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Transmission Power Control and Relay Strategy for Increasing Access Rate in Device to Device Communication

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ABSTRACT In cellular networks, Device to Device (D2D) communication can improve spectral efficiency by enabling proximity users to communicate directly without traversing the Base Station (BS). However, if not designed properly, the interference generated by D2D transmissions, may deteriorate the communication quality of the existing cellular and D2D users. In this paper, we study transmission power control-based interference management to increase access rate and sum rate while guaranteeing the Quality of Service (QoS) requirements for both D2D and cellular users. A four-step framework is proposed. First candidate D2D groups, potentially admissible for transmission, are arranged in order with respect to their distance from BS and required Signal to Interference and Noise Ratio (SINR). Next, upper and lower bounds on the transmission powers of the transmitters are calculated to determine the admissibility of the aspirant D2D group subject to the QoS requirements of the aspirant group, other scheduled D2D groups, and the cellular user. Then, relay-based communication protocol is considered for admitting the D2D groups that cannot be admitted directly. Finally, sum rate of each shared channel is improved through iterative incrementation of transmission powers of cellular and D2D transmitters constrained by the QoS requirements of all the admitted D2D groups and the cellular user and the existing sum rate. Simulation results show that the proposed framework can improve the access rate many folds across all the considered scenarios as compared to the baseline schemes. Moreover, higher access rates of the proposed scheme translate into significantly higher sum rates.

INDEX TERMS Access rate maximization, channel sharing, device to device communication, relay assisted D2D communication, transmission power control.

I. INTRODUCTION

Due to the rapid growth in communication technology, the number of connected devices has increased many folds in the last few years. By 2025, the number of connections among devices belonging to the Internet of Things (IoT) is expected to touch 30.9 billion-mark [1]. Due to this rapid increase in the number of connected devices, efficient management of the wireless spectrum has become imperative. In this regard, Device to Device (D2D) communication has been a key research direction. D2D communication enables devices in proximity to transfer data directly without traversing the network entities such as BS, thus mitigating the burden on network infrastructure. Direct communication between neighboring devices offers an opportunity for improving energy efficiency and latency. Moreover, higher throughput and access rates can be achieved through spatial reuse of the available resource blocks for D2D communication [2]. However, spatial reuse causes interference among concurrent transmissions which may deteriorate signal quality, thus making interference management a key challenge for D2D communication [3]–[5].

Several frameworks have been proposed for interference management by means of transmission power control in D2D communication systems. These frameworks can be broadly categorized as in-band [6]–[11] and out-band [12]–[16]. Inband refers to the sharing of the available licensed spectrum between D2D and regular traffic. It can be further classified

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as overlay where a part of the licensed band is dedicated to D2D traffic only and underlay where D2D and cellular users transmit over a common licensed band. The out-band model, on the other hand, refers to the utilization of unlicensed communication channels for D2D traffic. Both the deign choices, i.e., inband and outband D2D communication pose their own challenges. As such, the main challenge in the outband model is the lack of control over the interference from other wireless devices such as Bluetooth and WIFI operating in the same unlicensed band. In the Inband model, on the contrary, the cellular spectrum can be fully controlled by the BS. This offers an opportunity for centralized transmission power control for efficient interference management, which is a key concern in D2D communication.

Another important design decision vis-à-vis interference management is uplink/downlink resource sharing. Uplink spectrum offers better opportunity for interference management as it is often underutilized as compared to downlink spectrum in the frequency division duplexing based cellular systems [17], [18]. Moreover, from the view point of cellular user, uplink resource sharing in D2D communications only affects the BS thus simplifying interference management. Considering the complexities lied on the interference management for downlink resource sharing [19], [20], we argue the uplink resource sharing would offer better suit for interference management. Hence, in this work we will focus on uplink resource sharing for underlay D2D communication.

Interference management for uplink resource sharing using transmission power control in underlay cellular systems has been investigated in [21]–[37]. Attempting to limit D2D interference, the authors in [21] propose a backoff factor and a fixed booster factor in order to devise dynamic power control and limit D2D interference. Moreover, an interference limited area based on a predetermined interference to signal ratio was proposed in [22], where D2D users can share resources with a cellular user outside the interference limited area. However, these studies focus on either increasing the sum rate [21] or ensuring reliability of D2D communication [22]. The studies in [23]–[26] consider both reliability and sum rate simultaneously. In particular, the proposed schemes in [23], [26]–[30] aim at improving sum rate while considering QoS requirements of the cellular user only. In [27] aimed at maximizing the sum rate of D2D pairs while ensuring QoS requirement of cellular users, firstly, a heuristic algorithm is proposed for subcarrier assignment. Then successive convex approximation is employed to transform the non-convex power allocation problem into a series of convex subproblem which are then solved iteratively. Similarly aimed at guaranteeing QoS of cellular users, [28] proposes a two-step algorithm for many to many scenario where firstly a heuristic greedy method is proposed for resource allocation and then Lagrangian dual method is employed for power allocation. The algorithm in [29], jointly optimizes power and resource allocation for cellular users and D2D pairs by updating Lagrange multipliers. In [30] a fully distributed approach has been proposed where the problem is modeled as a Stackelberg game with pricing for ensuring QoS of cellular user. However, in [27]–[30] the resource allocation problem is formulated subject to the QoS requirement of the cellular users only while the QoS of D2D pairs is not guaranteed. In [24], [25], [31], [32], on the other hand, the QoS requirements of both cellular and D2D users have been considered. In [24], the D2D transmission power is chosen such that the additional interference experienced at the BS over the cellular link is kept at an acceptable level while the SINR of the D2D link is maximized. In [25], the authors formulate an optimization problem and find a solution where optimal power control for D2D and cellular users is devised to guarantee QoS requirements of both cellular and D2D users. In [31] aimed at maximizing the sum rate, joint resource allocation and mode selection between underlay and interlay modes have been investigated, while the successive interference cancellation (SIC) decoding constraint is considered. In [32], an algorithm for optimal resource allocation and throughput maximization in multicellular environment is proposed where the QoS requirements of both cellular and D2D users are guaranteed in the presence of inter and intra cellular interference.

Nevertheless, the aforementioned works consider channel sharing between one D2D pair and one cellular user and therefore do not fully utilize the available spectrum in terms of the number of serviceable D2D groups per channel and achievable sum rate. Some of the works such as [33]–[35] have proposed mechanisms that consider multiple D2D groups per channel. In [33], multiple D2D pairs are allowed to share a given channel with a cellular user in order to maximize the sum rate. The authors in [35] propose a distributed resource allocation algorithm for resource sharing between multiple D2D pairs and a cellular user. The resource allocation problem is formulated as a mixed strategy non-cooperative game and solution based on interference and power consumption minimization is proposed. However, the schemes proposed in [33]–[35] face issues such as inability to service D2D groups with relatively longer distances [34] between transmitters and receivers. Moreover, multicast D2D communication scenarios have not been considered. The methods proposed in [36], [37] consider D2D multicast. Aimed at improving network efficiency by maximizing sum throughput, [36], [37] formulate a resource allocation problem where feasible solution is first obtained by performing channel assignment followed by optimization of transmit power to maximize the throughput. Nevertheless, the use of relayed transmission for improvement in the sum and access rate has not been investigated.

Inspired by the aforementioned studies, in this paper, we propose a centralized underlay D2D communication framework where we focus on managing interference using transmission power control in order to maximize the access rate and thereby improve the sum rate by enabling channel sharing among one cellular user and one or more one-to-one and one-to-many D2D groups. Specifically, we propose a power control mechanism for interference management among simultaneous D2D and cellular transmissions for which we drive upper and lower bounds on the transmission powers of each aspirant transmitter. Moreover, we propose a mechanism for selection and use of relays in order to deal with situations where direct communication between D2D transmitter and D2D receivers may violate the QoS requirements of the scheduled transmissions. Furthermore, an iterative mechanism for the sum rate maximization of the shared channels is proposed.

Our contributions are as follows:

1) A weighted sum-based ordering of the candidate D2D groups is proposed whereby D2D groups are arranged in order (for admission consideration) based on their distance from the BS and their target SINR level. Incorporating target SINR results in improved access rate as compared to the only distance-based arrangement employed in [33]. The consequent increase in the access rate (Fig. 2) leads to increased system sum rate as more D2D groups can be scheduled to reuse the same resource.
2) A power control mechanism is proposed whereby we derive upper and lower bounds on the transmission powers of each aspirant transmitter subject to the QoS requirements of the aspirant D2D group, the cellular user, and other D2D groups scheduled to share channel with the cellular user. Unlike [28]–[30] where QoS guarantees are provided only for cellular users, subjecting the lower and upper bounds of D2D transmitters to the QoS requirements of the cellular and D2D users in the proposed scheme, results in guaranteeing the QoS requirement of all the users sharing the channel. Moreover, even though upper bounds have been used in the literature, though in different context, the derivation of upper bound has not been presented to the best of our knowledge. We believe, our derivation will help new researchers in understanding the rationale of the upper bound.
3) A relay-based transmission strategy is proposed that explores the possibility of selecting a relay node and carrying out relayed D2D transmission while keeping in view the QoS requirements of the cellular user, the scheduled D2D groups, and the aspirant D2D group. Using relays improves access and sum rate significantly as intermediate relay nodes allow both the original transmitter and the relay node to transmit with much smaller transmission powers as compared to direct communication. This results in lower interference levels thus creating room for more D2D groups. The use of relays improves the performance significantly as compared to non-relay based settings such as [36], [37].
4) Unlike most of the existing works [27]–[30] where the focus is on sum rate maximization, we address both access rate and sum rate maximization. In this regard, after D2D group admission phase, which aims at maximizing the access rate, the sum rate of each shared channel is further improved through iterative incrementation of the transmission powers of cellular and D2D transmitters constrained by the QoS requirements of all the admitted D2D groups and the cellular user and the existing sum rate.

The rest of the paper is organized as follows. In section II, we describe the system model and problem formulation. Then, in section III the methodology of the proposed framework is explained. Results are presented in Section IV. Finally, conclusions are presented in section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

In this work, we will investigate a centralized channel sharing model [38]–[40] for D2D communication underlaying cellular networks. Here we control transmission power to achieve spatial orthogonality among concurrent transmissions in order to increase the number of D2D groups that can share a given channel with a cellular user without violating the SINR requirements of the cellular and D2D users. In particular, we assume that there are a total M of candidate D2D groups that should coexist with N cellular users each of which occupies one of the N orthogonal channels[1] [8], [38], [41]. Moreover, a D2D group may consist of one transmitter and one or more than one receiver [42], [43] while the distance between a transmitter and each of its intended receivers must conform to an allowable distance.

All the links are assumed to experience independent block fading where the channel gain between any transmitter i and receiver j on a given subchannel is modelled by (1) [25], [27];

$$g_{i,j} = G\beta_{i,j}\Gamma_{i,j}d_{i,j}^{-\alpha} \tag{1}$$

where G, $\beta_{i,j}$, $\Gamma_{i,j}$, $d_{i,j}$ and α are the pathloss constant, fast fading gain from transmitter i to receiver j with exponential distribution, slow fading gain from i to j with log normal distribution, distance between i and j, and the pathloss exponent respectively.

We use uplink spectrum sharing [38]–[40] for D2D communication due to the reasons mentioned in section 1. In addition, we assume that the QoS requirement of both cellular and D2D users are represented in terms of target SINR [44], and the BS has the perfect Channel State Information (CSI) of all the links [25], [33]. Based on the CSI, the BS locally schedules cellular and D2D transmissions, i.e., it determines which D2D groups can share a given channel with the cellular user and what should be their transmission powers. Upon finalizing the schedule, the BS notifies the cellular user and the admitted D2D groups about the transmission powers they can use to transmit data.

B. PROBLEM FORMULATION

In this work we assume a single cell scenario [45] where given a pool of candidate D2D groups $\check{D}$ available for sharing a

[1] Our aim is to maximize the number of admitted D2D group in a given channel. Therefore, it is possible that the initially scheduled channels will accommodate all the available D2D groups. In such a case, the remaining channels will host only their corresponding cellular users.

given channel Ĥ with a cellular user Č, we aim at maximizing the number of admitted D2D groups Â that can share Ĥ with Č while guaranteeing the QoS requirements for all the users, i.e., Č and Â [25]. If Ŝ is the set of D2D groups that have been scheduled to share Ĥ with Č, then given Ŝ and Č, a new D2D group Ģ can be admitted if the target SINR of Ģ can be achieved without violating the minimum SINR requirements of Č and Ŝ [33].

Given the notations in Table 1, the D2D admission maximization problem can be represented as

$$\text{Maximize } (1 + \text{Ɲ})$$

$$\text{Subject to } £^{\check{C}} = \frac{P^{\check{C}}.g_{\check{C}}}{N + (\sum_i P^{\hat{A}_i}.h_{\hat{A}_i,B})} \geq £^{\check{C}}_{min}$$

$$\text{for} \quad \forall\ \hat{A}_i \epsilon \hat{A} \tag{2a}$$

$$£^{\hat{A}_i k} = \frac{P^{\hat{A}_i}.g_{\hat{A}_i k}}{N + P^{\check{C}}.h_{\check{C},\hat{A}_i k} + (\sum_{j \neq i} P^{\hat{A}_j}.h_{\hat{A}_j,\hat{A}_i k})}$$

$$\geq £^{\hat{A}_i}_{min} \text{ for } \quad \forall\ k \epsilon \hat{A}_i \text{ and } \hat{A}_i \epsilon \hat{A} \tag{2b}$$

$$P^{\check{C}} \leq P^{\check{C}}_{max} \tag{2c}$$

$$P^{\hat{A}_i} \leq P^{d2d}_{max} \text{ for } \quad \forall \hat{A}_i \epsilon \hat{A} \tag{2d}$$

Unlike [23]–[30] which focus on sum rate maximization, we formulate the problem as access rate maximization. The choice of problem modeling as access rate maximization is influenced by the following:

1. The number of connected devices is expected to increase many folds in the near future [1] thus over burdening the available spectrum. With this huge increase, simultaneous serviceability to a large number of devices becomes challenging. Therefore, there is a need to device mechanisms that can maximize spectral reuse while guaranteeing the QoS requirements of all the users.
2. Dense scenarios such as vehicle to vehicle communication during traffic congestion, public gatherings such as in case of demonstrations, stadiums etc. may generate significant demand for D2D connectivity over a limited spectral availability. Maximizing access rate with QoS guarantees creates a win-win situation for all.
3. In our opinion, in a high demand scenario such as those explained above, it is more appropriate to provide connectivity with QoS guarantees to majority instead of providing connectivity to a few with data rates much higher than the required data rates.

III. METHODOLOGY

In this section, we present the solution to the D2D admission maximization problem. We divide the problem into three steps. First, we set up a sequence in which the available D2D groups are considered for admission. Then, we define lower and upper bounds on the transmission power of each aspirant D2D transmitter to determine admissibility of the corresponding D2D group. Lastly, we introduce relay based D2D group admission to improve upon step 2. In addition, a sum rate maximization algorithm has been proposed, which aims at maximizing the sum rate of each channel through iterative incrementation of the transmission powers of cellular and D2D transmitters. The overall schematic of the proposed access rate and sum rate maximization frameworks are depicted in Fig. 1 and Fig. 3 respectively

TABLE 1. Frequently used notations.

Notations	Details
$\hat{H}$	*A Given Channel*
$\check{C}$	*Cellular user*
$\check{D}$	*Set of available D2D groups*
Ɲ	*Total number of admitted D2D groups*
$\hat{A}$	*Set of all the admitted D2D group*
N	*Noise*
Ģ	*Aspirant D2D group*
$\hat{S}$	*The set of D2D groups admitted before Ģ*
$C^{Ģ}$	*The criteria node for the aspirant group Ģ*
P^x	*Transmission power of the transmitter belonging to x*
$P^{\check{C}}_{max}$ and P^{d2d}_{max}	*Maximum Allowed transmission powers of cellular and D2D transmitters respectively*
T^x	*The transmitter belonging to x*
Pr^x_j	*Power received by the receiver j of group x*
Pr^{BS}	*Power received at the BS.*
$£^x$	*SINR Achieved by the receivers/criteria node in group x*
$£^x_{min}$	*Target SINR of x*
I_x and I^x_j	*Interference level at node x and interference level at receiver j ϵ group x respectively*
$h_{x,y}$	*Interference Channel gain from the transmitter in group x/cellular user x to the criteria node in y.*
$h_{x,yk}$	*Interference Channel gain from the transmitter in group x/cellular user x to receiver k in Group y*
$h_{x,B}$	*Interference Channel gain from the transmitter in group x to BS*
g_x	*Channel gain from the transmitter belonging to group x to the criteria node of group x,*
g_{xk}	*Channel gain from the transmitter belonging to group x to the receiver k ϵ group x*
$g_{\check{C}}$	*Channel gain from the cellular user to the BS*

A. SEQUENCING D2D GROUPS

In a channel sharing situation, where multiple D2D groups share a channel with a cellular user, the BS, by the virtue of its centralized position, is expected to experience the highest amount of interference. Without loss of generality, the distance between an interferer and interfered node has a major impact on the corresponding level of interference at the interfered node. Therefore, we can argue that multiple D2D transmitters, located farther away from the BS cause lesser interference to the BS as compared to the same or possibly smaller number of D2D transmitters located relatively near to the BS. Thus, keeping in mind the constraints in (2) (specifically 2(a)), it can be further argued that more D2D groups can be scheduled to share the channel with a cellular user if the D2D groups that are located farther away from the BS are considered first. However, distance is not

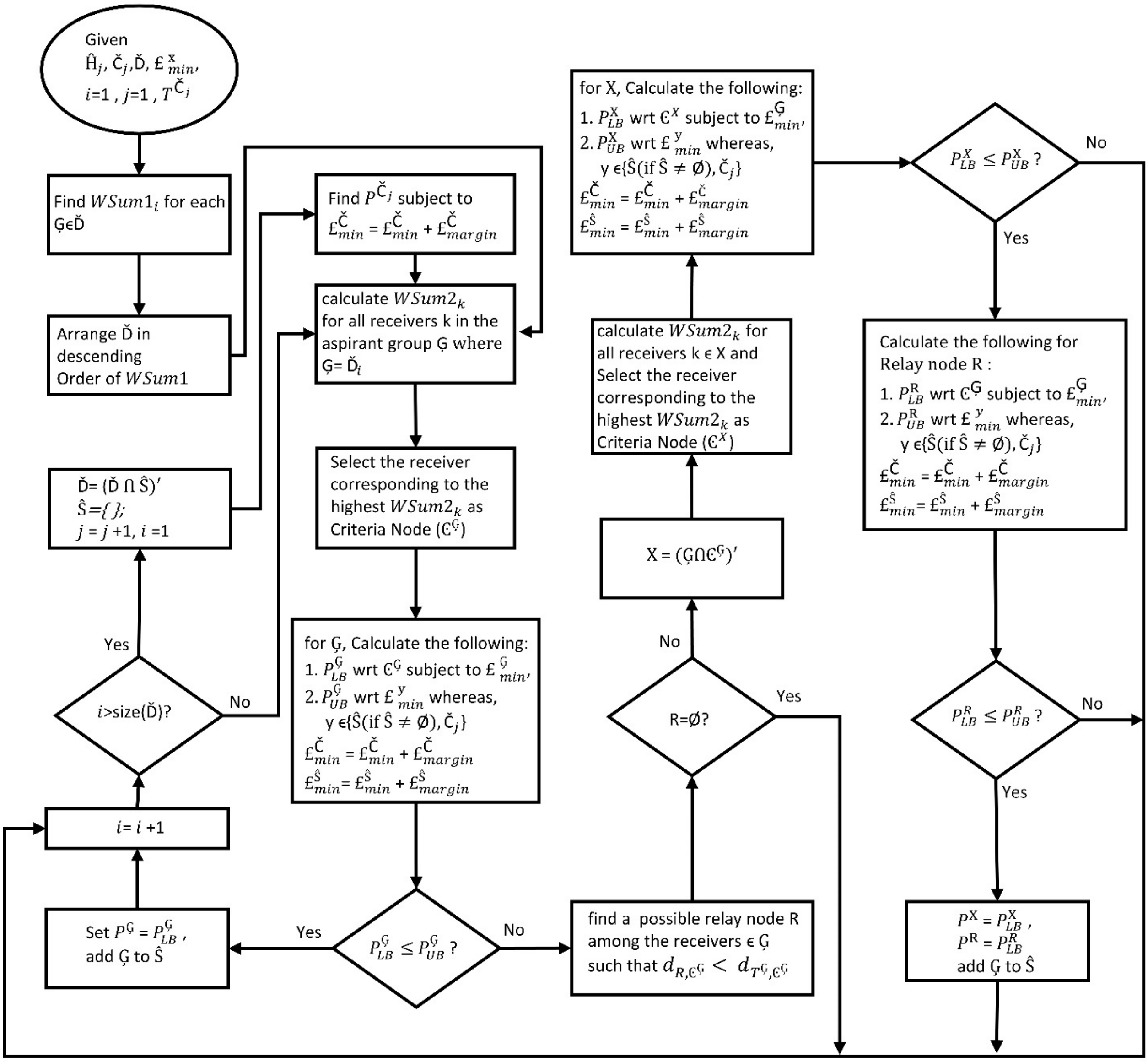


FIGURE 1. Flow diagram of access rate maximization.

the only factor that dictates the level of interference that a D2D transmitter may cause at BS. The transmission power of a D2D transmitter, which depends on the target SINR of the corresponding D2D group, also affects the interference level at the BS. Therefore, we claim that D2D groups should be considered for admission in the descending order of the weighted sum of their target SINR and the distance of the corresponding D2D transmitter from the BS as follows.

$$WSum1_i = w1 \times norm\left(d_{Ti,BS}\right) + \frac{w2}{norm\,(SINR_i)} \quad (3)$$

where $d_{Ti,BS}$ is the distance between the transmitter of group i and the BS.

The improvement in the number of admitted D2D groups brought about by the proposed ordering method is highlighted in Fig. 2, which shows the number of admitted D2D groups when the channel sharing method proposed in the subsection B of section 3 is used to schedule the same sets of available D2D groups in the descending order of distance only, in the descending order of the weighted sum defined in (3) and without considering any order. Similar to [46] where the number of available D2D groups increases from 5 to 40, in Fig. 2 we assume that the number increases from 10 to 50 with an increment of 10.

B. CHANNEL SHARING

In order to realize channel sharing between one cellular and multiple D2D users, transmission powers of the transmitters must be regulated such that the constraints in (2) are satisfied.

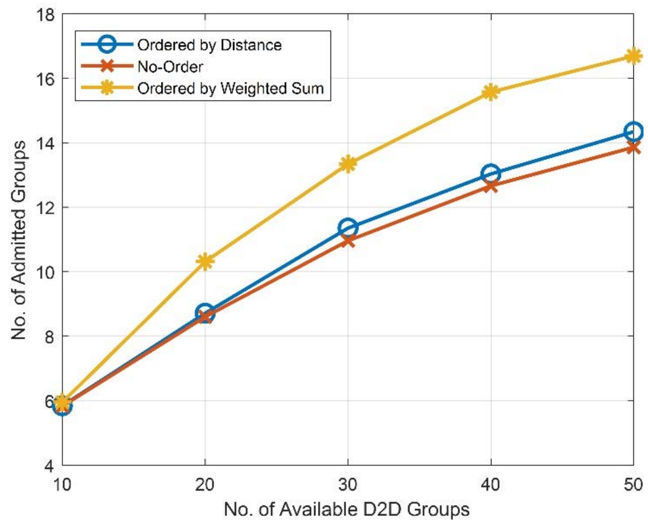


FIGURE 2. **Number of Admitted groups vs different number of available nodes for admitting D2D groups without any order, ordered by distance, and ordered by weighted sum of distance and SINR. Number of available channels = 1, allowed range = 21-40 meters and the number of available D2D groups = 10-50.**

In this regard, initially, the transmission power of the cellular user is estimated by (4), where the target SINR $£^{Č}_{min}$ is augmented with $£^{Č}_{margin}$ to compensate for the increase in interference that the BS may experience when D2D groups are admitted to share the channel with the cellular user.

$$P^{Č} = \frac{(£^{Č}_{min} + £^{Č}_{margin}) * (I_{BS} + N)}{g_{Č}} \quad (4)$$

After determining $P^{Č}$, D2D groups are considered for admission in the predefined order detailed in the subsection A of section 3. The admission process of a D2D group can be divided into two parts: Criteria node selection and D2D group admission based on upper bound (UB) and lower bound (LB) on the transmission power of the aspirant D2D transmitter.

1) CRITERIA NODE SELECTION

Given a D2D group Ģ having multiple receivers all of which have the same target SINR, the criteria node $Ȼ^{Ģ}$ for group Ģ can be defined as a node among the receivers in Ģ for which the minimum transmission power required to satisfy the target SINR is highest among all the receivers in the group. Therefore, if the transmitter sets its transmission power based on $Ȼ^{Ģ}$, all receivers in the group can be guaranteed to achieve the target SINR. Intuitively, the node farthest from the transmitter among the intended receivers can become the criteria node as the received power is inversely proportional to the distance between transmitter and receiver. However, if the transmission power is set based on the criteria node that is selected considering only the distance, then a relatively nearby node with interference level much higher than the criteria node may not achieve the target SINR. Therefore, we propose that $Ȼ^{Ģ}$ is selected based on the weighted sum of the normalized values of the distance between the transmitter and the receivers and the level of interference at the receivers (5). Then, the criteria node will be the node corresponding to the highest weighted sum.

$$WSum2_i = w3 \times norm(I) + w4 \times norm(d_{Tx,i}) \quad (5)$$

where *w3* and *w4* are assigned to have an equal value of 0.5, I is the interference level at receiver $i \epsilon Ģ$, and $d_{Tx,i}$ is the distance between the transmitter and node i.

2) DETERMINING LB AND UB ON THE TRANSMISSION POWER OF AN ASPIRANT D2D GROUP

In order to be admitted to a shared channel Ĥ, the transmission power of the transmitter $T^{Ģ}$ belonging to an aspirant D2D group Ģ must be set to a level $P^{Ģ}$ such that the following three constraints are satisfied:

a. The achieved SINR at the criteria node of group Ģ must be greater than or equal to the target SINR $£^{Ģ}_{min}$.

$$\frac{P^{Ģ}.g_{Ģ}}{N + P^{Č}.h_{Č,Ȼ^{Ģ}} + (\sum_i P^{Ŝ_i}.h_{Ŝ_i,Ȼ^{Ģ}})} \geq £^{Ģ}_{min} \quad (6a)$$

where $h_{Č,Ȼ^{Ģ}}$ and $h_{Ŝ_i,Ȼ^{Ģ}}$ represents the gain of the interference channel between Č and $Ȼ^{Ģ}$ and the gain of the interference channel between the transmitter of group $Ŝ_i$ and $Ȼ^{Ģ}$, respectively.

b. The additional interference caused by the transmitter ϵ Ģ (i.e. $T^{Ģ}$) to the BS and to the already scheduled D2D groups must not cause their respective SINRs to fall below their respective target SINR levels, i.e., the following constraints must be satisfied.

$$\frac{P^{Č}.g_{Č}}{N + (\sum_i P^{Ŝ_i}.h_{Ŝ_i,B}) + P^{Ģ}.h_{Ģ,B}} \geq £^{Č}_{min} \text{ for } \forall\, Ŝ_i \epsilon Ŝ \quad (6b)$$

$$\frac{P^{Ŝ_i}.g_{Ŝ_ik}}{N + P^{Č}.h_{Č,Ŝ_ik} + (\sum_{j \neq i} P^{Ŝ_j}.h_{Ŝ_j,Ŝ_ik}) + P^{Ģ}.h_{Ģ,Ŝ_ik}} \geq £^{Ŝ_i}_{min} \text{ for } \forall\, k \epsilon Ŝ_i \text{ and } Ŝ_i \epsilon Ŝ,\ Ŝ_j \epsilon Ŝ \quad (6c)$$

c. $P^{Ģ}$ must not exceed the maximum allowed D2D transmission power i.e.,

$$P^{Ģ} \leq P^{d2d}_{max} \quad (6d)$$

The minimum required transmission power that satisfies the constraint in (6a) serves as the lower bound on the transmission power of $T^{Ģ}$. However, if the lower bound violates the constraint (6d), then the corresponding group Ģ is considered ineligible for admission. In such a case, the upper bound on the transmission power of $T^{Ģ}$ is not calculated. Nevertheless, if both (6a) and (6d) are satisfied, then we determine the upper bound on the transmission power of $T^{Ģ}$

defined as the maximum transmission power level with which $T^{Ģ}$ can transmit without violating the constraints in (6b) and (6c). If the upper bound violates (6d), then the upper bound on the transmission power of $T^{Ģ}$ is set to P^{D2D}_{max}.

In the following text, the lower and upper bounds on the transmission power of the transmitter $T^{Ģ}$ belonging to an aspirant D2D group Ģ are formulated.

a: LOWER BOUND

SINR is the ratio of the received signal strength to the sum of interference and noise. Therefore, given a target SINR $£^{Ģ}_{min}$ for a D2D group Ģ, the minimum received signal strength at the criteria node $Ͼ^{Ģ}$ that can achieve $£^{Ģ}_{min}$ is calculated as follows:

$$Pr^{Ͼ^{Ģ}} = £^{Ģ}_{min} * (I_{Ͼ^{Ģ}} + N) \tag{7}$$

In general, for a given transmission power P_t and channel gain g between a transmitter and receiver, the power received P_r at the receiver is given by

$$P_r = P_t * g$$

Therefore,

$$Pr^{Ͼ^{Ģ}} = P^{Ģ} * g_{Ģ} \tag{8}$$

Substituting *LHS* in (7) with *RHS* of (8) and substituting $I_{Ͼ^{Ģ}}$ in (7) with the total interference level at $Ͼ^{Ģ}$, i.e., $(\sum_i P^{\hat{S}_i}.h_{\hat{S}_i,Ͼ^{Ģ}}) + P^{\check{C}}.h_{\check{C},Ͼ^{Ģ}}$, the lower bound on the transmission power of $T^{Ģ}$ is given by (9), as shown at the bottom of the next page.

The margin $£^{Ģ}_{margin}$ is added to compensate for the additional interference that group Ģ may experience if further groups are scheduled to share the same channel.

b: UPPER BOUND

The upper bound on the transmission power of $T^{Ģ}$ corresponds to the constraints in (6b) and (6c), which can be summarized as follows:

$$£^{\check{C}}_{min} \le £^{\check{C}}_{k} \text{ and } £^{\hat{S}_i}_{min} \le £^{\hat{S}_i}_{k} \text{ for } \quad \forall\, k\epsilon\{\check{C}, \hat{S}_i\} \text{ and } \hat{S}_i\epsilon\hat{S}$$

where $£^{\check{C}}_{k}$ and $£^{\hat{S}_i}_{k}$ represent the achieved SINR levels of the receiver $k\epsilon\check{C}, \hat{S}_i$.

For the sake of simplicity and brevity, we generalize and combine the above two inequalities by defining a set U such that $U = (\check{C} \bigcup \hat{S})$, then the above two inequalities can be represented in general form as

$$£^{U_i}_{min} \le £^{U_i}_{k} \text{ for } \quad \forall\, k\epsilon U_i \text{ and } U_i\epsilon U \tag{10}$$

In general, the SINR at a receiver $k\epsilon U_i$ can be represented as

$$£^{Ui}_{k} = \frac{Pr^{U_i}_{k}}{I^{U_i}_{k} + N} \text{ for } \quad \forall\, k\epsilon U_i \tag{11}$$

Therefore, by substituting RHS of (10) with the RHS of (11), we get

$$£^{Ui}_{min} \le \frac{Pr^{U_i}_{k}}{I^{U_i}_{k} + N} \text{ for } \quad \forall\, k\epsilon U_i \tag{12}$$

where $Pr^{U_i}_{k}$ represents the power received at the receiver k of group U_i or the BS (if $T^{U_i} = \check{C}$) from the corresponding transmitterT^{U_i}; and $I^{U_i}_{k}$ is the interference level at the receiver k of the group U_i or at the BS (if $T^{U_i} = \check{C}$).

The Lower bound on the transmission power of transmitter $T^{Ģ}$ is known from (9). Therefore, let

$$P^{Ģ} = P^{Ģ}_{LB} \tag{13}$$

Then, the interference that $T^{Ģ}$ will cause at user k of group U_i is given as:

$$\boldsymbol{I^{U_i}_{k,Ģ} = P^{Ģ}} \times \boldsymbol{h_{Ģ,U_ik}} \text{ for } \quad \forall\, \boldsymbol{k\epsilon U_i} \tag{14}$$

As $I^{U_i}_{k,Ģ}$ is the additional interference caused by $T^{Ģ}$ to the receiver $k\epsilon U_i$, therefore it is added in the denominator of (12) to get

$$£^{Ui}_{min} \le \frac{Pr^{U_i}_{k}}{I^{U_i}_{k,Ģ} + I^{U_i}_{k} + N} \text{ for } \quad \forall\, k\epsilon U_i \tag{15}$$

whereas $I^{U_i}_{k}$ is the level of interference at receiver k from sources other than $T^{Ģ}$ i.e., $T^{\hat{S}_i}$ and $T^{\check{C}}$.

Substituting $I^{U_i}_{k,Ģ}$ in (15) with the RHS of (14),

$$£^{U_i}_{min} \le \frac{Pr^{U_i}_{k}}{(P^{Ģ} \times h_{Ģ,U_ik}) + I^{U_i}_{k} + N} \text{ for } \quad \forall\, k\epsilon U_i \tag{16}$$

which gives us upper bound on $P^{Ģ}$ vis-à-vis one particular pair/group U_i (17).

$$P^{Ģ} \le \frac{1}{h_{Ģ,U_ik}} \left(\frac{Pr^{U_i}_{k}}{£^{U_i}_{min}} - I^{U_i}_{k} - N \right) \text{ for } \quad \forall\, k\epsilon U_i \tag{17}$$

The upper bound on $P^{Ģ}$ vis-à-vis all groups in U is given as

$$P^{Ģ}_{UB} = min \left(\frac{1}{h_{Ģ,U_ik}} \left(\frac{Pr^{U_i}_{k}}{£^{U_i}_{min}} - I^{U_i}_{k} - N \right) \right) \text{ for } \quad \forall\, U_i\epsilon U \tag{18}$$

Note that "less than or equal to (≤)" sign in (17) has been replaced with "equals (=)" sign in (18) to acquire upper bound value on transmitter $T^{Ģ}\epsilon$ Ģ.

i) D2D GROUP ADMISSION

Given $P^{Ģ}_{LB}$ and $P^{Ģ}_{UB}$ for a transmitter $T^{Ģ}\epsilon$ Ģ, the aspirant group Ģ is admitted to the shared channel Ĥ using transmission power $P^{Ģ} = P^{Ģ}_{LB}$ if

$$P^{Ģ}_{LB} \le P^{Ģ}_{UB} \tag{19a}$$

$$P_{LB}^{Ģ} \leq P_{max}^{Ģ} \tag{19b}$$

The satisfaction of (19a) implies that if $T^{Ģ}$ transmits with a transmission power level of $P_{LB}^{Ģ}$, then the target SINR of Ģ can be achieved without causing the achieved SINRs of any of the previously admitted groups and the cellular user to fall below their target SINR levels, i.e., all the constraints in (6a-c) are satisfied.

However, if the lower bound is not less or equal to the upper bound i.e.

$$P_{LB}^{Ģ} > P_{UB}^{Ģ} \tag{20}$$

then, admitting the group Ģ to Ĥ will result in failure of the transmissions of one or more of the other D2D groups and/or the cellular user scheduled to transmit on Ĥ. Therefore, the aspirant group Ģ cannot be admitted directly if (20) is true. In the next section, we propose a relay-based approach where we explore the possibility of admitting those D2D groups for which $P_{LB}^{Ģ} > P_{UB}^{Ģ}$.

C. RELAY BASED ADMISSION

Relay based D2D group admission is considered for the D2D groups that cannot be admitted directly because of the reasons detailed in the previous section. In such a case, one of the nodes among the intended receivers of the aspirant group Ģ is employed as a relay node subject to the following constraint.

$$d_{R,Ȼ^{Ģ}} < d_{T^{Ģ},Ȼ^{Ģ}} \tag{21}$$

where R, $T^{Ģ}$, $Ȼ^{Ģ}$ and d represent the relay node, the actual transmitter $T^{Ģ} \epsilon$ Ģ, the criteria node $Ȼ^{Ģ} \epsilon$Ģ and the distance between the given pair of nodes respectively.

Employing relays essentially converts one hop D2D group where one transmitter transmits with relatively high transmission power to a two-hop network where two transmitters i.e., $T^{Ģ}$ and R transmit with lower transmission powers; thus improving the chances of causing lesser aggregate interference to the BS and the receivers in other admitted groups. Moreover, as relay node R is employed for relaying signals to the criteria node $Ȼ^{Ģ}$, the lower bound on the transmission power of actual sender $T^{Ģ}$ is recalculated based on a new criteria node $Ȼ^{X}$ that is selected from set X according to the procedure explained in the subsection B of section III, where set X is given by (22).

$$X = (Ģ \cap Ȼ^{Ģ})' \tag{22}$$

Moreover, as the scope of $T^{Ģ}$ is now group X ⊆ Ģ, therefore, let

$$T^{Ģ} = T^{X} \tag{23}$$

The new criteria node $Ȼ^{X}$ may or may not be the relay node. Nevertheless, if the minimum transmission power of T^{X} is determined based on the criteria node $Ȼ^{X}$ of group X, it will result in achieving the required SINR threshold at the relay node as $R \epsilon$X. Moreover, the lower bound on the transmission power of R is calculated relative to $Ȼ^{Ģ}$, as R is employed to access $Ȼ^{Ģ}$. Then, given transmitter T^{X} and relay node R, Ģ can be admitted if the following are true.

a. The target SINR of the group Ģ can be achieved i.e.

$$\frac{P_{LB}^{X}.g_{X}}{N + P^{\check{C}}.h_{\check{C},X} + (\sum_i P^{\hat{S}_i}.h_{\hat{S}_i,X})} \geq £_{min}^{Ģ} \text{ for } \forall\ \hat{S}_i \epsilon \hat{S} \tag{24a}$$

$$\frac{P_{LB}^{R}.g_{R}}{N + P^{\check{C}}.h_{\check{C},R} + (\sum_i P^{\hat{S}_i}.h_{\hat{S}_i,R})} \geq £_{min}^{Ģ} \text{ for } \forall\ \hat{S}_i \epsilon \hat{S} \tag{24b}$$

It is important to mention that the interference caused by the relay node to the receivers in X and the interference caused by the actual transmitter to the intended receiver of the relay node is managed by adding the time shifted versions of the signals from the two transmitters. This makes sense as we assume that the relay node will act as repeater and simply boost the signal coming from the actual transmitter.

b. The aggregate interference from the group Ģ, i.e., from the transmissions of T^{X} and R must not violate the minimum SINR requirements of Č and $\hat{S}_i$ i.e. the constraints in (25) must be satisfied. The aggregate interference depends on the Lower bound transmission powers of $T^{Ģ}$ and $R^{Ģ}$ which can be calculated using equation 10.

$$\frac{P^{\check{C}}.g_{\check{C}}}{N + (\sum_i P^{\hat{S}_i}.h_{\hat{S}_i,B}) + P_{LB}^{X}.h_{X,B} + P_{LB}^{R}.h_{R,B}} \geq £_{min}^{\check{C}} \text{ for } \forall\ \hat{S}_i \epsilon \hat{S} \tag{25a}$$

$$\frac{P^{\hat{S}_i}.g_{\hat{S}_i k}}{N + P^{\check{C}}.h_{\check{C},\hat{S}_i k} + (\sum_{j\neq i} P^{\hat{S}_j}.h_{\hat{S}_j,\hat{S}_i k}) + P_{LB}^{X}.h_{X,\hat{S}_i k} + P_{LB}^{R}.h_{R,\hat{S}_i k}} \geq £_{min}^{\hat{S}i}$$
$$\text{for } \forall\ k \epsilon \hat{S}_i \text{ and } \hat{S}_i \epsilon \hat{S},\ \hat{S}_j \epsilon \hat{S} \tag{25b}$$

D. SUM RATE MAXIMIZATION

After the D2D groups have been assigned to their respective channels, the overall system sum rate is improved by maximizing the sum-rate of each channel $\hat{H}_z$ through power control (Fig. 3). As the sum rate maximization operation

$$P_{LB}^{Ģ} = \frac{(£_{min}^{Ģ} + £_{margin}^{Ģ}) * \left((\sum_i P^{\hat{S}_i}.h_{\hat{S}_i,Ȼ^{Ģ}}) + P^{\check{C}}.h_{\check{C},Ȼ^{Ģ}} + N\right)}{g_{Ģ}} \tag{9}$$

is carried out locally for each channel $\hat{H}_z$, therefore, the operations in one channel do not affect the operation of another channel. Hence, for the sake of simplicity and brevity, we assume that there exists only one channel $\hat{H}$ to which the sum rate maximization technique is applied.

We define T^x as the transmitter belonging to x, where x can be a D2D group or a cellular user-BS pair, R_j^x as the set of intended receivers j in group/pair $x \epsilon\ \hat{H}$, R_m (26) as the set of all the unintended receivers m of T^x on channel $\hat{H}$ i.e.

$$R_m = (R_j^x \cap R_{all})' \tag{26}$$

whereas R_{all} is the set of all the receivers on channel $\hat{H}$.

Channel sum rate of a given channel $\hat{H}$ is improved iteratively. During each iteration i, each $T^x \epsilon \hat{H}$ is considered for power increment in sequential manner. If the transmission by a given $T^x \epsilon \hat{H}$ with incremented transmission power P_{inc}^x (27) does not violate the two constraints given below, the transmission power of T^x is set to the incremented power level P_{inc}^x.

Constraint 1: The transmission from the transmitter $T^x \epsilon\ \hat{H}$ with incremented transmission power P_{inc}^x must not violate the target SINRs of other D2D groups and the cellular user admitted to $\hat{H}$.

Constraint 2: The transmission from transmitter $T^x \epsilon \hat{H}$ with incremented transmission power P_{inc}^x must result in increasing the sum-rate of channel $\hat{H}$.

For every iteration i the incremented transmit power P_{inc}^x of the transmitter $T^x \epsilon\ \hat{H}$ is determined using (27).

$$P_{inc}^x = P^{ini\_x} + i \times \hat{I}_x \tag{27}$$

whereas P^{ini_x} is the initial transmission power of T^x and i is the iteration counter. Moreover $\hat{I}_x$ is the transmission power increment which is calculated using (28) where Γ is the total number of iterations. Note that P_{UB}^x for all transmitters is recalculated at the start of sum-rate maximization function.

$$\hat{I}_x = \frac{\left(P^{ini\_x} - P_{UB}^x\right)}{\Gamma} \tag{28}$$

Then the SINR's and data rates of the intended receivers of T^x are calculated vis-à-vis P_{inc}^x using (29) and (30) respectively.

$$£_j^{x*} = \frac{P_{inc}^x \times g_{xj}}{N + I_j^x} \tag{29}$$

$$DR_j^{x*} = B \times log2\left(1 + £_j^{x*}\right) \tag{30}$$

where g_{xj}, I_j^x and DR_j^{x*} are the channel gain from T^x to its intended receiver j, the interference level at receiver j and the updated data rate of receiver j respectively.

Similarly, the interference powers at all the unintended destinations R_m are updated vis-à-vis P_{inc}^x followed by the calculations of their respective updated SINRs and data rates using (31) and (32)

$$£_m^* = \frac{Pr_m}{N + I_{inc}^x + I_O} \tag{31}$$

$$DR_m^* = B \times log2\left(1 + £_m^*\right) \tag{32}$$

where Pr_m, I_{inc}^x and I_O represent the power received at node m, interference from T^x to m and interference from other transmitters to m respectively. Moreover, DR_m^* represents the updated data rate of receiver m.

If the SINRs of all the receivers (all intended and unintended receivers of T^x) are above their respective SINR thresholds, then the overall updated sum-rate of the channel is calculated using (33).

$$SR_{\hat{H}}^{x*} = \sum_{a=1}^{NAG} \sum_{b=1}^{NR} Blog2(1 + £_{a,b}^*) \tag{33}$$

where NAG is the number of admitted groups, NR is the number of receivers in each group and $SR_{\hat{H}}^{x*}$ is the overall system sum rate after T^x's transmission with transmission power P_{inc}^x.

If the updated sum rate $SR_{\hat{H}}^{x*}$ is higher than the previous sum rate i.e. $SR_{\hat{H}}^{(x-1)*}$, then the transmission power of transmitter T^x and the received power levels Pr_j^{x*} at the intended destination(s) of T^x are updated to P_{inc}^x and $Pr_j^x = P_{inc}^x \times g_{xj}$ respectively. Likewise, the SINR levels, and the interference levels at all the nodes are updated. In each iteration, the same process is repeated sequentially for all the groups admitted to a given channel. The process continues until the channel sum rate cannot be increased any more or the maximum number of iterations is reached. It should be noted that the aggregate sum rate achieved at the end of any iteration i is given as input to the next iteration $i + 1$.

IV. NUMERICAL SIMULATION

The simulation environment is set as follows:

Node Deployment: We consider a single cell network where cellular users and D2D users are deployed uniformly across the simulation area. Similar to [45] where the number of available D2D pairs per cell is 48, the number for each range in Fig. 4 is assumed to be 50. Moreover, similar to [46] where the number of available D2D groups increases from 5 to 40, we assume that the number increases from 10 to 50 with an increment of 10 in case of Fig 5. Whereas in Fig. 6 and 7 and the total number of available D2D groups is 50 irrespective of the number of available channels or the sparsity level. All the groups are randomly deployed over the simulation area according to a uniform distribution. The choice of fixed number of predefined D2D groups is influenced by the ease of analysis that known number of available groups offer over the arbitrary case where all the nodes are deployed randomly over the simulation area and the number of available D2D groups is determined by the distance between the nodes.

Allowed Distance: The distance between the transmitter and receivers of a D2D group has a huge impact on the performance of a D2D communication system. Therefore, the proposed and compared schemes are subjected to different distance settings that are mentioned in the figure details. Our allowed distance ranges are similar to [31] where the ranges vary from 10 to 80.

Notations	Details
Γ	Number of iterations
i	Iteration index
NAG	Number of admitted Groups
x	Index of the D2D group or cellular pair under consideration.
R_j^x	Set of intended receivers in group x
T^x	The transmitter $\in x$
R_m	Set of unintended receivers m of T^x
$£_{min}^{\,x}$	SINR target of group/pair x
P^{ini_x}	Initial transmission power of T^x
P_{UB}^x	Upper bound on the transmission power of T^x
Pr_j^x	Power received at intended receiver j in group/pair x from T^x
I_m	Interference level at receiver m
$£_j^x$	SINR of the intended receiver j of T^x
$£_m$	SINR of the unintended receiver m of T^x
DR_j^{x*}	Updated data rate of intended receiver j of T^x
DR_m^*	Updated data rate of unintended receiver m of T^x
$SR_{\hat{H}}^i$	Sum rate during iteration i
$SR_{\hat{H}}^{x*}$	Overall sum rate after T^x's transmission with power P_{inc}^x
P^x	Transmission power of x in the previous iteration
*	Indicates update of the associated variable

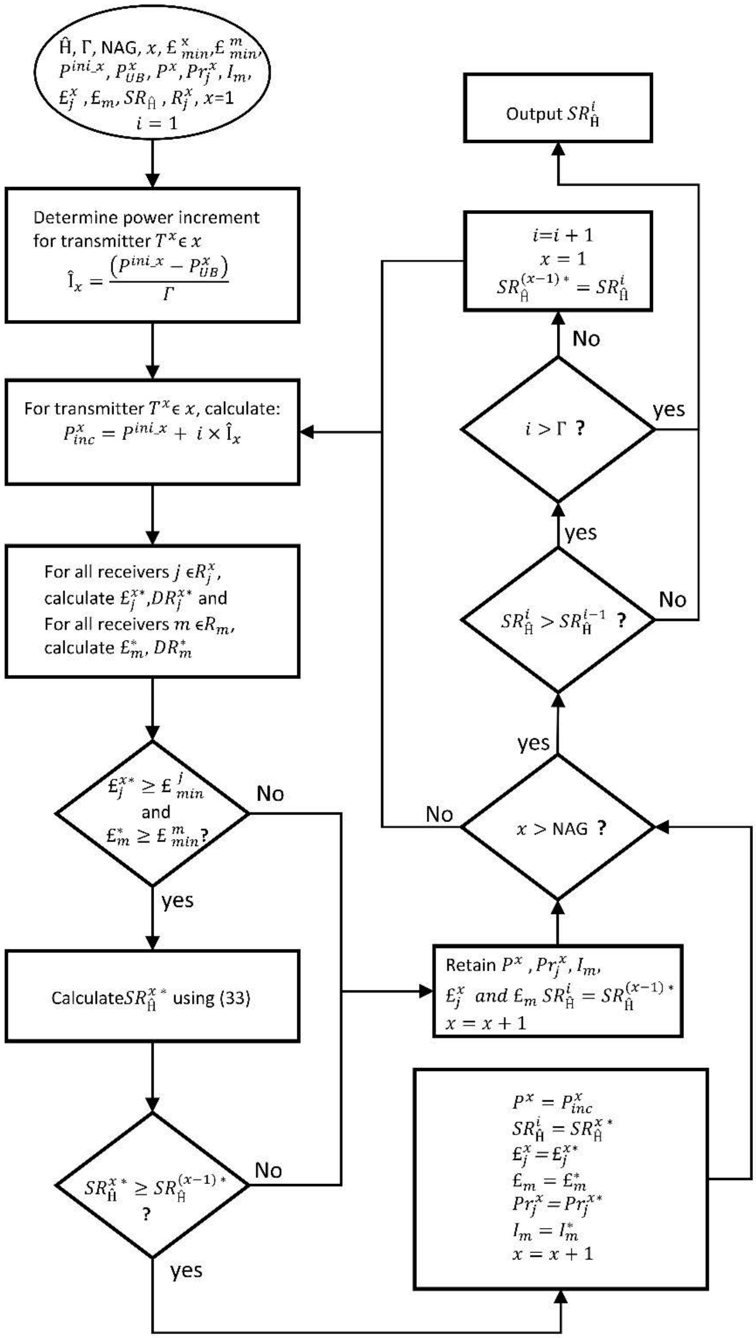


FIGURE 3. Flow diagram of sum rate maximization.

Number of Available Channels: The number of available channels is set to 1 for Fig. 4,5 and 7 so that a better analysis can be offered focusing only on the scenario being addressed in those figures. However, the performance of the proposed and compared schemes in case of multiple channels is separately evaluated in Fig. 6 where the number of available channels varies from 1 to 5. The choice on the range of the number of available channels (i.e., 1 to 5) is based on the number of available D2D groups i.e., 50. In most of the cases at most 5 channels can accommodate all of the available D2D groups due the ability of the proposed algorithm to maximize the access rate. Each channel has a bandwidth of 1 MHz.

Simulation Area: In order to test the effectiveness of the proposed schemes over different network sparsity levels, we consider three sparsity levels; 500, 1000 and 1500 meters. This facilitates analysis of the proposed schemes in terms of their effectiveness in different types of practical scenarios. For instance, offices, schools, stadiums etc. span

TABLE 2. Simulation parameters.

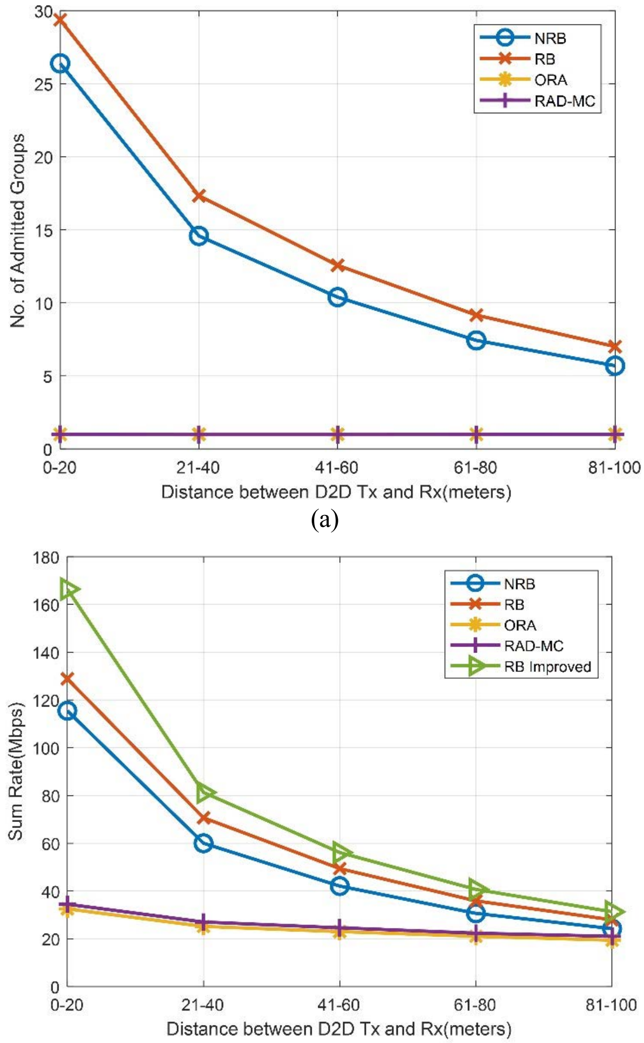
Notations	Details
Simulation runs	*5000*
Simulation Area	*500×500, 1000×1000, 1500×1500 meters*
Number of candidates D2D groups Ď	*10,20,30,40,50 (uniformly distributed over the simulation area).*
Allowable distance between D2D transmitter and receiver	*0-20, 21-40,41-60, 61-80, 81-100*
Number of available channels	*1-5(*Fig. *6) and 1(*Fig. *4,5,7)*
$Bandwidth$	*1MHz per channel*
Maximum Tx power ($P_{max}^{Ģ}, P_{max}^{Č}$)	*20 dBm*
D2D/cellular user target SINR $£_{min}^{Ģ}, £_{min}^{Č}$	*Uniformly distributed in {5,20} dB*
$w1, w2, w3, w4$	*0.5*
Noise Power(N)	*-114 dBm*
Pathloss exponent (α)	*3.5*
Multipath fading	*Exponential distribution with unit mean*
Shadowing	*Log-normal distribution with standard deviation of 8dB*

smaller areas but may have significant D2D communication demands. On the contrary markets span larger areas with sparse demand for D2D communication. In the literature, different sparsity levels have been assumed. For instance [30] assumes sparsity level (area) of 500 × 500 meters. The algorithms proposed in [31], [47] and [8] assume areas with radius of 200, 400 and 500 meters respectively.

We consider two metrics to evaluate the performance: the average number of admitted D2D groups per channel (also referred to as access rate) and sum rate. The sum rate is the total achievable per channel rate and is defined as the ratio of the overall rate achieved by all the channels to the total number of available channels. The results draw comparison between the baseline techniques proposed in [25] and [32] referred to as ORA and RAD-MC respectively and our proposed schemes of non-relay based D2D communication referred to as NRB, relay-based D2D communication referred to as RB and the proposed sum-rate improvement mechanism referred to as RB-Improved which employs iterative power incrementation to improve the sum rate achieved by the RB mechanism.

Simulation parameters are summarized in Table 2.

Fig. 4 demonstrates the performance for different allowable D2D ranges. In case of ORA and RAD-MC, because of one D2D group per channel policy, the average number of admitted D2D groups does not cross 1 (Fig. 4(a)). Moreover, as the number of available groups is much higher than the allowed number of groups per channel (i.e., 1), the probability of having at least one admissible group is high even for longer allowed distances. Therefore, the number of admitted groups in ORA and RAD-MC stays at almost 1, irrespective of the allowable ranges. On the other hand, in case of NRB and RB the number of admitted D2D groups decreases with the



(a)

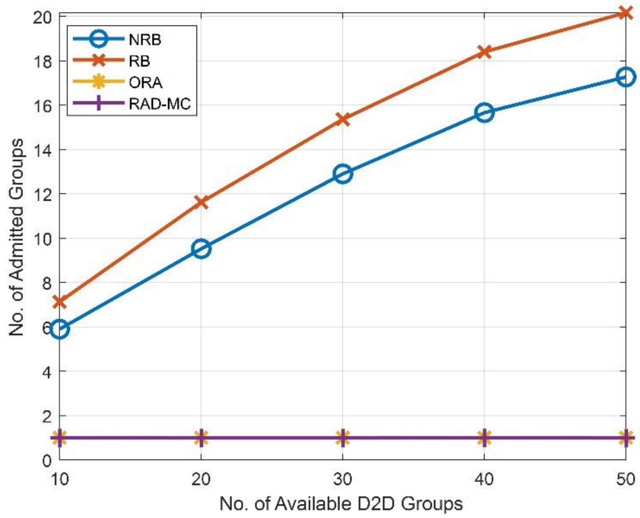
(b)

FIGURE 4. No. of admitted D2D groups and sum rate for different allowed D2D ranges where the number of available channels = 1, allowed range = 0-20,21-40,41-60,61-80,81-100 meters and number of available D2D groups = 50. (a) No. of admitted groups. (b) Sum rate (Mbps).

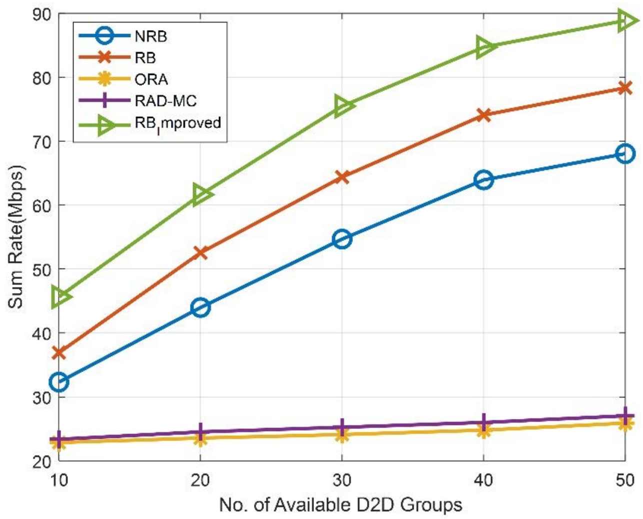
increase in allowable distance between D2D transmitter and receivers. This is because at bigger distances, transmitters are required to transmit with higher transmission power, which generates more interference thus decreasing the access rate as compared to smaller allowed distances where transmitters generate lesser interference due to relatively low power transmission. Moreover, RB achieves higher access rate as compared to NRB. This is because, in case of NRB, an aspirant D2D group is deemed inadmissible if the aspirant D2D transmitter is expected to violate the SINR requirement of the cellular user and other D2D groups that are scheduled to share the channel under consideration. However, in the case of RB, relay node may be employed. This allows the corresponding D2D transmitter and the relay node to transmit with lower transmission powers which may decrease the expected level of interference at other receivers which in turn increases the probability of admission of the corresponding D2D group. As a result, the number of admitted D2D groups increases. However, the increase in the number of admitted D2D groups by employing relays does not always translate equally to sum rate. More specifically, the sum rate response of RB decreases with increasing allowable distance between transmitter and receivers of D2D groups. This can be seen in Fig. 4(b) where the sum rate curve for RB slowly approaches the sum rate curve for NRB as the minimum allowable distance increases. This is because, when the distance between a D2D transmitter and receivers is high, the intermediary relay node is also expected to transmit with relatively higher transmission power. In such a case even if employing a relay does not violate the SINR requirements of the already scheduled transmissions (in which case the corresponding group is admitted), the higher transmission power of the relay node may eat up some of the SINR margins of the cellular and D2D pair/groups. This results in relatively lower achieved SINR (although still above or equal to the target SINR) at other D2D and cellular receivers which in turn reduces the sum rate. In the case of ORA and RAD-MC, the sum rate decreases with increasing allowable distance between D2D transmitters and receivers. This is because of the higher interference levels due to higher transmission powers in case of longer distances. As a result of higher interference levels, the SINR of the cellular and D2D receivers drops as the allowed distance increases which results in smaller overall sum rates in case of ORA and RAD-MC. Finally, the sum rate improvement curve i.e., RB-Improved shows that the relative improvement in the sum rate of RB drops as the allowed distance between D2D transmitter and receivers increases. This can be seen in Fig. 4(b) where the RB-Improved curve approaches the RB curve as the allowed distance increases. This is because at bigger distances transmitters transmit with higher transmission power thus generating more interference overall. Therefore, with high prevailing interference levels, the room for improvement decreases as compared to smaller distances where, due to low power transmissions, the overall level of interference is relatively small and therefore there is more room for improvement through power incrementation.

Scalability: With increasing distance, the performance of NRB will approach the performance of RAD-MC and ORA due to higher level of interference generated by high transmission power which will shrink the access rate of NRB. However, RB may still perform better due to the use of relays. In conclusion, the worst-case performance of the proposed scheme (i.e., in case of much longer distances between D2D transmitter and receivers) will match the baseline schemes in terms of access rate.

Fig. 5 demonstrates the performance for different number of available D2D groups when only one channel is available. In Fig. 5(a), overall, the average number of admitted groups in the RB and NRB schemes increases with increasing number of available groups. This is because availability of a bigger pool of aspirant D2D groups increases the number of groups that fit the admissibility criteria thus more node can be admitted. Moreover RB, achieves higher access rate as compared to NRB by employing relays to admit groups which otherwise cannot be admitted by NRB because of the intolerable amount of interference that the D2D transmitters may generate due to higher power direct communication in case of NRB. Furthermore, the difference between the access rates of RB and NRB increases with the increase in the number of available D2D groups. This is because a bigger pool of available D2D groups leads to admission of more D2D groups which in turn leads to higher interference levels in the channel thus decreasing the probability of admitting groups using high power direct communication links and increasing the probability of group admission using relays. The access rates of ORA and RAD-MC is much smaller as compared to NRB and RB and does not cross 1 due to the



(a)



(b)

FIGURE 5. No. of admitted D2D groups and sum rate for different number of available D2D groups where the number of available channels = 1, allowable range = 20-40 meters and number of available D2D groups = 10,20,30,40,50. (a) No. of admitted groups. (b) Sum rate (Mbps).

one D2D group per channel policy of the two former schemes. Moreover, as the number of available groups is much higher (even in the minimum case in our simulations i.e., 10 groups) than the number ORA and RAD-MC allows to admit per channel, ORA and RAD-MC can admit one group most of the times irrespective the number of available D2D groups, which explains the almost flat curves at 1 for ORA and RAD-MC.

The effect of access rate of the considered approaches translates to their achievable sum rate as shown in Fig. 5(b), The sum rates of ORA and RAD-MC is much smaller as compared to RB and NRB due their much smaller access rates. However, in RAD-MC and ORA, the sum rate increases with the number of available D2D groups. This is because, ORA and RAD-MC select only one group from the pool of available D2D groups subject to sum rate maximization. As bigger pool is more likely to offer better options, the sum rate increases with the number of available D2D groups. In comparison, the sum rates of RB and NRB also improves with the increasing number of available D2D groups because of the rise in their access rates with increasing size of the available pool. Moreover, RB achieves better sum rate performance as compared to NRB due to its higher access rate. Another reason for better sum rate performance of RB approach, is that the relative increase in the access rate of the RB approach is necessarily due to those D2D groups which are admitted using relays. As relayed groups generate lesser overall interference due to their smaller transmission powers, the relative sum rate per admitted group increases with increasing number of D2D groups that are admitted using relays thus improving the sum rate response of RB. Finally, the sum rate improvement (which is applied to RB) shows that the sum rate improvement increases with the number of available D2D groups. This is because, the sum rate improvement procedure (i.e., power incrementation) incorporates more nodes because of higher access rates in case of bigger pools.

Scalability: A we increase the number of available D2D groups beyond the simulation setting, the access rate and sum rate will increase until a saturation point after which the access rate and sum rate curves will become insensitive to the increase in the number of available D2D groups.

Fig.6 demonstrates the performance for the different number of available channels. Fig. 6(a) shows the average number of the admitted D2D groups per channel for the number of channels ranging from 1 to 5. In case of ORA and RAD-MC, the number of admitted groups per channel stays near 1 irrespective of the number of available channels for the reasons explained in the discussion on Fig. 4. In case of RB and NRB, the number of admitted groups per channel decreases as the number of available channels increases. The rationale for this is that the channels that are considered earlier have a bigger pool of available D2D groups to admit from and therefore can admit higher number of nodes. Whereas the available pool shrinks for successive channels due to group admission in the earlier channels which results in smaller access rates for the successive channels. Therefore, the per channel access

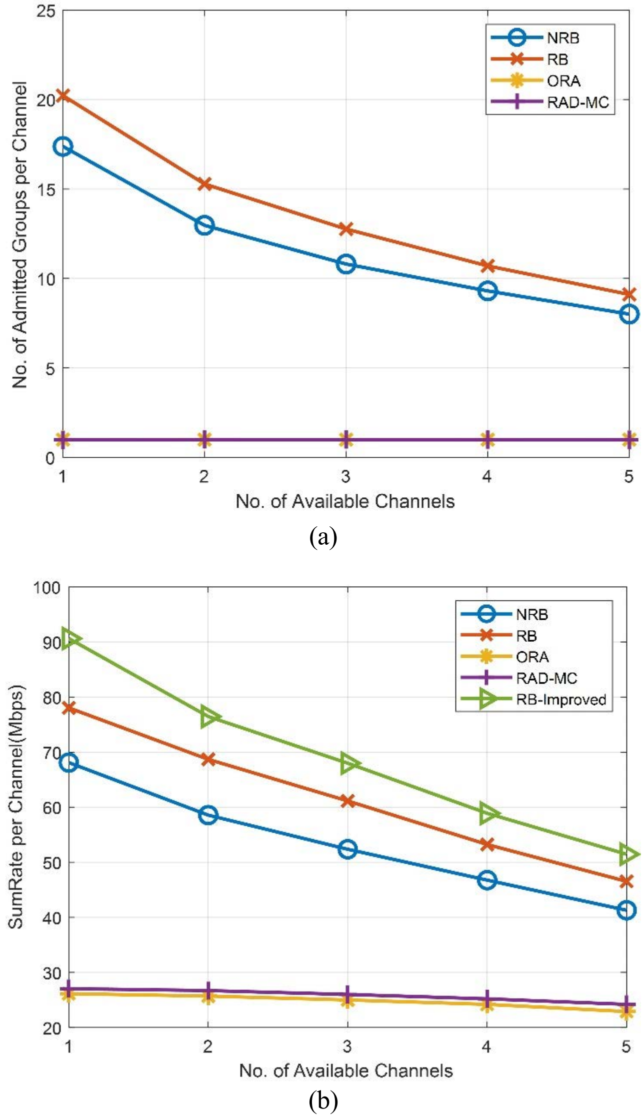


FIGURE 6. No. of admitted D2D groups and sum rate for different number of available channels, where allowable range = 20-40 meters, number of available D2D groups = 50. (a) No. of admitted groups. (b) Sum rate (Mbps).

rate for fewer available channels is higher as compared to higher number of available channels. Moreover, the need for employing relays reduces in the lately considered channels because of smaller levels of interference (due to dropping access rate of the lately considered channels). Therefore, if the number of available channels is high the number of relay-based admitted groups per channel decreases. Hence, in Fig. 6(a), RB curve narrows down on NRB curve as the number of available channels increases from 1 to 5.

The effect of the number of admitted groups per channel is translated into per channel sum rate as shown in Fig. 6(b) where the per channel sum rate of NRB and RB decreases with increasing number of available channels. Whereas the per channel sum rate of ORA and RAD-MC stays relatively less sensitive to the number of available channels due to their almost constant access rate. Finally, RB_improved curve

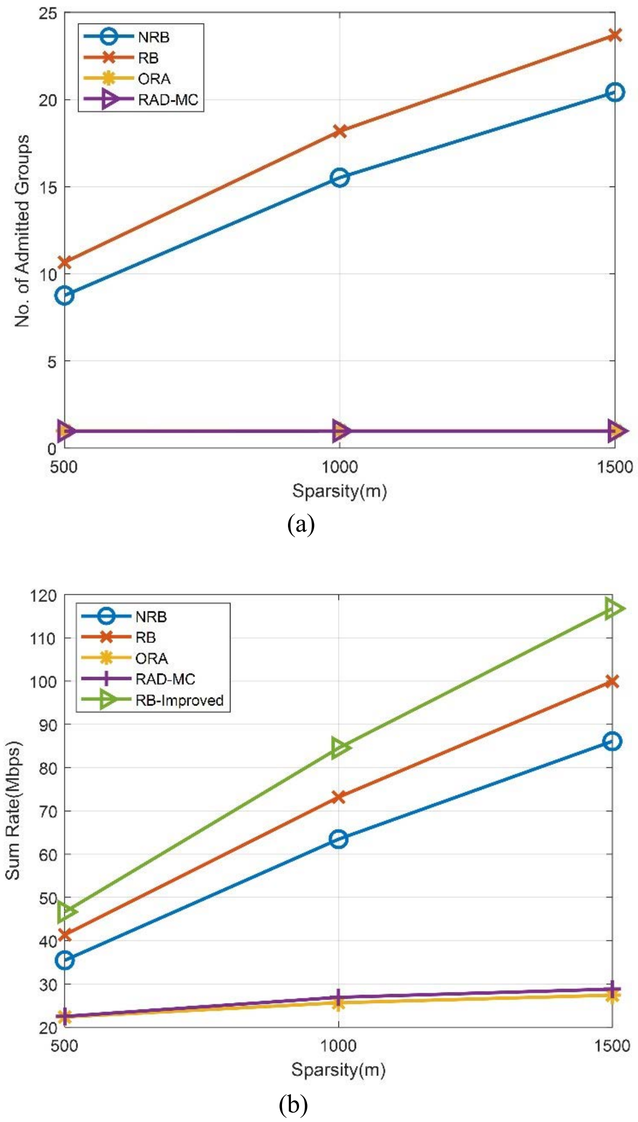


FIGURE 7. No. of admitted D2D groups and sum rate for different network sparsity levels where network sparsity = 500 × 500, 1000 × 1000 and 1500 × 1500 meters, the number of available channels = 1, allowable range = 20-40 meters and number of available D2D groups = 50. (a) No. of admitted groups. (b) Sum rate (Mbps).

shows improvement in the per channel sum rate for RB scheme.

Scalability: As the number of available channels increases beyond the ranges in the simulations, the per channel access rate will decrease for both NRB and RB due to the smaller pool of available nodes for the lately considered channels. Reduction in the access rate will translate into reduction in sum rates. Moreover, as the available channels are considered in sequence, the D2D groups available for the channels that are considered later may be those groups which could not be admitted to the earlier channels due to their higher SINR requirements and/or relatively shorter distance from the base station. This may reduce the access rate of the channels considered later. Thus, due to the smaller access rates of the lately considered channel the per channel access and sum rates may reduce when the number of available channels is higher.

Fig. 7 demonstrates the performance for different network sparsity levels. With increasing sparsity, the number of admitted groups increases in case of RB and NRB. This is because the D2D groups are located farther away from each other and from the BS on average in case of higher sparsity, thus causing lesser interference to each other. The access rate of ORA and RAD-MC stays near 1 irrespective of the sparsity level for the reasons explained in the discussion on Fig. 4.

The sum rates of RB and NRB increase with increasing sparsity due to higher access rates and reduction in the interference levels with increasing sparsity. Similarly, the sum rate of ORA and RAD-MC increases with increasing sparsity because of lower levels of interference in sparser networks. However, the sum rates of ORA and RAD-MC stay much smaller as compared to RB and NRB due to their smaller access rates. Finally, RB_improved curve shows that the sum rate of RB can be improved more at higher sparsity levels. This is because of the reduction of overall interference levels as sparsity increases which creates room for sum rate improvement through power increments.

Scalability: The access rates of RB and NRB will increase with increasing sparsity due to lesser interference. Moreover, the sum rates will increase faster because all receivers will be able to achieve higher SINR because of lesser interference levels.

V. CONCLUSION

In this work, aiming at maximizing the number of D2D groups over a given channel, a D2D communication framework is proposed where multiple D2D groups are admitted to a given channel using power control to mitigate interference and create room for spatial reuse of the channel. The upper and lower bounds on the transmission powers of aspirant D2D groups are derived to determine the admissibility of the groups to a given channel subject to the SINR requirements of all the users scheduled for sharing the channel. Moreover, in order to further improve the access rate, relay based D2D group admission is proposed to address issues related to selection and utilization of relay nodes. Furthermore, an iterative sum rate improvement mechanism is proposed to improve channel sum rate through power incrementation. The efficacy of the proposed techniques was demonstrated with different communication network settings, showing clear improvements in access rate and sum rate. Furthermore, we demonstrated improvement in access rate and sum rate for different network settings. Based on the proposed framework, the future work will include exploiting Non-Orthogonal Multiple Access (NOMA) to further improve the access rate and throughput. Moreover, we intend to investigate improvement in access rate in case of multiple channels. Furthermore, we also plan to study methods for CSI reporting that can minimize communication overhead.

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