellular networks. The problem can be optimally solved in offline by using the weighted bipartite matching algorithm. However, in long-term evolution and beyond (4G and 5G) systems, scheduling algorithms should be very efficient where the optimal algorithm is quite complex to implement. Hence, a low complexity algorithm that returns almost the optimal solution can be an alternative to this research problem. In this paper, we propose 2 less complex stable matching–based relax online algorithms those exhibit very close to the optimal solution. Our proposed algorithms deal with fixed number of cellular user equipments and a variable number of D2D pairs those arrive in the system online. Unlike online matching algorithms, we consider that an assignment can be revoked if it improves the objective function (total system sumrate). However, we want to minimize the number of revocation (ie, the number of changes in the assignments) as a large number of changes can be expensive for the networks too. We consider various offline algorithms proposed for the same research problem as relaxed online algorithms. Through extensive simulations, we find that our proposed algorithms outperform all of the algorithms in terms of the number of changes in assignment between 2 successive allocations while maintaining the total system sumrate very close to the optimal algorithm.

KEYWORDS

cellular UEs, D2D pairs, LTE, relax online algorithm, resource allocation

1 | INTRODUCTION

In recent decades, device-to-device (D2D) communication has become a buzz word with the popularity of hand-held devices. People are using various interdevice services in daily basis, eg, sharing files in a gathering, downloading media contents in concert, which are worth mentionable. This type of services can be offered by D2D communication underlay to traditional cellular network.[1] Long-term evolution (LTE) and beyond (4G and 5G) offer such features where D2D communication is enabled by reusing conventional radio resources under the supervision of an eNB (eNodeB, base station [BS] in LTE). This new mode of personal communication increases bit-rate gain (as the distance between the receiver and the sender is decreasing), reuse gain (as the D2D pairs and the cellular user equipments [UEs] simultaneously use the common radio resources), hop-gain (as D2D communication uses a single link rather than using uplink (UL) and downlink (DL) resources for sending and receiving), and coverage gain (as D2D communication can be possible at some place where signal strength of the eNB is too low for cellular communication).[2] Moreover, D2D communication is more power efficient than the conventional cellular communication via the eNB. [3]

The D2D pairs can communicate by reusing the appropriate resource blocks (RBs) of the existing cellular network, which increases system capacity and spectral efficiency. To use this opportunity in greater extent, it is very much necessary to use an efficient resource (spectrum) allocation algorithm. The major challenges faced by a resource allocation algorithm include time, dynamic distribution of the cellular UEs and the D2D pairs, the channel state information required for the optimal solution and more importantly interference, although orthogonal frequency division multiplexed radio resources are used to avoid interchannel interference in LTE and beyond systems. However, because of a bad design, sharing resources with the D2D pairs may introduce potential cochannel interference in the cellular network, which can affect the primary users.[4,5] So several research works in the area of resource allocation in D2D communication are focusing on different aspects including maximizing system sumrate, minimizing system interference, energy efficiency, and improving spectrum usage.

This paper addresses the research question of maximizing the total system sumrate by sharing the RBs among the cellular UEs and the D2D pairs while maintaining the quality of service (QoS) in a D2D communication underlaying cellular networks. The research problem is initially addressed by Zulhasnine et al.[6] They propose a greedy heuristic–based resource allocation algorithm as a solution to the problem. A local search technique is applied to solve the same research problem in Islam et al,[7] which uses the result of the greedy heuristic[6] as the initial feasible solution. A stable matching algorithm–based[8] solution is proposed in Islam et al[9] to solve the sumrate maximization problem where preference list is calculated on the basis of the proximity of the cellular UEs and the D2D pairs. A graph-based solution is proposed in Zhang[10] where the resource allocation problem is formulated as a maximum weight problem. An optimal algorithm based on weighted bipartite matching algorithm is proposed in Hussain et al[11] to maximize the same objective function. All of the existing solutions are based on different offline algorithms, and the research problem can be solved optimally in polynomial time using offline weighted bipartite matching algorithm as shown in Hussain et al.[11] However, in LTE system, the scheduling algorithm needs to be very efficient as the scheduling period is very short preferably less than 1 millisecond. The weighted bipartite matching algorithm (optimal) is quite complex to implement in such a short scheduling period. So, to comply with the fast scheduling requirement, a possible remedy to the problem is to run the algorithms online. In an online implementation, an algorithm is run with a smaller instance of the problem specifically with the newly arrived nodes (D2D pairs or cellular UEs) with the available resources (RBs) and the assignments among the nodes are irrevocable. However, in the current research problem, a strict online algorithm might leave some of the D2D pairs unassigned if none of the available cellular UEs can satisfy the constraints like signal-to- interference-plus-noise ratio (SINR), QoS requirement etc. which contradict the research goal. On the other hand, if we allow the revocation of an existing assignment, then we could assign the new D2D pair (considering that there exists at least one cellular UE that satisfies its QoS requirements and this assignment improves the overall system sumrate) to the revoked cellular UE and the revoked D2D pair to one of the available cellular UEs. In theory, if an online algorithm relaxes the irrevocable feature, then it is called relax online algorithm.[12] Hence, a relax online algorithm that performs near to the optimal solution can be a potential alternative to the research problem. The revocation of assignments introduces a new research challenge that is the number of changes in resource allocation between 2 consecutive states of the system. Because of a bad design of an algorithm, the number of changes may increase, which might be a potential reason for a significant system overhead.[4,13] Though in the literature there exists few online algorithms in D2D communication,[14,15] to the best of our knowledge, no other research works discuss an online/relax online algorithm for the same research problem that we consider in this paper for D2D communication in inband underlay scenario.

In this paper, we propose 2 stable matching[16] based relax online algorithms to allocate the RBs among the cellular UEs and the D2D pairs in inband underlay mode while maximizing the total sumrate of a system. In the existing online weighted bipartite algorithm[17] and stable matching algorithm,[18] an assignment is irrevocable. However, in our proposed solution, we allow revocation of an assignment to meet our research goal that is the maximization of the total system sumrate. Our proposed relax online algorithms assume the cellular UEs as a fixed set and the D2D pairs as an adversary set that means the total number of D2D pairs varies in different states of the system as they arrive in system online. Our proposed algorithms run when a new D2D pair arrives into the system and we define the arrival of a D2D pair as a system event. An occurrence of such a system event leads to a change in the state of the system, and it triggers our proposed algorithms to change the current resource allocation. In our proposed solution, we present 2 different assignment schemes, ie, restricted assignment scheme and fair assignment scheme. The restricted assignment scheme avoids a sharing that decreases the total system sumrate whereas there is no such restriction on the fair assignment scheme. The main contribution of this research work is to design the relax online algorithms in such a way that leads to a minimum number of changes in assignment between 2 successive allocation, hence incurs minimal system overhead while maximizing the total system sumrate. Simulation results suggest that our proposed algorithms outperform the existing offline algorithms in terms of both total system sumrate and the number of changes in successive allocation for both of the assignment schemes. Moreover, our proposed algorithms perform very close to the optimal algorithm[19] in terms of total system sumrate with less number of changes in successive allocation.

The remaining part of the paper is organized as follows. Section 2 presents the background and some notable related works. Section 3 discusses the system model and channel model of D2D communication underlay to a cellular network. Section 4 contains the problem formulation. Section 5 presents the proposed algorithms with analysis. Section 6 presents the simulation result and performance evaluation. Section 7 concludes the paper with remarks.

2 | BACKGROUND AND RELATED WORKS

To avail the utmost benefits of D2D communication, several research works are ongoing where researchers are deploying different schemes like interference control, mode selection, power control, and spectral resource allocation to exploit the diversity of the communication links. This is achieved by adaptively allocating network resources to optimize some network performance metric like throughput, delay, and interference. A number of surveys have been done on different aspects of D2D communication. A survey in Asadi et al[4] provides the role of D2D communication in 4G cellular networks area. The survey work presented in Liu et al[20] provides a summary of the outcomes for D2D communication in a cellular network. Another survey[21] discusses the cooperative communication and issues degrading the performance of the network. Authors in Ali and Ahmad[22] present a detailed and systematic survey of D2D communication on the aspect of mode selection, interference management, and resource allocation. They also point out some open research problems in D2D communication. Depending on spectral utilization, the D2D communication can be deployed in 2 major categories, ie, outband and inband.[22] The outband D2D communication uses the unlicensed spectrum band; hence, there is no issue of interference among the cellular UEs and D2D pairs. The outband D2D communication is divided into controlled and autonomous D2D communication. However, in outband D2D communication, a mobile device requires 2 wireless interfaces, one for the cellular system and another (Wifi, Zigbee, Bluetooth) for the utilization of unlicensed spectrum; hence, it requires more energy to handle 2 wireless interfaces. The inband D2D communication suffers from the issue of power control and the interference between the cellular UEs and D2D pairs as they share the radio resources in the licensed spectrum band. The inband D2D communication can be deployed either underlay or overlay to the existing cellular network depending on the licensed spectrum dedication. In the case of underlay mode, each D2D pair can use same radio resource that a cellular UE uses, while in overlay mode, a dedicated portion of the cellular spectrum is used by the D2D pairs. Several surveys suggest that from the energy and spectrum utilization point of view D2D communication is most convenient and beneficial in inband underlay mode.[4,21,22] This mode of D2D communication is attracting more researchers from academia, standardization bodies, and industry for further insight, and a lot more research is still necessary to achieve power and spectral efficiency by developing more efficient resource allocation schemes.

There are mainly 2 types of resource allocation schemes in the D2D communication, namely, centralized scheme and distributed scheme. Although both the schemes have their relative advantages and disadvantages, distributed schemes are more complex and inefficient from the signal processing point of view.[4] Moreover, in distributed schemes, multiple nodes take decision independently, so the joint decision might not comply with the system goal. Numerous research works have been conducted on various resource allocation problems recently those follow the centralized scheme as this paper deals with. Apart from a very few works, most of the existing centralized algorithms are offline. Now, we discuss some of the related offline algorithms (summarized in Table 1) those address the same research problem we are considering.

In Zulhasnine,[6] a greedy heuristic is proposed to select the D2D pairs on the basis of channel quality information to reduce the interference of the cellular network. A D2D pair with the lowest channel gain that is not yet assigned is selected for a cellular UE that has a higher channel quality information given that the QoS constraints are maintained. However, this process may not terminate in the worst case. Moreover, some of the D2D pairs might be missed out to be allocated or some of the D2D pairs selected earlier for some of the cellular UEs might give better sumrate to some other cellular UEs chosen later on.

TABLE 1 Existing offline resource allocation algorithms for D2D communication addressing the same research problem

Algorithm	Resource	Approach	Flaws	Complexity
Greedy heuristic[6]	Uplink/ downlink	• Greedy approach. • Use CQI 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 Zulhasnine et al[6] 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 sumrate and n is the number of total cellular UEs
DARA[9]	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	$O(n^2)$
Graph based[10]	Downlink	• Maximum weight matching algorithm. • Use sumrate as evaluation weight.	• QoS is not considered	$O(mn)$, m is the number of D2D pairs and n is the number of cellular UEs.
Optimal[11]	Downlink	• Weighted bipartite matching algorithm. •QoS constraints are maintained. •Consider the fact that every sharing does not necessarily increase the system sumrate.	Computationally extensive.	$O(n^3)$

Abbreviations: CQI, channel quality identifier; DARA, deferred acceptance–based algorithm for resource allocation; D2D, device to device; LORA, local search–based resource allocation; QoS, quality of service; UE, user equipment.

A local search algorithm[7] is designed to solve the same resource allocation problem where the target is to maximize the system sumrate while maintaining some QoS constraints. The result of the greedy heuristic[6] is considered as the initial feasible solution of this algorithm. Since the final result of a greedy heuristic might miss out some assignments of D2D pairs that is considered in the optimal solution, these D2D pairs can also be missed out in the final assignments returned by this local search algorithm. In practice, the local optima of the algorithm can be far away from the global solution too. Moreover, as local search is an iterative improvement technique, it might take much more time to reach the final solution and may not be very useful in LTE and beyond networks.

A deferred acceptance–based algorithm is proposed in Islam et al[9] to solve the same problem where the D2D pairs and the cellular UEs maintain a preference list of nodes (D2D pairs or cellular UEs) they wish to share with. The preference list is calculated on the basis of the increasing order of the proximity, which is not the best approach for this optimization problem. Moreover, the preference matrix does not consider the QoS requirements. Examples can be shown easily where an assignment is possible using this algorithm where QoS requirements are not met.

A graph-based algorithm[10] is proposed to solve the resource allocation problem in the UL channel, which is similar to the problem we are considering. They formulate the allocation of the channel to the D2D pairs to obtain the maximum system capacity as a maximum weight matching problem. However, they do not consider QoS requirements as well as allow some D2D pairs to share which may incur lower sumrate.

Hussain et al[11] propose an optimal resource allocation algorithm for maximizing the system sumrate. It is found that some sharing can also decrease the system sumrate. Considering this observation, they design an optimal algorithm based on weighted bipartite matching, which avoids such sharing and maximizes the total system sumrate. Consider that we have a set of already known cellular users and D2D pairs are coming online and once a D2D pair arrives, we assign it to one of the available cellular users. However, if none of the available cellular users can satisfy its QoS, then we cannot assign it. On the other side, if we could break an existing assignment, then we could assign this new D2D pair (considering there exists at least one cellular user that satisfies its QoS requirements and this assignment improves the overall system sumrate). In addition, the revoked D2D pair can also be assigned to any of the available channels (if QoS requirements are met). We summarize all of the discussed algorithms in Table 1.

Apart from the aforementioned algorithms, there are some other notable works in the area of D2D communication those do not address the same research problem we address in this paper. We present some of them as they are useful for better understanding of the D2D communication. Cai et al[23] propose a graph coloring–based heuristic algorithm where the D2D pairs are represented as vertexes and the RBs of the cellular UEs are represented as a set of colors. They formulate the research problem as a mixed integer nonlinear programming problem with the objective to maximize the system capacity. However, they consider an unrealistic scenario where the total number of the D2D pairs is larger than that of the cellular UEs. To justify this scenario, they consider many-to-many relationship among the D2D pairs and cellular UEs that means one D2D pair can share the resources of multiple cellular UEs as well as multiple D2D pairs can share the resource of a single cellular UE. Such scenario is not found in any other resource allocation problem for D2D communication, and the model is very complex. A number of research works[24-27] address the research problem of interference minimization while maintaining a target sumrate by sharing the radio resources among the cellular UEs and the D2D pairs. In Islam et al,[27] a knapsack-based approximation algorithm is proposed to solve the resource allocation problem. In Islam et al,[26] a bi-phase resource allocation algorithm is proposed where an auction-based fair algorithm is used in the first phase to allocate the resources, and in the second phase, a local search technique is used to improve the solution of the first phase. A similar algorithm is proposed in Hassan et al[24] where a weighted bipartite matching algorithm is used in the first phase to minimize the system interference at the time of allocating the resources among the cellular UEs and the D2D pairs. Janis et al[28] introduce an interference aware resource allocation scheme that uses the UL radio resources. This approach works in a coordinated fashion where the D2D pairs sense the radio environment and send it to the BS. Then the BS creates the local awareness of the radio environment among the D2D pairs and the cellular UEs and exploits the multiuser diversity of the cellular network to minimize the interference. A similar work is presented in Min et al[29] that suggests an interference limited area for the cellular UEs where the D2D pairs share the UL resources. Similarly, a restricted zone is also modeled for the DL medium. In both of the cases, a candidate set of D2D pairs is selected for the allocation. However, the allocation of a candidate D2D pair may not be the optimal one.

Feng et al[30] proposes a 3-step scheme that performs admission control of the D2D pairs initially to check whether the QoS requirement for both a D2D pair and a cellular UE is met or not and then performs an optimal power control scheme to maximize the overall throughput of the system, and finally, a maximum weighted bipartite matching is used for the final allocation. The admissibility of a D2D pair is calculated depending on the transmission range of the D2D pair and a cellular UE . They also formulate an estimation process of required power and adopt the maximum weighted bipartite matching algorithm to calculate the feasible solution. However, some of the D2D pairs might be considered in the admissible set, which reduces the system capacity. Huang et al[31] propose a game theory–based resource allocation algorithm for the multicell environment that uses UL resources. They have characterized each BS as a player competing for the RBs where the utility of each player is defined as the revenue collected from both the cellular UEs and the D2D pairs by using the RBs. They claim that each player is blind to their peer's payoff information that means the information about the peer's transmission parameter may be incomplete. In this approach, a player uses some probabilistic methods to determine the strategy of other players.

An analysis of the D2D communication on both spectrum overlay and underlay to the existing cellular network with ad hoc networks is discussed in Huang et al.[32] They present the major implications of the coexistence cellular and ad hoc networks. They also applies a technique called successive interference cancellation to generate a good transmission capacity. A similar research problem is addressed by Huang et al,[33] where they propose that frequency separation of cellular network from an ad hoc network overlaying the cellular network would give maximum transmission capacity rather than spatial diversity, ie, disjoint sets of subcarriers are used by the ad hoc network. The performance of D2D communication underlay to a cellular communication is analyzed in Yu et al,[34] which reduces the performance degradation of the existing cellular network by controlling the transmitting power of the D2D pairs.

3 | SYSTEM MODEL AND CHANNEL MODEL

This paper considers a system with a single cell area consisting of a single eNB, some D2D pairs, and some cellular UEs. In a normal scenario, total number of the cellular UEs is much higher than the total number of the D2D pairs. We consider the similar scenario used in previous studies[6,7,9] with n cellular UEs and m D2D pairs ($n \gg m$), and a cellular UE can share the RBs with a single D2D pair. The set of the cellular UEs is represented as $C = \{c_1, c_2, c_3, \dots, c_n\}$, whereas the set of the D2D pairs is represented as $D = \{d_1, d_2, d_3, \dots, d_m\}$. A D2D pair $d_j \in D$ contains a receiving device d_j^r and a transmitting device d_j^t. Though the D2D pairs directly communicate with each other, the connection establishment and the resource allocation are handled by the eNB.[9]

LTE network consists of both UL and DL resources. In our work, we only consider the DL resources, and Figure 1 represents the system model we consider. The eNB transmits a signal to the cellular UEs using DL resources, so the cellular UEs only experience interference from their shared D2D transmitters (c_1 is affected by d_2 and c_2 is affected by d_1), whereas D2D receivers encounter interference from the eNB (both d_1 and d_2 are affected by the eNB). As c_3 does not share the RBs with any of the D2D pairs, c_3 experiences no interference.

We consider an urban microsystem, which follows Rayleigh fading path loss model.[6,7,9] As the channels are assumed to be orthogonal, only intrachannel interference is present. The path loss (db unit) equation is

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

where $dist$ (meter) is the distance between a D2D transmitter and a receiver and f_c (GHz) is the medium frequency. Now, the channel gain between these 2 devices is

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

where x and y are the 2 devices and $PL^{x,y}$ is the distance dependent path loss between x and y.

We consider the total number and the relative position of the cellular UEs and the D2D pairs in the system at any moment as a state of the system. The state of the system changes over time because of the arrival or departure of the D2D pairs into the system as well as because of the mobility of both of the cellular UEs and the D2D pairs. Figure 2 depicts different states of the system with the arrival and departure of the D2D pairs. We consider the D2D arrival/departure as a system event that triggers the resource allocation process to allocate the RBs for the new state of the system. In

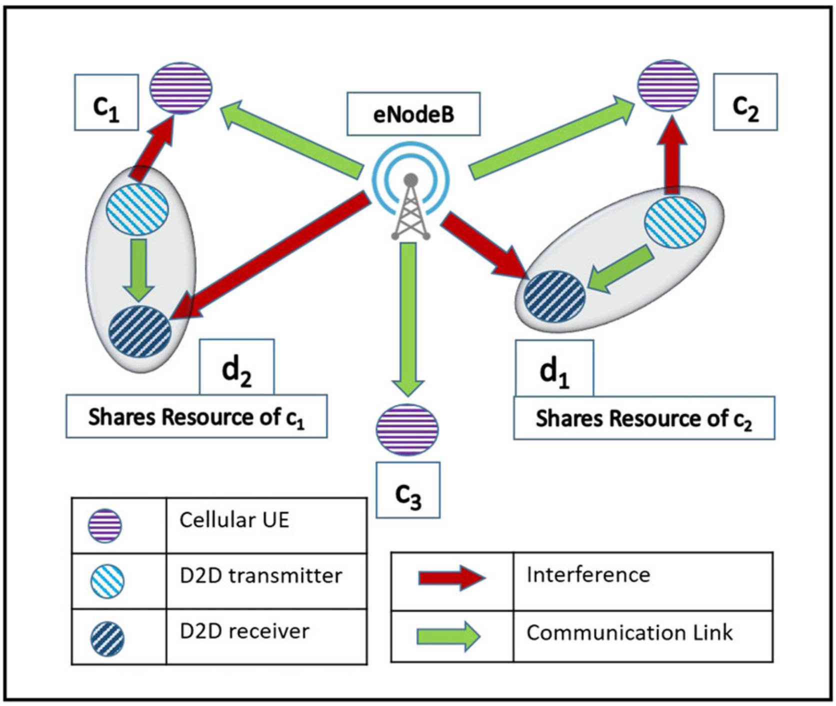


FIGURE 1 System model using downlink resources. D2D, device to device

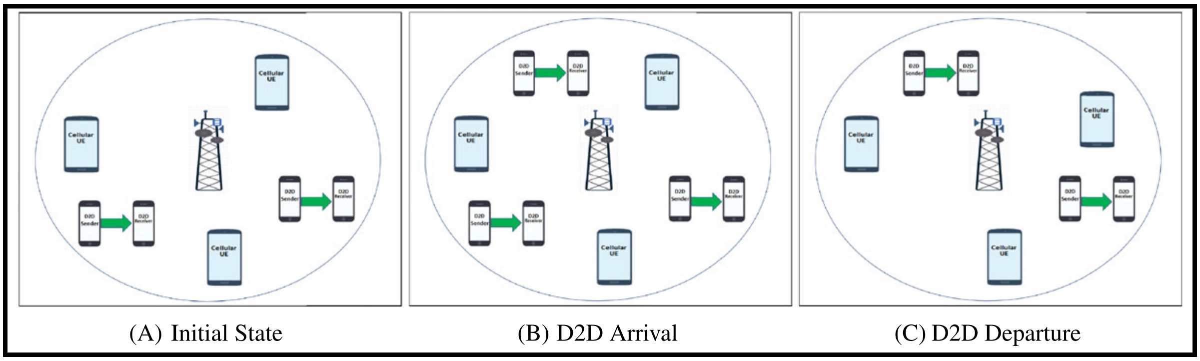


FIGURE 2 Different states of the system. D2D, device to device; UE, user equipment

other words, we can say when a new D2D pair arrives into the system, the necessary RBs for communication need to be allocated to the newcomer as this event changes the state of the system. We also accommodate user mobility in our model by defining some decision points where we trigger our resource allocation scheme with the new location of the devices (cellular UEs and D2D pairs). Every decision point is considered as a system event because it represents a new state of the system as the location of the devices are changed. However, we impose restrictions on the minimal interval between 2 decision points. We limit this just to keep the model simple; otherwise, implementation of user mobility in our system would be impractical.

4 | PROBLEM FORMULATION

The SINR of a receiver is the ratio between the received signal power and the interference with the noise power. In a DL interference model, the SINR value of a cellular UE depends on the transmitting power of the eNB, channel gain between the eNB and the cellular UE, and the intrachannel interference. Let us consider the individual transmitting power of the eNB, a cellular UE c_i, and a D2D transmitter d_j^t are P^{eNB}, P^{c_i}, and $P^{d_j^t}$, respectively. The thermal noise that is also known as the energy of additive white Gaussian noise introduced at the receiver end is denoted by σ. So the SINR of a cellular UE c_i in DL phase[6] can be represented as

$$\gamma_{c_i}^{DL} = \frac{P^{eNB} G^{eNB,c_i}}{\sigma + \sum_{d_j} x_{c_i}^{d_j} P^{d_j^t} G^{d_j^t,c_i}}, \tag{3}$$

where $G^{d_j^t,c_i}$ implies the channel gain between a D2D transmitter d_j^t and a cellular UE c_i. A binary variable $x_{c_i}^{d_j}$ indicates whether the D2D pair d_j shares the RBs of the cellular UE c_i or not. In the denominator, summation refers to the total interference of all the D2D pairs sharing the RBs of the cellular UE c. If none of the D2D pairs share the RBs of the cellular UE c_i, no intracell interference is incurred. So the SINR of such the cellular UE using DL resources can be represented as

$$\gamma_{c_i^0}^{DL} = \frac{P^{eNB} G^{eNB,c_i}}{\sigma}. \tag{4}$$

Similarly, the SINR at the receiving end of a D2D pair d_j using DL resources[6] can be presented as

$$\gamma_{d_j}^{DL} = \frac{\sum_{c_i} x_{c_i}^{d_j} P^{d_j^t} G^{d_j^t,d_j^r}}{\sigma + P^{eNB} G^{eNB,d_j^r}}, \tag{5}$$

where $G^{d_j^t,d_j^r}$ implies the channel gain between the transmitting end d_j^t and the receiving end d_j^r of the D2D pair d_j. Summation on the numerator indicates the total signals incurred from a D2D pair d_j for different cellular UEs sharing the same D2D pair d_j.

If B is the channel bandwidth, then according to the Shannon's capacity formula, the sumrate contribution of a cellular UE c_i using DL resources can be presented as

$$R_{c_i}^{DL} = B \log_2 \left(1 + \gamma_{c_i}^{DL}\right). \tag{6}$$

If none of the D2D pairs share the RBs of the cellular UE c_i, then the sumrate contribution of c_i can be presented as

$$R^{DL}_{c_i^0} = B\log_2\left(1+\gamma^{DL}_{c_i^0}\right). \tag{7}$$

Similarly, the sumrate contribution of the D2D pair d_j using DL resources can be presented as

$$R^{DL}_{d_j} = B\log_2\left(1+\gamma^{DL}_{d_j}\right). \tag{8}$$

Now, on the basis of Equations 6, 7, and 8, the optimization problem of maximizing the total system sumrate while satisfying the QoS requirements can be formulated as

$$\max\left(\sum_{c_i}^{C}\left(1-\sum_{d_j}^{D}x^{d_j}_{c_i}\right)R^{DL}_{c_i^0}N_{c_i}+\sum_{c_i}^{C}\sum_{d_j}^{D}x^{d_j}_{c_i}\left(R^{DL}_{c_i}+R^{DL}_{d_j}\right)N_{c_i}\right) \tag{9}$$

subject to,

$$\gamma^{DL}_{c_i} \geqslant \gamma^{DL}_{c_i,target},\ \forall\, c_i \in C \tag{10}$$

$$\gamma^{DL}_{d_j} \geqslant \gamma^{DL}_{d_j,target},\ \forall\, d_j \in D \tag{11}$$

$$\sum_{d_j} x^{d_j}_{c_i} \leqslant 1\,,\quad \forall\, c_i \in C \tag{12}$$

$$\sum_{c_i} x^{d_j}_{c_i} \leqslant 1\,,\quad \forall\, d_j \in D \tag{13}$$

$$x^{d_j}_{c_i} = \{0,1\}\,,\quad \forall\, c_i \in C \quad \text{and} \quad \forall\, d_j \in D, \tag{14}$$

where $x^{d_j}_{c_i}$ is a decision variable that indicates whether a D2D pair d_j shares the RBs of a cellular UE c_i or not and N_{c_i} implies the number of RBs allocated to a cellular UE c_i. The first part of the objective function (Equation 9) maximizes the total sumrate contribution of the unassigned cellular UEs where the optimization variable $R^{DL}_{c_i^0}$ represents the sumrate contribution of an unassigned cellular UE c_i^0. The second part of the objective function maximizes the total sumrate contribution of the assigned cellular UEs with the D2D pairs where the optimization variables $R^{DL}_{c_i}$ and $R^{DL}_{d_j}$ represent the individual sumrate contributions of a cellular UE c_i and a D2D pair d_j, respectively, when d_j reuses the RBs of c_i. $\gamma^{DL}_{c_i,target}$ and $\gamma^{DL}_{d_j,target}$ represent the SINR thresholds for a cellular UE c_i and a D2D pair d_j respectively. Constraints (10) and (11) ensure the QoS requirements by maintaining a minimum required SINR value for normal transmission rate. Constraint (12) implies that a cellular UE might share the RBs with a maximum of one D2D pair, and constraint (13) indicates that a D2D pair might share the RBs of a maximum of one cellular UE. Both of the constraints (12) and (13) ensure the orthogonality among the cellular UEs and the D2D pairs while sharing the RBs. Finally, constraint (14) confirms that the decision variable $x^{d_j}_{c_i}$ is a binary variable.

Although Equations 3 and 5 suggest the concept of multiple sharing among the D2D pairs and the cellular UEs, our proposed algorithms avoid multiple sharing among them. As sharing the RBs of a single cellular UE with multiple D2D pairs generates higher interference to the existing cellular network that might not be acceptable and sharing the RBs of multiple cellular UEs by a single D2D pair produces a complex model. However, these constraints are presented here to reflect the general idea. So the stated optimization problem is to maximize the total system sumrate (Equation 9) while satisfying the constraints (10) to (14).

We define 2 types of assignment schemes, ie, the restricted assignment scheme and the fair assignment scheme of our proposed solution. In the restricted assignment scheme, if an assignment returns a negative sumrate gain for a particular cellular UE and a D2D pair, then that particular sharing is avoided. More specifically, for a cellular UE $c_i \in C$ and a D2D pair $d_j \in D$, if the value of $(R^{DL}_{c_i} + R^{DL}_{d_j}$ - $R^{DL}_{c_i^0})$ is negative, then the restricted assignment scheme does not assign the RBs of c_i to d_j. However, there is no such restriction on the fair assignment scheme that means every D2D pair gets a fair chance of sharing the RBs of a cellular UE given that constraints (10) and (11) are satisfied. This paper aims to maximize the total system sumrate contributed by all of the individual cellular UEs and the D2D pairs in a particular allocation in both of the fair and the restricted assignment schemes. Moreover, a special attention is given to maintain a minimal number of changes in assignment between 2 successive states of the system.

5 | PROPOSED ALGORITHMS

We propose 2 relax online resource allocation algorithms for D2D communication in inband underlay mode. We name our first algorithm as relax online resource allocation (RORA) algorithm. Our second algorithm is a variant of our first algorithm, and we name our second algorithm as conservatively relax online resource allocation (CRORA) algorithm. Both RORA and CRORA are based on stable matching algorithm.[16] A stable matching algorithm is applied on a bipartite graph of 2 disjoint sets where all of the members of each set prepare a list that represents their degree of preference for all of the members of another set. To prepare the preference list, every member of a set ranks all of the members of another set on the basis of some criteria. The stable matching algorithm finds a matching between 2 members from 2 disjoint sets on the basis of the preference list. In other words, we can say a stable matching algorithm maps the elements from one set to the elements of another set. We treat the resource allocation problem as a bipartite matching problem and apply our proposed algorithms to find a stable matching or an assignment between a D2D pair and a cellular UE. The performance of a stable matching algorithm depends on the different criteria on the basis of which preference list is calculated. So before describing our proposed algorithms, we shed some light on the calculation of preference list of any node (D2D pair or cellular UE) in the following subsection.

5.1 | Weight-based preference list

Preference list of a node of a bipartite graph is the main element of a stable matching algorithm. Existing stable matching–based algorithm[9] for resource allocation in D2D communication uses proximity as the basis of preference list calculation where a node with a lower distance is preferred over a node with a higher distance. In our proposed algorithms, instead of using the proximity, we use sumrate gain as a weight value to generate the preference list of a node. As our prime goal is to maximize the total system sumrate, so in preference calculation, sumrate gain is the weight value.

Assume that, $R_{c_i}^{d_j}$ is the sumrate contribution when a cellular UE c_i shares the RBs with a D2D pair d_j and $R_{c_i}^{0}$ is the sumrate contribution when the cellular UE c_i does not share the RBs with any of the D2D pairs. So

$$\Delta R = R_{c_i}^{d_j} - R_{c_i}^{0} \tag{15}$$

implies the gain in total system sumrate when a cellular UE c_i shares the RBs with a D2D pair d_j. So if the value of ΔR is nonnegative, then that particular sharing does not reduce the total system capacity. So ΔR is the weight based on which the preference lists of all of the nodes are calculated. In our proposed algorithms, a D2D pair d_j prefers a cellular UE c_i over another cellular UE c_i' if (c_i, d_j) provides better sum rate gain than (c_i', d_j) and same thing is true for a cellular UE. The sumrate gain can be either positive or negative that means the total system sumrate can either increase or decrease if a D2D pair shares the RBs of a cellular UE. We define a binary variable p_{c_i,d_j}^{R} to indicate the presence of a node (cellular UE or D2D pair) in the preference list of another node for the restricted scheme as

$$p_{c_i,d_j}^{R} = \begin{cases} 1, & \text{if } \Delta R \text{ is non-negative and constraints (10) and (11) are satisfied,} \\ 0, & \text{otherwise.} \end{cases}$$

which indicates that in the case of the restricted assignment scheme, if a D2D pair d_j and cellular UE c_i return nonnegative sumrate gain and satisfy constraints (10) and (11), then only d_j is kept in the preference list of c_i and vice versa. In the case of the fair assignment scheme, all of the nodes are always kept in the preference list whether they are providing positive or negative sumrate gain given that constraints (10) and (11) are satisfied. Similarly for the fair assignment scheme, we define a binary variable p_{c_i,d_j}^{F} as

$$p_{c_i,d_j}^{F} = \begin{cases} 1, & \text{if constraints (10) and (11) are satisfied,} \\ 0, & \text{otherwise.} \end{cases}$$

5.2 | Algorithm scheduler

Algorithm 1 is a scheduler that triggers our proposed algorithms RORA (Algorithm 2) and CRORA (Algorithm 3) on the basis of 2 system events, namely, arrival event and mobility event. We define the arrival of a D2D pair in the system as an arrival event and the movement of the cellular UEs and the D2D pairs as mobility event. The occurrence of any one or both of the events trigger our proposed algorithms (RORA and CRORA) to give a new assignment for the new state.

To accommodate the mobility of the nodes in our proposed solution, we define some decision points where we calculate the location of the devices (cellular UEs and D2D pairs). In every decision point, mobility event triggers both of our proposed algorithms because every decision points represent the new state of the system as the location of the devices are changed. In the current implementation, we do not consider the departure event of the D2D pairs to keep the model simple. Although departure event would make the system more realistic, its exclusion does not add any demerit point to our proposed algorithms as any of the arrival and departure event would trigger our proposed algorithms (RORA and CRORA) with a new set of cellular UEs and D2D pairs.

5.3 | Relax online resource allocation algorithm

Our first proposed algorithm RORA (Algorithm 2) is based on the stable matching algorithm [16] that assumes the cellular UEs as a fixed set and the D2D pairs as an adversary set that means the total number of the D2D pairs varies in the system in course of time. In Algorithm 2, we consider the resource allocation problem as a bipartite graph with n cellular UEs in one set and m D2D pairs in another set. At the beginning, we initialize the newly arrived D2D pairs and the unassigned cellular UEs as free (Line 2 of Algorithm 2). Then we calculate the preference lists for both of the cellular UEs and the D2D pairs on the basis of Equation 15 and the binary variables $p^R_{c_i,d_j}$ and $p^F_{c_i,d_j}$ as described in Section 5.1 (Line 3 of Algorithm 2). In RORA, the D2D pairs facilitate the proposal part of the stable matching algorithm (Line 5 of Algorithm 2). RORA (Algorithm 2) assigns a cellular UE and a D2D pair together such that there is no other cellular UEs and D2D pairs that would provide better sumrate than their current assignment (Lines 4-7 of Algorithm 2). If there are no such cellular UE or D2D pair, then all of the assignments are stable. If such assignments occur (Line 10 of Algorithm 2), then RORA revokes those assignments. Line number 10 of Algorithm 2 actually facilitates the relaxation property of RORA, which allows the revocation of an existing assignment. The RBs of the revoked cellular UEs are assigned to the newly arrived D2D pairs, and the revoked D2D pairs are added to the list of free D2D pairs. When all of the D2D pairs are assigned to the cellular UEs, then RORA stops its execution and returns the allocation as the final result.

5.4 | Conservatively relax online resource allocation algorithm

Our second proposed algorithm CRORA (Algorithm 3) is a variant of our first proposed algorithm RORA and works in a similar way as RORA works with some extra carefulness. To leverage the extra system overhead due to the relaxation property (revocation of assignment), we design CRORA in a conservative way. Up to line number 10 of CRORA is similar to that of RORA where CRORA calculates the preference lists of both of the cellular UEs and the D2D pairs and considers the D2D pairs as the proposer of the stable matching algorithm. CRORA is a conservative variation of RORA as an extra condition is checked (Line 11 of Algorithm 3) at the time of assignment where there is a necessity of revocation. This new condition ensures that if the revoked D2D pair would contribute negative system sumrate gain along with its new partner, then this revocation is not allowed. Hence, the number of changes is reduced, and at the same time, the objective of sumrate maximization is achieved. The new condition (Line 11 of Algorithm 3) considers $c_m \in C$ as the next available preferred cellular UE for the associated D2D pair d_k. If c_m is empty, ie, there is no such free cellular UE for d_k, then the sumrate contribution $S_{c_m,d_j} = 0$. As c_m is free, so $S_{c_m,0}$ represents the sumrate contribution c_m when it does not share the RBs with any of the D2D pairs. In other words, we can say if there is a necessity of revocation (Line 10 of Algorithm 3) right away CRORA will not revoke the assignment, rather it will check the new condition (Line 11 of Algorithm 3). If the new condition is satisfied only, then it revokes the assignment; otherwise, CRORA go with the existing assignment hence reducing the number of changes in assignment between 2 successive allocations.

Algorithm 1 Algorithm scheduler

```
procedure SCHEDULER(D(d_1, d_2, ..., d_m), C(c_1, c_2, ..., c_n))   ▷ An allocation from C(cellular UEs) to D(D2D pairs)
    Call RAAlgorithm1(D, C) for RORA or RAAlgorithm2(D, C) for CRORA
    while TRUE do
        if Event_Arrial || Event_Mobility then
            Call RAAlgorithm1(D, C) for RORA or RAAlgorithm2(D, C) for CRORA
```

Algorithm 2 Relax online resource allocation (RORA) algorithm

procedure RAALGORITHM1($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$) ▷ An allocation from C(cellular UEs) to D(D2D pairs)
  Newly arrived D2D pairs and the unassigned cellular UEs are initialized as free.
  Calculate the preference lists for the free cellular UEs and the D2D pairs using Equation (15)
  while $\exists$ free D2D pair $d_j \in D$ who still has a cellular user $c_i \in C$ to request to **do**
    c_i = first cellular user on d_j's preference list to whom d_j has not yet requested
    if c_i is free **then**
      (c_i, d_j) become assigned
    else
      For another D2D pair $d_k \in D$ an assignment (c_i, d_k) already exists
      if c_i prefers d_j to d_k **then**
        (c_i, d_j) become assigned
        Add d_k to the list of free D2D pairs.
      else
        (c_i, d_k) remain assigned

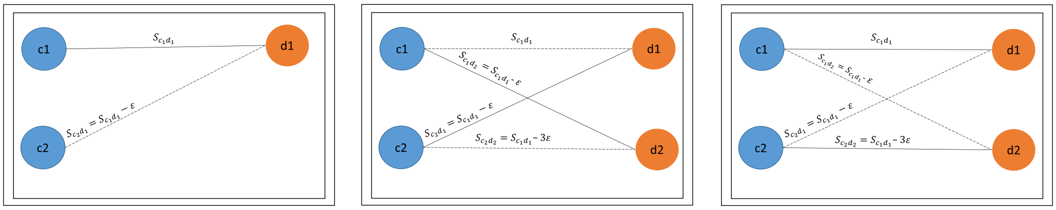
Algorithm 3 Conservatively relax online resource allocation (CRORA) algorithm

procedure RAALGORITHM2($D(d_1, d_2, \ldots, d_m), C(c_1, c_2, \ldots, c_n)$) ▷ An allocation from C(cellular UEs) to D(D2D pairs)
  Newly arrived D2D pairs and unassigned cellular UEs are initialized as free.
  Calculate the preference lists for the free cellular UEs and the D2D pairs using Equation (15)
  while $\exists$ free D2D pair $d_j \in D$ who still has a cellular user $c_i \in C$ to request to **do**
    c_i = first cellular user on d_j's preference list to whom d_j has not yet requested
    if c_i is free **then**
      (c_i, d_j) become assigned
    else
      For another D2D pair $d_k \in D$ an assignment (c_i, d_k) already exists
      if c_i prefers d_j to d_k **then**
        if $S_{c_i,d_j} + S_{c_m,d_k} - S_{c_m,0} > S_{c_i,d_k}$ **then** ▷ $c_m \in C$ is the next available preferred channel for d_k.
          (c_i, d_j) become assigned
          (c_m, d_k) become assigned
        else ▷ we are not changing the assignment as it will not improve the global solution.
          (c_i, d_k) remain assigned
      else
        (c_i, d_k) remain assigned

5.5 | Analysis on assignment strategy

In this subsection, we focus on the assignment strategy of the optimal Hungarian and our proposed algorithms. Here, we present a simple example (Figure 3) that explains why our proposed algorithms in general need less number of changes in assignment between 2 successive allocations compared with the Hungarian algorithm, which provides the optimal result in terms of total system sumrate.[11] Let us consider the state of Figure 3A with 2 cellular users c_1, c_2 and one D2D pair d_1. The sumrate contributions of d_1 are S_{c_1,d_1} and $(S_{c_1,d_1} - \varepsilon)$ when it shares the RBs of c_1 and c_2, respectively, where ε is a very small real number. According to both optimal and our proposed algorithms, d_1 would share the RBs of c_1 (solid lines represent a valid assignment). Suppose in the next state a new D2D pair d_2 enters into the system. The sumrate contributions of d_2 are $(S_{c_1,d_1} - \varepsilon)$ and $(S_{c_1,d_1} - 3\varepsilon)$ when it shares the RBs of c_1 and c_2, respectively. Now, according to the Hungarian algorithm (Figure 3B), new associations would be $c_1 d_2$ and $c_2 d_1$ with a total sumrate contribution of $2(S_{c_1,d_1} - \varepsilon)$, and it encounters one change in resource allocation (d_1 is revoked from c_1 and d_2 is assigned to c_1). However, according to our proposed algorithms (Figure 3C), the new associations would be $c_1 d_1$ and $c_2 d_2$ with a total sumrate contribution of $(2S_{c_1,d_1} - 3\varepsilon)$. It is noted that our proposed algorithms do not encounter any change in resource allocation, hence less system overhead contribution.

Now, we present a small example in Figure 4 that shows the output traces of the optimal Hungarian algorithm, RORA, and CRORA. We generate the output traces for a simple scenario with a fixed number of 5 cellular UEs and a variable



(A) Initial State (B) Hungarian Algorithm (C) RORA and CRORA

FIGURE 3 Assignment strategy (Hungarian vs proposed algorithms)

No of D2D Pairs	c_1	c_2	c_3	c_4	c_5	No of Changes	Sumrate
1			d_1			0	134.883
2			d_1		d_2	0	138.948
3			d_1	d_2	d_3	1	157.935
4	d_3		d_1	d_4	d_2	2	159.211
5	d_3	d_4	d_1	d_5	d_2	1	152.61

(A) Hungarian Algorithm

No of D2D Pairs	c_1	c_2	c_3	c_4	c_5	No of Changes	Sumrate
1			d_1			0	134.883
2			d_1		d_2	0	138.948
3			d_2	d_1	d_3	2	156.716
4	d_1		d_2	d_4	d_3	1	157.621
5	d_1	d_5	d_2	d_4	d_3	0	149.567

(B) RORA

No of D2D Pairs	c_1	c_2	c_3	c_4	c_5	No of Changes	Sumrate
1			d_1			0	134.883
2			d_1		d_2	0	138.948
3			d_1	d_2	d_3	1	157.935
4		d_4	d_1	d_2	d_3	0	158.02
5	d_5	d_4	d_1	d_2	d_3	0	149.345

(C) CRORA

FIGURE 4 Trace analysis (Hungarian [optimal] algorithm vs proposed algorithms). CRORA, conservatively relax online resource allocation; D2D, device to device; RORA, relax online resource allocation

number of D2D pairs. We start with a single D2D pair, and in course of time, more D2D pairs arrive in the system online, and finally, there are 5 D2D pairs in the system (all of the algorithms terminate when the total number of D2D pairs exceeds the total number of cellular UEs in the system). Figure 4A-C represents the output trace of the optimal algorithm (Hungarian), RORA, and CRORA, respectively, where individual row represents a state of the system with different number of D2D pairs. For all of the algorithms, total system sumrate and number of changes (revocations) in different states of the system are presented in respective columns of Figure 4A-C. The column index of a D2D pair represents the cellular UE, to which it is currently assigned to. In every row, green color represents the newly arrived D2D pair, and red color represents the revoked D2D pairs from the previous state. For example, in Figure 4A, row number 3 represents the state of the system with 5 cellular UEs and 3 D2D pairs where d_3 is the newly arrived D2D pair. For this state, Hungarian algorithm returns a total sumrate of 157.935 with a single change in the assignment where d_2 is revoked from c_5 and assigned to c_4. By analyzing the output traces of Figure 4A-C, we can see that the optimal Hungarian algorithm returns a total sumrate of 152.61 and performs a total of 4 revocations whereas RORA returns a total sumrate of 149.567 and performs a total of 3 revocations. On the other hand, CRORA returns a total sumrate of 149.345 with only one revocation. Both RORA and CRORA return close to the optimal total system sumrate with less number of changes in allocation (revocation). We need to mention that although RORA and CRORA return similar total system sumrate, CRORA returns remarkably less number of changes in successive allocation. This is due to the extra carefulness (Line 11 of Algorithm 3) at the time of revocation. This observation will be more vivid when we present the simulation data in Section 6 with a bigger instance of the system.

We observe that although the Hungarian algorithm is optimal in terms of total system sumrate that ensures the highest achievable system sumrate, it might assign less number of D2D pairs than the other algorithms. To prove this observation, let us consider the similar scenario of Figure 3 where the sumrate contributions of d_1 are 10 and 5 when it shares the RBs of c_1 and c_2, respectively. According to both Hungarian and our proposed algorithms, d_1 would share the RBs of c_1. Suppose in the next state a new D2D pair d_2 enters into the system and the sumrate contribution of d_2 is 4 when it shares the RBs of c_1. However, d_2 does not meet the QoS constraints when it shares the RBs of c_2. In this state of the system, the Hungarian algorithm returns a total sumrate of 10 with c_1 assigned to d_1 and leaves d_2 unassigned. However, our proposed algorithms return a total sumrate of 9 with the associations c_1d_2 and c_2d_1.

5.6 | Run time complexity

We design stable matching–based relax online algorithms (RORA and CRORA), which in practice give a very close to the optimal solution. Stable matching–based algorithms converge (become stable) after $O(n^2)$[8] steps where n represents the total number of elements in both sets of the bipartite graph. So both RORA and CRORA have a complexity of $O(n * m)$ in the worst case and $O(nlogn)$ in the average case where n is the total number of cellular UEs and m is the number of total D2D pairs while $m \ll n$. We can easily prove that both RORA and CRORA terminate after at most $m * n$ number of iterations. In the case of RORA and CRORA, in each iteration (Line 4 of Algorithms 2 and 3), an unassigned D2D pair proposes (for the only time) to a cellular UE it has never proposed to before. Let us consider $\rho(t)$ as the set of pairs (d_j, c_i) such that a D2D pair d_j proposes to a cellular UE c_i by the end of the iteration t. We can easily observe that for all of the iterations, the size of $\rho(t+1)$ is necessarily greater than the size of $\rho(t)$. However, there are only $m * n$ number of possible pairs of a cellular UE and a D2D pair in total in the system, so the value $\rho(\cdot)$ can increase at most $m * n$ in course of time with the progress of both RORA and CRORA. It proves that both of our proposed algorithms terminate within a maximum of $m * n$ number of iterations. It is to be noted that CRORA is conservatively designed, and because of the extra condition checking (Line 11 of Algorithm 3), the number of revocation is less than RORA, so the run time complexity of CRORA is normally less than RORA. In the worst case, CRORA requires a $m * n$ number of iterations to terminate, whereas in the average case, it requires less number of iterations than RORA to terminate. The running time of RORA and CRORA are same as deferred acceptance–based algorithm for resource allocation (DARA)[9] and better than local search–based resource allocation algorithm (LORA)[7] and the Hungarian algorithm.[19] LORA has a complexity of $O(n^2S)$ where S is the total sumrate of the system with n cellular users. For the Hungarian algorithm, the run time complexity is $O(n^3)$.

6 | PERFORMANCE EVALUATION

6.1 | Different algorithms for performance comparisons

We consider different resource allocation algorithms to compare the performance of our proposed algorithms (RORA and CRORA) in terms of total system sumrate and number of changes in assignment between 2 consecutive states of the system. Each of the algorithms is briefly explained here with their key points.

6.1.1 | Deferred acceptance–based algorithm for resource allocation

DARA[9] also follows the stable matching algorithm presented in Gale and Shapley.[35] However, preferences for both the cellular UEs and the D2D pairs are calculated depending on their location. A device in close proximity is preferred over the far one. Depending on the given preference, a D2D pair selects a cellular UE to share the RBs. But distance is not the only factor behind better sumrate. It is assumed that 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, this algorithm allows a cellular UE and a D2D pair to share the RBs even though QoS is not satisfied.

6.1.2 | Local search–based resource allocation algorithm

A local search algorithm LORA[7] uses the allocation given by the greedy algorithm[6] as the initial feasible solution. Then it swaps assignment between a D2D pair and a cellular UE only if the swapping improves the objective function, as well as the constraints are satisfied. LORA can also face the similar problem encountered by the greedy algorithm.[6] The final result of the greedy heuristic might miss out some of the D2D pairs for assignments those are considered in the optimal solution. These D2D pairs can also be missed out in the final assignments returned by the local search algorithm, and in practice, the local optima of this algorithm can be far away from the global solution.

6.1.3 | Optimal algorithm

Hungarian algorithm[19] is a weighted bipartite matching–based algorithm used in previous studies[10,11,30] for similar resource allocation problems in D2D communications. Hungarian algorithm is an optimal algorithm that outperforms other heuristics. In our simulation study, we also consider a similar algorithm. [19]

In simulation graphs, our proposed algorithms are named as “RORA” and “CRORA,” and the optimal Hungarian algorithm is named as “optimal.'.

6.2 | Simulation environment

We simulate different scenarios to evaluate the efficiency of our proposed algorithms (RORA and CRORA). We use the C++ programming language to build our simulator that supports LTE system. The research problem we consider is a type of assignment problem which is one of the fundamental combinatorial optimization problems in the branch of optimization. In our simulation, our main objective is to find the assignments of the D2D pairs with the cellular UEs. On the basis of the assignments, we need to calculate SINR, interference, and system sumrate from their respective equations. We need to mention that as we do not need to implement the physical layer (PHY), medium access control layer (MAC) and network layer to implement our proposed relax online resource allocation algorithms, so a networking simulator is not essential for our simulation study. We use the same simulation parameters (Table 2) as in previous studies[6,7,9] as well as some other variants of these parameters for the performance evaluation of the proposed algorithms. A single cell network is considered in the simulations. We consider that the cellular UEs and the D2D pairs are uniformly distributed in the cell area where D2D pairs (D2D transmitters and D2D receivers) are uniformly distributed in a random cluster with a maximum radius of 15 m. All of the simulation results presented in this paper are an average of 50 different runs for a particular scenario.

6.3 | Input data model

For all of the simulation results presented in this paper, we start with 300 cellular UEs and a single D2D pair. On the basis of the system events, the number of D2D pairs in the system varies over time, whereas the number of cellular UEs is fixed. We stop the simulation when the number of D2D pairs in the system becomes 225 (75% of the number of the cellular UEs as we are considering a system where the number of the cellular UEs is much greater than the number of the D2D pairs). However, on the basis of the mobility system event, the relative positions of both the D2D pairs and the cellular UEs change over time. We use Markov-modulated Poisson process (MMPP)[36] to model the arrival and mobility event. With MMPP arrival/mobility, event rate λ_s is determined by the phase s of the Markov chain,[37] where the total number of states is S (ie, s = 1,2, … ,S). In our simulation, we consider only 2 states of the Markov chain working in a discrete time where λ_1 is the rate of state 1 and λ_2 is the rate of state 2. So we can say both arrival event (D2D pairs) and mobility event (both D2D pairs and cellular UEs) are modeled using discrete time MMPP. At the time of an arrival event, we consider any random number of D2D pairs in between 1 and 9. However, our algorithm can handle any number of D2D pairs at a single arrival event. Moreover, we perform extensive simulations with a different number of cellular users and a different number of initial D2D pairs with different arrival rates, and we find that all of the simulation results are almost identical to the result we present here in terms of performance.

6.4 | Result comparison

We compare our proposed algorithms (RORA and CRORA) with the existing offline algorithms for both of the fair assignment scheme and the restricted assignment scheme. For both of the assignment schemes, we compare the algorithms with respect to the total system sumrate and number of changes in assignment between 2 successive allocations. Figure 5

TABLE 2 Simulation parameters

Parameter	Value
Cell radius	1000 m
Maximum D2D pair distance	15 m
Cellular user transmit power	20 dBm
D2D transmit power	20 dBm
Base station transmit power	46 dBm
Noise power (AWGN)	−174 dBm
Carrier frequency	1.7 GHz for LTE
$\gamma^{DL}_{c_i,target}$	Random
$\gamma^{DL}_{d_j,target}$	Random

Abbreviations: AWGN, additive white Gaussian noise; D2D, device to device; LTE, long-term evolution.

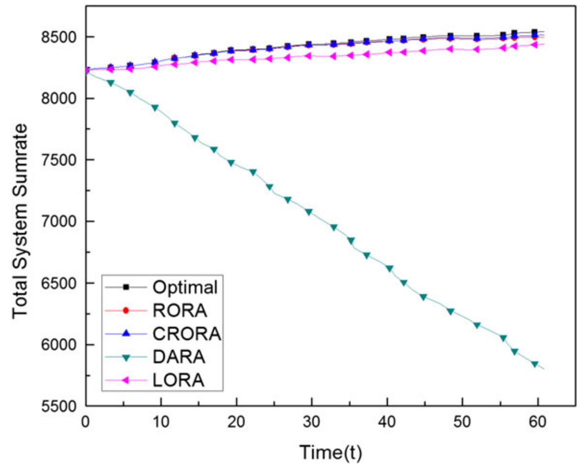


FIGURE 5 Total system sumrate in each state of the system for the fair assignment scheme. CRORA, conservatively relax online resource allocation; DARA, deferred acceptance–based algorithm for resource allocation; LORA, local search–based resource allocation; RORA, relax online resource allocation

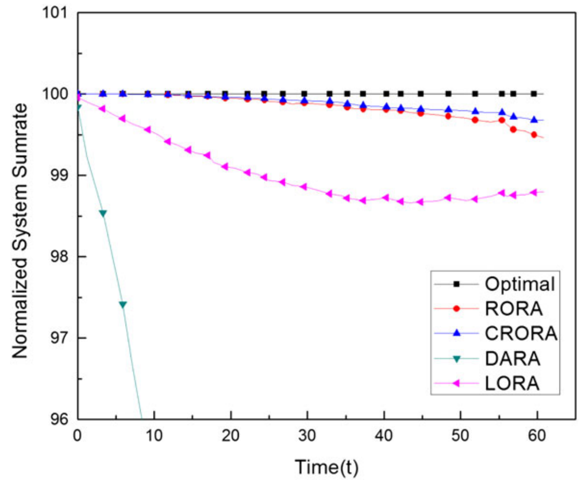


FIGURE 6 Normalized system sumrate in each state of the system for the fair assignment scheme (normalized with respect to the optimal Hungarian algorithm). CRORA, conservatively relax online resource allocation; DARA, deferred acceptance–based algorithm for resource allocation; LORA, local search–based resource allocation; RORA, relax online resource allocation

represents the comparison of the total system sumrate returned by the algorithms in different states of the system for the fair assignment scheme. From the graph presented in Figure 5, we can observe that both RORA and CRORA perform very close to the optimal algorithm, and LORA performs next to our proposed algorithms, whereas DARA performs the worst. The reason for DARA's poor performance is that the preference list of DARA is based on the increasing order of the proximity, which is not the best approach for this optimization problem. For clarity, we present the normalized system sumrates returned by different algorithms in Figure 6 where the graph is normalized with respect to the optimal algorithm. From Figure 6, we can observe that in the fair allocation scheme, both RORA and CRORA performs almost 99.95% of the optimal algorithm and, by a very narrow margin, CRORA outperforms RORA in terms of total system sumrate. Figure 7 represents the comparison of different algorithms in terms of the number of changes in successive allocation. We exclude DARA from this comparison as it performs remarkably poor in terms of system sumrate. Figure 7 suggests that both RORA and CRORA outperform LORA and the optimal algorithm where the individual line represents cumulative number of changes for different algorithms in discrete time event. RORA performs approximately 55% less number of changes than LORA and 5% less number of changes than the optimal algorithm, whereas CRORA performs remarkably approximately 92% less number of changes than LORA and 75% less number of changes than the optimal algorithm. In terms of the number of changes, CRORA outperforms RORA by performing approximately 70% less number of changes in assignment between 2 successive states.

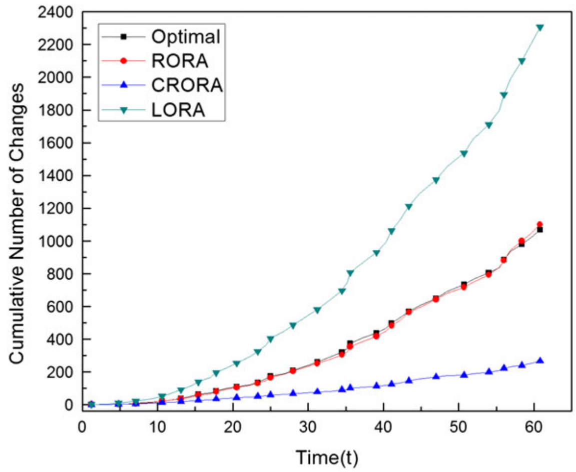


FIGURE 7 Cumulative number of changes in each state of the system for the fair assignment scheme. CRORA, conservatively relax online resource allocation; DARA, deferred acceptance–based algorithm for resource allocation; LORA, local search–based resource allocation; RORA, relax online resource allocation

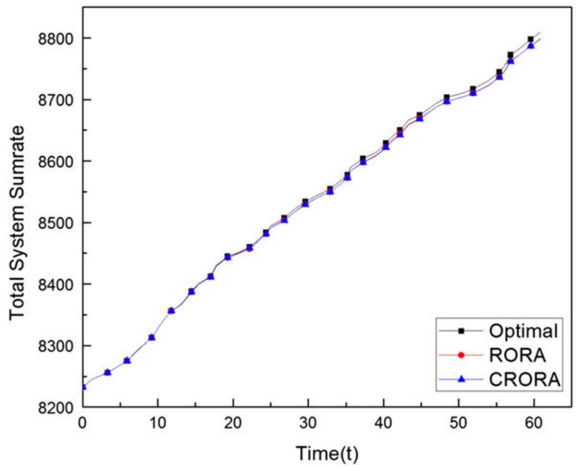


FIGURE 8 Total system sumrate in each state of the system for the restricted assignment scheme. CRORA, conservatively relax online resource allocation; RORA, relax online resource allocation

For the restricted assignment scheme, we compare RORA and CRORA with the optimal Hungarian algorithm only as there is no existing variant of the restricted version. Figure 8 shows the comparison of the algorithms in terms of the total system sumrate where individual line represents the increase of the total system sumrate returned by the algorithms with respect to time. Like the fair assignment scheme in the restricted assignment scheme, RORA and CRORA perform very near to the optimal (Hungarian) algorithm. For better visualization, we present the normalized system sumrate returned by different algorithms in the restricted assignment scheme in Figure 9 where the graph is normalized with respect to the optimal algorithm. From Figure 9, we can easily observe that in the restricted assignment scheme, the performance of RORA and CRORA is almost similar, which is approximately 99.97% of the optimal Hungarian algorithm. Figure 10 represents the comparison of the algorithms in the restricted assignment scheme in terms of the number of changes in assignment between 2 successive states. In the restricted assignment scheme, RORA outperforms the optimal algorithm by performing approximately 20% less number of changes in assignment between 2 successive allocations. On the other hand, CRORA outperforms both RORA and the optimal algorithm where CRORA performs approximately 60% less number of changes than CRORA and approximately 68% less number of changes than the optimal algorithm. We need to mention that in the restricted assignment scheme, presumably some D2D pairs cannot be assigned those provide negative sumrate gain. The number of assigned D2D pairs by the optimal algorithm is 153 of a total of 225 D2D pairs, whereas RORA assigns 150 D2D pairs and CRORA assigns 155 D2D pairs of 225 D2D pairs finally present in the system.

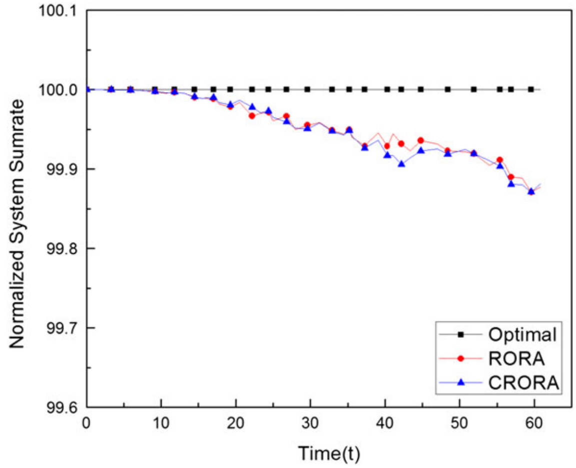


FIGURE 9 Normalized system sumrate in each state of the system for the restricted assignment scheme (normalized with respect to the optimal Hungarian algorithm). CRORA, conservatively relax online resource allocation; RORA, relax online resource allocation

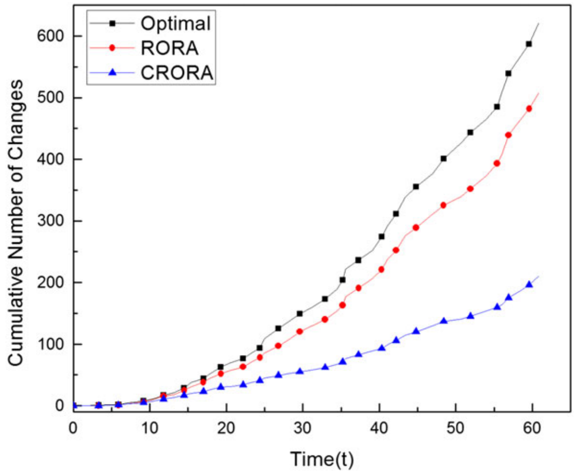


FIGURE 10 Cumulative number of changes in each state of the system for the restricted assignment scheme. CRORA, conservatively relax online resource allocation; RORA, relax online resource allocation

On the basis of all of the simulation results, we can say that in both of the assignment schemes, our proposed algorithms (RORA and CRORA) return a total system sumrate that is very close to the total system sumrate returned by the optimal algorithm. Moreover, in the fair assignment scheme, RORA and CRORA outperform LORA and DARA in terms of total system sumrate. On the other hand, in terms of the number of changes, both RORA and CRORA outperform all of the algorithms in both of the assignment schemes.

7 | CONCLUSION

D2D communication in underlay inband mode is the most beneficial as sharing the radio resources of existing cellular users with the D2D pairs increases the system capacity. This mode of personal communication is attracting more researchers from academia, standardization bodies, and industry for further insight, and a lot more research is still necessary to achieve power and spectral efficiency by developing more efficient resource allocation schemes. This paper addresses the research problem of maximizing the system sumrate by sharing the RBs among the cellular UEs and the D2D pairs while maintaining the QoS. To the best of our knowledge, most of the existing research works in this area deal with offline resource allocation algorithms. The addressed research problem can be solved optimally in polynomial time using the weighted bipartite matching algorithm. However, in LTE and beyond (4G and 5G) systems, scheduling algorithms should be very efficient where the optimal algorithm is quite complex to implement. Hence, a low complexity algorithm that returns almost the optimal solution can be an alternative to this research problem. In this paper, we propose 2 relax online resource allocation algorithms for D2D communication in inband underlay mode. Our proposed algorithms consider 2 assignment schemes, namely, the restricted assignment scheme and the fair assignment scheme. The restricted assignment scheme provides better system sumrate by avoiding the assignments those contribute negative sumrate gain. On the other hand, the fair assignment scheme assigns more D2D pairs than the restricted assignment scheme by sacrificing some system sumrate gain. Network providers may choose any one of the schemes on the basis of their need. We have done extensive simulations to validate our algorithms. Simulation results suggest that our proposed algorithms outperform the existing offline algorithms in terms of both total system sumrate and number of changes in successive allocation. Moreover, our proposed algorithms perform very close to the optimal algorithm in terms of system sumrate with less number of changes in successive allocation. According to the definition of online stable matching algorithm, our current implementation considers the cellular UEs as a fixed set and D2D pairs as an adversary set. However, assuming both of the cellular UEs and the D2D pairs as adversary sets would be an interesting research problem. We plan to investigate this issue in our future work.

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How to cite this article: Hossen MS, Hassan MY, Hussain F, Choudhury S, Alam MM. Relax online resource allocation algorithms for D2D communication. *Int J Commun Syst*. 2018;e3555. https://doi.org/10.1002/dac.3555