Joint Channel and Power Allocation for Device-to-Device Underlay ☆

Gökhan Kılıç[a], Tolga Girici[a,*]

[a] *TOBB University of Economics and Technology , Sogutozu Cad. No 43, Sogutozu 06560 , Ankara, Turkey*

Abstract

Device-to-Device transmission is one of the enabling technologies of 5G, with a potential of significantly improving the spectral efficiency. Spectral reuse in D2D underlay necessitates interference management. A challenge in D2D underlay systems is the increased number of D2D and interfering links and CSI feedback requirement. In this work we propose a solution for D2D channel allocation, which requires only the neighbor information of D2D communicating nodes. We aim to maximize the supported D2D pairs with a constraint on the interference caused at the base station, at each subchannel. We formulate the channel allocation problem as a Mixed Integer Programming (MIP). We also combine it with an iterative power control scheme in order to fit more D2D pairs in the channels. We also propose a suboptimal channel allocation algorithms and evaluate and compare their performances by simulations. Numerical results reveal that the proposed algorithms perform quite close to the MIP-based solution and power control significantly increases the number of served D2D pairs..

Keywords: Device-to-device (D2D), Cellular network, Underlay, Resource Allocation, Partial CSI, Interference, Power Control, Mixed Integer Programming.

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*Corresponding author

Email address: tgirici@etu.edu.tr (Tolga Girici)

1. Introduction

Device-to-device (D2D) communications is one of the novel features of next generation broadband wireless access networks. D2D transmission facilitates the direct communication of two nearby devices, without the base station (BS) being involved in routing. This will lead to new proximity based services and applications such as D2D caching and content retrieval. D2D transmission can also be used for terminal relaying [2], in order to extend coverage. D2D technique has the potential of significantly improving the spectral efficiency and reduce the delay. Due to these potential benefits D2D communications is listed among the 10 enabling technologies of 5G [1]. However, the multiple access and radio resource management methods proposed for D2D communications should take into account the interference created at the cellular network [3].

Three main research problems in D2D resource allocation are 1) mode selection 2) channel allocation, and 3) power allocation. Mode selection is the problem of deciding whether two nodes will communicate via the BS or directly by D2D transmission [4], [5]. Channel allocation is the problem of deciding which channels will be used by the D2D pairs. Due to the close proximity of users, D2D transmission is promising in terms of spectral efficiency. However, D2D communications still need channel resources. In some scenarios D2D users use an unlicensed (ISM) band. In many other works however, D2D transmissions are assumed to use the regular licensed cellular bandwidth. In terms of resource sharing there are two main choices 1) Overlay (Orthogonal) 2) Underlay (Non-orthogonal). In overlay, D2D and regular cellular transmissions use orthogonal channels [6]. This provides a much predictable and interference-free environment. However, this may not be spectrally efficient especially if the number of D2D pairs reach to a significant level. This necessitates D2D pairs reusing the cellular transmissions' bandwidth. This is called D2D underlay [7]. Resulting interference makes resource allocation problems challenging and interesting. In this study, we will concentrate on D2D underlay.

There are several work that study D2D resource allocation for the underlay case. For example , in [8], [9], [10], [11],[12], [13], [14], [5], [15], [16], [17], [18], [19],[20], [21], [22] the authors propose interference-aware schemes for power and subchannel allocation algorithm for D2D users for maximum total throughput. Again, there are a number of possibilities for bandwidth sharing. The most restricting case is allowing only one D2D pair for each subchannel and cellular user. Secondly, as we assume in this work, multiple D2D pairs can share a single CU's channel. Also, a D2D pair can reuse multiple CUs' resources and can use a part of each of them. In a great majority of the works, first, the resources are allocated (or assumed given) to the CUs and then channel allocation and reuse of the D2D pairs are then performed. In order to manage and control the interference, some channels are prohibited to some D2D pairs (based on channel conditions) [11]. Some works maximize total D2D rate subject to SINR constraints of CUs [23], [16]. The work in [24] does not consider the problem of grouping, but only considers power optimization for the grouped users subject to outage probability constraints. Some works disregard fading and shadowing and only consider distance-based path loss in grouping D2D users and pairing them with a cellular resource.

Another objective of resource allocation is energy efficiency. The works in [4] minimize total power expenditure of users subject to minimum SINR constraints. [25] aims at maximizing the total rate divided by the total power expenditure. The work in [26] minimizes the maximum interference in the network. [27] addresses max-min fairness of D2D pair rates. The work in [28] maximizes the BS-CU exclusive RB's. The objective of the work in [29] is minimizing the outage probability of Machine-Type links. The work [30] aims to minimize the delay.

Majority of the D2D literature proposed power control schemes [23], [24], [12], [13], [14] [4],[15], [16], [27], [28], [31], [32], [30], [18], [19], [20], [21], [25], [22]. There are also works that considered the transmit power fixed [9], [11], [5], [17]. In this work we study the joint allocation of subchannels and power to the D2D links.

Resource allocation problems in D2D-enabled networks are usually hard to solve optimally. The reason is the non-convex nature, due to the interference and binary integer-characteristics of channel allocation. This makes the problem a Mixed Integer Nonlinear Programming, which takes prohibitively long time even for professional software like GAMS. The works such as [8], [13], [5], [16], [27], [18], [21], [25] follow an optimization based approach.

There are many works that follow an algorithmic/heuristic approach [9], [11], [23], [17], [22]. A majority of the works proposed simple greedy schemes. Some works utilize Stackelberg games [4],[20], [33] or maximal bipartite matching for channel allocation [13], [14]. Auction is another useful method, where the D2D users bid for cellular resources and based on costs (interference) [15]. The work in [17] construct a coalitional game, where D2D pairs form coalitions in order to reuse the cellular resources. Stackelberg game, Auction methods and coalitional games also facilitate distributed implementations.

Another classification for D2D resource allocation is the choice of subframe for resource sharing. D2D pairs can be chosen to communicate in the cellular downlink and/or uplink subframe. In this work we will assume sharing of the *uplink* subframe. The reason is that the uplink subframe is less crowded and the BS may create serious interference in the downlink subframe. In the uplink subframe, the interference is directed to the BS, which has a better ability to cope with interference. The works in [8], [9], [11], [23], [24],[12] assume sharing in the downlink subframe. The works like [13], [14], [4], [16], [31], [17],[18],[20], [33],[25] utilize the uplink subframe for resource reuse. Some works assume more freedom, where D2D transmissions can utilize both subframes [5], [28].

An important factor in optimizing D2D resource sharing and allocation is the channel information. In a regular cellular scenario all that is needed is the channel state between the BS and each CU. On the other hand, in D2D-enabled networks new parameters are added to the problem, such as 1) Channel gains from each D2D transmitter to the BS, 2) Channel gains from each CU to each D2D receiver, 3) Channel gains from each D2D transmitter to each D2D receiver. This points to a dramatic increase in the number of channels to be estimated. In almost all of the above works the authors assume to have complete channel state information. The work in [34] is an exception, where the authors formulate a learning-based approach for D2D channel allocation. However, there it is assumed that CU's and D2D pairs do not use the same channels and D2D pairs only fill the vacancies. In [35] allocations are based on average channel conditions and outage probability, a CU channel is only allowed to be shared by a single D2D pair. In [18] the BS is assumed to know the pathloss and shadowing and throughput is maximized subject to outage probability constraints based on small scale fading. The authors in [36] propose a distance based channel allocation, but do not take into account intracell interference. The work in [20] also addressed limited CSI, but authors formulate only a probabilistic channel access mechanism. Stackelberg Game framework in [33] reduces the CSI overhead, however the algorithm converges slowly and is feasible for a low number of D2D pairs.

The contribution of this work is as follows. Unlike the great majority of the above works, we consider the problem of joint subchannel and power allocation in the underlay case. The objective is to maximize the D2D pairs that are served. Again unlike many other works, we assume that the channel gains among devices (i.e. among CU's and D2D pairs) are unknown. We only assume that through a signaling scheme, each device knows its set of neighbors. Based on this neighborhood information, we formulate the D2D channel allocation as a mixed integer program (MIP), which is solved by the BS in a centralized manner. Then we propose greedy algorithms that perform quite close to the MIP-based solution. Given the channel allocation, we also define an iterative power control algorithm for the D2D transmitters. The proposed channel allocation and power control algorithms are iteratively applied, which results in more and more D2D pairs that are allocated a channel.

2. System Model

We consider L D2D pairs of set $\mathcal{D}$ that coexist with K cellular users (CU's) of set $\mathcal{C}$ in an isolated cellular area. Figure 1 illustrates a sample cellular network topology. Each D2D pair communicates in the uplink subframe of cellular transmissions by reusing the resource blocks that are primarily allocated to the CU's. We assume that the uplink spectrum is divided into N subchannels and each subchannel is assigned to a single CU. We assume that the channel allocation for the CU's is given. Without loss of generality we assume that subchannel i is allocated to CU i. More than one D2D pairs can reuse the same subchannel if they satisfy the QoS (interference) requirements. Let P_i^c and P_j^d be the transmit power of CU i and D2D transmitter j, respectively. We assume that the CU's use their maximum power, but the D2D transmitters may perform power control. Cellular transmit power is fixed for all CU's and maximum transmit power of a D2D transmitter is P_{max}^d.

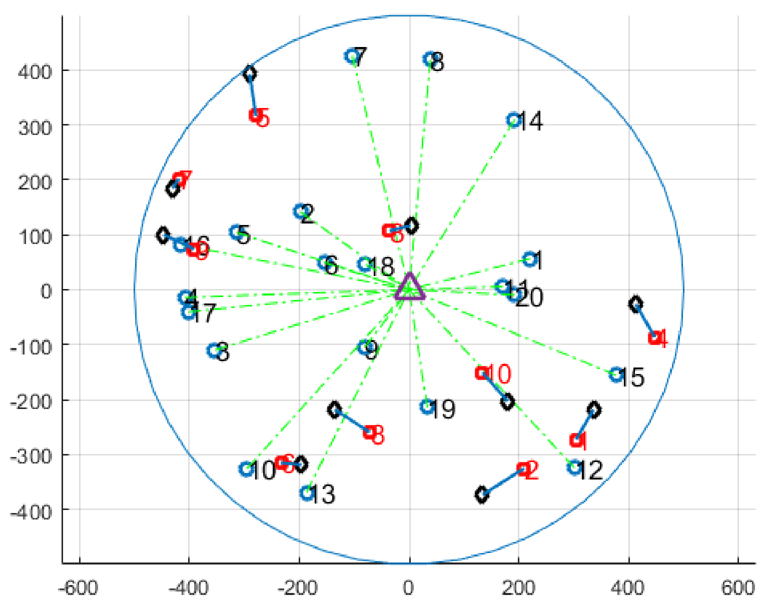

Figure 1: A sample network topology. Dashed green lines show to cellular transmission links. Solid blue lines show the D2D links.

Channel gain between any two terminals consists of distance based pathloss, slow fading due to shadowing and fast fading due to multipath propagation effects. Multipath fading is independent for each subchannel and user. We assume a block fading model, where the channel gain is constant in a time slot and each slot is independent.

Parameter	Explanation	CSI
$g_{BS}^{(i)}$	From CU i to the BS	available
$g_{j,D}^{(i)}$	From CU i to D2D rx j	not available
$h_{j,BS}^{(i)}$	From D2D tx j to BS at channel i	available
$h_{j,C}^{(i)}$	From D2D tx j to CU i	not available
$h_{j,j,D}^{(i)}$	From D2D tx j to D2D rx j in channel i	available
$h_{j,j',D}^{(i)}$	From D2D tx j to D2D rx j' in channel i (interference)	not available

Table 1: Channel gain parameters, their explanations and their availability at the BS.

Table 1 shows the channel parameters in the network, along with their explanations and status of their availability at the BS. Channels directed to BS ($g_{BS}^{(i)}, h_{j,BS}^{(i)}$) can be obtained at the BS by the classical channel estimation methods and the BS gets information about D2D channel gain ($g_{j,D}^{(i)}$) when D2D connection request is sent. Thereby we assume that the BS has perfect knowledge of $g_{BS}^{(i)}, h_{j,BS}^{(i)}, \forall i, j$. However, the interference channels $h_{j,j',D}^{(i)}, h_{j,C}^{(i)}, , g_{j,D}^{(i)}$ are not perfectly known. We assume that the BS only knows the neighborhood information of CU's and D2D pairs based on an assumed beacon based discovery scheme. The power of additive white Gaussian noise on each channel is assumed to be σ^2.

3. Problem Formulation

All D2D pairs and CU's have a minimum rate constraints in order to satisfy their QoS requirements. These minimum rate requirements can be translated into minimum SINR constraints. Objective of the optimization problem is to maximize the number of served D2D pairs. This is subject to minimum SINR constraints for the cellular and D2D transmissions. Since we know all the related channel gains, $g_{BS}^{(i)}$, $h_{j,BS}^{(i)}$, rate constraint can be translated into an SINR constraint. SINR constraint for the CU i is expressed in Equation (1),

$$\Gamma_i^c := \frac{P_i^c g_{BS}^{(i)}}{\sigma_N^2 + \sum_{j \in \mathcal{D}} \phi_{i,j} P_j^d h_{j,BS}^{(i)}} \geq \Gamma_i^{min} \tag{1}$$

where $\phi_{i,j}$ is a binary indicator, which takes value 1 if D2D pair j shares the channel of CU i, and becomes 0 otherwise. P_i^c is the fixed transmit power of CU i, $P_j^d h_{j,BS}^{(i)}$ is the interference from D2D pair j, and Γ_i^{min} is minimum required SINR which satisfies the QoS requirement of CU i. Due to fixed SINR constraint, inequality (2) is the interference constraint that the D2D pairs need to obey, if they reuse the subchannel of CU i,

$$\frac{P_i^c g_{BS}^{(i)}}{\Gamma_i^{min}} - \sigma_N^2 \geq \sum_j \phi_{i,j} P_j^d h_{j,BS}^{(i)}, \forall i \in \mathcal{C} \tag{2}$$

On the other hand SINR requirement of D2D pair j is expressed in Equation (3),

$$\Gamma_j^d := \frac{\phi_{i,j} P_j^d h_{j,j,D}^{(i)}}{\sigma_N^2 + \sum_{j' \neq j \in \mathcal{D}} \phi_{i,j'} P_{j'}^d h_{j',j,D}^{(i)}} \geq \Gamma_j^{d,min} \tag{3}$$

3.1. Joint Centralized Optimization of Channel Allocation and Transmit Powers

Jointly optimal channel and power allocation for D2D pairs aims to maximize the number of D2D pairs that are allocated a subchannel. The optimization variables are the binary allocation variables $\phi_{i,j}, \forall i \in \mathcal{C}, j \in \mathcal{D}$ and the D2D transmission powers $P_j^d, \forall j \in \mathcal{D}$.

$$\max_{\phi_{i,j}, P_j^d, \forall i \in \mathcal{C}, j \in \mathcal{D}} \left\{ \sum_{i \in \mathcal{C}} \sum_{j \in \mathcal{D}} \phi_{i,j} \right\} \tag{4}$$

s.t.:

$$
\begin{aligned}
\frac{P_i^c g_{BS}^{(i)}}{\Gamma_i^{min}} - \sigma_N^2 &\geq \sum_j \phi_{i,j} P_j^d h_{j,BS}^{(i)}, \forall i \in \mathcal{C} && (5)\\
\phi_{i,j}\left(\frac{P_j^d h_{j,j,D}^{(i)}}{\Gamma_j^{d,min}} - \sigma_N^2\right) &\geq \phi_{i,j} \sum_{j' \neq j \in \mathcal{D}} \phi_{i,j'} P_{j'}^d h_{j',j,D}^{(i)}, \forall j \in \mathcal{D}, i \in \mathcal{C} && (6)\\
\sum_{i \in \mathcal{C}} \phi_{i,j} &\leq 1, \forall j \in \mathcal{D} && (7)\\
P_j^d &\leq P_{max}^d, \forall j \in \mathcal{D} && (8)\\
\phi_{i,j} &\in \{0,1\} && (9)\\
P_j^d &\geq 0, \forall j \in \mathcal{D} && (10)
\end{aligned}
$$

The objective function in (4) aims to maximize the number of D2D pairs that are allocated a subchannel. Constraint (5) denotes the maximum interference limit for each cellular user. Constraint (6) denotes the maximum interference limit for each D2D receiver. This constraint is in effect only if D2D pair is allocated a subchannel. Constraint (7) enforces each D2D pair be allocated at most one subchannel. Constraint (8) denotes the maximum power limit for the D2D transmitters. (9) and (10) enforces the allocation and power variables to be binary and positive, respectively.

The constraints (5) and (6) in the above optimization problem involves product of binary allocation variables with the continuous power variables. The problem is a mixed integer nonlinear programming (MINLP) problem, the solution of which is prohibitively complex. Besides the centralized solution of the above problem requires the BS to know all the channel state information (CSI) listed in Table 1. CSI for the links between different D2D pairs has to be obtained by the D2D receivers and forwarded to the BS. This would result in a dramatic increase in the communication complexity.

4. Proposed Channel Allocation Methods

4.1. Channel Allocation Based on Neighborhood Information

Considering the complexity of the above-mentioned MINLP-based optimization problem and in order to reduce the CSI requirements, in this part we formulate a mixed integer linear programming (MIP) based problem. In this problem formulation we aim to maximize the number of transmitting D2D pairs, for *fixed* and given transmit powers. Interference channel gains from CU's to D2D pair receivers and from a D2D pair transmitters to another D2D pair's receiver ($h_{j,C}^{(i)}$ and $h_{j,j',D}^{(i)}$) are assumed to be unknown. However it is reasonable to assume that devices apply a beacon-based neighbor discovery procedure and know their neighbors. Let $a_{i,j}$ and $b_{j,j'}$ be the neighborhood indicators. $a_{i,j} = 1$ if the CU i and D2D receiver j are not neighbors and 0 otherwise. $b_{j,j'} = 1$ if neither the transmitter of D2D pair j and receiver of D2D pair j' nor the transmitter of D2D pair j' and receiver of D2D pair j are neighbors and 0 otherwise. The neighborhood parameter is related to the signal to noise ratio between the nodes. We assume that if the SNR between a pair of nodes is above a certain threshold, beacon signal can be heard and the pair of nodes are considered to be neighbors.

With the known channel $g_B^{(i)}$ and for given transmit powers $P_j^d, \forall d \in \mathcal{D}$ the maximum interference limit for a CU i can be expressed as,

$$I_{Lim}^{(i)} = \frac{P_i^c g_B^{(i)}}{\Gamma_i^{min}} - \sigma_N^2, \forall i, \qquad (11)$$

where $I_{Lim}^{(i)}$ denotes interference limit to satisfy required SINR in CU i's channel.

In this model both the D2D receiver and BS considers interference as noise. CUs transmission need to satisfy minimum signal to interference noise ratio (SINR) requirements, because CUs are primary users of the network. In this problem formulation we assume that the D2D transmitters transmit with a fixed and given power. A long a D2D pair uses a subchannel together with a non-neighbor CU and a set of non-neighbor D2D pairs, interference on the D2D receivers are assumed negligible so that their SINR constraints are always satisfied. A channel can be allocated to a set of D2D pairs only if the corresponding CU suffers an interference below its interference limit. Our aim is to maximize the number of D2D pairs that can be served subject to these SINR (interference) constraints. The problem is formulated as follows,

$$\max_{\phi_{i,j}, \forall i \in \mathcal{C}, j \in \mathcal{D}} \left\{ \sum_i \sum_j \phi_{i,j} \right\} \tag{12}$$

s.t.:

$$\phi_{i,j} \leq a_{i,j}, \forall, i \in \mathcal{C}, j \in \mathcal{D} \tag{13}$$

$$\phi_{i,j} + \phi_{i,j'} \leq b_{j,j'} + 1, \forall i \in \mathcal{C}, j \neq j' \in \mathcal{D} \tag{14}$$

$$\sum_{i \in \mathcal{C}} \phi_{i,j} \leq 1, \forall j \in \mathcal{D} \tag{15}$$

$$\sum_{j \in D2D} \phi_{i,j} I_j^{(i)} \leq I_{Lim}^{(i)}, \forall i \in \mathcal{C} \tag{16}$$

The objective in (12) is to maximize the number of served D2D pairs. Constraint (13) allows that a D2D pair j can reuse the CU i's channel if and only if the CU i and D2D pair j are not neighbors. Constraint (14) enforces that D2D pairs j and D2D pairs k can together reuse CU i's channel if j and k are not neighbors. Constraint (15) implies that each D2D pair can use only one CU's channel. Total interference in channel i must be lower than the interference limit of CU i as seen in constraint (16). This is a mixed-integer programming (MIP) problem and can be solved via the CPLEX solver.

We proposed three Algorithms to solve previously defined problem. All of the algorithms operate given D2D transmission power levels and require neighborhood information of the all nodes and CUs interference limit for desired transmission quality. With these information, channel allocation problem is solved in centralized way by the BS. First two algorithm only slightly differ. Last algorithm is less complex than the first two.

4.2. Interference Aware Channel Allocation (IACA)

The proposed algorithm requires interference values from the D2D transmitters to the BS, neighborhood information of the CU's and the D2D pairs and interference limits of the CU's. At each iteration the available CU's and D2D pairs are searched and the CU-D2D pair (i^*, j^*) that obeys the constraints (13), (14) and results in minimum interference is found (Lines 5-14). If there is no such pair, then the algorithm terminates (Line 22). If there is such (i^*, j^*) and if the resulting total interference to CU i^* is below its limit and j^* is not neighbor with ($\phi_{i^*, j'^*} = 1, \forall j^{'*}$) previously allocated D2D pairs $j^{'*}$ that use CU i^*'s channel (Line 8), then the allocation is successful and the D2D pair j^* is dropped from the set of available D2D pairs (Line 17). Otherwise, the CU i^* is dropped from the list of available CU's. Algorithm continues until there is no available D2D pair or CU.

4.3. Weighted Interference Aware Channel Allocation (W-IACA)

Weighted minimum algorithm is very similar to the previous IACA algorithm. In this algorithm while searching the optimal (i^*, j^*) pair, normalized interference information is used. Interference is normalized with number of D2D neighbors of D2D pair j, $\frac{I_j^{(i)}}{\sum_k b_{j,k}}$. This normalization brings advantage for D2D pairs with fewer neighbors. Thus, conflicts are avoided more and more D2D pairs are expected to reuse the same channel.

4.4. Cellular User Based Selection (CUBS)

This algorithm differs from the others as follows: the BS checks the CUs one-by-one. For CU i the BS allocates the feasible D2D pairs(not neighbor with CU i and all other D2D pairs) in the ascending order of created interference, until $I_{Lim}^{(i)}$ is reached. Allocated D2D pairs are dropped from the set of available D2D pairs. Then the BS passes to the next CU and the same procedure is repeated, either until all CU's are finished or all feasible D2D pairs are finished.

5. Joint Channel and Power Allocation

The above mentioned channel allocation methods operate for given D2D transmission powers. In order to pack more D2D pairs in each subchannel and satisfy the minimum SINR requirements of both CU's and D2D pairs, a

Algorithm 1 Interference Aware Channel Allocation (IACA)

Inputs: Sets $\mathcal{C}$ and $\mathcal{D}$, interferences $I_j^{(i)}$, interference limits $I_{Lim}^{(i)}, \forall i$ and neighborhood parameters $a_{i,j}$, $b_{j,k}$
Output: $\phi_{i,j}$.
Initialize: $\phi_{i,j} = 0, \forall i, j$. $I^{(i)} = 0, \forall i$, $\mathcal{D}_{rem} = \mathcal{D}$, $\mathcal{C}_{rem} = \mathcal{C}$
while $\mathcal{D}_{rem} \neq \emptyset$ and $\mathcal{C}_{rem} \neq \emptyset$ **do**
    $i^* = 0, j^* = 0, I_{min} = \infty$
    for $\forall i \in \mathcal{C}_{rem}$ **do**
        for $\forall j \in \mathcal{D}_{rem}$ s.t. $a_{i,j} = 1$ **do**
            if $\nexists k \in \mathcal{D}$ s.t. $\phi_{i,k} = 1, b_{j,k} = 0$ **then**
                if $I_j^{(i)} \leq I_{min}$ **then**
                    $i^* = i, j^* = j, I_{min} = I_j^{(i)}$
                end if
            end if
        end for
    end for
    if $i^* \neq 0$ and $j^* \neq 0$ **then**
        if $I_{i^*} + I_{j^*}^{(i^*)} \leq I_{Lim}^{(i^*)}$ **then**
            $\phi_{i^*,j^*} = 1$, $\mathcal{D}_{rem} = \mathcal{D}_{rem} - j^*$
        else
            $\mathcal{C}_{rem} = \mathcal{C}_{rem} - i^*$
        end if
    else
        return
    end if
end while

power control mechanism has to be applied. The authors in [37] propose a joint scheduling and power control framework. In that framework first a *valid scheduling scenario* (set of node pairs that can communicate simultaneously on the same channel) is found. This is similar to the methods that we proposed in the previous section. Finding a valid scenario avoids transmission of neighbor pairs and prevents serious interference. Let $\mathcal{S}_i$ be set of D2D pairs in the valid scenario for channel i. In our problem, a valid scenario corresponds to a set of D2D pairs $\mathcal{S}_i$, which 1) do not collectively exceed the interference limit of CU i 2) are not a neighbor of each other. After determining a valid scenario, the nodes in $\mathcal{S}_i$ perform the following iterative power control algorithm:

$$P_j^d(t+1) = \min\left[P_{max}^d, \frac{\Gamma_j^{d,min}}{\Gamma_j^d(t)} P_j^d(t)\right], \forall j \in \mathcal{S}_i, \forall i \in \mathcal{C} \tag{17}$$

, where $P_j^d(t)$ is the transmit power of D2D pair j in the t^{th} iteration of the algorithm. $\Gamma_j^d(t)$ is the SINR in the t^{th} iteration, which is calculated according to (3). As seen in (17) D2D transmission power is limited by P_{max}^d. On the other hand CU's do not join in the power control, they transmit with a fixed power. The power control algorithm typically converges in a few iterations. If at least one of the D2D pairs in $\mathcal{S}_i$ stay below the minimum SINR (i.e. above P_{max}^d) the pair with minimum SINR is taken out and power control is repeated. This continuous until an admissible set of D2D pairs are found. This power control algorithm is amenable for distributed implementation and performed in parallel for all channels.

After transmit powers are found, the first stage is repeated. Channel allocation is repeated with the new power levels. The unscheduled users join in channel allocation with their maximum power. A valid scenario is found and this new set of D2D pairs are fed into the power control algorithm. This main iteration goes on until there is no more improvement in the set and number of served D2D pairs. Flow chart of this joint channel and power allocation scheme is illustrated in Figure 2.

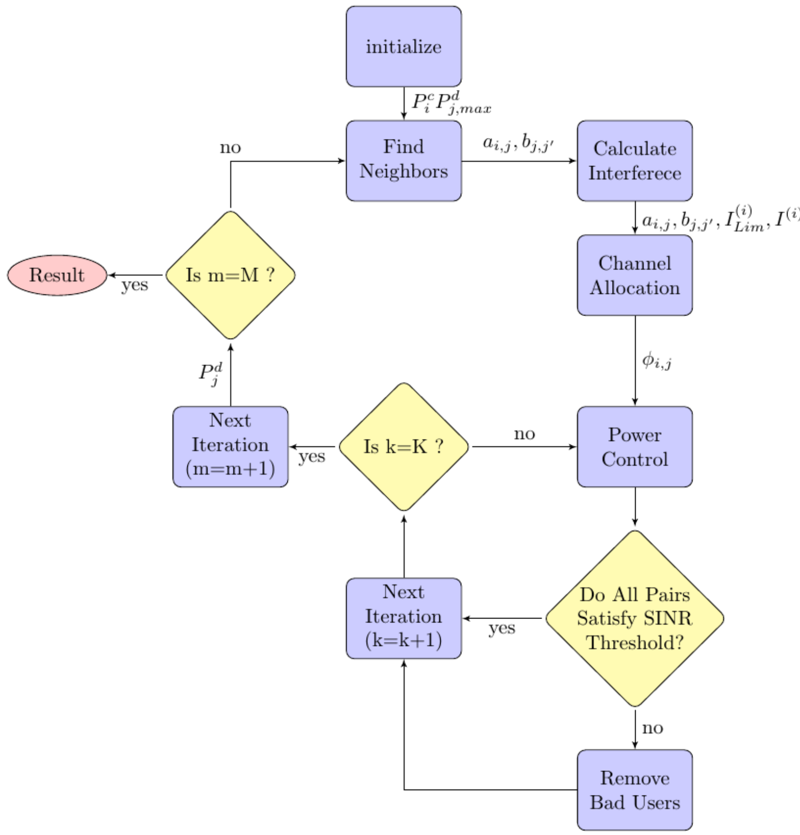

Figure 2: Flowchart of the Proposed Joint Channel and Power Allocation Algorithm for the D2D Pairs.

6. Numerical Evaluations

A single cellular network is considered and a BS is located at the cell center. CUs and D2D pairs are distributed uniformly over the system area. CUs are the primary users of a cellular network. D2D pairs aim to use the frequency spectrum efficiently without harming CUs . Used simulation parameters are provided in Table 2 We consider a simulation model that is similar to that of [38].

All results were obtained as an average of 100 different random scenarios for all number of CUs and D2D pairs. Table 3 shows the average number of D2D pairs served within the network with 20 CUs for 100 different scenarios. All pro-

Table 2: Simulation Parameters

Parameter	Value
Cellular Layout	Isolated cell
Cellular Area	Circular with radius 500 m
Pathloss model for BS link	$15.3 + 37.6 \log_{10}(d_m)$
Pathloss model for device link	$2.8 + 40 \log_{10}(d_m)$
Noise spectral density	-174 dBm/Hz
Cellular User Bandwidth	200kHz
Antenna Gain	BS: 14 dBi, Device: 0dBi
Maximum distance between D2D transmitter and receiver	50 meters
Cellular User Transmit Power	P_i^c = 24dBm
Maximum D2D transmitter power	P_j^d = 21dBm
CU SINR Constraint	15, 20, 25 dB
D2D SINR Constraint	15, 20, 25 dB
Neighborhood Constraint (for CU's & D2D's)	10,15 dB
Number of cellular users	5 - 15 - 25
Number of D2D pairs	25 - 30 - 35 - 40 - 45 - 50

posed algorithm results are close to the CPLEX-based results and the proposed algorithms do not differ much in terms of performance. Among the proposed algorithms, IACA is the best algorithm even if there is a very small difference between IACA and W-IACA. The performance gap is approximately 5% from the GAMS-based solution. From now on will only compare CPLEX-based and IACA methods jointly used with the iterative power control algorithm.

Figure 3 shows the average number of allocated D2D pairs for increasing number of D2D pairs. As seen in the figure the gap between CPLEX and IACA is high for 5 (low) number of CU's (i.e. subchannels) while it gets lower as the number of channels increase. For 5 CU's the performance saturates at 45 D2D pairs.

Table 3: Average Number of Served D2D Pairs for 20 CUs. Neighborhood SNR constraint is 10dB and SINR constraint for communication is 20dB.

# D2D pairs	35	40	45	50	55	60
GAMS	25.32	28.63	32.31	35.63	39.16	41.93
IACA	23.59	26.31	29.07	31.90	34.35	35.89
W-IACA	22.76	25.84	28.43	31.11	34.23	35.80
CUBS	23.33	26.24	29.30	31.82	34.77	36.59

In Fig. 4 we increase the rate constraints while keeping the neighborhood SNR requirement at 10dB. As the rate requirement got tougher the served D2D pairs got lower.

In Figure 5 neighborhood requirement is increased to 15dB and rate requirement is decreased again to 20 dB. Results reveal that since the neighborhood SNR requirement is decreased each D2D pair has less neighbors, which leads to more D2D pairs being packed into each channel (than the (10,20) case). Besides, the gap between the MIP-based solution and proposed IACA got lower (approximately 2%) for high number of CU's. This shows that the proposed iterative method and the iterative power control handles the interference successfully.

In Figure 6 neighborhood requirement is kept at 15dB and rate requirement is increased again to 25 dB. As expected, number of served D2D pairs decreased. The gap between MIP-based method and IACA is at 10%.

Table 4 shows the effect of number of main iterations on the performance. Allowed number of iterations is increased from 1 to 7. Here the SNR requirement for neighborhood is 10dB and SINR requirement for communication (rate constraint) is 20 dB. Results show that increasing number of iterations from 1 to 7 improves the performance. The improvement is dramatic (%40) especially in the case of low number of channels (e.g 5) and high number of D2D pairs (e.g 50). The improvement is insignificant especially if the number of CU's and D2D pairs is close (e.g. 25-25). This implies that the proposed methods are suitable for dense (massive) multiple access for the Internet of Things, where

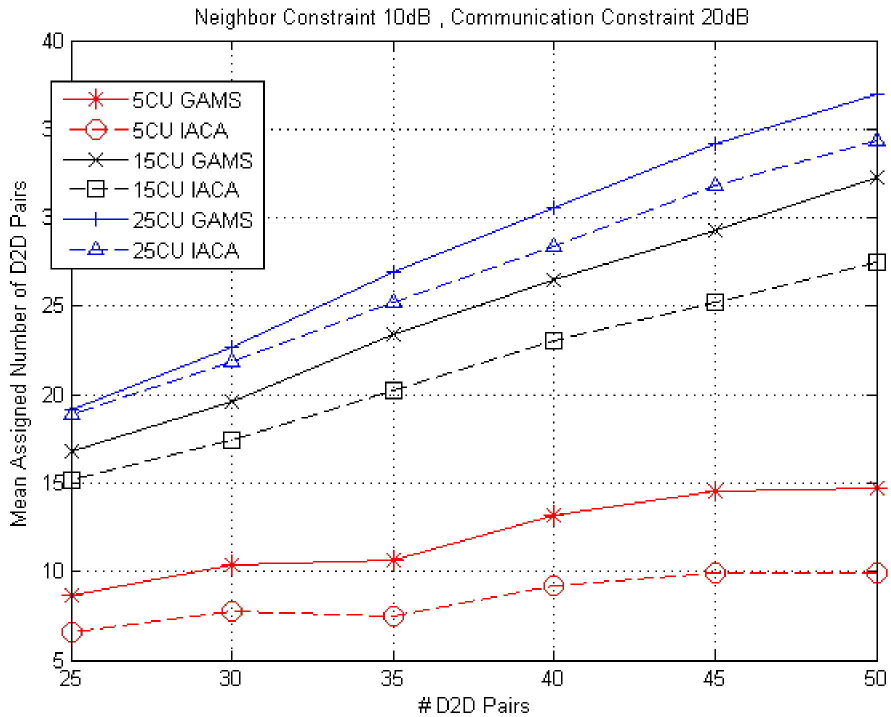

Figure 3: Average number of allocated D2D pairs vs available number of D2D pairs. Neighborhood and communication SINR constraints are 10 and 20 dB, respectively. Proposed algorithms perform within 8% of the MIP-based solution for high number of CU's.

the number of contending devices are much higher than the number of channels. Results show that for low number of CU's (i.e. subchannels) the gap between GAMS-based solution and proposed IACA is high and it gets higher with increased iterations. On the other hand, for higher number channels and D2D pairs (e.g. 25-50) the gap is much lower and drops with increasing iterations to 5 %. In other words, the iterative power control algorithm compensates for the suboptimality of IACA algorithm.

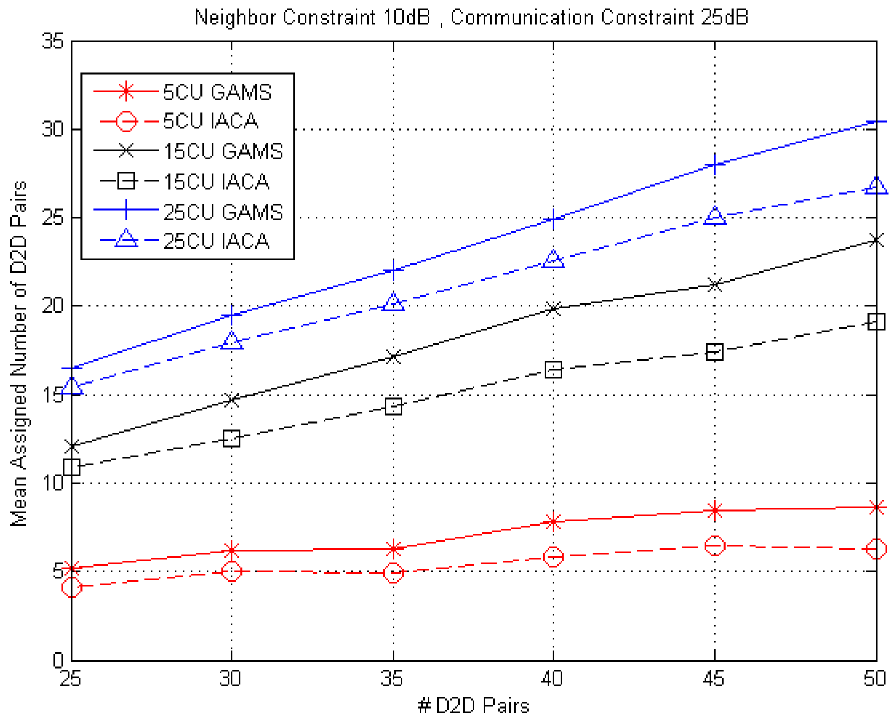

Figure 4: Average number of allocated D2D pairs vs available number of D2D pairs. Neighborhood and communication SINR constraints are 10 and 25 dB, respectively. Proposed algorithms perform within 14% of the MIP-based solution for high number of CU's.

7. Conclusion

We studied the joint problem of channel and power allocation for D2D pairs that reuse the subchannels of regular cellular users (CU's). Problem of joint channel and power allocation has a mixed integer and nonlinear nature, which led us to divide the problem into channel and power allocation problems. It is impractical to obtain the channel information of every link in a D2D network. Therefore we assume a system where each device is only able to learn its set of neighbors and feeds it back to the BS. An optimal channel allocation problem is formulated that is based on neighborhood information of CU's and D2D pairs in order to limit the interference to the BS and maximize the served D2D

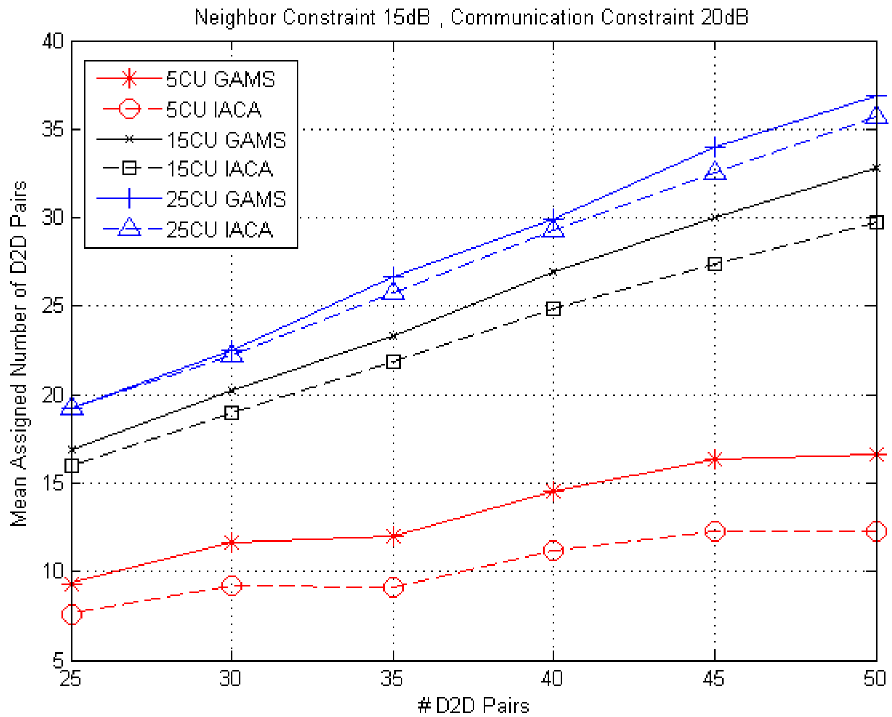

Figure 5: Average number of allocated D2D pairs vs available number of D2D pairs. Neighborhood and communication SINR constraints are 15 and 25 dB, respectively. Proposed algorithms perform within 5% of the MIP-based solution.

pairs. Then, greedy algorithms are proposed and performances are compared by simulations. This is combined with a distributed and iterative power control algorithm for the D2D pairs. Channel and power allocation methods are iteratively applied and numerical performance results are obtained. Results reveal that the proposed algorithms perform on average within 5% of the mixed integer programming based solution. Proposed channel allocation algorithm performs especially well for the case of high number of D2D pairs and a typical number of subchannels.

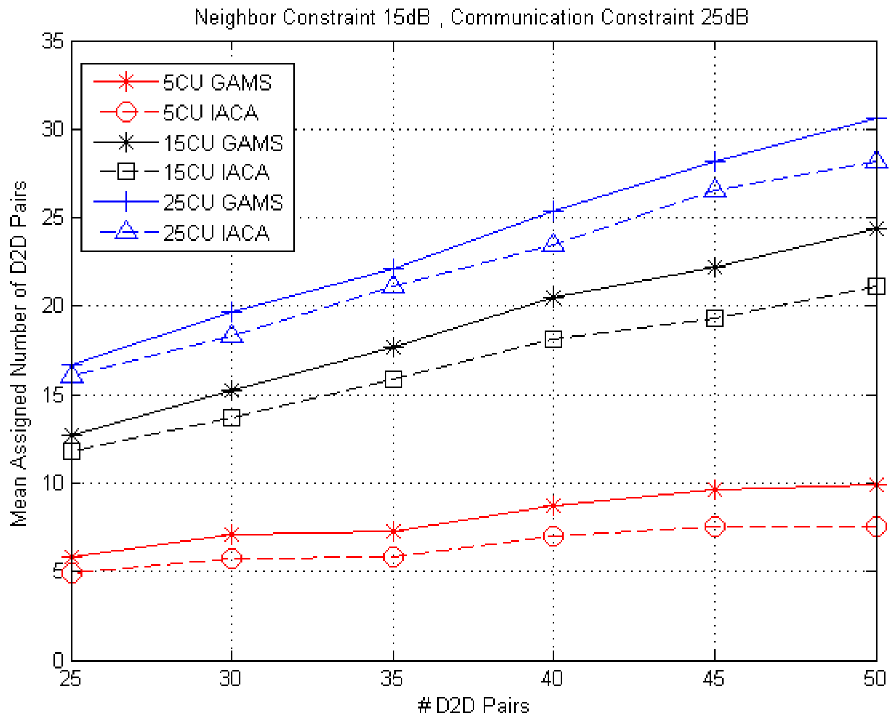

Figure 6: Average number of allocated D2D pairs vs available number of D2D pairs. Neighborhood and communication SINR constraints are 15 and 25 dB, respectively. Proposed algorithms perform within 5% of the MIP-based solution.

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		Number of Iterations			
		1	3	5	7
5 CU's & 25 D2D	GAMS	6.87	8.01	8.41	8,65
	IACA	5.87	6.36	6.43	6.52
5 CU's & 50 D2D	GAMS	10.15	13.06	14.12	14.48
	IACA	8.44	9.50	9.78	9.89
15 CU's & 25 D2D	GAMS	15.62	16.46	16.55	16.73
	IACA	13.58	14.77	15.00	15.24
15 CU's & 50 D2D	GAMS	27.53	31.20	32.07	32.41
	IACA	22.42	25.29	26.42	27.02
25 CU's & 25 D2D	GAMS	18.99	19.08	19.40	19.24
	IACA	17.88	18.55	18.61	18.85
25 CU's & 50 D2D	GAMS	35.35	36.71	36.72	36.88
	IACA	30.81	32.88	33.57	34.00

Table 4: Effect of number of main iterations on the performance.

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