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RESEARCH ARTICLE

Efficient Power Control and Resource Allocation for LTE-D2D Communication: A Multi-Objective Optimization Approach

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ABSTRACT Device-to-device (D2D) communications underlaying cellular networks enhance system capacity and bandwidth utilization. In this approach, secondary users (D2D devices) share the radio resources allocated to primary users (cellular UE), achieving increased system capacity and spectrum efficiency. However, the allocation of inappropriate resources and transmission power to devices introduces excessive co-channel interference, which could impair primary user communication. The proposed research addresses this challenge by developing a Multi-Value Bipartite Matching (MBM) Algorithm that jointly allocates resources and transmission power for both primary and secondary users maintaining individual data rate constraints. Numerical analyses show that this approach outperforms existing algorithms in determining appropriate power levels while meeting specified constraints, ultimately improving system capacity and reducing interference.

INDEX TERMS Bipartite matching algorithm, co-channel interference, joint optimization, power control, resource allocation, sumrate.

I. INTRODUCTION

Mobile traffic demand has increased manifold due to rapid development as well as the ease of use of this technology for the last few decades. The number of mobile subscriptions will grow to around 6 billion (70 percent of the global population) by 2023 [1]. In traditional cellular networks, transmitting and receiving nodes (known as cellular User Equipment (UE)) communicate through eNodeB (eNB) using authorized radio frequencies overseen by eNB. Cellular UEs exchange control information with the eNB to assign resources and adjust transmission power to maintain certain quality [2]. The transmitting and receiving devices in close proximity can communicate directly, offloading the data from eNB. This direct communication is known as Device to Device (D2D) communication.

D2D communication is becoming popular in both personal and corporate settings, facilitating various inter-device services such as Vehicle-to-Vehicle (V2V) communication, local guiding, social discovery, gaming, content sharing, media downloading during social events, multicast, and relay communication for coverage extension [3]. D2D communication implementations can be categorized into Outband (unlicensed) and Inband (licensed). Inband communication can further divided into Underlay and Overlay modes. Inband Underlay, where D2D and cellular UEs share spectrum resources (also known as Resource Block (RB)), is considered more practical and advantageous, offering benefits such as higher spectral efficiency, increased system capacity, reduced eNB traffic load, and lower device power consumption [4], [5], [6]. Inband Underlay D2D communication, introduced with 4G/LTE, has paved the way for 5G and beyond [7], with implications for future 6G technologies [8].

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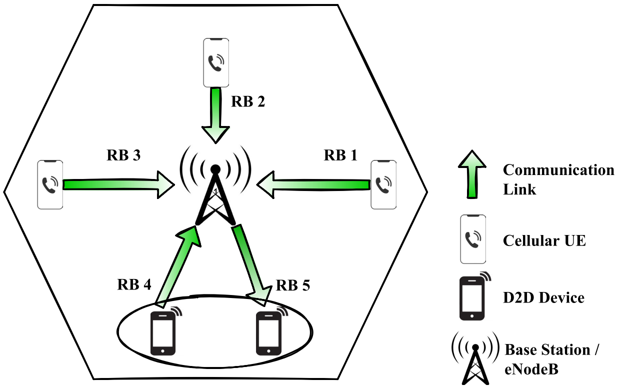


FIGURE 1. Traditional cellular communication.

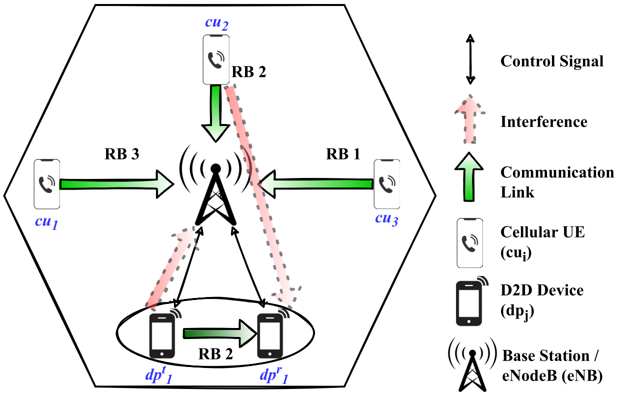


FIGURE 2. Inband underlay D2D communication (sharing the uplink resource blocks of the traditional cellular network).

Inband Underlay D2D communication will introduce co-channel interference to the primary users of the cellular network. Intelligent resource sharing and power control mechanisms can decrease this interference to an acceptable level which will maximize the entire system sumrate (capacity) and minimize the system interference. Figure 1 represents the traditional cellular communication. Figure 2 represents a scenario of D2D communication where the transmitting and receiving devices in close proximity reuse the RB to communicate directly.

Many state-of-the-art resource allocation solutions for both capacity maximization [9], [10], [11], [12], [13] and interference minimization [14], [15], [16], [17] algorithms consider the fixed power level of the devices. However, the transmission power of devices sharing the same RB can impact the received signal strength of those devices. So the resource assignment problem and the power level selection problem need to be considered as a single joint optimization problem. Numerous researchers are actively developing diverse resource allocation algorithms and power control mechanisms for D2D communication within cellular networks. Their efforts aim to achieve varied objectives across different system models, highlighting the ongoing need for further research in this area.

Many researchers offered a sequential solution to the joint optimization problem where first the power level is selected and later the resources are allocated [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28]. However, sequential solutions may lead to sub-optimal resource allocations due to dependencies between power-level selection and resource allocation. Many works offer joint optimization algorithms but use meta-heuristic approaches, machine learning, or distributed approaches [29], [30], [31], [32], [33], [34], [35], [36]. However, these approaches are non-deterministic, and randomness inherent in these methods can result in inconsistent performance and difficulty in guaranteeing convergence to optimal solutions. In this research, we aim to develop polynomial-time solvable deterministic algorithms to achieve the theoretical maximum sumrate and minimum interference.

This paper formulates a joint optimization problem involving resource allocation and power control. Two different objectives have been addressed, namely capacity maximization and interference minimization. Our suggested method demonstrates comparable performance to state-of-the-art approaches, and the key contributions to this study include the following.

- Two separate objective functions are identified which are capacity maximization and interference minimization. We introduce two novel weight calculation algorithms to address these objective functions. We also incorporate a mechanism to identify and mitigate invalid assignments, ensuring the feasibility and efficiency of our approach.
- Development of a deterministic algorithm that jointly handles the resource allocation and power level selection for D2D devices. This algorithm addresses both objective functions separately based on the weight calculation algorithm.
- A polynomial time solution approach is proposed which supports the short scheduling time of the cellular network. The temporal complexity of the proposed approach is $O(n^3)$ ensuring efficient execution and scalability in real-world deployment scenarios.

The format of the paper is as follows: Section II provides a review of the existing research works on D2D communication. Section III briefs the system architecture and the formulation of the problem. Section IV describes the proposed method and analyzes the temporal complexity. In Section V, we conduct a numerical analysis and compare our proposed algorithm with existing ones. Section VI summarizes contributions and outlines future research directions.

II. LITERATURE REVIEW

D2D communication can provide several benefits like spectral efficiency, energy efficiency, improved capacity, and fairness among devices in close proximity. However, this mode of communication opens up different challenges [37], [38] like resource allocation, power optimization, mode selection, etc. in different kinds of system models. Recent studies have chosen these challenges in different combinations, like considering one or more challenges in their solution.

The assignment of available network resources to D2D devices is addressed in the resource allocation problem. The researchers working on this problem are focusing on different goals while presenting their solutions. The authors of [9], [10], [11], [12], and [13] proposed resource allocation schemes to maximize the system capacity. The optimal solution for this scenario is presented in [13] for different cardinality of D2D devices and cellular UEs. On the other hand, the authors of [14], [15], [16], and [17] designed the resource allocation scheme to minimize the interference provided that a certain level of system capacity will be attained. The authors of [39] and [40] proposed online algorithm-based solutions to reduce the number of changes in resource assignment in each iteration. It should be noted that these strategies are deterministic approaches. Some meta-heuristic solutions are also available in the literature.

Yang et al. address the resource allocation and user matching (D2D users to cellular users) in D2D communication underlay cellular networks using uplink resources [41]. Initially, resources are dispersed among cellular users in the order of priority. Following that, a genetic algorithm-based strategy is used to associate D2D devices with cellular users to maximize the throughput of each set of resource blocks shared by D2D devices and cellular users. The breeding process of the proposed scheme is divided into six steps: selection (selecting parents from a generation based on the fit function), crossover (two offspring are produced from swapping some genes between two parents), self-adaptive mutation (mutation of any gene based on self-adaptive modulation probability), modification (to correct the gene to satisfy the constraint), elitism strategy prevention (entry of the best gene to the next generation without going through any breeding process to avoid randomness of GA), iteration (the number of genetic generations to reach a convergence state).

Ashtiani et al. address the problem of malicious eavesdroppers in the system along with cellular users and D2D pairs [42]. They formulate the problem to optimize the cell's secrecy capacity. They proposed a solution Tabu Search for Resource Management - TSRM based on the meta-heuristic algorithm Tabu Search. To find out the neighborhood of a solution - Swapping, Insertion, and Reversion moves are applied. When a best-found solution is not improved for a few iterations, perturbation is performed.

These studies mainly focus on resource allocation strategies, assuming the mode of communication and transmission power are already selected. Besides these, there are several studies [43], [44], [45], [46], [47] based on distributed algorithms. However, a decentralized approach failed to perform well due to partial knowledge of the system configuration.

The transmission power of sending nodes has a very large impact on system performance. Several studies [48], [49], [50], [51], [52] focused on setting transmission power levels for all cellular UEs and D2D pairs to increase the system capacity or decrease the system interference.

Najla et al. address the problem of setting the transmission power of D2D users in the case when channel gains among D2D users are unknown [48]. The authors assume a system model where multiple BSs are present and multiple D2D users are present. First, the relation between the channel gain of D2D users and cellular users is calculated. Later this relation is exploited to set the transmission power of D2D users using a power control scheme based on Deep Neural Network (DNN).

Yu et al. address the power control problem in D2D communication [49] considering two cases. D2D and cellular users receive equal precedence in the first case. A greedy approach is applied in this case to increase the throughput while adhering to maximum transmission power constraint. In the alternate case, precedence is given to cellular users with a constraint of an upper limit of transmission rate by coding method and modulation. The authors classified resource blocks into three types. The first type involves a non-orthogonal resource-sharing scheme, where cellular and device-to-device (D2D) users share resources, and the base station manages transmit power. Secondly, a separate resource sharing mode where D2D and cellular users use separate resource blocks, thus no co-channel interference. Therefore, maximum transmission power returns to maximum throughput. Thirdly, D2D users communicate via eNB following cellular systems. In this case, the maximum transmission power also returns the maximum throughput.

In these studies, the authors focused on the power control scheme irrespective of resource allocation strategies. Moreover, few studies [50], [53], [54], [55] focused on the minimization of total power consumption instead of the optimization of total system capacity or system interference.

Effective system performance relies on both optimal resource allocation strategies and precise transmission power control. Many studies [29], [30], [31], [32], [33], [56], [57], [58] consider these two problems as joint optimization problems instead of assuming they are separate problems.

Takshi et al. propose a genetic algorithm for joint optimization of resource allocation and power assignment to maximize the spectral efficiency of an overlay network [29]. Authors represent a resource block as a chromosome that might be used by multiple cellular users and D2D users with individual transmission power. It should be noted that the optimization constraints are satisfied by all chromosomes. Following the traditional genetic algorithm, the authors designed a fitness function. Parent chromosomes are proportionally selected based on a given fitness value. Then a crossover operation is applied to these parent chromosomes to generate a new generation following all constraints. The authors also mentioned a mutation process in 20% cases to avoid local optimum solutions.

Tan et al. formulate the problem statement to maximize the weighted sumrate (WSR) of the overlay D2D network, jointly optimizing the channel selection and the transmission power [31]. It should be noted that the authors identified the problem as non-convex and NP hard. They developed a Fractional Programming (FP) based centralized algorithm for benchmark algorithm. A distributed Deep Reinforcement Learning (DRL) based algorithm with local information is proposed to reduce the signaling overhead compared to FP FP-based scheme. As the transition probabilities are difficult to acquire, instead of the Markov Decision Process (MDP) model, the model-free RL Q-learning method is applied.

Gao et al. propose a Quantum Coral Reefs Optimization Algorithm (QCROA) [32] to optimize jointly the resource allocation and power control, maximizing the total throughput in cooperative D2D heterogeneous networks. QCROA integrates the strengths of the conventional coral reefs optimization algorithm and the quantum evolution algorithm.

Wang et al. work on a system model where D2D devices can reuse multiple channels [30] to maximize the total capacity. To achieve high-quality communication for cellular users, a joint channel selection and power control method is considered. Increasing the reuse of D2D users will in turn increase the transmitting power of D2D devices, causing interference in cellular communication. Their model is designed to help a D2D pair learn power control and channel selection methods adaptively by interacting with the environment using Deep Q-learning Network (DQN).

These studies utilize non-deterministic approaches to solve the problem. Generally, any approach based on a meta-heuristic or machine learning solution may perform better in terms of execution time. However, they may be stuck in a local minima.

Few studies consider other combinations of challenges like only resource allocation, both resource allocation and mode selection, only mode selection, only power control, etc. It should be noted that, in the mode selection problem, the authors consider that the communicating devices will not decide whether they will establish a direct link (D2D Communication) or communicate via a base station (Cellular Communication), but rather the proposed approach will select the mode of communication.

Li et al. devised a max-flow optimization problem to address the mode selection and resource allocation. The authors assumed a system model where traditional cellular users are not present. They considered multiple BSs and under each of the BS, several relay devices, senders, and receivers are present instead of different cellular users and D2D pairs. These devices may act as either traditional cellular users or D2D pairs (may or may not use a relay device). They first model the D2D communication using a graph. They formulate the problem as a flow maximization problem using this graph. To emulate realistic behavior, they consider human mobility traces as proposed in Orlando [59] and Infocom06 [60].

Sun et al. propose a hierarchical game theory-based solution [61] to solve the problems of mode selection, spectrum allocation and power control, considering a sufficient amount of spectrum resources are available to the cellular network. To address the mode selection and resource allocation issues, a hedonic coalition game-based approach is put forward. Next, to further enhance performance, a non-cooperative game-based power control mechanism is implemented.

Zhou et al. design a resource allocation scheme jointly considering mode selection, Modulation and Coding Scheme (MCS) assignment, resource allocation and power control [20]. They simplify the complex constraint using the Lagrangian relaxation technique by adding the complex constraint in the objective function assigned with weight. The unsatisfied constraint add penalty in the solution represented by the weight. The authors' proposed sub-problems are the resource Block Allocation Problem (RAP) and Model Selection and MCS Assignment sub-problem (MSMAP). RAP and MSMAP sub-problems are addressed with a greedy technique and the Tabu search technique.

Addressing the issues of mode selection, resource allocation, power control, and other related issues would improve the efficacy of D2D communication, which supports cellular networks. Existing studies provide measures for various problem combinations. Resources and power control are examined independently in several research. While user transmission power could enhance efficiency, it also interferes with other users who are using the same resources. System performance suffers as a result of addressing these two issues independently. Non-deterministic solutions are taken into consideration in recent studies that address the challenges of power control and resource allocation together. The distance between the communication devices, on the other hand, is the primary factor influencing the mode selection difficulty, which may be handled independently. However, the challenges of power control and resource allocation need to be addressed jointly to enhance the system's performance.

III. PROBLEM FORMULATION

In this paper, two different objective functions will be addressed separately. Thus, two separate problems are formulated. In order to understand the problem formulation, first the system model and channel model are laid down in the beginning.

A. SYSTEM MODEL

This paper examines the same system and channel models as in [11] and [15]. Though LTE network resources include both uplink (UL) and downlink (DL) components, the UL resources are considered here. D2D receivers are susceptible to interference from cellular UE when using uplink resources. On the other hand, D2D transmitters introduce interference at eNB [15]. D2D pairs can interact directly in such an underlay system, but the eNB monitors power level allocation, connection formation, and resource distribution [9].

In the experimental setup, it is considered that an omnidirectional antenna is present in eNB, cellular UEs and D2D pairs. The eNB communicates through control signals with cellular UEs and D2D pairs to share important information. The eNB informs the cellular UEs and D2D pairs about the transmission power and the RBs to use for transmission using this control signal. This paper examines a single cell area with one eNB, m D2D pairs and n cellular UEs which is depicted in Fig. 2. The set of D2D pairs is denoted as $DP = \{dp_1, dp_2, dp_3, \ldots, dp_m\}$. The set of cellular UEs is denoted as $CU = \{cu_1, cu_2, cu_3, \ldots, cu_n\}$. Each D2D pair dp_j, is composed of a transmitting device dp_j^t and a receiving device dp_j^r.

B. CHANNEL MODEL

An Urban Micro System is considered, which uses the Rayleigh fading path loss model with orthogonal channels and separate RBs for each cellular UE [9], [15]. No co-channel interference is present in the case of cellular communications. However, D2D communication will introduce co-channel interference in the channel when it shares the RB. We follow the same path loss model and channel gain recommended in [9] which is used by most of the existing research work in this domain. $G^{p,q}$ represents the channel gain where p is the receiver and q is the transmitter.

C. PROBLEM FORMULATION

This research deals with resource assignment and power allocation problems simultaneously. The D2D pair shares the resources of existing cellular UEs in the inband mode of D2D communication. The term assignment of D2D pair dp_j to cellular UE cu_i or vice-versa implies that both dp_j and cu_i share the same resource blocks. Power allocation denotes the setting of transmission power to a cellular UE cu_i or D2D pair dp_j.

Two optimization objectives are addressed in this paper. It should be noted that these two objectives are not considered in the same problem statement. Two different problem statements are proposed. The aim is to find a set of allocations of transmission power and RBs to cellular UEs and D2D pairs that give a good solution to the individual optimization problem.

Before presenting the problem statement, several essential equations pertinent to the researched problem are outlined here. It assumes the transmitting powers of eNodeB, cu_i, D2D transmitter dp_j^t, and eNB as p_{eNB}, p_{cu_i}, and $p_{dp_j^t}$ respectively. Additionally, the environmental noise is represented by σ.

The Signal to Interference plus Noise Ratio (SINR) during uplink communication between a cellular UE cu_i and the eNB, considering the shared resources with D2D pair dp_j is

$$\gamma_{eNB,cu_i,dp_j} = \frac{p_{cu_i} G^{cu_i,eNB}}{\sigma + p_{dp_j^t} G^{dp_j^t,eNB}}, \tag{1}$$

where, $G^{dp_j^t,eNB}$ implies channel gain between the D2D transmitter dp_j^t of D2D pair dp_j and the eNB, and $G^{cu_i,eNB}$ implies the channel gain between the eNB and the cellular UE cu_i [62]. If there is no D2D pairs sharing the RBs of cu_i, the equation (1) can be reformulated as

$$\gamma_{eNB,cu_i,0} = \frac{p_{cu_i} G^{cu_i,eNB}}{\sigma}, \tag{2}$$

here, the term denoting the co-channel interference present in the denominator of equation (1) is zero as no D2D pair is reusing the RBs of cu_i. Similarly, if the D2D pair dp_j is reusing the same RBs as cu_i, then SINR at the D2D receiver is

$$\gamma_{dp_j,cu_i} = \frac{p_{dp_j^t} G^{dp_j^t,dp_j^r}}{\sigma + p_{cu_i} G^{cu_i,dp_j^r}}, \tag{3}$$

Thus, the total system interference introduced is

$$I_{cu_i,dp_j} = p_{dp_j^t} G^{dp_j^t,eNB} + p_{cu_i} G^{cu_i,dp_j^r}. \tag{4}$$

According to Shannon's capacity formula [63], sumrate contribution of a cellular UE cu_i and a D2D pair dp_j (provided that D2D pair dp_j is sharing the resources) can be represented as

$$S_{cu_i,dp_j} = B\log_2(1+\gamma_{eNB,cu_i,dp_j}) + B\log_2(1+\gamma_{dp_j,cu_i}), \tag{5}$$

where, γ_{cu_i,dp_j} indicates the SINR at eNB while communicating with cellular UE cu_i and γ_{dp_j,cu_i} indicates the SINR at D2D receiver dp_j^r while communicating with D2D transmitter dp_j^t and B is the bandwidth of the channel. If a cellular UE cu_i uses dedicated RB (no D2D pair is sharing the RB), then the sumrate offering of cellular UE cu_i is

$$S_{cu_i,0} = B\log_2(1+\gamma_{cu_i,0}). \tag{6}$$

Now, based on the above equations, we formulate two separate problems of capacity maximization and interference minimization as follows.

1) CAPACITY MAXIMIZATION

The system sumrate is based on the equation (5) and equation (6). There are some QoS requirements that need to be considered as well. Therefore, the optimization problem of maximizing the total system sumrate can be formulated as

$$\begin{aligned}
\underset{x,y_{cu},y_{dp}}{\arg}\ \max &\sum_{i=1}^{n}\Big(1-\sum_{j=1}^{m} x_{cu_i}^{dp_j}\Big) S_{cu_i,0} N_{cu_i} \\
&+ \sum_{i=1}^{n}\sum_{j=1}^{m} x_{cu_i}^{dp_j} S_{cu_i,dp_j} N_{cu_i} \\
&= \sum_{i=1}^{n}\Big(1-\sum_{j=1}^{m} x_{cu_i}^{dp_j}\Big) B\log_2(1+\gamma_{cu_i,0}) N_{cu_i} \\
&+ \sum_{i=1}^{n}\sum_{j=1}^{m} x_{cu_i}^{dp_j} B\Big(\log_2(1+\gamma_{eNB,cu_i,dp_j})
\end{aligned}$$

$$
\begin{aligned}
&+\log_2(1+\gamma_{dp_j,cu_i})\Big)N_{cu_i}\\
&=\sum_{i=1}^{n}(1-\sum_{j=1}^{m}x_{cu_i}^{dp_j})B\log_2(1\\
&+\frac{(\sum_{w=1}^{l_{cu_i}}y_{cu_i}^{w}p_{cu_i}^{w})G^{cu_i,eNB}}{\sigma})N_{cu_i}\\
&+\sum_{i=1}^{n}\sum_{j=1}^{m}x_{cu_i}^{dp_j}B\Big(\log_2(1\\
&+\frac{(\sum_{w=1}^{l_{cu_i}}y_{cu_i}^{w}p_{cu_i}^{w})G^{cu_i,eNB}}{\sigma+(\sum_{z=1}^{k_{dp_j}}y_{dp_j}^{z}p_{dp_j}^{z})G^{dp_j^t,eNB}})\\
&+\log_2(1+\frac{(\sum_{z=1}^{k_{dp_j}}y_{dp_j}^{z}p_{dp_j}^{z})G^{dp_j^t,dp_j^r}}{\sigma+(\sum_{w=1}^{l_{cu_i}}y_{cu_i}^{w}p_{cu_i}^{w})G^{cu_i,dp_j^r}})\Big)N_{cu_i}
\end{aligned}
\tag{7}
$$

$$\text{subject to, } S_{cu_i}\geqslant S_{cu_i}^{demand},\ \forall\, cu_i\in CU \tag{8}$$

$$S_{dp_j}\geqslant S_{dp_j}^{demand},\ \forall\, dp_j\in DP \tag{9}$$

$$p_{cu_i}=\{p_{cu_i}^{1},p_{cu_i}^{2},\ldots,p_{cu_i}^{l_{cu_i}}\},\ \forall\, cu_i\in CU \tag{10}$$

$$p_{dp_j}=\{p_{dp_j}^{1},p_{dp_j}^{2},\ldots,p_{dp_j}^{k_{dp_j}}\},\ \forall\, dp_j\in DP \tag{11}$$

$$x_{cu_i}^{dp_j}=\{0,1\}\ ,\ \forall\, cu_i\in CU\,\text{and}\ \forall\, dp_j\in DP, \tag{12}$$

$$y_{cu_i}^{w}=\{0,1\}\ ,\ \forall\, cu_i\in CU\,\text{and}\ 1\leqslant w\leqslant l_{cu_i}, \tag{13}$$

$$y_{dp_j}^{z}=\{0,1\}\ ,\ \forall\, dp_j\in DP\ \text{ and }\ 1\leqslant z\leqslant k_{dp_j}, \tag{14}$$

$$\sum_{w=1}^{l_{cu_i}}y_{cu_i}^{w}=1,\quad \forall\, cu_i\in CU \tag{15}$$

$$\sum_{z=1}^{k_{dp_j}}y_{dp_j}^{z}=\begin{cases}0 & \text{if}\displaystyle\sum_{i=1}^{n}x_{cu_i}^{dp_j}=0\\ 1 & \text{otherwise}\end{cases}\quad,\ \forall\, dp_j\in DP \tag{16}$$

$$\sum_{j=1}^{m}x_{cu_i}^{dp_j}\leqslant 1\ ,\quad \forall\, cu_i\in CU \tag{17}$$

$$\sum_{i=1}^{n}x_{cu_i}^{dp_j}\leqslant 1\ ,\quad \forall\, dp_j\in DP \tag{18}$$

The joint optimization problem presented here considers three decision variables - shared status x, power level selection status of cellular UE y_{cu} and power level selection status of D2D pair y_{dp}.

The initial segment of the objective function pertains to the cumulative sumrate from unassigned cellular UEs (those without D2D pair sharing), denoted by $S_{cu_i,0}$ for an unassigned cellular UE cu_i. The subsequent section of this expression signifies the aggregate sumrate from the assigned cellular UEs involved with D2D pairs, where S_{cu_i,dp_j} stands for the sumrate involving a cellular UE cu_i and a D2D pair dp_j when dp_j shares the RBs of cu_i. By leveraging equations (5) and (6), the objective function expands. Furthermore, the utilization of equations (1), (2), and (3) leads to further expansion of the objective function. In this context, N_{cu_i} in the objective function (7) signifies the number of RBs allocated to a cellular UE cu_i. If a D2D pair is associated with cellular UE cu_i, then a corresponding allocation of N_{cu_i} number of RBs will also be assigned to D2D pair dp_j.

In this objective function, the transmission power of cellular UE and D2D pair is controlled by the decision variables y_{cu} and y_{dp} respectively. Additionally, the shared status of any cellular UE and D2D pair is controlled by the decision variable x.

Constraint (12) represents that the variable $x_{cu_i}^{dp_j}$ is a binary indicator determining whether a D2D pair dp_j shares the RBs of a cellular UE cu_i or not.

On the other hand, $y_{cu_i}^{w}$ in Constraint (13) indicates if a cellular UE cu_i will set the transmission power to $p_{cu_i}^{w}$. Here p_{cu_i} is a set of discrete transmission power level available for cellular UE cu_i mentioned in the constraint (10) and $p_{cu_i}^{w}$ is the w^{th} element in the set.

Similarly constraint (14) denotes that, $y_{dp_j}^{z}$ is a binary variable that indicates whether the transmitting device of a D2D pair dp_j will set the transmission power to $p_{dp_j}^{z}$. Here p_{dp_j} is a set of discrete transmission power levels available for transmitting device of D2D pair dp_j mentioned in the constraint (11) and $p_{dp_j}^{z}$ is the z^{th} element in the set.

Constraint (8) and constraint (9) denote the individual demand sumrate constraint for cellular UE cu_i and D2D pair dp_j.

Constraint (15) denotes that only one power level can be selected for any cellular UE. Moreover, constraint (16) denotes that only one power level can be selected for any D2D pair but transmission power of a D2D pair will be zero, if no resources is allocated to that D2D pair.

Constraint (17) and constraint (18) represent the one to one allocation - the first constraint is one cellular UE cu_i cannot be assigned to multiple D2D pairs and second one is a D2D pair dp_j can be assigned to at-most one cellular UE.

2) INTERFERENCE MINIMIZATION

The total system interference is based on the equation 4. Therefore, the optimization problem of minimizing the total system interference is

$$
\begin{aligned}
&\underset{x,y_{cu},y_{dp}}{\arg}\ \min\sum_{i=1}^{n}\sum_{j=1}^{m}x_{i,j}I_{cu_i,dp_j}\\
&=\sum_{i=1}^{n}\sum_{j=1}^{m}\Big(x_{i,j}(\sum_{z=1}^{k_{dp_j}}y_{dp_j}^{z}p_{dp_j}^{z})G^{dp_j^t,eNB}\\
&+(\sum_{w=1}^{l_{cu_i}}y_{cu_i}^{w}p_{cu_i}^{w})G^{cu_i,dp_j^r}\Big)
\end{aligned}
\tag{19}
$$

$$\text{subject to, } S_{cu_i} \geqslant S_{cu_i}^{demand}, \ \forall \, cu_i \in CU \tag{20}$$

$$S_{dp_j} \geqslant S_{dp_j}^{demand}, \ \forall \, dp_j \in DP \tag{21}$$

$$p_{cu_i} = \{p_{cu_i}^1, p_{cu_i}^2, \ldots, p_{cu_i}^{l_{cu_i}}\}, \quad \forall \, cu_i \in CU \tag{22}$$

$$p_{dp_j} = \{p_{dp_j}^1, p_{dp_j}^2, \ldots, p_{dp_j}^{k_{dp_j}}\}, \quad \forall \, dp_j \in DP \tag{23}$$

$$x_{cu_i}^{dp_j} = \{0, 1\}, \quad \forall \, cu_i \in CU \text{ and } \forall \, dp_j \in DP, \tag{24}$$

$$y_{cu_i}^{w} = \{0, 1\}, \quad \forall \, cu_i \in CU \text{ and } 1 \leqslant w \leqslant l_{cu_i}, \tag{25}$$

$$y_{dp_j}^{z} = \{0, 1\}, \ \forall \, dp_j \in DP \text{ and } 1 \leqslant z \leqslant k_{dp_j}, \tag{26}$$

$$\sum_{w=1}^{l_{cu_i}} y_{cu_i}^{w} = 1, \ \forall \, cu_i \in CU \tag{27}$$

$$\sum_{z=1}^{k_{dp_j}} y_{dp_j}^{z} = \begin{cases} 0 & \text{if} \sum_{i=1}^{n} x_{cu_i}^{dp_j} = 0 \\ 1 & \text{otherwise} \end{cases}, \quad \forall \, dp_j \in DP \tag{28}$$

$$\sum_{j=1}^{m} x_{cu_i}^{dp_j} \leqslant 1, \ \forall \, cu_i \in CU \tag{29}$$

$$\sum_{i=1}^{n} x_{cu_i}^{dp_j} \leqslant 1, \ \forall \, dp_j \in DP \tag{30}$$

where the optimization problem mentioned here is to minimize the total system interference. I_{cu_i,dp_j} represents interference introduced at eNB and D2D pair when a cellular UE cu_i shares RBs with a D2D pair dp_j. Like the optimization problem of capacity maximization discussed in Section III-C1 this optimization problem has three decision variables - x, y_{cu}, and y_{dp}. The representation of this variable is the same as discussed in Section III-C1.

The individual target sumrate constraint is presented in (20) and in (21) for cellular UE cu_i and D2D pair dp_j. Individual power level availability constraints are given in (22) and (23). Constraint (27) and (28) represent that a cellular UE and a D2D pair will transmit using only one of the available transmission power levels. However, the transmission power of a D2D pair will be zero, if no resources is allocated to that D2D pair. Constraint (29) and (30) represent the one to one allocation of RBs to cellular UEs and D2D pairs. The details of the constraints are not reiterated as they have similar meaning to the first optimization problem presented in Section III-C1.

The system model is explained in Section III-A. In this system model, D2D pairs reuse the uplink resources of cellular UEs. The channel model is explained in Section III-B, where the channel model of the Urban Micro System is considered. Section III started with the formulation of SINR, sumrate, and interference. Based on these equations, two separate objective functions are presented in Section III-C1 and III-C2.

IV. SOLUTION APPROACH

This section addresses the problem statement devised in the previous section. The working principle of the proposed solution approach can be explained with an exhaustive search approach to the problem. First, the exhaustive search approach will be discussed in Section IV-A, then the proposed solution approach will be discussed in Section IV-B. Later, the complexity analysis is shown in Section IV-C.

A. EXHAUSTIVE SEARCH

Assume that there are two cellular UEs cu_1 and cu_2 and two D2D pairs dp_1 and dp_2. Two transmission power levels, p_1 and p_2 available for cu_1, cu_2, dp_1 and dp_2. Figure 3 shows all possible combinations of assignment with all possible power levels.

Figure 3 (a), $cu_1^{p_1}$ row indicates cu_1 with transmission power p_1, $cu_2^{p_1}$ row indicates cu_2 with transmission power p_1, $dp_1^{p_1}$ column indicates dp_1 with transmission power p_1 and lastly, $dp_2^{p_1}$ column indicates dp_2 with transmission power p_1. If the power level is fixed, then only one combination is possible. The Hungarian bipartite matching algorithm can solve that in polynomial time with a complexity of $O(n^3)$.

For the given condition, there are 16 different possible combinations as shown in Figure 3 (a)-(p). Assuming a minimization problem, first the bipartite matching needs to be applied and the minimum matching weight value has to be calculated for each combination. Then, the minimum among these 16 combinations will be selected. The assignment of power levels and resources of the selected combination will be the optimal solution. In the given scenario, combination (a) of Figure 3 returns the lowest value. Moreover, the assignment returned from the Hungarian algorithm for Figure 3 (a) is $cu_1^{p_1}$ with $dp_1^{p_1}$ and $cu_2^{p_1}$ with $dp_2^{p_1}$. So, the power level of cu_1, cu_2, dp_1 and dp_2 will be p_1 and cu_1 share RBs with dp_1 and cu_2 share RBs with dp_2.

Assume that the number of cellular UE is n, number of D2D pairs is m and $n > m$. Moreover, the number of power levels of cellular UE cu_i, is represented by l_{cu_i} and that of D2D pair dp_j is represented by k_{dp_j}. Let $U = \prod_{i=1}^{n} l_{cu_i}$ and $V = \prod_{j=1}^{m} k_{dp_j}$. So, there will be a maximum of $U \times V$ combinations. So the complexity of the exhaustive approach will be $O(U \times V \times n^3)$.

B. PROPOSED SOLUTION APPROACH

The proposed solution addresses both the two optimization problems, i.e. the maximization of the system capacity and the minimization of the system interference, while maintaining some constraint. The solution approach is divided into two steps, namely - Step 1: Preparation Stage and Step 2: Execution Stage. The Preparation Stage is subdivided into two steps: 1. Formation of the bipartite graph, and 2. Assignment of weight. Similarly, the execution stage is

	$dp_1^{p_1}$	$dp_2^{p_1}$
$cu_1^{p_1}$	2	3
$cu_2^{p_1}$	4	5

(a)

	$dp_1^{p_2}$	$dp_2^{p_1}$
$cu_1^{p_1}$	3	3
$cu_2^{p_1}$	6	5

(b)

	$dp_1^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_1}$	2	5
$cu_2^{p_1}$	4	6

(c)

	$dp_1^{p_2}$	$dp_2^{p_2}$
$cu_1^{p_1}$	3	5
$cu_2^{p_1}$	6	6

(d)

	$dp_1^{p_1}$	$dp_2^{p_1}$
$cu_1^{p_2}$	3	5
$cu_2^{p_1}$	4	5

(e)

	$dp_1^{p_2}$	$dp_2^{p_1}$
$cu_1^{p_2}$	5	5
$cu_2^{p_1}$	6	5

(f)

	$dp_1^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_2}$	3	7
$cu_2^{p_1}$	4	6

(g)

	$dp_1^{p_2}$	$dp_2^{p_2}$
$cu_1^{p_2}$	5	7
$cu_2^{p_1}$	6	6

(h)

	$dp_1^{p_1}$	$dp_2^{p_1}$
$cu_1^{p_1}$	2	3
$cu_2^{p_2}$	5	7

(i)

	$dp_1^{p_2}$	$dp_2^{p_1}$
$cu_1^{p_1}$	3	3
$cu_2^{p_2}$	7	7

(j)

	$dp_1^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_1}$	2	5
$cu_2^{p_2}$	5	8

(k)

	$dp_1^{p_2}$	$dp_2^{p_2}$
$cu_1^{p_1}$	3	5
$cu_2^{p_2}$	7	8

(l)

	$dp_1^{p_1}$	$dp_2^{p_1}$
$cu_1^{p_2}$	3	5
$cu_2^{p_2}$	5	7

(m)

	$dp_1^{p_2}$	$dp_2^{p_1}$
$cu_1^{p_2}$	5	5
$cu_2^{p_2}$	7	7

(n)

	$dp_1^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_2}$	3	7
$cu_2^{p_2}$	5	8

(o)

	$dp_1^{p_2}$	$dp_2^{p_2}$
$cu_1^{p_2}$	5	7
$cu_2^{p_2}$	7	8

(p)

FIGURE 3. **All possible combinations of the matrix.**

	$dp_1^{p_1}$	$dp_1^{p_2}$	$dp_2^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_1}$	2	3	3	5
$cu_1^{p_2}$	3	5	5	7
$cu_2^{p_1}$	4	6	5	6
$cu_2^{p_2}$	5	7	7	8

FIGURE 4. **Single matrix combining all possible combination.**

subdivided into two steps: 1. Multi-value bipartite matching algorithm, and 2. Final assignment of power level and resources.

The proposed solution starts with the preparation stage. First, a weight matrix is initialized according to the number of cellular UEs and D2D pairs. This initialized matrix is then expanded according to the available transmission power levels for each cellular UE and each D2D pair. Following the objective function of the problem, the weight matrix will then be populated. The Multi-value Bipartite Matching Minimization Algorithm will be applied to the weight matrix which returns a boolean matrix containing the initial assignment of resources and transmission power levels of cellular UEs and D2D pairs. This initial assignment undergoes a finalization stage which ensures the satisfaction of constraints.

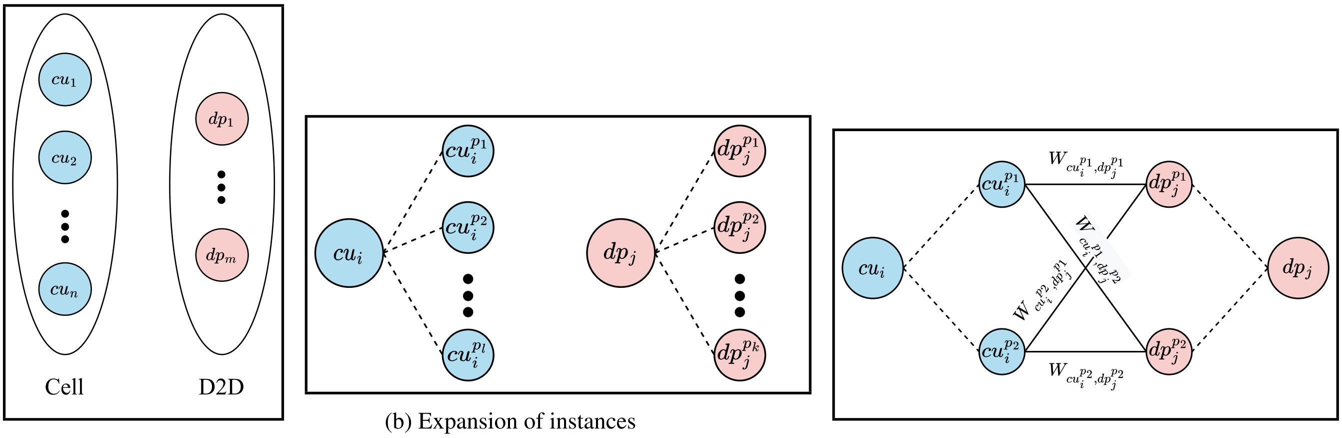
In the subsequent sections, these approaches are discussed.

1) STEP 1: PREPARATION STAGE

In the preparation stage, the problem is formulated into a bipartite graph. After that, the weight of the edge is assigned. In the following, the working procedures for the sub-tasks of the preparation stage are described.

a: GRAPH FORMULATION

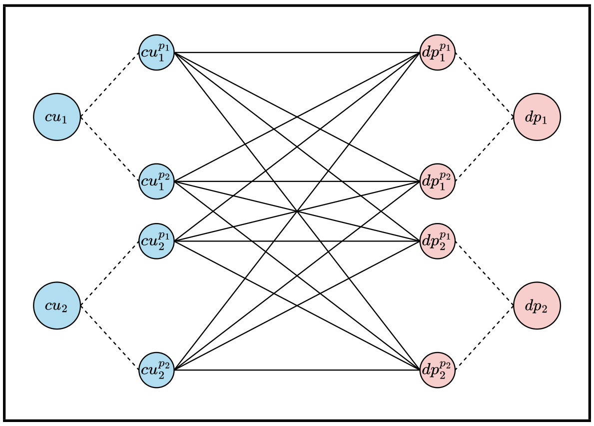
Figure 5 shows the step-by-step formulation of the bipartite graph. Firstly, the system has a set of D2D pairs D and a set of cellular UEs C. These two sets conform to the *initial bipartite graph* shown in Figure 5 (a). After that, each node of the two sets will be expanded according to the number of power levels available according to the constraints (22) and (23). Therefore, each cellular UE cu_i will be expanded to a l_{cu_i} number of instances and each D2D pair dp_j to a k_{dp_j} number of instances. Figure 5 (b) shows the expansion of instances for one arbitrary cellular UE cu_i and one arbitrary D2D pair dp_j. Figure 5 (d) depicts the bipartite graph with the expanded



(a) Initial bipartite graph

(b) Expansion of instances

(c) Weight Assignment of expanded instance



(d) Final bipartite graph

FIGURE 5. **Formulation of the multi-value bipartite graph.**

instances of all cellular UEs and all D2D pairs, defined as *expanded bipartite graph.*

A node, $cu_i^{p_l}$ of the expanded bipartite graph, represents the cellular UE cu_i with power level p_l. Similarly, $dp_j^{p_k}$ represents the D2D pair dp_j with power level p_k. It should be noted that, at the same moment, any cellular UE/D2D pair cannot be assigned multiple power levels. So, selecting one power level will make the other power levels invalid (if there are any). It necessarily means that after the final match, only one of the expanded nodes of all the initial nodes will be present in the solution.

b: ASSIGNMENT OF WEIGHT

The selection of weight for an edge is crucial to getting a global optimum result. For two different objectives, two different appropriate weights should be calculated. Figure 5 (c) depicts the weight assignment between any two nodes cu_i and dp_j, of the initial bipartite graph. Here it is assumed that, the cellular UE cu_i has two power levels available p_1 and p_2 and the D2D pair dp_j has two power levels available p_1 and p_2. The weight between $cu_i^{p_l}$ and $dp_j^{p_k}$ is denoted by $W_{cu_i^{p_l},dp_j^{p_k}}$.

c: CAPACITY MAXIMIZATION

The weight matrix calculation for the capacity maximization problem is presented in Algorithm 1. Sumrate of cellular UE cu_i (if shared with D2D pair dp_j) is S_{cu_i,dp_j} using equation (5) and if not shared by any D2D pairs $dp_j \in DP$ is $S_{cu_i,0}$ using equation (6). On the other hand, if dp_j shared the RBs of cu_i the sumrate is S_{cu_i,dp_j}. If the RBs of a cellular UEs are shared with a D2D pair, it is not certain that the total sumrate contribution after sharing will be greater than before sharing [12]. In some cases, the sumrate contribution after sharing may decrease. Thus, in line 4, the gain of the sumrate contribution is checked. The proposed algorithm should select the assignments earlier that have a positive sumrate contribution. After that, the individual demand rate of cellular UE will be checked. In any case, if the individual demand rate of cellular UE is not met, the proposed approach should avoid selecting it earlier. Thus, the weight is $-\infty$ in line 10 and 17. Moreover, if a D2D pair dp_j does not reuse the RB of a cellular UE cu_i then the sumrate of cellular UE becomes the sumrate contribution. Thus, in line 5, if the sumrate demand $S_{dp_j}^{demand}$ is not satisfied by a D2D pair dp_j, then the weight $S_{cu_i,0}$ is selected. It should be noted that if any

Algorithm 1 Weight of Capacity Maximization Problem

```
1:  procedure WeightSumrate($cu_i^{pl}$, $dp_j^{pk}$)
2:      $cu_i$'s transmission power $= p_l$
3:      $dp_j$'s transmission power $= p_k$
4:      if $S_{cu_i,dp_j} \geq S_{cu_i,0}$ then
5:          if $S_{dp_j} \geq S_{dp_j}^{demand}$ and $S_{cu_i} \geq S_{cu_i}^{demand}$ then
6:              $W_{cu_i^{pl},dp_j^{pk}} = S_{cu_i,dp_j}$
                    ▷ According to [12] the weight is chosen
7:          else if $S_{cu_i} \geq S_{cu_i}^{demand}$ then
8:              $W_{cu_i^{pl},dp_j^{pk}} = S_{cu_i,0}$ and MARK it.
            ▷ sumrate demand of D2D pair is not satisfied, but
    cellular UE is satisfied.
9:          else
10:             $W_{cu_i^{pl},dp_j^{pk}} = -\infty$ and MARK it.
11:         end if
12:     else
13:         if $S_{cu_i} \geq S_{cu_i}^{demand}$ then
14:             $W_{cu_i^{pl},dp_j^{pk}} = S_{cu_i,0}$ and MARK it.
15:             ▷ sumrate demand of D2D pair is not
    satisfied.
16:         else
17:             $W_{cu_i^{pl},dp_j^{pk}} = -\infty$ and MARK it.
18:         end if
19:     end if
20: end procedure
```

sharing is not possible in this step, we mark them in lines 10 and 17. This mark will be necessary in the Execution Stage.

Algorithm 2 Weight of Interference Minimization

```
1: procedure WeightInterference($cu_i^{pl}$,$dp_j^{pk}$)
2:     $cu_i$'s transmission power $= p_l$
3:     $dp_j$'s transmission power $= p_k$
4:     if $S_{dp_j} \geq S_{dp_j}^{demand}$ and $S_{cu_i} \geq S_{cu_i}^{demand}$ then
5:         $W_{cu_i^{pl},dp_j^{pk}} = I_{cu_i,dp_j}$
                   ▷ According to [16] the weight is chosen
6:     else
7:         $W_{cu_i^{pl},dp_j^{pk}} = \infty$ and MARK it.
8:     end if
9: end procedure
```

d: INTERFERENCE MINIMIZATION

The weight matrix calculation for the interference minimization problem is presented in Algorithm 2. The problem formulation considers only co-channel interference. If there is no sharing, then the interference is zero. If dp_j shares the RBs of cu_i, then interference is denoted by I_{cu_i,dp_j}. The sumrate demand of cell cu_i and D2D pair dp_j is checked in line 4. If the sumrate demand of any user is not satisfied due to any assignment, then the weight ∞ is selected in line 7 and these assignments are marked for the Execution Stage.

2) STEP 2: EXECUTION STAGE

In this step, the multi-value bipartite matching (MBM) algorithm is applied to the expanded matrix. After step 1, a single matrix with $\sum_{i=1}^{n} l_{cu_i}$ number of rows and $\sum_{j=1}^{m} k_{dp_j}$ number of columns will be prepared. Figure 4 denotes a single matrix containing all possible combinations. This matrix will be used in step 2.

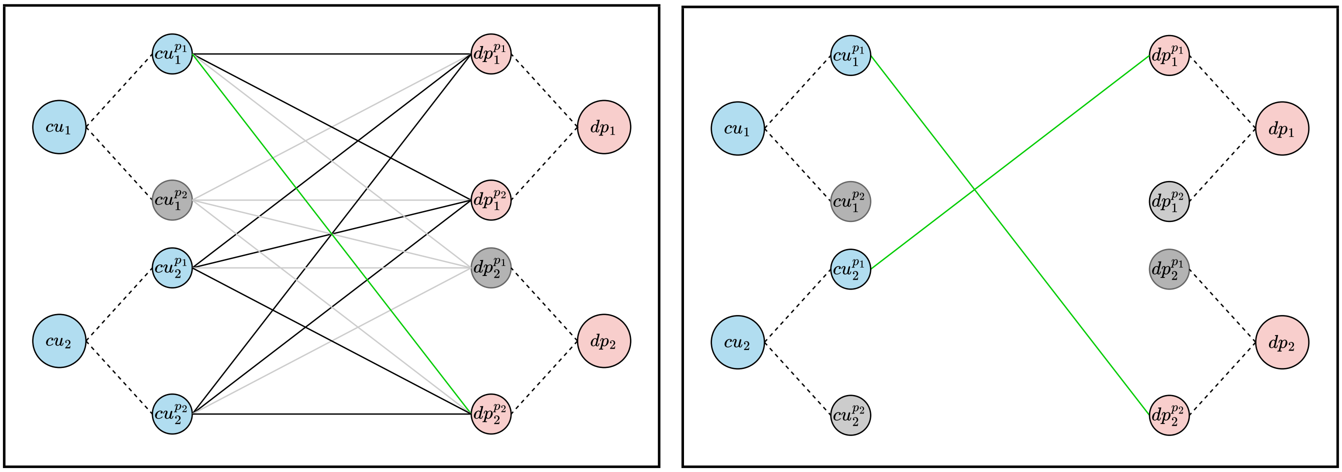
a: MULTI-VALUE BIPARTITE MATCHING (MBM) ALGORITHM

A multi-value bipartite matching algorithm is shown in Algorithm 3. This algorithm is designed with inspiration from the many-to-many Khun Munkres algorithm with backtracking (KMB) [64]. This algorithm has a halting state. To avoid the halting state, authors in [65] provided a modified version of the KMB algorithm. MBM adapts the modified KMB algorithm. Only the adaptation is discussed in the following. It should be noted that Algorithm 3 has similar steps to the original Khun Munkres algorithm.

b: ADAPTATION OF MBM ALGORITHM

As any D2D pair or cellular UE can adopt only one power level it will be invalid to have assignment of two different power levels by a particular cellular UE and D2D pairs. At any step of the algorithm if an expanded instance is selected as a candidate solution then all other instances associated to that cellular UE and D2D pair will be invalid. Figure 6 (a) shows that edge between cu_1^{p1} and dp_2^{p2} is selected in an intermediate step and cu_1^{p2} and dp_2^{p1} is needed to be made unavailable. So that MBM algorithm do not assign an invalid match. In the line 7 and 13 of Algorithm 3, **make other row column unavailable** is performing same operation shown in Fig. 6 (a). This operation takes place when a starring operation is done. Starring a cell in cu_i^{pl} row and dp_j^{pk} column of the matrix implies, a candidate solution is chosen where RBs of cu_i will be shared with dp_j. Moreover, in the candidate solution, the power level of cu_i is p_l and power level of dp_j is p_k. As one candidate solution selected p_l power level for cu_i, all other power levels of cu_i (in other words all other rows) must be made unavailable for further consideration as they may produce invalid solution. Similarly all other power levels of dp_j (in other words all other columns) must be made unavailable. Therefore, MBM algorithm avoids assigning invalid matching with **make other row column unavailable** operation.

Like the operation of KMB and modified KMB, in line 24 backtracking is executed. In this case the unavailable rows and columns of the matrix will be available again. This operation takes place when a starred element is un-starred, which represents a matching is deselected. Assume a cell in cu_i^{pl} row and dp_j^{pk} column of the matrix is un-starred. In this step no power level of cu_i and dp_j is invalid as the said matching is not present in the candidate solution after un-starring. Hence, all other unavailable power levels of cu_i and dp_j can be considered. Therefore, backtracking



(a) Selecting an edge for candidate solution - an intermediate step

(b) Final Assignment

FIGURE 6. **Assignment in multi-value bipartite graph.**

operation allows the MBM algorithm to search for matching with different power levels which was unavailable.

c: A SIMPLE RUN OF MBM

In Fig. 7, we have demonstrated the step-by-step working mechanism of our proposed algorithm for a given arbitrary weight matrix. Note that this example does not require all the steps of MBM algorithm to reach the solution. At first *row reduction* is done. Later *column reduction* takes place to reduce the matrix. The next step is opening starring step. In this particular bipartite matching if one element is starred then the other rows and columns of that starred element needs to be made unavailable. In fourth state of the diagram, first element (cu_1^{p1}, dp_1^{p1}) becomes green as it is starred and other associated columns and rows of that cellular UE dp_1 and cu_1, respectively, is made unavailable with grey color. U represents that particular row/column is unavailable. In fifth state, opening starring is continued and (cu_2^{p1}, dp_2^{p1}) is starred and associated rows and column is made unavailable. No starring is possible after that. Now in the column cover step dp_1^{p1} and dp_2^{p1} is covered. The number of column covered is two which is equal to number of available columns. So this is the final match returned by the MBM algorithm.

3) FINAL ASSIGNMENT OF POWER LEVEL AND RESOURCES

This step is after the assignment returned from the MBM algorithm. MBM algorithm will return a solution of the expanded bipartite graph. It will only return the available nodes of the expanded graph which indicates that for one cellular UE or one D2D pair only one level will be selected. While assigning a weight in Section IV-B1b, some edges were marked as they do not maintain the individual constraint. There may be some cases even after a correct weight this type of marked edge may be selected by the algorithm. So in this step of post-processing, these marked edges will not be assigned which ensures the correctness of the algorithm.

C. COMPLEXITY ANALYSIS

Let $u = \sum_{i=1}^{n} l_{cu_i}$ and $v = \sum_{j=1}^{m} l_{dp_j}$. Assume $Y = max(u, v)$ In step 1, first, a bipartite graph is created which is equivalent to preparing a matrix which is constant time. Next, the assignment of weight the sumrate contribution needs to be calculated which is $O(Y^2)$. The complexity of the MBM algorithm is $O(Y^3)$. Analyzing each step of the MBM algorithm 3, it is seen that each step of the algorithm is not more than $O(Y^3)$. In the post-processing step, the complexity is $O(n^2)$. Thus the complexity of the total approach is $O(Y^3)$.

In Section IV, first an exhaustive search approach is presented. Later proposed solution approach is discussed. The proposed solution approach is divided into two steps. In the first step, the bipartite graph is formed and the appropriate weight is assigned. Note that, based on two objective functions the weight is calculated. Later multi-value bipartite matching algorithm is applied to the graph to get the intermediate solution. This solution is filtered by the post-processing approach to avoid assignments or power allocation which may lead to failure in meeting the individual demand sumrate.

V. RESULT ANALYSIS

A C++ program is used to write the code for the numerical simulation. Our research problem is a type of assignment problem. The main goal of the simulations is to find out how the D2D pairs are connected to the cellular UEs and choose the right power level. Based on this assignment, and using necessary equations mentioned in Section III the numerical values of SINR, sumrate, and interference are calculated.

We follow the similar simulation parameters as [10] and [11]. Our proposed algorithm performs consistently in this environment. The environment considers a single eNB which can be extended. The maximum distance allowed between the transmitter and receiver of a D2D pair is 15 meters as many consider that D2D communication takes place within

Algorithm 3 Multi Value Bipartite Matching Algorithm

```
procedure MBM($M$)
    Step 1: (Row Column Minimization)
        Deduct the row minimum from each element of that row.
            ▷ Each row will contain at least one zero value now.
        Deduct the column minimum from each element of that column.
            ▷ Each column will contain at least one zero value now.
    Step 2: (Opening Starring)
        Star an element - having the value zero and does not have any starred zero in its row and column.
    Make other row column unavailable.
            ▷ Unavailable the instance of any expanded node other than the selected instance as in Fig. 6 (a)
    Step 3: (Covering Column)
        Cover each columns that contain a starred zero.
        If the number of covered columns are equal to available columns go to Step 8 else go to Step 4.
    Step 4: (Prime Some Uncovered Zero)
        Prime an uncovered zero.
    Make other row column unavailable.
            ▷ Make unavailable the instance of any expanded node other than the selected instance as in figure 6
    if There exists a starred zero in the row containing primed zero. then
            Cover this row and uncover the column
    else
            Go to step 5
    end if
        Repeat Step 4 until there is no uncovered zero left.
    Step 5: (Increasing Starred Zero)
        Find a sequence comprising alternating prime and starred zeros in the following manner:
            • $z_0$: The uncovered primed zero identified in step 4.
            • $z_1$: The starred zero present in the column of $z_0$ (if available).
            • $z_2$: The prime zero located in the row of $z_1$ (if $z_1$ exists, $z_2$ will always exist).
        Continue this process until the sequence concludes at a primed zero lacking a starred zero in its column.
        Remove the star from each starred zero and apply a star to each primed zero. Eliminate all primes and reveal all previously covered rows and columns.
        Backtracking: Avail all unavailable row columns of same cellular and same D2D pair of erased Starred zero.
    Step 6: (Increasing Zeros)
        Find the smallest value which is not covered and add it to every element in the covered row and subtract it from each element in the uncovered column
        Go to step 7 removing all stars, prime and covering.
( See following page for remaining part of Algorithm 3)
    Step 7: (Next Starring)
(Continuation of Algorithm 3)
        Find all zeroes which do not have any starred zeros present in their row or column and star them.
    Make other row column unavailable.
            ▷ Unavailable the instance of any expanded node other than the selected instance as in figure 6
        Go to Step 4.
    Step 8: (Solution)
    return the solution $M$
end procedure
```

close proximity [66]. Generally, the macro-cell radius is 1000 m [67]. The individual sumrate demand of a Cellular UE, S_d^{demand} is selected randomly from a range of $1 \sim 3bps/Hz$ and the individual sumrate demand of a D2D pair, S_d^{demand} is selected randomly from a range of $1 \sim 15bps/Hz$. For analysis, the number of D2D pairs is varied from 10 to 90 where the number of cellular UE is kept fixed at 100. Each simulation result is an average of 20 separate runs for a certain scenario.

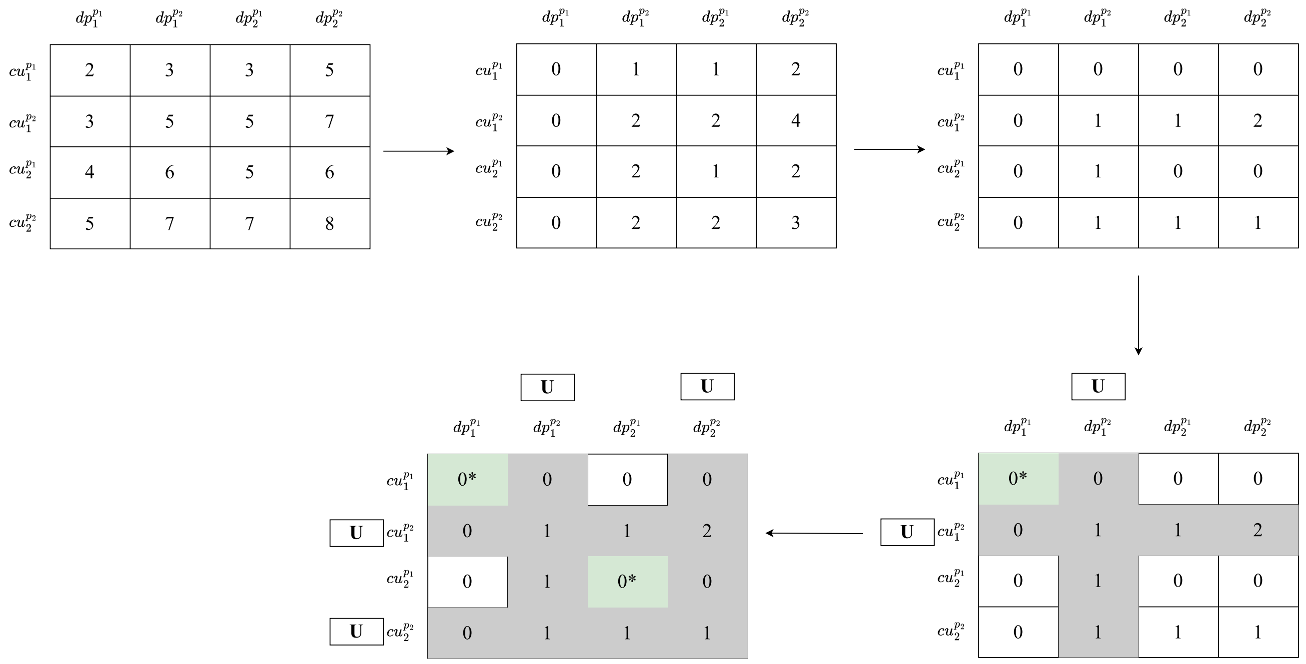
Our proposed algorithms are compared with existing capacity maximization in Section V-A and interference minimization in Section V-B to assess the effectiveness.

A. MAXIMIZATION OF TOTAL SYSTEM CAPACITY

For the numerical study, several existing algorithms are compared with the proposed solution. For the system capacity maximization problem, the proposed algorithm is compared with CCNC [12], genetic [29], and a random algorithm.

Figure 8 illustrates the comparison of total system capacity obtained by our proposed algorithm with the existing algorithms and it is noticed that our proposed algorithm obtains a substantial advantage in total system capacity over the other algorithms. Among these algorithms, the random algorithm obtained the lowest system capacity compared to others, which is almost 400 bps/Hz less than our algorithm on average. It can also be observed from Figure 8 that the genetic algorithm performed better at first and the overall performance of the genetic algorithm deteriorated gradually. For a genetic algorithm to perform at its peak, the population needs to be increased exponentially, assuming an increasing number of D2D pairs, which increases the required computation power. Since increasing the required computation power exponentially with respect to the number of D2D pairs is not feasible for real-life applications, we used a fixed population size of 50 in our implementation. While the fixed population value exceeded the required population for peak performance of the genetic algorithm, its performance started to deteriorate.

Though our objective is to maximize sumrate, it is also important to maintain a certain quality of service to the end



	$dp_1^{p_1}$	$dp_1^{p_2}$	$dp_2^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_1}$	2	3	3	5
$cu_1^{p_2}$	3	5	5	7
$cu_2^{p_1}$	4	6	5	6
$cu_2^{p_2}$	5	7	7	8

	$dp_1^{p_1}$	$dp_1^{p_2}$	$dp_2^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_1}$	0	1	1	2
$cu_1^{p_2}$	0	2	2	4
$cu_2^{p_1}$	0	2	1	2
$cu_2^{p_2}$	0	2	2	3

	$dp_1^{p_1}$	$dp_1^{p_2}$	$dp_2^{p_1}$	$dp_2^{p_2}$
$cu_1^{p_1}$	0	0	0	0
$cu_1^{p_2}$	0	1	1	2
$cu_2^{p_1}$	0	1	0	0
$cu_2^{p_2}$	0	1	1	1

			U		
		$dp_1^{p_1}$	$dp_1^{p_2}$	$dp_2^{p_1}$	$dp_2^{p_2}$
	$cu_1^{p_1}$	0*	0	0	0
U	$cu_1^{p_2}$	0	1	1	2
	$cu_2^{p_1}$	0	1	0	0
	$cu_2^{p_2}$	0	1	1	1

			U		U
		$dp_1^{p_1}$	$dp_1^{p_2}$	$dp_2^{p_1}$	$dp_2^{p_2}$
	$cu_1^{p_1}$	0*	0	0	0
U	$cu_1^{p_2}$	0	1	1	2
	$cu_2^{p_1}$	0	1	0*	0
U	$cu_2^{p_2}$	0	1	1	1

FIGURE 7. Step-by-step iterations of the MBM algorithm.

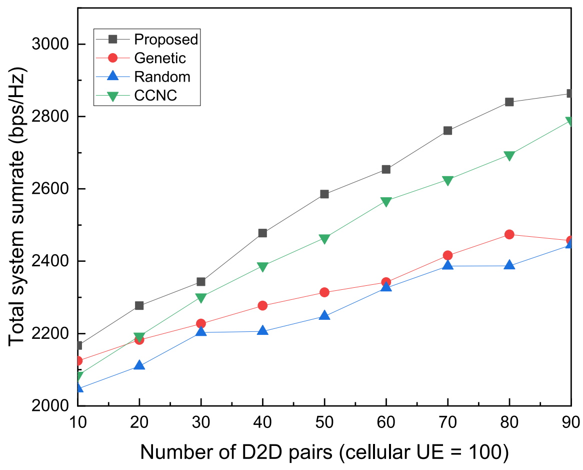


FIGURE 8. Comparison of total system capacity in sumrate maximization (number of cellular UE = 100).

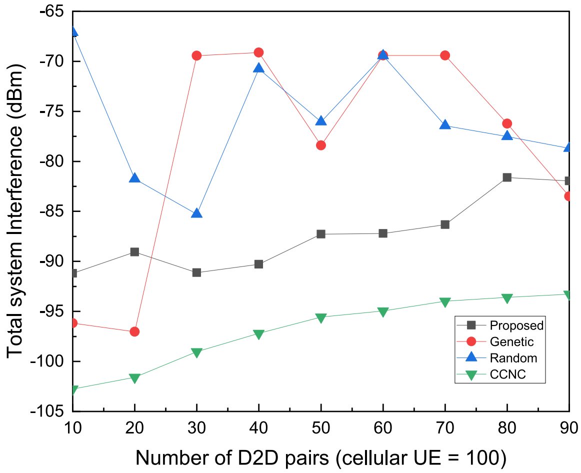


FIGURE 9. Comparison of total system interference in sumrate maximization (number of cellular UE = 100).

users with respect to the other performance metrics, such as interference, admission rate, fairness, etc. While achieving the maximum total system sumrate, our proposed algorithm achieved a comparable total system interference, which is on par with the existing prominent algorithms as depicted in Figure 9. Our proposed algorithm performed better than both CCNC with and without constraint in terms of total system interference as well as provided more stable performance than genetic and random algorithms for various numbers of D2D pairs.

The admission rate is a vital metric in terms of performance for a resource allocation algorithm. As observed from the figure 10, the proposed algorithm performs better than the genetic, random, and CCNC in most of the scenarios, which makes our algorithm give a higher fairness score than these algorithms for various numbers of D2D pairs as depicted in Figure 11.

The maximization of total system capacity leads to higher data throughput. It shows the upper bound of the network in terms of throughput. Higher data throughput and improved QoS can attract more subscribers and increase user satisfaction, ultimately leading to higher revenues for operators.

B. MINIMIZATION OF TOTAL SYSTEM INTERFERENCE

We compare the performance of our proposed algorithm, which was developed considering interference minimization

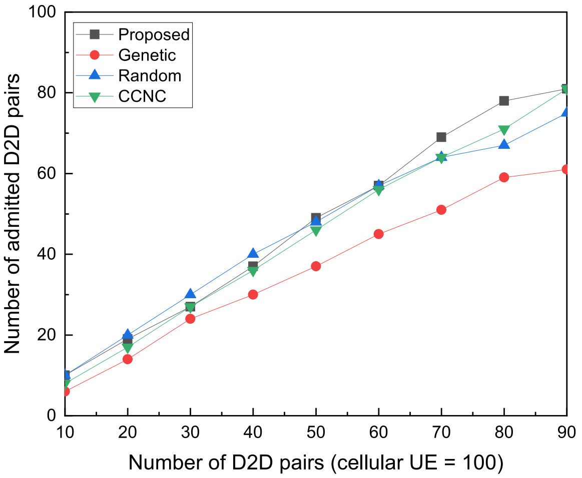


FIGURE 10. Comparison of admission rate of D2D in sumrate maximization (number of cellular UE = 100).

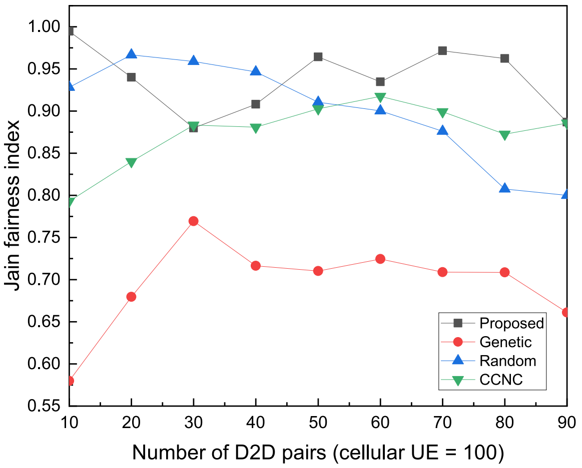


FIGURE 11. Comparison of jain fairness in sumrate maximization (number of cellular UE = 100).

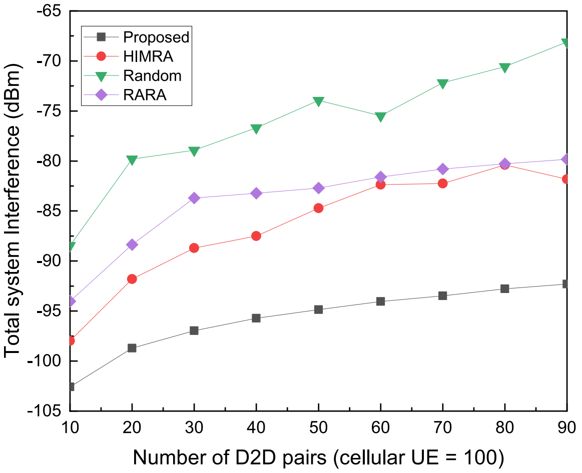


FIGURE 12. Comparison of total system interference in interference minimization (number of cellular UE = 100).

as an objective, with other interference minimization resource allocation algorithms, namely, HIMRA [65], RARA [16], and Random.

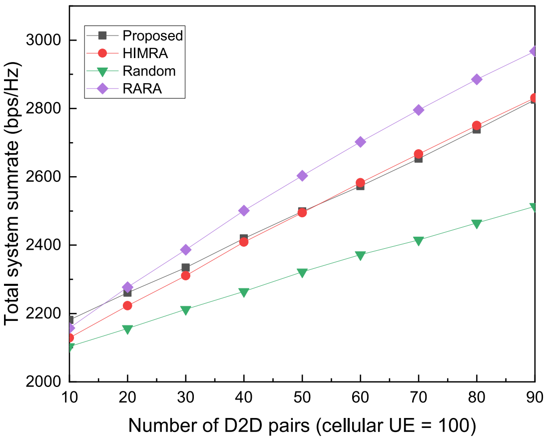


FIGURE 13. Comparison of total system capacity in interference minimization (number of cellular UE = 100).

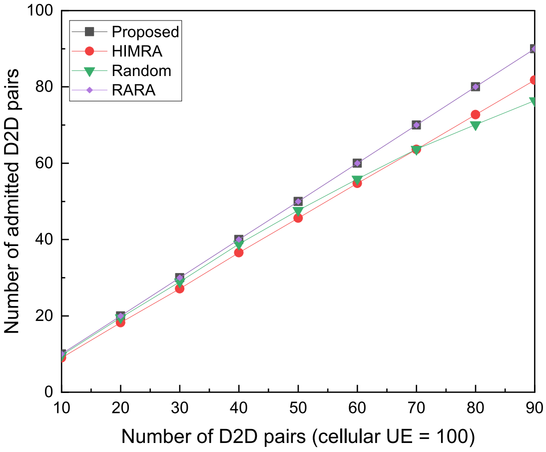


FIGURE 14. Comparison of admission rate of D2D in interference minimization (number of cellular UE = 100).

Figure 12 shows the total system interference obtained by our algorithm as well as other interference minimization resource allocation algorithms and it is observed that our proposed algorithm obtains the lowest interference for various number of D2D pairs. The Hungarian algorithm-based solution, HIMRA performed the closest to our proposed algorithm in terms of total system interference and the random algorithm performed the worst. Our algorithm achieved almost 20 dBm less interference on average than the random algorithm.

While achieving the lowest system interference, our proposed algorithm was able to achieve comparable performance in terms of total system capacity as well as shown in Figure 13. It achieved better system capacity than the random algorithm and almost similar total system capacity to the HIMRA algorithm.

Our algorithm also admits a higher number of D2D pairs than other interference minimization algorithms, as depicted in Figure 14 which is on par with the RARA algorithm.

Minimization of interference improves the overall quality of service experienced by users. The power consumption will be reduced as lower transmission power is acceptable to operate in low interference areas. Both operators and users will spend less on energy consumption and indirectly reduce carbon emissions.

VI. CONCLUSION

Over the past decade, the surge in device-to-device (D2D) communication has gained widespread traction, becoming integral in both industrial and personal realms due to the prevalence of smart handheld devices. This mode of communication facilitates various inter-device services, including file sharing and media content downloading. Our study specifically targeted inband underlay D2D communication, enabling direct interface between two user equipment (UEs) in close proximity, bypassing the eNodeB. Utilizing Resource Blocks (RBs) from a traditional cellular network for this purpose offers a myriad of advantages, such as enhanced spectrum efficiency, increased system capacity, diminished eNB traffic load, and reduced power consumption in devices. Moreover, inband underlay D2D communication not only presents gains in bit-rate, spectrum reuse, hop, and coverage but also aligns with the framework of LTE and subsequent generations (4G, 5G, and 6G), where an eNodeB supervises radio resource reuse for D2D communication. The challenge of interference generated by shared radio resources necessitates appropriate resource and power allocation mechanisms without compromising the target sumrate.

This paper addresses two optimization problems in this domain. While existing research presents various Resource Allocation (RA) algorithms, deterministic solutions are relatively scarce. Our study employs a Hungarian-based deterministic algorithm, achieving the theoretical maximum sumrate and minimum interference, showcasing superior performance compared to existing algorithms in mitigating total system interference, maximizing total system sumrate, and enhancing admission rates.

This paper does not consider one to many and many to many sharing approaches. Therefore, in the future, those variants could be analysed. It could be difficult to identify an optimal solution for many to many sharing approach. However, a Hungarian-based solution could be modified to address the same problem for many to many sharing approach as well on an approximate weight matrix. Study of a system model with different categories of D2D services is also required. As there are different RA algorithms available aiming at different scenarios and different goals, it is essential to combine this solution to suggest which algorithm should be deployed by an operator in different user demography with different demand rates.

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