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An online resource allocation algorithm to minimize system interference for inband underlay D2D communications

Md Yeakub Hassan[1] | **Faisal Hussain**[2] | **Md Sakhawat Hossen**[2] | **Salimur Choudhury**[3]

[1]Department of Computer Science, University of Manitoba, Winnipeg, Manitoba, Canada

[2]Department of Computer Science and Engineering, Islamic University of Technology, Dhaka, Bangladesh

[3]Department of Computer Science, Lakehead University, Thunder Bay, Ontario, Canada

Correspondence
Salimur Choudhury, Department of Computer Science, Lakehead University, Thunder Bay, Ontario, Canada.
Email: salimur.choudhury@lakeheadu.ca

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Summary

This paper addresses the research question of total system interference minimization while maintaining a target system sum rate gain in an inband underlay device-to-device (D2D) communication. To the best of our knowledge, most of the state of the art research works exploit offline resource allocation algorithms to address the research problem. However, in Long-Term Evolution (LTE) and beyond systems (4G, 5G, or 5G+), offline resource allocation algorithms do not comply with the fast scheduling requirements because of the high data rate demand. In this paper, we propose a bi-phase online resource allocation algorithm to minimize the total system interference for inband underlay D2D communication. Our proposed algorithm assumes D2D pairs as a set of variable elements whereas takes the cellular user equipment (UEs) as a set of constant elements. The novelty of our proposed online resource allocation algorithm is that it incurs a minimum number of changes in radio resource assignment between two successive allocations among the cellular UEs and the D2D pairs. Graphical representation of the simulation results suggests that our proposed algorithm outperforms the existing offline algorithm considering number of changes in successive allocation for a certain percentage of sum rate gain maintaining the total system interference and total system sum rate very similar.

KEYWORDS

cellular UEs, D2D pairs, LTE, online avlgorithm, resource allocation

1 | INTRODUCTION

Device-to-device (D2D) communication has gained enormous popularity as a mean of personal communication over the past decade. As a technology, this mode of communication is invading the enterprise as well as private usage with the popularity of smart hand-held devices. Various inter-device services like file sharing, media content downloading etc are some of the notable sectors where D2D communication can be exploited. D2D communication is primarily implemented in two ways, namely, outband and inband, based on the utilization of spectral resources. Inband D2D communication is implemented in the existing cellular network using underlay or overlay mode. Of these two, inband underlay is convenient and beneficial considering the spectrum utilization and energy efficiency, suggested by a number of surveys.[1-3] In this paper, we focus on the inband underlay D2D communication where two user equipment (UEs) in close proximity interact directly rather than via Evolved Node B (eNodeB or eNB).[4,5] The advantages of using this technique are increased spectral efficiency, increased total system capacity, reduced traffic load of the eNB, and reduced power consumption of the cellular

UEs provided that the appropriate resource blocks (RBs) of a traditional cellular network are reused.[6] Inband undelay D2D communication was introduced with the commencement of fourth generation (4G) or Long-Term Evolution (LTE) and since then, it has been one of the leading technologies in laying the ground works for the fifth generation (5G) and beyond (5G+).[7] The media enriched high data rates of 5G is used in vehicle-to-vehicle (V2V) communication. Apart from the aforementioned advantages of inband underlay D2D communication, it also provides increased bit-rate gain, spectral reuse gain, hop gain, and coverage gain.[8]

To further the utilization of all the aforementioned gains, it is desirable to have an efficient radio resource management scheme. A resource allocation scheme is massively handicapped by the introduced interference due to radio resource sharing among the cellular UEs and the D2D pairs. Moreover, the overall system interference in the existing cellular network rises to a catastrophic level when ill-fitting RBs are selected.[9] Because of this reason, a good number of researchers are developing resource allocation algorithms to minimize the system interference while maintaining the target sum rate and still this field begs further exploration. In this paper, we address this issue.

To the best of our knowledge, all the existing algorithms those portray a solution to the aforementioned problem are offline based algorithms. These offline algorithms can solve the addressed problem near optimally but suffers from long execution time and incompatibility with the fast scheduling period (less than 1 ms) of LTE and beyond. In the studies of Hassan et al,[10,11] interference minimization algorithms of D2D communication are proposed for a fixed set of cellular UEs and D2D pairs where the position of the cellular UEs and D2D pairs are static. These algorithms are referred to offline algorithms for this problem. However, in practical scenario, cellular UEs and D2D pairs have mobility, and they can leave or arrive in the system at any time. In these type events, using the offline algorithms, each time can move assigned resources from one D2D pair to another D2D pair, which is not suitable for LTE and beyond. An alternative approach to finding the solution of the addressed problem can be an online algorithm, which runs on a smaller portion of the input. A few research works[12-14] exploit online algorithm but none of them address the issue of interference minimization, which is addressed in this paper.

In this research article, we present an online resource allocation algorithm for inband underlay D2D communication using the uplink (UL) resources to minimize the total system interference at the time of allocating the RBs. We name our proposed algorithm as interference minimization online resource allocation (IMORA) algorithm that assumes D2D pairs as a set of variable elements whereas takes the cellular UEs as a set of constant elements. In this paper, the arrival, departure, and mobility of any D2D pair are regarded as a system event. When any such system event occurs, IMORA gets triggered, which subsequently changes the state of the existing resource allocation.

The primary contribution of this paper is to design the first ever online algorithm for the addressed research problem, which minimizes the number of changes between two successive allocations of RBs while minimizing the total system interference and maintain a target system sum rate. Simulation results suggest that IMORA outperforms the existing offline algorithm RARA (so far best offline algorithm) in terms of the number of changes in successive allocation, but in terms of interference, its performance is almost similar to that of RARA.

Organization of the remaining paper is described in the following. Section 2 presents some of the related algorithms. The system model and channel model of inband underlay D2D communication are described in Section 3. Section 4 contains the problem formulation as an optimization problem. Section 5 presents an analysis and description of the proposed algorithm. Section 6 presents the numerical analysis and comparison of results of our proposed online algorithm with existing offline algorithm. Finally, we conclude the paper in Section 7.

2 | RELATED WORKS

Researchers are working on different aspects of D2D communication to relish the benefits of this communication technique. There are a number of survey papers,[1-3,15] which lay down the existing solutions of the problem space of D2D communication like the role of D2D communication, outcomes from D2D communication in a cellular network, performance of the network, protocol design issues, selection of mode of transmission, management of interference, resource allocation, etc.

D2D communication can be deployed as outband or inband mode,[1] where devices use the unlicensed band in outband mode and licensed band in inband mode. This paper deals with the inband mode where D2D communication may affect the primary users in respect of power control, interference management, and resource shortage etc as D2D devices and cellular UEs share radio resources in this mode. Overlay mode keeps a dedicated portion of the bandwidth of the primary user for D2D communication while underlay mode allocates the radio resources to each D2D pair, which is also shared by some cellular UE. Inband underlay mode is the most convenient and beneficial D2D communication technique in respect of energy and spectrum utilization point of view.[1-3]

There are few offline algorithms that work on interference minimization problem discussed in the following. Among these, the algorithms discussed in previous studies[10,11,16,17] run on similar problem statements as this paper. A comparison in Table 1 shows the summary of these algorithms. It should be noted that all the compared algorithms reuse the UL RBs.

Islam et al[17] proposes a two-phase auction-based fair resource allocation algorithm (TAFIRA)[17] to minimize the total system interference maintaining a target system throughput. In the first phase, TAFIRA allocates RBs of at least one cellular UE to each D2D pair following greedy mechanism. The greedy mechanism is to allocate resources of the cellular UE to a D2D pair such that the total system interference incurred in the allocation is the minimum. In the second phase, TAFIRA swaps the allocated RBs of each D2D pair with the unallocated cellular UEs in the system trying to improve the system capacity. It should be noted that in some cases, TAFIRA returns solutions, which are not feasible. Moreover, the worst case the performance ratio of TAFIRA is unbounded.[11]

TABLE 1 State of the art algorithms for inband underlay D2D communication for interference minimization

Algorithm	Approach	Flaws	Complexity
MIKIRA[16]	•Knapsack-based approximation algorithm.	•Does not return optimal solution in most cases.[11] •Does not return any solution in some cases though solution exists.[10]	$O(n^2 log(n))$, n is the number of total cellular UEs
TAFIRA[17]	•Two-phase auction-based algorithm.	•Performance is unbounded in the worst case.[11]	$O(m^2 n)$, m is the number of total D2D pairs and n is the number of total cellular UEs
	•TAFIRA guarantees fairness of resource allocation as it allocates every D2D pair cellular resource irrespective of channel condition.	•Does not return any solution in some cases though solution exists.[11]	
	•Two phase algorithm-Assignment Phase and Improvement Phase.	•Some D2D pairs are deprived from communication as they decrease system sum rate if share RBs of any cellular UE of the system.	$O(max(n^3, n * m * W))$, n is the number of total cellular UEs, m is the number of D2D pairs, W is the amount of interference generated from the assignment of Phase-I
	•If first phase succeeded, then optimal solution is returned.	•If first phase failed, then the returned solution in second phase may not be an optimal one.	
RARA[11]	•If first phase failed, then improvement phase comes to play with a feasible solution. •Ensure solution if exists in the assignment phase. This method returns the solution with highest system sum rate.		
	•Interference weight matrix and sum rate weight matrix are calculated differently than RARA to allow all D2D pairs to share some RBs.	•If first phase failed then a near optimal solution is returned in second phase.	$O(max(n^3, n * m * W))$, n is the number of total cellular UEs, m is the number of D2D pairs, W is the amount of interference generated from the assignment of Phase-I
FARA[10]	•Similar to RARA on other aspects.		

Abbreviations: D2D, device-to-device. RARA, restricted assignment resource allocation; RBs, resource blocks; TAFIRA, two-phase auction-based fair resource allocation algorithm; UE, user equipment.

Authors in the study of Islam et al[16] propose an interference-aware algorithm named MIKIRA, to solve the similar resource allocation problem. MIKIRA uses a knapsack-based approximation algorithm. It is noteworthy that, as soon as the demand of target sum rate is satisfied, MIKIRA stops allocating RBs to D2D pairs. It implies that the algorithm is not fair as some D2D pairs are not getting any resources to communicate. Moreover, the algorithm does not give the feasible solution in most cases.[11]

Hassan et al[11] propose a two-phase resource allocation algorithm for similar problem. Phase I finds candidate matching by using a bipartite matching algorithm in such a way that the generated interference is at the minimum. This phase also avoids those assignments, which can lower the total system capacity. Because of the use of the optimum assignment algorithm, the solution of the first phase will return the optimum allocation if succeeded. If the first phase failed, that is, if the target sum rate is not attained by the allocation of the first phase, then the second phase comes to play. The second phase starts with the maximum sum rate possible to check whether the target sum rate can be attained or not. After that, it will use a local search method to improve the solution, ie, reduce the interference by swapping the allocation. This two-phase algorithm ensures solution if exist and returns the optimum solution or very near to the optimum solution. Very recently, it has been proved that this minimization problem can be solved in a polynomial time for uniform interference (a special case).[18]

Authors in the study of Hassan et al[10] proposed two types resource allocation method. They termed them as fair and restricted assignment. The proposed algorithms for both variations are of two phase with the aim to minimize the interference maintaining a target system sum rate. In fair assignment scheme, all of the D2D pairs get the opportunity to be coupled with any of the cellular UEs. On the contrary, in the restricted assignment scheme, some of the D2D pairs are restricted to be coupled with any of the cellular UEs whenever their sharing lower the total system capacity.

It should be mentioned that, so far as we know, no online algorithm is available to solve the addressed research problem. Although there is one online algorithm[12] that handles a different research problem, ie, maximize the total system sum rate maintaining QoS constraint, two less complex stable matching based relax online algorithms are proposed in Hossen et al,[12] and those exhibit very close to the optimal solution. The system model of this work considers the cellular UEs as a set of constant elements and D2D pairs as a set of variable elements. Whenever there is an improvement of the objective function, this algorithm revokes the assignments with an aim of minimizing the number of revocations.

There are more notable research works on D2D communication underlaying cellular network. Authors in the previous studies[19-22] work on the resource allocation algorithm, which works for the maximization of the system capacity. They use DL resource so that they can put more emphasis on system capacity rather on the total system interference. Because for DL resource, eNB has more flexibility to increase the signal strength to nullify the effect of interference produced by the D2D pairs.

Several kinds of research are progressing on the various problem in the field of D2D communication discussed in the following. Sun et al[23] propose relay-aided D2D communication in where direct communication is unfavorable between D2D peers, enhancing both the reliability and flexibility of D2D communications. They consider the power control of the devices and interference constraints while designing the resource allocation protocol. Wu et al[24] study the D2D communication to support the V2V communications. They propose a novel location-partition-based RA scheme satisfying the requirement that the interference generated by all V2V links to the reused cellular user (CU) is below a certain threshold. Three types of power control methods are adopted in this paper to maximize the minimum achievable rate of the V2V links. Takshi et al[25] propose a genetic algorithm-based mechanism to minimize the interference and maximize the spectral efficiency. They argue that their method considers interference mitigation and minimum SINR constraint for all cellular UEs and can escape from local maximums and evolves towards the global maximum. A two-stage coalition formation and resource allocation scheme is proposed in Zhao et al.[26] Stage 1 follows the Bron-Kerbosch algorithm, and stage 2 depends on the total number of RBs requested by D2D pairs to form the coalition. Furthermore, the Nash bargaining solution (NBS) is used to allocate RBs to D2D pairs in that stage 2 coalition. Hu et al[27] propose an overlapping coalition formation game to conduct joint interference management and resource allocation in D2D communications to maximize the system utility.

3 | SYSTEM MODEL AND CHANNEL MODEL

We examine a system model consisting of one eNB, a number of D2D pairs, and a number of cellular UEs. Generally, the number of the D2D pairs is lower than the number of the cellular UEs.[20,21,28] Accordingly, we consider a system with n cellular UEs and m D2D pairs where a D2D pair reuses the RBs of a cellular UE.

In this paper, the set of cellular UEs is denoted as $C = \{c_1, c_2, c_3, \dots, c_n\}$, whereas the set of D2D pairs is denoted as $D = \{d_1, d_2, d_3, \dots, d_m\}$. Any D2D pair $d_j \in D$ consists of a transmitting device d_j^t and a receiving device d_j^r. Though the D2D pairs interact directly, the eNB handles the resource allocation.[21]

LTE network consists of two types of radio resources, namely, UL and downlink (DL). This paper only considers the UL resources following the works of the previous studies.[10,11,16,17] The cellular UEs transmit a signal to the eNB using UL resources, so interference from shared D2D transmitters affects eNB. Therefore, if the interference from the shared D2D transmitter is not limited, then the cellular UE needs to transmit with a greater signal strength which will cost the cellular devices battery power. So its very important to reduce the generated interference by the underlaying D2D communication while sharing UL resources. On the other hand, the D2D communication will face the interference from the shared cellular UEs.

This paper follows Urban Micro System, which comply with Rayleigh fading path loss model.[20,21,28] The equation of path loss (dB unit) can be presented as follows:

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

where the distance between a receiver and a D2D transmitter is represented by d. The medium frequency is represented as f_c (GHz). The channel gain between these two devices can be represented as follows:

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

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

The state of the system in this paper is determined based on the total number of D2D pairs and cellular UEs and their relative locations present in the system at any instant of time. Any occurrence of the system events triggers a change in the state of the system. Whenever there is any change in the state of the system, the system needs to reconsider the resource allocation of the D2D pairs. The events are described in the following with the help of Figure 1. The initial state of the system is indicated by Figure 1A where three D2D pairs and four cellular UEs are present. After each event, the state of the system changes.

- Arrival event: The arrival event occurs when one or more D2D pairs enter into the system at any instance of time. After this event, RBs need to be allocated to these new D2D pairs. This event is shown in Figure 1C where a new D2D pair D_4 enters into the system. Arrival event is indicated by $E_{arrival}$ in the rest of the paper.
- Departure event: The departure event occurs when one or more D2D pairs depart from the system at any instance of time. After this event, RBs allocated to those D2D pairs are free and available to be used for further allocation. This event is shown in Figure 1D where the D2D pair D_1 leaves from the system. Departure event is indicated by $E_{departure}$ in the rest of the paper.
- Mobility event: The mobility event occurs when one or more D2D pairs change their position in the system at any moment. This event is shown in Figure 1B where the D2D pair D_3 changes its position in the system. Mobility event is indicated by $E_{mobility}$ in the rest of the paper. To generalize and simplify the algorithm, the mobility event is considered as the combination of departure from the previous position then arrival to the new position in the system.

4 | PROBLEM FORMULATION

This section presents the formulation of the resource allocation problem that is addressed in this paper. We need to design a resource allocation algorithm, which assigns each D2D pair d with the RBs of a cellular UE c to reuse. It should be noted that our problem formulation does not change the allocation of RBs of the cellular UEs in the cellular network rather the RBs of cellular UEs are assigned to D2D pairs. The goal of this paper is to find a set of assignments, which returns the minimum interference, provided that a target system sum rate will be maintained. It is noteworthy that this paper deals with the online version where the algorithm changes assignment minimally to fit any small change(leaving, incoming, or location changes of D2D pairs) in the system.

Necessary equations for the addressed research questions are defined and explained in the following. Let the signal power be P_c and P_{d^t}, respectively, for any cellular UE c and D2D transmitter d^t. The thermal noise at the receiver is denoted by σ, which is also known as energy of Additive White Gaussian Noise (AWGN). Thus, the SINR at enodeB BS, given that the D2D pair transmitter d^t is sharing the RBs of the cellular UE c, is as follows:

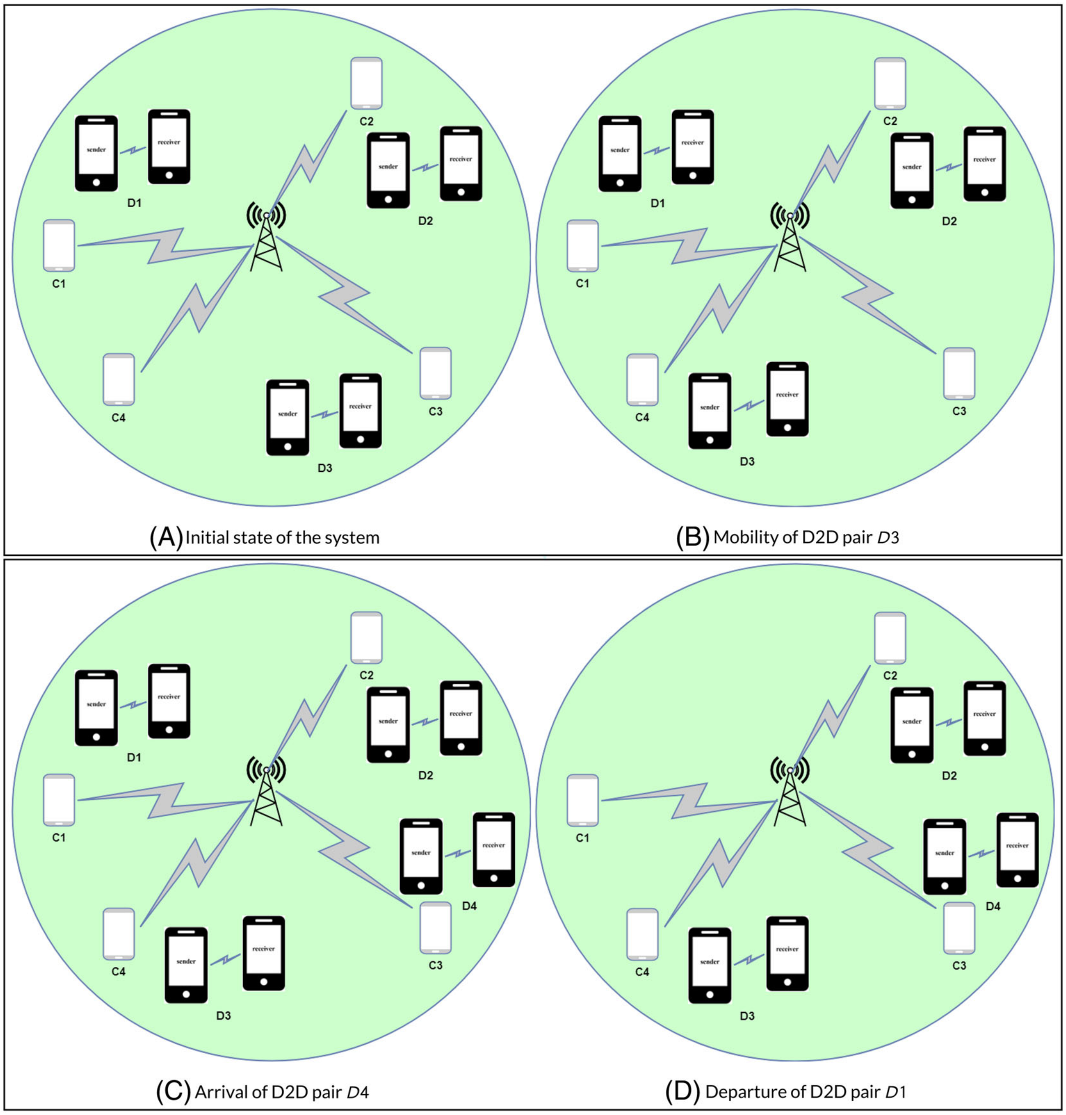


FIGURE 1 Different consecutive scenarios of the system

$$\gamma_c = \frac{P_c G_{c,BS}}{\sigma^2 + P_{d^t} G_{d^t,BS}}, \tag{3}$$

where $G_{c,BS}$ implies the channel gain between cellular UE c and enodeB BS, and $G_{d^t,BS}$ is the channel gain between the D2D transmitter d^t and the enodeB BS. It should be noted that in this paper, it is considered that only one D2D pair can share the RBs of one cellular UE. Therefore, in the denominator of Equation 3, only one D2D transmitter d^t is present, which introduces the interference to cellular UE c. If no D2D pair is assigned to share the RBs of the cellular UE c, Equation 3 changes into the following:

$$\gamma_{c_0} = \frac{P_c G_{c,BS}}{\sigma^2}. \tag{4}$$

Similarly, the SINR at D2D receiver d^r provided that D2D pair d is sharing the RBs of cellular UE c is as follows:

$$\gamma_d = \frac{P_{d^t} G_{d^t,d^r}}{\sigma^2 + P_c G_{c,d^r}}, \tag{5}$$

where G_{d^t,d^r} implies the channel gain between the D2D transmitter d^t and the D2D receiver d^r, and G_{c,d^r} is the channel gain between the cellular UE c and the D2D receiver d^r. In this paper, it is considered that one D2D pair is sharing RBs of one cellular UE. Therefore, one cellular UE c is present in the denominator of Equation 5. However, the interference generated in the system when a cellular UE c and D2D pair d is sharing RBs is as follows:

$$I_{c,d} = P_{d^t} G_{d^t,BS} + P_c G_{c,d^r}. \tag{6}$$

This intra-channel interference is an important factor, as this interference changes drastically based on the assignment. Following Shannon's capacity model system capacity contributed when a D2D pair d is sharing, the RBs of a cellular UE c can be expressed as follows:

$$R_{c,d} = B \log_2(1 + \gamma_c) + B \log_2(1 + \gamma_d), \tag{7}$$

where the bandwidth of the channel used is represented by B. The SINR at the enodeB while receiving signals from the cellular UE c is denoted by γ_c whereas γ_{d^r} represents the SINR at the D2D receiver d^r while receiving signals from the D2D transmitter d^t, provided the D2D pair d is assigned to share the same cellular UE c.If no D2D pair is assigned to share the RBs of the cellular UE c, then the sum rate contribution is as follows:

$$R_{c,0} = B \log_2(1 + \gamma_{c,0}). \tag{8}$$

Therefore, the total system capacity or system sum rate is as follows:

$$S = \sum_{c}^{C} \left(1 - \sum_{d}^{D} x_{c,d}\right) R_{c,0} N_c + \sum_{c}^{C} \sum_{d}^{D} x_{c,d} R_{c,d} N_c, \tag{9}$$

here, N_c is the number of RBs allocated to cellular UE c. $x_{c,d}$ is the binary variable with the value one indicate that cellular UE c and D2D pair d is sharing RBs. In opposition, $x_{c,d}$ with the value zero indicate that cellular UE c and D2D pair d is not sharing RBs. C is the set of all cellular UEs and D is the set of all D2D pairs in the system. The first term of Equation 9 deals with the sum rate contribution of cellular UEs, which does not share RBs with any D2D pair whereas the last part deals with the sum rate contribution all cellular UEs which share RBs with some D2D pair. The target system sum rate is designed as follows:

$$T = (1 + \alpha) \sum_{c}^{C} R_{c,0}, \tag{10}$$

where the value of α is non-negative. $R_{c,0}$ is the sum rate contribution of cellular UE c provided that no D2D pair is sharing RBs of d. This constraint ensures that the target system sum rate must be equal or above the system sum rate of traditional* system sum rate.

Now, the objective function can be formulated as follows:

$$\text{minimize} \sum_{c}^{C} \sum_{d}^{D} x_{c,d} I_{c,d} \tag{11}$$

subject to,

$$S \geqslant (1 + \alpha) \sum_{c}^{C} R_{c,0} \tag{12}$$

$$R_{c,d} \geqslant R_{c,0}; \quad \forall\, c \in C \text{ and } \forall\, d \in D \tag{13}$$

$$\sum_{d}^{D} x_{c,d} \leqslant 1\,; \quad \forall\, c \in C \tag{14}$$

$$\sum_{c}^{C} x_{c,d} \leqslant 1\,; \quad \forall\, d \in D \tag{15}$$

$$x_{c,d} \in \{0, 1\}\,; \quad \forall\, c \in C \text{ and } \forall\, d \in D. \tag{16}$$

*In the traditional network, no D2D pair reusing the RBs of existing cellular UE, is present.

The objective of this research work is to minimize the interference in the system (Equation 11). Constraint (4) implies that the solution should maintain a given target system sum rate. Constraint (13) implies that the sum rate contribution of any cellular UE c and d, sharing the same RBs needs to be greater or equal to that of the cellular UE c alone (with no D2D pair sharing the RBs of the cellular UE c). Constraint (14) implies that at most one D2D pair can be assigned to share the RBs of each cellular UE. On the other hand, Constraint (15) implies that each D2D pair can be assigned to share the RBs of at most one cellular UE. Constraint (16) implies that $x_{c,d}$ is a binary variable that may have the value 0 or 1.

5 | PROPOSED ALGORITHM

We propose an IMORA algorithm for UL D2D communication. In online resource allocation algorithm, we start with running the algorithm for an entire system. Then, whenever an event (D2D pair arrival, D2D pair departure, mobility of D2D pairs) occurs towards the system, our algorithm only deals with the changes happened due to that event rather than running the algorithm for the entire system. Therefore, our algorithm produces significantly less number of changes (revocations) in the system. In this paper, we use restricted assignment resource allocation (RARA) algorithm[10] for the initial state of the system. Afterwards, the occurrence of the events triggers our algorithm to provide a new assignment for the new state of the system. In case of arrival of a D2D pair, we use weighted bipartite matching and local search approaches to find an assignment for new arrived D2D pairs. In case of the departure of a D2D pair, we use a greedy assignment approach to assign a D2D pair with the cellular UE left by that D2D pair. We define the mobility event of a D2D pair as a combination of arrival and departure event. Even though RARA is an offline algorithm, we use it to obtain the system's initial state. Since RARA is the best offline algorithm for this problem, running it initially provides optimal result for the initial configuration. Moreover, The execution of this offline algorithm occurs only to achieve the initial state. Nevertheless, a service provider may choose any existing offline algorithm for the initial configuration.

In algorithm 1, an online resource allocation algorithm is proposed where the objective is to minimize the system interference while maintaining a target system sum rate. The main goal of this algorithm is to allocate RBs to D2D pairs based on three system events, namely, arrival event, departure event, and mobility event. The algorithm initially runs *InitialAssignment* (algorithm 2) to assign RBs of cellular UEs to all D2D pairs satisfying Equations 4 and 13 at the initial state of the system. The occurrence of any of the events allows our algorithm to allocate RBs to free D2D pairs with the minimum number of changes in the system (lines 5 to 13 of algorithm 1). A brief discussion of algorithm 2 is presented in the following subsection.

Algorithm 1 Interference Minimization Online Resource Allocation (IMORA)

1: **procedure** IMORA($C(c_1, c_2, \ldots, c_n)$, $D(d_1, d_2, \ldots, d_m)$, α) ▹ An allocation from C to D, α is sum rate improvement percentage. Initially no D2D pair is assigned with any Cellular UEs
2: Calculate target system sum rate T for α using (equation)
3: Let $S[n][n]$, $I[n][n]$ be two weight matrices ▹ $S_{i,j}$, $I_{i,j}$ is the sum rate and interference respectively when d_j shares RBs of c_i
4: InitialAssignment(C, D, T)
5: **while** $TRUE$ **do**
6: Calculate target system sum rate T for α using (equation)
7: **if** $E_{arrival}$ **then**
8: Arrival(C, D, T)
9: **else if** $E_{departure}$ **then**
10: Departure(C, D, T)
11: **else if** $E_{mobility}$ **then** ▹ The mobility of D2D pairs are initially considered as their departure from the system and later, arrival to the system in a new location
12: Departure(C, D, T)
13: Arrival(C, D, T)

5.1 | Initial assignment

We use a weighted bipartite matching approach in algorithm 2 for the initial assignment of the D2D pairs to cellular UEs. We construct a bipartite graph of two disjoint set, ie, a set of cellular UEs C and a set of D2D pairs D.[27] An edge between c_i and d_j represents the interference and sum rate because of the sharing of RBs between c_i and d_j. In line 2 of

Algorithm 2 Initial Assignment

1: **procedure** INITIALASSIGNMENT($C(c_1, c_2, \ldots, c_n), D(d_1, d_2, \ldots, d_m), T$) ▹ An allocation from C to D, T is the target system sum rate
2: Calculate interference weight matrix IN
3: **if** HUNGARIANMIN(IN) $\geqslant T$ **then**
4: Allocate RBs of c_i to d_j based on HungarianMin assignment
5: **Return Current Allocation.**
6: **else**
7: Calculate sum rate weight matrix SM
8: **if** $T >$ HUNGARIANMAX(SM) **then**
9: **Allocation satisfying T is not possible.**
10: **else**
11: Allocate RBs of c_i to d_j using HUNGARIANMAX(SM)
12: Go to **LOCALSEARCH**(C, D, T)

Algorithm 3 Local Search

1: **procedure** LOCALSEARCH($C(c_1, c_2, \ldots, c_n), D(d_1, d_2, \ldots, d_m), T$) ▹ An allocation from C to D, T is the target system sum rate
2: **while** $improvement$ **do**
3: **for** each pair $(c_i, c_j) \in C$ where $i \neq j$ **do**
4: d_i, d_j are D2D pairs assigned with c_i and c_j respectively
5: $K = \{(c_i d_i, c_j d_j), (c_i d_j, c_j d_i), (c_i d_\phi, c_j d_i), (c_i d_j, c_j d_\phi), (c_i d_i, c_j d_\phi), (c_i d_\phi, c_j d_j), (c_i d_\phi, c_j d_\phi)\}$
6: Select an element from K for (c_i, d_i) and (c_j, d_j) which gives lowest interference and minimize the current total interference by maintaining (equation)
7: **if** such element found **then**
8: Allocate RBs accordingly and update system interference
9: **Return Current Allocation.**

Algorithm 4 Arrival Action

1: **procedure** ARRIVAL($C(c_1, c_2, \ldots, c_n), D(d_1, d_2, \ldots, d_m), T$)
2: Newly arrived and unassigned D2D pairs D' , and unassigned cellular UEs C' are initialized as free.
3: Calculate current system sum rate Z
4: Calculate sum rate weight matrix SM considering C' and D'
5: **if** HUNGARIANMAX(S) $+ Z \geqslant T$ **then**
6: Assign RBs of D' to C' using HungarianMax assignment
7: Go to **LOCALSEARCH**(C, D, T)
8: **else**
9: Allocation satisfying T is not possible. All free D2D pairs and free cellular UEs remain unassigned.

Algorithm 5 Departure Action

1: **procedure** DEPARTURE($C(c_1, c_2, \ldots, c_n), D(d_1, d_2, \ldots, d_m), T$)
2: Let cellular UEs C' became free for departure of D2D pairs
3: **for** each $c \in C'$ **do**
4: find a D2D pair d from free D2D pairs that produces minimum interference with c as well as satisfies (equation). If no such D2D pair found, then c remains unassigned

algorithm 2, we calculate interference weight matrix IN for the initial cellular UEs and D2D pairs. Here, IN is a $n \times n$ matrix, and $IN_{i,j}$ is the interference when a D2D pair d_j shares RBs of a cellular UE c_i. We use Hungarian minimization algorithm[29] to calculate the minimum system interference generated by sharing RBs among the initial set of cellular UEs and D2D pairs. Hungarian algorithm is an optimization algorithm that uses primal-dual method to solve the assignment problem.[30] The algorithm solves both maximization and minimization version of the assignment problem. The assignment problem can be formulated as a matrix or a bipartite graph. In our algorithm, we use the matrix representation to solve the problem. As we are following restricted assignment, for some cellular UEs and D2D pairs if the Equation 13 is not satisfied, we put interference weight infinity (∞) to those edges in order to avoid these type of sharing. In line 3 of algorithm 2, if Hungarian minimization produces more or equal system sum rate than our target system sum rate T, then we allocate RBs of cellular UEs to D2D pairs based on Hungarian minimization assignment and keep it as our initial assignment. However, if Hungarian minimization produces lower system sum rate than our target sum rate T, then we use the Hungarian sum rate maximization approach[31] to find an initial solution. Here, we use a sum rate weight matrix SM (similar to IN) where

$SM_{i,j}$ is the sum rate when D2D pair d_j shares RBs of a cellular UE c_i. In sum rate matrix, in order to ensure restricted assignment, we put the weight using Equation 8 to those cellular UEs and D2D pairs who do not satisfy Equation 13. If Hungarian sum rate maximization satisfies target sum rate constraint (line 8), we assign RBs of cellular UEs to D2D pairs based on Hungarian maximization assignment. After that, we use local search technique (algorithm 3) that takes this initial feasible solution of Hungarian sum rate maximization and tries to minimize the total interference iteratively until it reaches the local optima. The details explanation of algorithm 3 can be found in the study of Hu et al.[27] However, if Hungarian sum rate maximization fails to satisfy the target sum rate constraint, then all the D2D pairs and cellular UEs remain unassigned. In such case, we confirm that no allocation satisfying target sum rate constraint is possible as the Hungarian algorithm provides us the optimal result based on our constraints.

5.2 | Arrival of a D2D pair

After completing the initial assignment, our online algorithm waits for any of the events to be triggered and performs required actions to give the system a newly feasible sate. Our goal is to accommodate the change to the system due to the occurrence of the events in such a way that the total number of the change in the system gets fewer. In case of arrival event, we use the Hungarian sum rate maximization and local search approach to allocate RBs to newly arrived D2D pairs. Whenever a D2D pairs arrives in our system, we first formulate a set of newly arrived and unassigned D2D pairs D', and a set of unassigned cellular UEs C' (line 2 in algorithm 4). Then, we calculate a sum rate weight matrix SM for D' and C' and apply Hungarian sum rate maximization approach to SM in order to find the assignment for D' and C'. If the addition of system sum rate from Hungarian maximization approach and current system sum rate satisfies the target sum rate constraint, then we allocate RBs of cellular UEs C' to D2D pairs D' according to the Hungarian maximization result. Finally, we apply a local search approach to the whole system to minimize the total interference iteratively. It is clearly observed that in the arrival event, we apply the Hungarian algorithm to a small number of cellular UEs and D2D pairs, which significantly reduces the computational complexity of the system. Furthermore, we do not change any of the previous assignments until local search algorithm finds a better solution in order to minimize the system interference. Therefore, the total number of changes due to the revocation is significantly reduced in our algorithm.

We can derive the following lemma from the arrival action of our proposed algorithm.

Lemma 1. *Our algorithm always finds a free cellular UEs for newly arrived D2D pairs if they exist and satisfies the target sum rate constraint.*

Lemma 2. *In our local search approach, total system sum rate never gets increased.*

5.3 | Departure of a D2D pair

In algorithm 5, we propose a greedy approach to accommodate the change to the system due to the departure of a D2D pair. Whenever a D2D pair leaves our system, it releases a cellular UE, and the cellular UE becomes unassigned. In line 2 of algorithm 5, we formulate a set of unassigned cellular UEs C' due to departure event of D2D pairs. Then, for an unassigned cellular UE, we find a D2D pair from all unassigned D2D pairs, which generates minimum interference while satisfying Equation 13 and allocate RBs of that cellular UE to the D2D pair. However, if no such D2D pair is found for an unassigned cellular UE, that cellular UE remains unassigned in the system. In average cases, our algorithms apply the greedy approach to a small number of cellular UEs as it runs only for unassigned cellular UEs. Therefore, the computational complexity becomes reduced. Moreover, the total number of changes due to the departure event does not affect the system as we are not allowing any revocation for this event.

5.4 | Mobility event

The mobility of a D2D pair occurs when a D2D pair changes its geographic position from one place to another. We define such type of event as a combination of arrival and departure event in algorithm 1. When a D2D pair moves from its initial place, we consider that the D2D pair leaves the system from that position. Therefore, we apply the actions of departure event to the system. When the D2D pair finishes its movement to a new location, we consider that the D2D pair arrives in our system on that location. Then, we apply the actions of arrival event to the system for that D2D pair.

5.5 | Complexity analysis

Initial assignment (algorithm 2) of our online algorithm is dominated by Hungarian algorithm, which has the running time of $O(n^3)$ with n being the number of cellular UEs for our system.[29] The running time of our local search approach is $O(n * m * W)$ where n is the number of cellular UEs, m is the number of D2D pairs, and W is the total interference returned[27] by algorithm 2. However, the overall running time of algorithm 2 is $O(max(n^3, n * m * W))$ as in the worst case, the total interference can get reduced to 0 at the end of the local search approach. Nevertheless, our local search approach can produce an $(1 - \frac{1}{\epsilon})$ approximation solution in time that is polynomial in input size and $(1 - \frac{1}{\epsilon})$. [32] Furthermore, the running time of arrival action (algorithm 4) is $O(max(p^3, n * m * W))$ where p is the number of unassigned cellular UEs in the system. In the departure action (algorithm 5) of our algorithm, we use a greedy approach where we only deal with the unassigned cellular UEs and the unassigned D2D pairs. Hence, the running time of the departure action is $O(p * q)$ where p and q are the unassigned cellular UEs and the unassigned D2D pairs, respectively. However, our proposed algorithm is an online algorithm. It works on the changes of system with an aim to change less amount of RBs. As it works on less amount of input in each iteration, it would perform better than any offline algorithm. Our results also show that although it is online algorithm, the total system sum rate or total system interference is not worsen drastically compared with the online algorithm.

6 | NUMERICAL ANALYSIS

6.1 | Simulation environment

In our simulation, we consider a single cell network with a number of cellular UEs. There are devices in the system, which undergoes D2D communication. The distance between the D2D transmitter and receiver is not more[33] than 15 m. Because a larger distance does not satisfy the benefits that can be offered by D2D communication, the cell radius is 1000 m as the standard radius of a macro cell is 1000 m. The α value, which regulates the value of the target system sum rate greater than 0. This value will be set by the network operator. It is noteworthy that, the value of α should not make the target system sum rate greater than the optimal system sum rate. We follow simulation parameters as in Hassan et al and Zulhasnine et al[11,28] (Table 2). We use NS3 (network simulator),[34] which supports D2D communication underlaying the LTE system for all our simulations. Each result presented in this paper is the average of 20 different runs for a particular scenario.

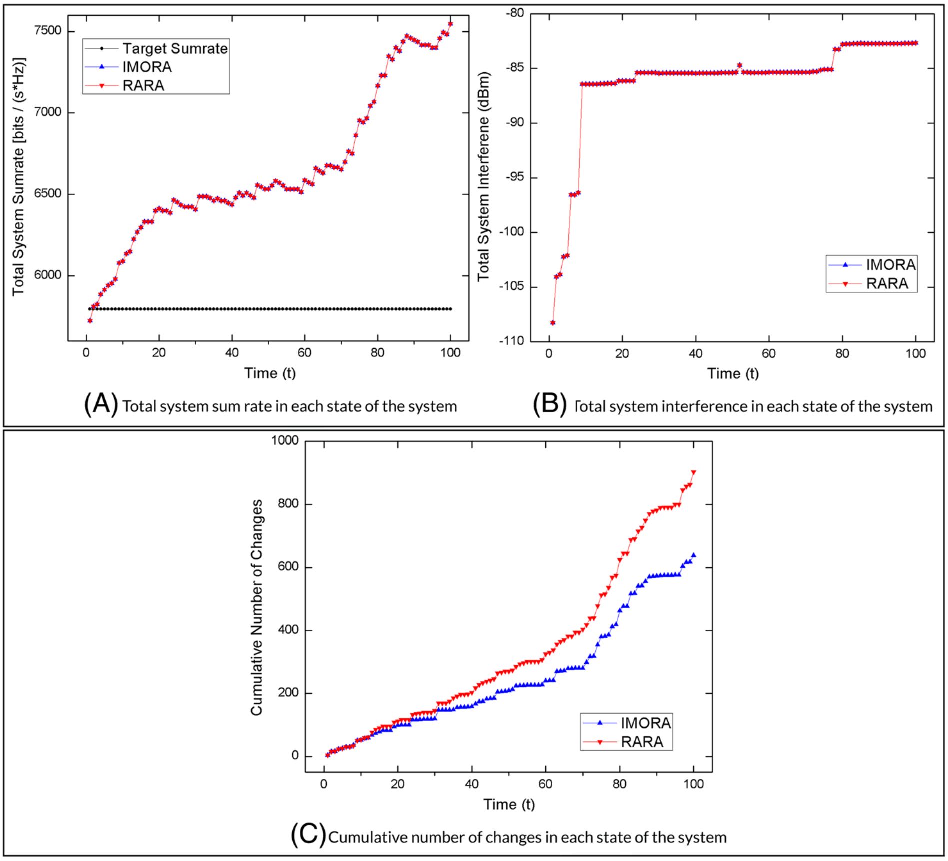
6.2 | Result comparison

We compare our proposed algorithm (IMORA) with existing offline RARA[10] algorithm. It is noteworthy that, RARA algorithm outperforms other resource allocation algorithms in the interference minimization problem. Thus, comparing our proposed algorithm with RARA algorithm is sufficient for the performance analysis of our proposed online algorithm. We compare both the algorithms with respect to the total system sum rate, total system interference, and the number of changes in assignment between two successive allocations. The total number of changes of the system at a time t is, the number of cellular UEs those were assigned with D2D pairs at $t - 1$ time and changed their assignment with a different D2D pair at t time. We run the simulations for different values of α to observe the existence of a solution for a different

TABLE 2 Simulation parameters

Parameter	Value
Cell radius	1000 m
Cellular users	300
D2D pairs	10 to 250 (increments of 10)
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
Bandwidth, B	180 kHz[28]
α	Greater or equal to 0, such that resulting target sum rate does not cross optimal achievable sum rate[31]

Abbreviations: AWGN, Additive White Gaussian Noise; D2D, device-to-device. LTE, Long-Term Evolution.



(A) Total system sum rate in each state of the system (B) Total system interference in each state of the system

(C) Cumulative number of changes in each state of the system

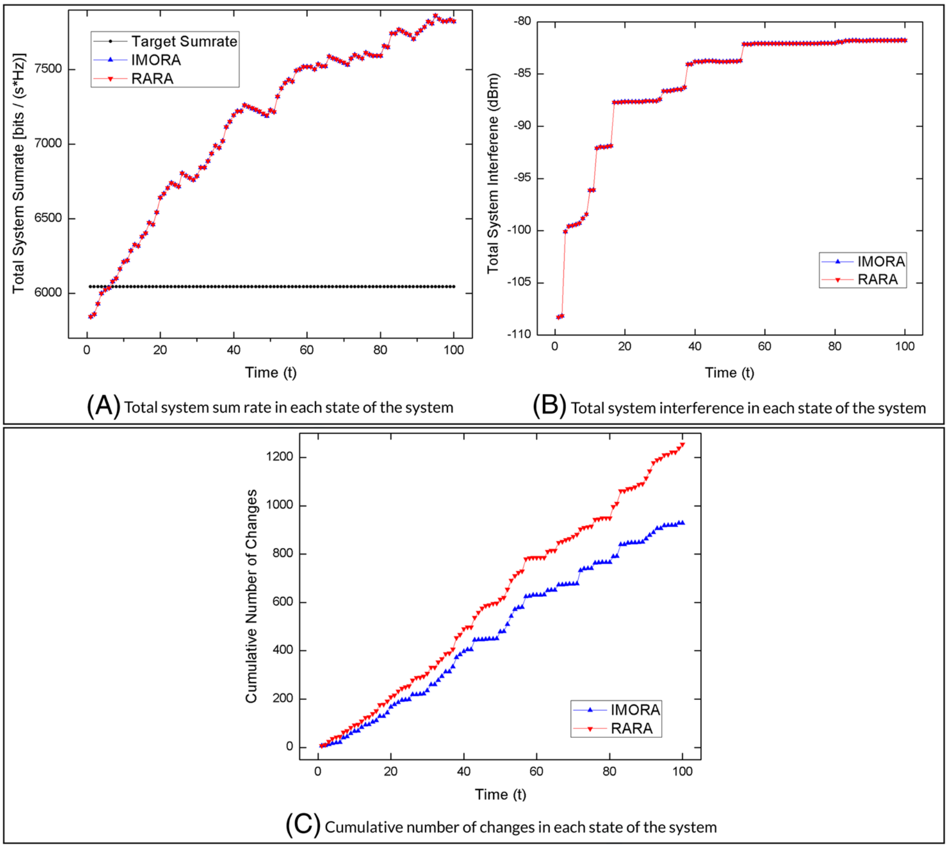
FIGURE 2 Result comparison between interference minimization online resource allocation (IMORA) and restricted assignment resource allocation (RARA) for 2% sum rate improvement with 300 cellular user equipment (UEs). The experiment starts with 1 device-to-device (D2D) pair and ends with 179 D2D pairs

number of cellular UEs as the target sum rate is only depended on the number of cellular UEs. We start all the simulations with 300 cellular UEs and a single D2D pair. Depending on the execution of different events, the number of D2D pairs in the system varies over time, but the number of cellular UEs is fixed.

In order to model the arrival, departure and mobility event, we use the Markov Modulated Poisson Process (MMPP).[35] We determine the event rate λ_r by Markov chain[36] where r is the phase of the Markov chain and the total number of states is S (ie, $r = 1, 2, \ldots, S$). Since we are using two states (λ_1 for state 1, λ_2 for state 2) of the Markov chain working in a discrete time, our arrival departure and mobility events are modeled using discrete time MMPP(dMMPP).

Figure 2 represents the comparison between IMORA and RARA algorithm with respect to total system sum rate, total system interference, and the total number of changes for 2% target sum rate improvement. In Figure 2A,B, it is shown that IMORA and RARA algorithms maintain almost similar system sum rate throughout the simulation. In discrete time event, the cumulative number of changes for RARA and IMORA algorithms are presented in Figure 2C. IMORA algorithm executes around 39% less number of changes than RARA algorithm.

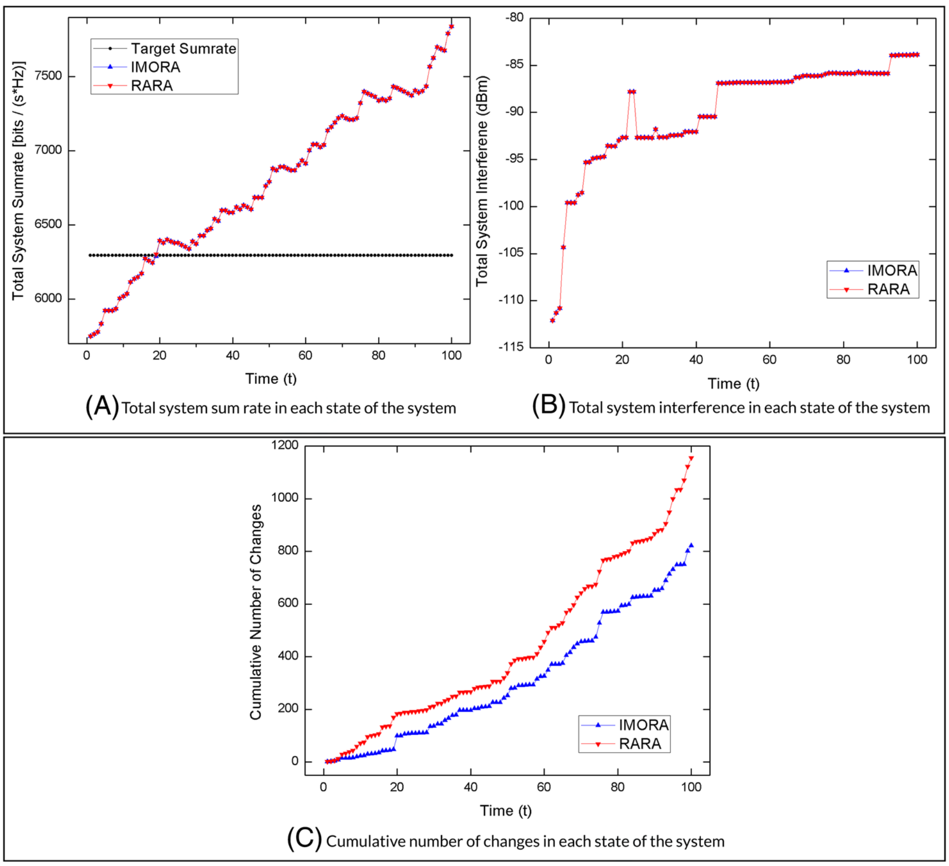
Figures 3 and 4 also represent the comparison between IMORA and RARA algorithm for 5% and 10% target sum rate improvement, respectively. It is clearly observed that, for a large value of α, both the algorithms fail to achieve the target sum rate at initial stages due to the small number D2D pairs in the system. Figures 2A, 3A, and 4A show that, in case of sum rate, both the results of RARA and IMORA algorithm are very close that they overlap. It is also visible from the graph that, it takes some time to achieve the system sum rate goal. The reason is that at the very beginning, the number of D2D pairs is very low, which is not enough to surpass the target system sum rate. As the number of D2D pair increases over time, both the algorithms achieve the target sum rate after a period of time. However, the system sum rate also gets decreased due to the occurrence of the departure event. Figures 2B, 3B, and 4B confirm that the interference produced by IMORA algorithm is very close to that of RARA algorithm. In the literature, RARA algorithm produces less interference than other state of the art resource allocation algorithms for the same research problem.[27] Therefore, in terms of interference, our algorithm performs the same as RARA algorithm and better than other resource allocation algorithms. Moreover, Figures 2C, 3C, and 4C are the important evidence that IMORA algorithm needs less changes than the RARA algorithm. In Figures 3C and 4C, our proposed algorithm performs approximately 31% and 32% less number of changes than RARA algorithm, respectively.



(A) Total system sum rate in each state of the system (B) Total system interference in each state of the system

(C) Cumulative number of changes in each state of the system

FIGURE 3 Result comparison between interference minimization online resource allocation (IMORA) and restricted assignment resource allocation (RARA) for 5% sum rate improvement with 300 cellular user equipment (UEs). The experiment starts with 1 device-to-device (D2D) pair and ends with 213 D2D pairs



(A) Total system sum rate in each state of the system (B) Total system interference in each state of the system

(C) Cumulative number of changes in each state of the system

FIGURE 4 Result comparison between interference minimization online resource allocation (IMORA) and restricted assignment resource allocation (RARA) for 10% sum rate improvement with 300 cellular user equipment (UEs). The experiment starts with 1 device-to-device (D2D) pair and ends with 215 D2D pairs

7 | CONCLUSION

Interference minimization is a prominent research area in the fields of cellular and wireless networks based on cooperative communication. This paper addresses the research question of total system interference minimization while maintaining a target system sum rate gain in an inband underlay D2D communication. To the best of our knowledge, most of the state of the art research works exploit offline resource allocation algorithms to addresses the research problem. However, in LTE and beyond (4G, 5G, or 5G+) systems, offline resource allocation algorithms do not comply with the fast scheduling requirements because of the high data rate demand. Hence, an online resource allocation algorithm that performs close to an offline resource allocation algorithm with less complexity might be a potential alternative to the research problem. In this paper, we propose a bi-phase online resource allocation algorithm for interference minimization, and we claim to be the first ever online algorithm for the addressed research problem for inband underlay D2D communication. The phase I of our proposed algorithm is based on the weighted bipartite matching algorithm that minimizes the interference while gets an initial feasible solution, and phase-II of our proposed algorithm uses a local search technique to improve the solution. Our proposed algorithm assumes D2D pairs as a set of variable elements whereas takes the cellular UEs as a set of constant elements. The number of D2D pairs in the system varies over time as the D2D pairs arrive into the system and depart from the system online. The arrival, departure, and the mobility of the D2D pairs are considered as system events. The occurrence of such a system event triggers our proposed online algorithms to give a new assignment for the new state of the system, and we model the system events using dMMPP.[35] The novelty of our proposed online resource allocation algorithm is that in between two consecutive allocations, it causes a minimum number of changes in the assignments while minimizing the total interference in the system maintaining a certain increase in the total system sum rate. To validate our proposed online algorithm, we have gone through extensive simulation, and simulation results suggest that our proposed algorithm outperforms one of the best offline algorithm RARA (near optimal)[10] in terms of total system interference and number of changes in successive allocation for a certain percentage of sum rate gain.

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ORCID

Salimur Choudhury https://orcid.org/0000-0002-3187-112X

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