Decentralized Spectrum Allocation in D2D Underlying Cellular Networks

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***Abstract*—The proliferation of novel network access devices and demand for high quality of service by the end users are proving to be insufficient and are straining the existing wireless cellular network capacity. An economic and promising alternate to enhance the spectral efficiency and network throughput is device to device (D2D) communication. However, enabling D2D communication poses significant challenges pertaining to the interference management. In this paper, we address the resource allocation problem for underlay D2D pairs. First, we formulate the resource allocation optimization problem with an objective to maximizes the throughput of all D2D pairs by imposing interference constraints for protecting the cellular users. Second, to solve the underlying mixed-integer non linear resource allocation problem, we propose a stable, self-organizing and distributed solution using matching theory. Finally, we simulate our proposition to validate the convergence, cellular user protection, and network throughput gains achieved by the proposal. Simulation results reveal that D2D pairs can achieve significant throughput gains (i.e., up to $45-91\%$) while protecting the cellular users compared to the scenario in which no D2D pairs exist.**

***Index Terms*—resource allocation, device to device (D2D) communication, matching games, cellular networks.**

I. Introduction

The introduction of bandwidth hungry devices i.e., tablets, smart phones and bandwidth hungry applications i.e., on-line gaming, video conferencing, rich multimedia local services have strained the existing cellular network's capacity. To satisfy this ever increasing demands of the end users, many efforts focus on improving the wireless resource capacity by exploring new coding schemes, installing multiple antennas, and deploying small cells in the existing cellular networks. Although these technologies are successful for increasing the resource capacity, they do not solve the network capacity problem due to many reasons: a) wireless resource capacity has physical limitations, b) additional cost is involved in new hardware installations and c) traffic growth is faster compared to technology advancements [1]. As an alternative, device to device (D2D) communication underlying the existing cellular network has been proposed for long term evolution (LTE) advanced [2]. This technology is envisioned to be very successful especially for the network capacity congestion issues.

In D2D communication, the D2D transmitter can directly

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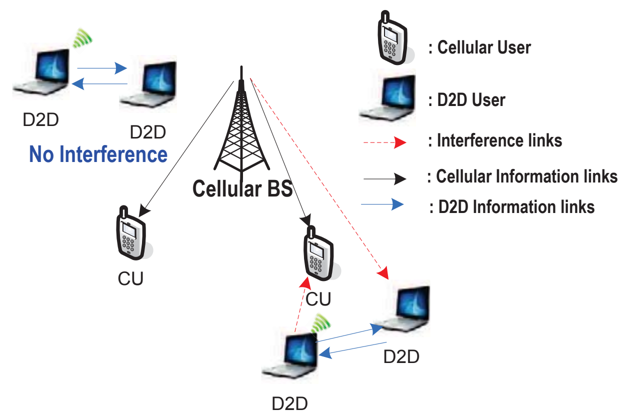

Figure 1: A D2D communication system. Solid line showing the downlink information links while dotted line showing the interference.

transmit to the D2D receiver without routing its traffic through the cellular base station (BS) if both D2D devices are in proximity of each other. However, D2D pairs use the same licensed cellular resource for carrying out their transmissions. The D2D phenomena also allows to offload data traffic to D2D links, thus enabling multiple users in a single collision domain. Moreover, other advantages of using D2D communication include higher throughput, energy efficiency and coverage to blind zones [1]. Although D2D communication enables many promising advantages, it also poses new challenges [9], [10].

One of the most critical challenge is the interference problem which is caused by the reuse of cellular resources. Thus, in order to utilize the cellular resources efficiently, an efficient interference coordination scheme guarantee a target performance threshold of the cellular communication. We in this work focus on downlink transmission of the cellular system in which BS transmits to the cellular users (CUs) and a D2D transmitter transmits to a D2D receiver using the same resource as shown in Fig. 1. There exist two cases, in which interference takes place in the network, shown by red dotted line in Fig. 1. In the first case, the interference occurs at the CU when a D2D pair transmits using the same resource. The second case is at the D2D receiver, when the BS transmits to its CU. In either case, interference will degrade the system's performance.

In this work, our objective is to optimize the throughput of D2D pairs underlaid in a cellular network while protecting the cellular users (co-channel interference avoidance). In order to practical implementations and network scalability, we aim to develop a decentralized and self organizing resource allocation scheme in which D2D pairs and BS can interact and make resource allocation decisions based on local information without relying on central coordinator for coordination. Our contribution to resource allocation can be summarized as follows:

- First, we formulate the resource allocation problem with cellular users protection as a mixed-integer non-linear optimization problem which is NP-hard and requires exponential computation efforts to obtain the optimal solution through the exhaustive search. Therefore, it is difficult to obtain a global optimal in a reasonable amount of time for any network of realistic size.
- Second, in order to attain a distributed, low overhead, and self-organizing solution, we map this problem to a two sided matching game and propose a resource allocation scheme using the concept of matching theory. Furthermore, we proof the stability of the proposed matching based resource allocation algorithm.
- Finally, we validate our proposal through extensive simulations. Simulation results reveal that by enabling D2D pairs, network can achieve throughput gains of up to 66 to 100% while protecting the cellular users compared to the scenario in which no D2D pairs exists.

The remainder of this paper is organized as follows. In the next section we present the related work. Section III explains the system model and problem formulation. Section IV describes in detail, how we map the proposed optimization problem into a matching game and present the proposed resource allocation algorithm. In Section V, we present the numerical results to validate the performance of our device-to-device scheme. Concluding remarks and future extensions appear in Section VI.

II. Related Works

In D2D communication, typically, the system throughput is considered as the optimization objectives which can degrade drastically if resources allocation and interference is not manged efficiently [2]. There has been a recent surge in the literature that proposes new mathematical tools such as game theory [2], auction theory [1], optimization theory [4] and graph theory [5] to solve the resource allocation problem in D2D communication. Additionally, in [6], [9], [10] a number of interference avoidance techniques have been presented for D2D resource allocation. In [1], the authors used the concept of conflict graph to mitigate interference and assumed resources could be reused only if the players did not interfere with each other. In [4], the authors optimize the throughput over the shared resources while fulfilling prioritized cellular service constraints. However, optimization based approaches are mostly centralized and require heavy message passing, which may not be desirable for a dense D2D network. Similarly in [2], authors proposed a game based approach, which has a slow convergence, thus, not desirable for large set of D2D pairs. In [6], a practical and efficient resource allocation scheme is presented for interference awareness between the cellular and D2D terminals at the base station. In all aforementioned works, resource allocation in D2D communication is completely BS controlled. This centralized control can cause significant overheads for a dense D2D settings which will be a part in the future cellular network architecture [7]. Moreover, device-centric architecture is a novel concept coined by [8]. The past and existing cellular architectures were all cell-centric where the BS controlled the complete cells along with the user devices in the cell. However, it is expected that a given user device should be able to control, thus, distributing the control in the network [8].

A distributed dynamic spectrum protocol for resource allocation is presented to enable overlaid multi-hop adhoc D2D networks during uplink transmission of the cellular system in [9], [10]. This scheme renders gain in the system's throughput while providing protection to the cellular users. However, this scheme requires significant message passing to operate in a distributed manner.

III. System Model and Problem Definition

Consider a cellular network with a set $\mathcal{K} = \{1, 2, ..., K\}$ representing D2D pairs, located within the coverage of one cellular base station (BS) as shown in Fig. 1. The set of cellular users (CUs) are denoted by $\mathcal{C} = \{1, 2, ..., C\}$. The BS and D2D pairs use the same set of orthogonal resource blocks (RBs) $\mathcal{R} = \{1, 2, ..., R\}$.[1] However, for any given RB $r \in \mathcal{R}$, a predefined interference threshold $I^r_{\max}$ must be maintained for protecting the CUs. Finally, note that D2D pairs and CUs only differ in their modes of communicating with each other, i.e., direct transmission or via BS. In fact, both type of users would be composed of the same type of wireless devices. D2D users are simply cellular users who could not be served by the base station due to limited RBs.

A. Resource Allocation and Link Models

We focus on the downlink transmission in our system in which we have limited number of RBs. Furthermore, the D2D transmissions are managed by the network such that they are synchronized to the cellular transmissions. Note that, we assume that all transmitters use a slowly changing transmit power (fixed power) over the RB allocation for carrying out their respective transmissions and thus the interference power is also constant over the RB. The D2D pairs at each time slot need to determine which RB is feasible in order to maximize the utility of the system while protecting CUs. For RB allocation optimization, we introduce binary variables x^r_k, as follows:

$$x^r_k = \begin{cases} 1, & \text{if D2D pair } k \text{ is assigned RB } r, \\ 0, & \text{otherwise.} \end{cases}$$

We always set $x^r_k = 0$ for any D2D pair k, that is not assigned RB r. The received SINR pertaining to the transmission of D2D pair k over RB r with transmit power P^r_k is:

$$\gamma^r_k = \frac{x^r_k P^r_k g^r_k}{P^r_M g^r_{M,k} + \sigma^2}, \tag{1}$$

[1]One resource block can correspond to one sub-carrier of the OFDM-based LTE network.

where P_M^r represent the transmit powers of the BS. The RB gain between D2D pair k is g_k^r whereas $g_{M,k}^r$ is the RB gain from the BS to D2D pair k. The noise power is assumed to be σ^2. Similarly, the SINR of a CU c is given by

$$\gamma_c^r = \frac{P_M^r g_{M,c}^r}{x_k^r P_k^r g_{k,c}^r + \sigma^2}, \tag{2}$$

where $g_{M,c}^r$ and $g_{k,c}^r$ represent the RB power gains from the BS M to CU c and D2D pair k to CU c, respectively. Then, the data rate of the D2D pair k and CU c on RB r are respectively as follows:

$$R_k^r = W^r \log(1+\gamma_k^r), \tag{3}$$

$$R_c^r = W^r \log(1+\gamma_c^r), \tag{4}$$

where W^r is the bandwidth of RB r.

B. Problem Statement

Our goal is to maximize the sum rate of the D2D pairs by reusing the RBs already occupied by CUs. It should be noted that a D2D pair can only use a RB if the interference level is less than the predefined interference threshold $I_{\max}^r$ set by the BS. Moreover, the interference experienced by CU c on RB r is given by $I_k^r = x_k^r P_k^r g_{k,c}^r$, where $g_{k,c}^r$ is the RB gain between D2D pair k and CU c, on RB r. Note that the binary RB allocation variables x_k^r ensure that we only account for the interference created by D2D pair that is assigned the same RB. The considered RB allocation problem can be stated as follows:

$$\begin{aligned}
\textbf{P1:} \underset{x_k^r \in \mathcal{X}}{\text{maximize}} \quad & \sum_{r\in\mathcal{R}}\sum_{k\in\mathcal{K}} W^r \log(1+\gamma_k^r) && (5)\\
\text{subject to} \quad & I_k^r \le I_{\max}^r,\ \forall r \in R, && (6)\\
& \sum_{k\in K} x_k^r \le 1,\ \forall r\in R, && (7)\\
& \sum_{r\in R} x_k^r \le 1,\ \forall k\in K, && (8)\\
& x_k^r \in \{0,1\},\ \forall k\in K,\ \forall r \in R. && (9)
\end{aligned}$$

In **P1**, constraint (6) is to ensure the protection of CU by keeping interference produced by D2D transmitter below a predefined threshold. This allows the re-usability of a RB r to increase the RB efficiency, if the interference constraint can be maintained. Constraint (7) ensures that each RB can be allocated to at most one D2D transmitter. Additionally, constraint (8) ensures that each D2D transmitter can be allocated one RB only. The binary RB allocation indicator variable is represented by the last constraint (9). Problem **P1** is a mix integer non linear programming, and finding the solution becomes NP-hard, for a large set of D2D pairs and RBs in a reasonable amount of time [11].

In order to have a low complexity, self-organizing and a distributed solution, we aim that **P1** can be solved in a distributed manner by each D2D pair such that it maximizes its own rate. Therefore, we employ the concept of matching theory to map problem **P1** into a matching game and then discuss the details of the solution in the following section.

IV. Matching-based Resource Allocation

Matching theory is a promising technique that can be applied for RB allocation problem and can overcome the limitations of optimization, problems with combinatorial structures [12]. The benefits of matching theory comes from the distributive nature of control in the system. Furthermore, matching theory allows each player (i.e., D2D pairs and RBs) to define its individual utilities depending upon his local information. It also facilitates a decentralized and self organizing solution for the RB allocation problem. The matching problems can be broadly classified: two sided matching games with two sided preferences, two sided matching games with one sided preferences and one sided matching game with preferences. In this work, we use the two sided matching game with two sided preferences class to solve the proposed RB allocation problem. This technique of matching theory divides the matching players into two distinct disjoint sets and each member of a set ranks a subset of the members of the other set in order of preference. The preference of one set over the other set is derived from the local information available to each member. The RB allocation matching problem is defined as to find a match between D2D pairs and RBs, given their individual preferences derived from different objectives.

A. Matching Game Formulation

Matching theory is a mathematical framework that can be used to solve RB allocation problem. Here, we formulate the RB allocation as a matching game problem, then we define the utility and finally present a low-complexity algorithm that can find a stable matching which is a key concept for a matching game.

We assume each D2D pair forms a set which can use a single RB, to enable constraint (7) and (8). However, to use this RB, the interference produced by D2D pairs to RBs should be under the tolerable predefined interference level i.e., (6). Similarly, every RB also forms a set to accommodate a D2D pair among all the pairs. Therefore, our design corresponds to a *one-to-one matching* given by the tuple $(\mathcal{K}, \mathcal{R}, \succ_{\mathcal{K}}, \succ_{\mathcal{R}})$. Here, $\succ_{\mathcal{K}} \triangleq \{\succ_k\}_{k\in\mathcal{K}}$ and $\succ_{\mathcal{R}} \triangleq \{\succ_r\}_{r\in\mathcal{R}}$ represent the set of the preference relations of the D2D pairs and RBs, respectively. Formally, we define the matching as follows:

Definition 1: A *matching* μ is defined by a function from the set $\mathcal{K}\cup\mathcal{R}$ into the set of elements of $\mathcal{K}\cup\mathcal{R}$ such that:

1) $|\mu(k)| \le 1$ and $\mu(k) \in \mathcal{R}$,
2) $|\mu(r)| \le 1$ and $\mu(r) \in \mathcal{K}\cup\phi$,
3) $\mu(k) = r$ if and only if k is in $\mu(r)$,

where $\mu(k) = \{r\} \Leftrightarrow \mu(r) = \{k\}$ for $\forall r\in R, \forall k \in K$ and $|\mu(.)|$ denotes the cardinality of matching outcome $\mu(.)$. The first two properties state that the matching is a one-to-one relation in the sense that a D2D pair k can be allocated with only one RB r and cannot be shared among different D2D pairs which are the constraints (7) and (8) of problem **P1**. Additionally, when a D2D pair k is not allowed to use a RB r due to the violation of the interference constraint (6), we have $\mu(r) = \phi$.

1) Preference profiles of players: In order to evaluate each other, players from both sides build a preference profile in order to rank the players of the opposite side. In the proposed RB allocation problem, the two sides i.e., D2D pairs and RBs make their preference profiles by utilizing local information available at each side. The preference profile for the D2D pairs is based on the following preference function of achievable data rate on RB r:

$$U_k^r = W^r \log(1 + \gamma_k^r). \tag{10}$$

The intuition for such a preference function comes from the objective of our problem, where each D2D pair wants to maximize its sum rate. Hence, each D2D pair ranks all the RBs r in non-increasing order in its preference profile represented by $\mathcal{P}_k$. Note that, a RB $r \in \mathcal{R}$ which produces a higher utility (consequently data rate achieved by using the more preferred RB is higher) according to (10) will be preferred over a RB $r' \in \mathcal{R}$ by a D2D pair k i.e., $r \succ_k r'$, for carrying out its transmission and would be placed higher in its preference profile.

Similarly, each RB r also needs to have a preference profile of the D2D pairs $k \in \mathcal{K}$ ranked according to its preference function. This preference list for each RB is formed by the BS. The information required at the BS includes the power level of D2D transmitters p_k, the predefined maximum interference threshold $I_{\max}^r$ for each RB, and the RB power gain between CU and D2D transmitter $g_{k,c}^r$. The preference function is given by :

$$U_r^k = I_{\max}^r - I_k^r. \tag{11}$$

According to this preference function, a RB gives less utility to a D2D pair which creates more interference I_k^r than the predefined threshold. Furthermore, to calculate the ranking of each D2D pair, BS for each r needs to calculate the interference induced I_k^r by the D2D pair k if a RB r is in use. As we assume the power levels of the SBS are fixed and known to the BS, calculation of I_k^r only depends upon the RB gain $g_{k,c}^r$.

Remark: The RB power gain $g_{k_c}^r$ can be estimated by CUs and sent back to BS by using the pilot signal or any standard RB estimation technique [15]. The total interference for each CU can be estimated as follows. All CUs estimate the total received power and send this value to the BS. BS can then calculate the interference induced by the D2D pair on RB r. Therefore, calculation of the interference only requires the standard RB estimation of $g_{k,c}^r$. In addition, signaling is only involved in sending these values from the CU to the BS, which is relatively mild and can be conducted over the air. Once these information are acquired, I_k^r is calculated, and the BS ranks each D2D pair k for each RB r in the preference profile of r represented by $\mathcal{P}_r$.

B. Resource Allocation algorithm

In this section, we present the RB allocation algorithm based on the proposed matching game. The aim of this algorithm is to find a stable allocation which is a key solution concept in matching theory [13], [14] and can be defined as follows:

Definition 2: A matching μ is stable if there exists no blocking pair (k, r), where $k \in \mathcal{K}, r \in \mathcal{R}$, such that $r \succ_k \mu(k)$ and $k \succ_r \mu(r)$, where $\mu(k)$ and $\mu(r)$ represent, respectively, the current matched partners of k and r.

Algorithm 1 D2D Resource Allocation Algorithm

1: ***Phase 1: Initilization***:
2: **input**: $\mathcal{P}_k$, $\mathcal{P}_r$, $I_{\max}^r$ $\forall r, k$
3: **initialize**: $t = 0$, $\mu^{(t)} \triangleq \{\mu(k)^{(t)}, \mu(r)^{(t)}\}_{k \in \mathcal{K}, r \in \mathcal{R}} = \emptyset$, $\mathcal{L}_r{}^{(t)} = \emptyset$ $\mathcal{P}_k{}^{(0)} = \mathcal{P}_k$, $\mathcal{P}_r{}^{(0)} = \mathcal{P}_r$, $\forall r, k$
4: ***Phase 2: Matching***:
5: **repeat**
6:     $t \leftarrow t + 1$
7:     **for** $k \in \mathcal{K}$, propose r according to $\mathcal{P}_k{}^{(t)}$ **do**
8:         **while** $k \notin \mu(r)^{(t)}$ and $\mathcal{P}_k^{(t)} \neq \emptyset$ **do**
9:             **if** $I_{\max}^r \geq I_k^r$, **then**
10:                 **if** $k \succ_r \mu(r)^{(t)}$ **then**
11:                     $\mu(r)^{(t)} \leftarrow \mu(r)^{(t)} \setminus k'$
12:                     $\mu(r)^{(t)} \leftarrow k$
13:                     $\mathcal{P}'^{(t)}_r = \{k' \in \mu(r)^{(t)} | k \succ_r k'\}$
14:                 **else**
15:                     $\mathcal{P}''^{(t)}_r = \{k \in \mathcal{K} | \mu(r)^{(t)} \succ_r k\}$
16:             **else**
17:                 $\mathcal{P}'''^{(t)}_r = \{k \in \mathcal{K} | I_{\max}^r \leq I_k^r\}$
18:                 $\mathcal{L}_r{}^{(t)} = \{\mathcal{P}'^{(t)}_r\} \cup \{\mathcal{P}''^{(t)}_r\} \cup \{\mathcal{I}'^{(t)}_r\}$
19:                 **for** $l \in \mathcal{L}_r{}^{(t)}$ **do**
20:                     $\mathcal{P}_l{}^{(t)} \leftarrow \mathcal{P}_l{}^{(t)} \setminus \{r\}$
21:                     $\mathcal{P}_r{}^{(t)} \leftarrow \mathcal{P}_r{}^{(t)} \setminus \{l\}$
22: **until** $\mu^{(t)} = \mu^{(t-1)}$
23: ***Phase 3: Resource Allocation***:
24: **output**: $\mu^{(t)}$

The output is the allocation vector of D2D pairs which maximizes the objective of the optimization problem **P1** and the pseudo code is given in Algorithm 1 . The presented algorithm is guaranteed to converge to a stable allocation as it is a variant of "deffered-acceptance algorithm" [13].

The algorithm is a three phases namely, *the initialization phase, the matching phase* and the *RB allocation phase*. In the *initialization phase*, local information is attained by both sides to rank the other side. It starts by BS broadcasting its available RBs that can be reused by the D2D pairs. Based on this information of RBs $r \in \mathcal{R}$, each D2D pair constructs its preference profile $\mathcal{P}_k$. Similarly, the BS has the information of all the D2D pairs, it then constructs the preference profile $\mathcal{P}_r$ for the available RBs r (lines 1-3). In the second phase *matching*, each unassigned D2D pair k proposes to its most preferred RB r according to its preference profile $\mathcal{P}_k$ (lines 7-8). Then, the BS first determines the interference I_k^r produced by D2D pair k. If interference I_k^r is below the predefined maximum interference threshold $I_{\max}^r$ it further proceeds. Otherwise, the D2D pair k is rejected and added in the rejected list $\mathcal{P}'''_r{}^{(t)}$ (lines 9-17). If not rejected, then BS checks the preference ranking according to $\mathcal{P}_r$ for the D2D pairs k (i.e., do not violate the interference constraint (6)). If D2D pair k has a higher preference utility than the current match $(\mu(r)^t)$, the current match k' will be rejected and the D2D pair k will be matched to the r (lines 10-12). Furthermore, the rejected D2D pair k' will be added in the rejection list $\mathcal{P}'^{(t)}_r$ (Line 13). Similarly, if the D2D pair k has a lower preference than the current match $(\mu(r)^t)$,

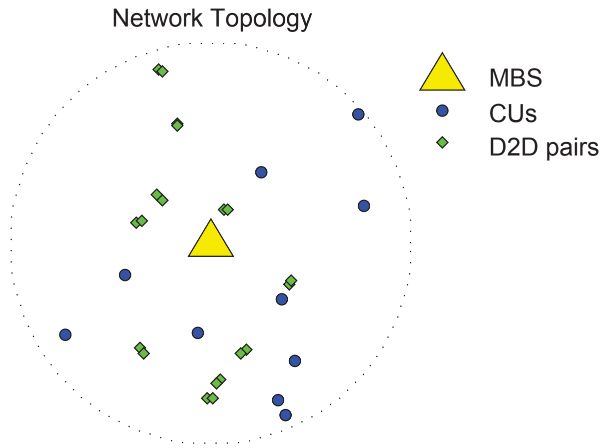

Figure 2: Network topology

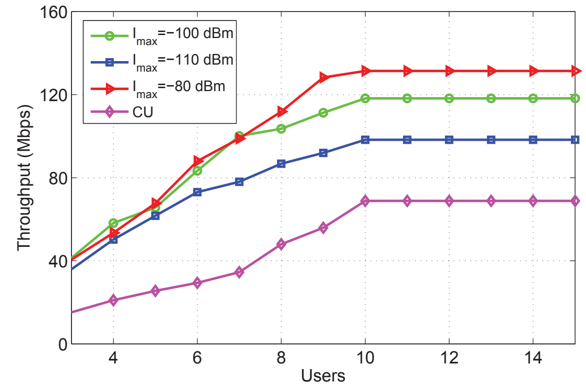

Figure 3: Average throughput under various tolerance levels.

k will be rejected and added in the rejection list $\mathcal{P}''^{(t)}_r$ (lines 14-15). Finally, all the rejected D2D pairs at iteration t,i.e., the set $\mathcal{L}_r{}^{(t)}$, is then used by both the sides to update their preference profiles. This means all RBs r removes the rejected D2D pairs k from the $\mathcal{P}_r{}^{(t)}$, and similarly these D2D pairs also remove r from their respective $\mathcal{P}_k{}^{(t)}$ (lines 20-21). The matching process is carried out iteratively until a stable match is found between both the sides (line 22). The process will terminate when all the D2D pairs which can maintain the interference tolerance level are assigned to RBs. The algorithm will converge when the matching of two consecutive iterations t remains unchanged (line 22). The final stage is the *RB allocation* phase in which the matched D2D pairs are allowed to transmit on the matched allocated RBs (lines 23-24).

Theorem 1. *Algorithm. 1 converges to a stable allocation.*

Proof: We prove this theorem by contradiction. Assume that Algorithm 1 produces a matching μ with a blocking pair (k, r) i.e., $\exists\ k' \in \mu(r) : k \succ_r k'$, by Definition 2. Similarly, $r \succ_k \mu(k)$, then k must have proposed to r. Since, k has proposed and not been matched, it implies, k has been rejected due to interference violation on r (line 9 of Algorithm 1). When k was rejected, then k' will also be rejected either before or after k as it resides lower than k in $\mathcal{P}_r$ i.e., $k \succ_r k'$. Thus, k' cannot be the matched to r, i.e., $k' \notin \mu(r)$, which contradicts with the assumption, so a contradiction. ∎

V. NUMERICAL RESULTS

In this section, we perform extensive simulations under various topologies and scenarios to demonstrates the performance and effectiveness of the RB allocation algorithm. The network topology for our simulations contains an BS, with an number of CUs and D2D pairs which are randomly located inside circles of radius of $r_1 = 500$ m and the communication radius of each D2D pair is randomly chosen to be within the range of $(20 - 40)$ m. We consider a network with 10 D2D pairs, with 10 RBs, and 10 CUs using these RBs unless stated otherwise as shown in Fig. 2. The RB gain is given by $g_{m,n} = 10^{(-PL(d_{m,n}))/10}$ (no fading), where function $PL(d_{m,n})$ represents path loss (in decibels) and $d_{m,n}$ (in meters) is the distance between D2D pair and CU connected to BS n. We assume that $L(d_{M,k}) = 16.62 + 37.6 \log_{10}(d_{M,k})$ for the RB gain from the BS to CU k and $L(d_k) = 37 + 32 \log_{10}(d_k)$ for the RB gain between the D2D pair k. The RB bandwidth W^r is set to a normalized value of 1. Finally, the maximum BS transmission power is fixed to 43 dBm [15] which is uniformly dived among the available RBs whereas all the D2D pairs transmit with a varying power over simulation runs ranging from 20 to 24 dBm. Note that, all statistical results stated are averaged over a large number of independent runs of random locations of D2D pairs, CUs and RB gains.

In order to evaluate the performance of our proposal i.e., how and when our algorithm work, first we show the comparison and average throughput gain by enabling the D2D pairs in a network. Second, we show the transmission power used by the D2D pairs for carrying out their transmission under various scenarios i.e., max interference tolerance by the cellular tier. Finally, we show the convergence of the algorithm in terms of achievable throughput for D2D pairs.

In Fig. 3, the achievable throughput by D2D pairs are shown with respect to three different maximum interference tolerance thresholds set by the cellular tier i.e., $I_{\max} = -110, -100, -80\ dBm,\ \forall r \in \mathcal{R}$. In this simulation, we increased the number of users (both D2D and CU) and observed that the average throughput increases with more users under all scenarios, which, however, saturates as the number of users becomes sufficiently large. This is because of the limited number of RBs ($r = 10$) available and both users are only allowed to use one RB each. Furthermore, it can also be seen that the system throughput increase by at least 45% and goes up to 91% under three different maximum interference tolerance threshold for a network with 10 users. Moreover, it is inferred that the CUs throughput is unaffected under all scenarios i.e., maintain the same quality, whereas the throughput of D2D pairs is significantly decreased under tight tolerance threshold i.e., $I_{\max} = -110\ dBm$, compared to loose threshold $I_{\max} = -80\ dBm$. This occurs due to the fact that some D2D pairs may not be allowed to transmit in order to protect CUs.

Fig. 4 presents cumulative distribution of the interference produced on all RBs by D2D pairs reuse under three maximum interference tolerance threshold scenarios

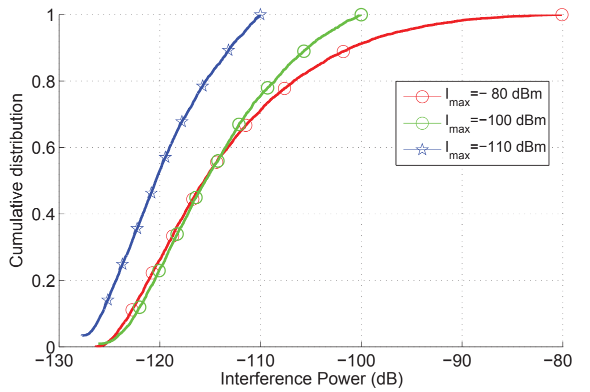

Figure 4: Power of D2D pairs under various tolerance levels.

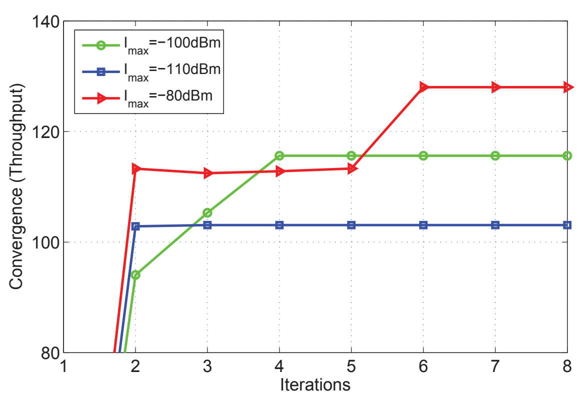

Figure 5: Convergence of algorithm.

$I_{\max} = -110,\ -100,\ -80\ dBm$. It can be seen that in all the cases, the interfering power is always less than the predetermined maximum threshold for cellular tier protection. This ensures that the D2D transmission is not carried out, if the transmitting power violates the maximum predefined interference threshold $I_{\max}$, thus guarantees CU's protection. This is one of the most fundamental requirement for D2D operation under the cellular coverage.

In Fig. 5, the convergence of Algorithm 1 is shown in terms of throughput at each iteration. The convergence is basically achieved when both the set of players (i.e., RBs and D2D pairs) achieve a stable match and do not have any motive to deviate from its current allocation. Therefore, the throughput would be stabilized as the D2D pairs cannot be benefited over their current allocation (matching). Moreover, under all scenarios, the proposed RB allocation algorithm converges to a stable allocation in terms of throughput after limited number of iterations i.e., less than 7 for a network with 10 RBs and 10 D2D pairs. Furthermore, if the interference tolerance level is set to be very tight i.e. $I_{\max} = -110\ dBm$, it takes less number of iteration to converge as compared to a relatively relaxed tolerance level $I_{\max} = -80\ dBm$. It can be explained that because with a tighter interference tolerance level, more number of D2D pairs get rejected initially (line 9 of Algorithm 1) as compared to a relaxed interference tolerance level.

VI. Conclusion

In this paper, we have proposed a RB allocation algorithms for the underlying D2D pairs. We used the matching theory to formulate the RB allocation problem and propose a stable, self-organizing and decentralized solution while protecting the cellular users. We also discuss the distributed implementation of this algorithms in detail. Numerical studies have shown that the proposed algorithm can provide interference protection and significantly enhance the network throughput. Furthermore, we also validate the stability and convergence of the algorithm. As a future extension, we intend to include power control and quality of service constraints for the D2D pairs with heterogeneous tolerance temperature over all the RBs dependent on cellular users quality of service. We would expect to see even more performance gains than those presented here if these extensions are considered.

References

[1] Li, P.; Guo, S.; Stojmenovic, I., "A Truthful Double Auction for Device-to-device Communications in Cellular Networks," in IEEE J. Sel. Areas Commun., vol.PP, no.99, 2015.

[2] C. Xu, L. Song, and Z. Han, Resource Management for Device-toDevice Underlay Communication. New York, NY, USA: SpringerVerlag, 2013.

[3] O. Semiari, W. Saad, S. Valentin, M.Bennis, and H. V. Poor, "Context-Aware Small Cell Networks: How Social Metrics Improve Wireless Resource Allocation," IEEE Transactions on Wireless Communications,

[4] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," IEEE Transactions on Wireless Communications, vol. 10, no. 8, pp. 2752–2763, 2011.

[5] D. Feng et al., "Device-to-device communications underlaying cellular networks," IEEE Trans. Commun., vol. 61, no. 8, pp. 3541–3551, Aug. 2013.

[6] P. Janis, V. Koivunen, C. Ribeiro, J. Korhonen, K. Doppler, and K. Hugl, "Interference-aware resource allocation for device-to-device radio underlaying cellular networks," in Proc. IEEE Vehicular Technology Conference, 2009, pp. 1–5.

[7] A. Osseiran et al., "Scenarios for the 5G Mobile and Wireless Communications: the Vision of the METIS Project," accepted for publication in IEEE Communications Magazine; Feature Topic on 5G Wireless Communication Systems: Prospects and Challenges.

[8] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," IEEE Communications Magazine, vol. 52, pp. 74–80, Feb. 2014.

[9] B. Kaufman, J. Lilleberg, and B. Aazhang, "Spectrum sharing scheme between cellular users and ad-hoc device-to-device users," IEEE Transactions on Wireless Communications, vol. 12, no. 3, pp. 1038–1049, 2013.

[10] B. Kaufman and B. Aazhang, "Cellular networks with an overlaid device to device network," in Proc. 42nd Asilomar Conf. Signals, Syst. Comput., Pacific Grove, CA, USA, Oct. 2008, pp. 1537–1541.

[11] S. Boyd, and L. Vandenberhe "Convex Optimization", *Cambridge University Press,* 2004.

[12] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, "Matching theory for future wireless networks: fundamentals and applications," IEEE Commun. Mag., vol. 53, no. 5, pp. 52–59, May 2015.

[13] A. E. Roth, "Deferred acceptance algorithms: History, theory, practice, and open questions," Int. J. Game Theory, vol. 36, no. 3-4, pp. 537–569, 2008.

[14] D. Gale and L. Shapley, "College Admissions and the Stability of Marriage," The American Mathematical Monthly, vol. 69, no. 1, pp. 9–15, January 1962.

[15] K. Son, S. Lee, Y. Yi, and S. Chong, "Refim: A practical interference management in heterogeneous wireless access networks," IEEE J. Sel. Areas Commun., vol. 29, no. 6, pp. 1260–1272, 2011.