Computer Communications xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

On improving SINR in LTE HetNets with D2D relays

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ARTICLE INFO

Article history:
Received 6 July 2015
Revised 13 October 2015
Accepted 19 December 2015
Available online xxx

Keywords:
Femto cells
LTE
SINR
HetNets
D2D

ABSTRACT

Femtos, with frequency reuse one, can be deployed in hotspots, offices and residences alike to provide high indoor data rates and reduce traffic load on Macro. However, arbitrarily deployed Femtos could decrease SINR significantly because of inter-cell interference and obstacles present in the building. Hence, to attain a desirable SINR Femtos have to be placed efficiently. At the same time, minimizing the power leakage from indoor Femtos in order to improve the SINR of outdoor users in the high interference zone (HIZone) around building areas is also important. To guarantee minimum SINR to both indoor UEs (*IUEs*) and outdoor UEs in HIZone (*HIZUEs*), we apply the concept of device-to-device (D2D) communication wherein free/idle IUEs act like UE-relays for HIZUEs. We first formulate a D2D MILP model which establishes D2D pairs between free/idle *IUEs* and *HIZUEs* and also guarantees certain SINR threshold ($SINR_t h$) for both *IUEs* and *HIZUEs*. As D2D MILP model takes more computation time, it is not usable in real-world scenarios for establishing D2D pairs on the fly. Hence, we propose a two-step D2D heuristic algorithm for establishing D2D based relay pairs. In step one (called as hDPRA), it efficiently chooses potential D2D based relay pairs and allocates radio resources to them. In step two (called as hDPA), a Linear Programming (LP) model is formulated for power control of D2D links. We have evaluated the performance of the proposed D2D heuristic algorithm for different scenarios (i.e., 500 topologies) by varying densities of IUEs and HIZUEs. From our evaluation, we find that the proposed algorithm maintains almost the same SINR as that of *Full Power Femto scheme* (i.e., Femto transmits with maximum power) for *IUEs* and also guarantees certain minimum $SINR_t h$ for *HIZUEs*. Our simulation results show that in comparison to the *Optimal Femto Power* (OptFP; Sathya et al., 2014) scheme (i.e., Femto transmits with optimal reduced power), it improves SINR of IUEs by 40%. However, the degradation in SINR of IUEs is only 1.6% when compared to the *Full Power Femto scheme*.

1. Introduction

The increased use of mobile devices has led to an increase in the demand for data services over cellular networks. This is partly addressed by intensifying the deployment of Macro Base Stations (MBSs) in the Long Term Evolution (LTE) cellular networks. The mobile operators can boost data rates for outdoor user equipments (*OUEs*) but are not able to increase the data rates for indoor user equipments (*IUEs*). This is because it is difficult for electromagnetic signals to penetrate through walls and floors. Thus, the *IUEs* suffer with low signal strengths. To demonstrate this, let us consider a single-floor building with a single MBS (interchangeably used as Macro in rest of this paper) placed at a distance of 350 m [2] on the south west side of the building. By taking into account path losses due to walls and floors, the region up to which the signal from MBS can penetrate into the building is then measured and shown in Fig. 1. This figure shows the radio environmental map (REM) of the building where *Z*-axis is used to list out signal to noise ratio (SNR) values at various sub-regions (X, Y) inside the building. Owing to the walls inside the building, *IUEs* on average receive low SNR (e.g., −8 dB, −9 dB) compared to *OUEs* (e.g., 4, 2, 0, −1 dB).

Cisco VNI Mobile Forecast [3] (2014–2019) tells that although only 3.9% of mobile connections were LTE based they accounted for 40% of the mobile traffic and this will rise to 51% by 2019, by which the mobile data usage will grow 11 fold to over 15 exabytes per month. Reports by Cisco and Huawei [4] tell that 70% of the traffic is caused by indoor users (*IUEs*). Hence, it is very important for telecom operators to improve coverage of indoor areas and boost data rates of *IUEs*. To achieve this, one can deploy a large number of low power nodes (LPNs) a.k.a. small cells (e.g., Picos and Femtos [5]) under an umbrella MBS coverage and thereby form an LTE heterogeneous network (HetNet). This increases spectrum

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http://dx.doi.org/10.1016/j.comcom.2015.12.004

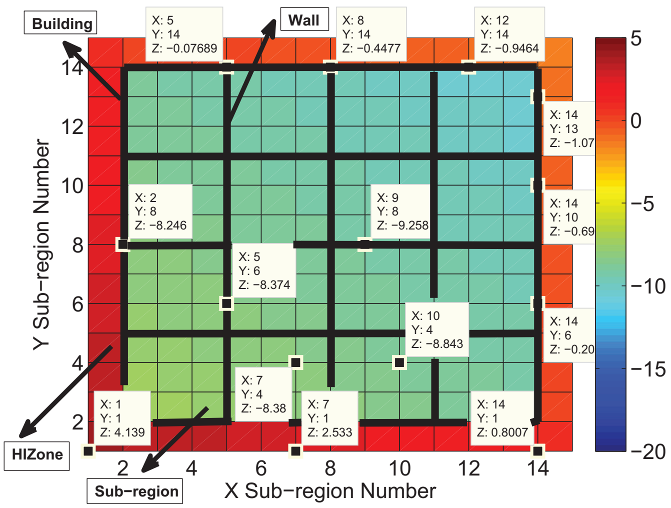

Fig. 1. REM of sub-regions inside building without any Femto cells deployed indoor.

Table 1
Notations used in our work.

Notation	Abbreviations
D2D	Device-to-device
HIZUE	*OUE* in *HIZone*
HIZone	High interference zone
IUE	Indoor UE
LPN	Low power node
LP	Linear Programming
MBS	Macro Base Station
MILP	Mixed Integer Linear Programming
MinNF	Minimize the Number of Femtos
OptFP	Optimal Femto Transmission Power
PRS	Position Reference Signal
RB	Resource block
SINR	Signal-to-interference plus noise ratio
$SINR_{th}$	Threshold SINR
SON	Self Organizing Network
UE	User Equipment

efficiency by allowing spatial reuse of the same spectrum. Small cells can be installed by end users in residences and in large office environments and hotspots. But, co-tier interference among Femtos can occur, if they are placed arbitrarily and the operator tries to reuse the same spectrum, which would decrease the system capacity. In order to make the usage of spectrum more efficient for *IUEs*, placement of Femtos needs to be optimal. Optimal placement of Femtos ensures good SINR and thereby improves system capacity. In this work, we apply the Minimize Number of Femtos (MinNF [1]) model (explained in detail in Section 4) to determine the optimal count and the optimal placement of Femtos and hence reduces operator's CAPEX and OPEX. Hence, we expect that large scale enterprises could benefit from MinNF model based deployment. However, in some scenarios, operator's may need to go for sub-optimal or arbitrary deployment (due to physical constraints) which will lead to deployment of more number of Femtos than that in MinNF to ensure that there are no coverage holes. Even optimal placement of Femtos inside a building leads to power leakage at the edges/corners of the building. This degrades the performance of the *OUEs* (i.e., Macro connected) in high interference zone (HIZone) around the building area because both Macros and Femtos operate at the same frequency due to reuse one in LTE HetNets. In our work we specifically refer the *OUEs* in *HIZone* as *HIZUEs*.

To guarantee certain minimum SINR to both *IUEs* and *HIZUEs*, we apply the concept of device to device (D2D) communication in LTE HetNets. In D2D, devices (i.e., UEs) communicate directly with each other while the serving BS assists in setting up of D2D links and managing the control plane, authentication, handovers, etc. D2D helps in improving the cellular network capacity and power efficiency. In our work, we make use of idle *IUEs* as relays between Femtos and *HIZUEs* through *D2D* as an underlay to the LTE HetNet. We formulate a Mixed-Integer Linear Programming (*MILP*) model that chooses D2D pairs, and assigns radio resources and transmission power to each of D2D pairs. To reduce the time complexity, we propose a two-step heuristic algorithm. In step one, we find the sub-optimal D2D pairs and assign the radio resources for them. In step two, a Linear Programming (*LP*) model is used to determine the transmit power for D2D pairs.

Table 1 shows notations used in this work. Rest of the paper is organized in the following manner. Section 2 describes the related research works. Proposed LTE HetNet system architecture with D2D links is presented in Section 3. In Section 4, proposed placement MILP model which minimizes number of Femtos to be deployed, D2D MILP model and D2D heuristic algorithm are discussed. Performance results are explained in Section 5. Finally, Section 6 contains concluding remarks.

2. Related research work

Many approaches to placing Femtos have been discussed in literature with sufficient insight, keeping in mind various parameters such as building dimensions, interference from Macro BSs and other Femto BSs. In [6], small cell locations are optimized in an airport environment depending upon the traffic demand. In [7,8], Guo et al. suggested an automated small cell deployment model which attempts to find the optimal location of a new cell, subject to knowledge about the locations of existing cells, UEs and the building environment. A closed-form equation is given for the new cell's deployment location which is a function of transmit power, transmission scheme and path loss parameters. In [9], the authors investigated a joint Femto placement and power control optimization problem in enterprise buildings with the aim to prolong UEs' battery life. They proposed a novel two-step reformulation approach to convert the original mixed-integer non-convex problem (MINCP) into a MILP and then devised a global optimization algorithm by utilizing the MILP. But their system model did not consider co-tier and cross-tier interferences. In [10], Femtos are optimally placed in a multi-story enterprise building by not considering co-tier and cross-tier interferences. In [11], the authors proposed an iterative algorithm for optimizing deployment locations of cells based on a novel utility function (i.e., area proportional fairness utility which accounts for both user distribution and fair resource allocation) while accounting for mutual interference. Authors in [12] proposed an algorithm which gives the optimal transmission power of each of the Femtos deployed in a HetNet scenario by guaranteeing $SINR_{th}$ for IUEs and lesser degradation for *HIZUEs*. However, Femto power adaptation has not factored in occupancy level of *HIZUEs* outside the building.

In one of our previous works [13], an optimization problem is formulated for Femtos deployment which guarantees $SINR_{th}$ inside the building by considering co-tier interference, cross-tier interference and impedance caused by walls. We also varied the $SINR_{th}$ depending on average user density in each region inside the building. This resulted in improving spectral efficiency of Femtos deployed in indoors. However, *HIZUEs* suffered degradation in SINR due to cross-tier interference between Macros and Femtos. In [1], optimal placement of Femtos and dynamic control of their transmit powers are studied by solving two optimization models, namely MinNF and OptFP. MinNF determines the minimum number of Femtos and their respective coordinates to guarantee a minimum $SINR_{th}$ of 0 dB for all indoor regions, assuming full transmission power of the Femtos. Configuration of Femtos at the full transmission power degrades SINR values of *HIZUEs*. To address this issue, OptFP model is used to find the optimal power of the Femtos to reduce degradation in SINR for the *HIZUEs*. The maximum fall in SINR for *HIZUEs* is limited to 2 dB after the deployment of Femtos. Since Femto power is reduced, $SINR_{th}$ of *IUEs* is also reduced to -2 dB. This optimal power dynamically changes according to the occupancy of HIZUEs in the *HIZone*. But the presence of even a single *HIZUE* decreases SINR of numerous *IUEs*, which is not fair to *IUEs*. To ensure fairness for *IUEs* and *HIZUEs*, we apply the concept of device-to-device (D2D) communication in this work.

D2D is one of the most promising and challenging aspects toward 5G. In D2D communication, two UEs communicate directly with each other by means of data plane (D-plane) transmission using E-UTRA technology [14,15]. BS controls and optimizes the use of shared radio resources for cellular and D2D sessions. D2D is standardized by 3GPP in Rel-12 for proximity-based services [16]. Some of the challenges in D2D include interference management, resource allocation, power control, session management, mobility management, security, location estimation and multi-hop D2D [17–19]. Session management [20,21] in D2D is controlled by BS. Core network is used for authentication, control channel establishment and policy control. Authors of [22] proposed a resource allocation scheme to share resource blocks (RBs) among D2D pairs and traditional cellular users. In [23], the authors proposed an accurate model of the system and applied approximate dynamic programming model to do a fast resource scheduling in a HetNet system with D2D support. In [24] Phantom cell concept (UE-like BS) was proposed as a solution using D2D links to offload the traffic but different frequencies for the C-plane and D-plane were used. In [25], a holistic approach to efficiently offload with D2D was proposed and it incorporated a two-time scale scheduling solution with joint uplink and downlink scheduling between D2D pairs. It was shown that reuse of spectrum using Fractional Frequency Reuse (FFR) is limited but has not adapted any dynamic power control in the solution. In [26], the authors studied different techniques to expand the cell edge coverage. They showed that using D2D for cell edge users decreases the overall power consumption. Authors of [27] proposed an optimization problem based on practical link data model with the objective of minimizing power consumption while meeting user data requirements. To solve it in a polynomial time, the authors proposed a joint mode selection, channel allocation and power assignment for D2D pairs by using a heuristic algorithm, but they predetermined and fixed the number of D2D pairs.

Multi-hop D2D communication [28–30] is one of the most promising technologies in LTE used for military communication and disaster management. The two-hop or multi-hop can be applied to the problem where the UE with poor direct link to the MBS will forward data to a nearby UE over a high quality D2D link in uplink communication [31]. Here the receiving UE uploads its own data and relayed data to the MBS over its good uplink. This decreases the transmission time of the UE when compared to poor direct link to the MBS. Similarly, other work in uplink communication [32] describes the multi-hop D2D networking and resource management scheme for M2M communication to enhance end-to-end connectivity in an LTE network. In [33], the authors have proposed a novel distributed utility function for maximizing the D2D power control scheme which enables to balance spectral efficiency and resource allocation constraints that are essential in a given integrated cellular-D2D environment. During mode selection the impact of interference with other devices has not been considered. Also it is to be noted that the allocation of resources are random, which leads to inefficient D2D pairing.

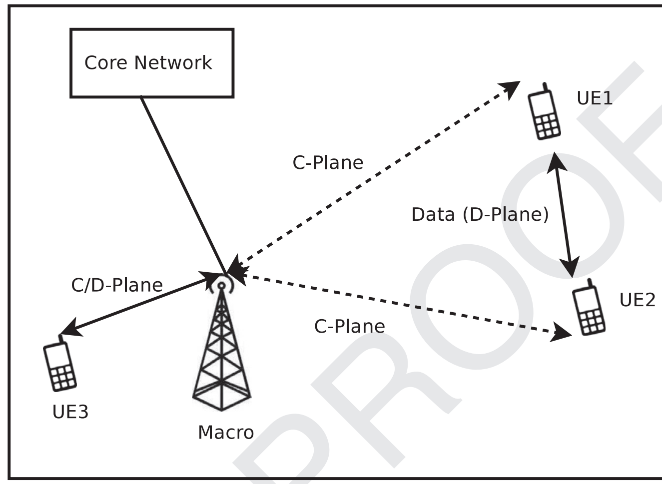

Fig. 2. Architecture of HetNet system with traditional and D2D links.

2.1. Our contributions

In this work, we have considered obstacles (walls and floor) present inside buildings, and co-tier and cross-tier interference in LTE HetNets. We use MinNF MILP model (referred henceforth as MinNF) to guarantee $SINR_{th}$ for *IUEs*. In MinNF model, Femtos transmit with full power which could degrade the performance of HIZUEs. In order to ensure fairness and improve achievable data rates for both *IUEs* and *HIZUEs*, we apply the concept of *D2D* communication wherein *IUEs* act like UE-relays (i.e., UE-like BS, forwarding data-plane traffic for some of the outdoor UEs). We first formulate a D2D *MILP* model to guarantee a certain $SINR_{th}$ for both *IUEs* and *HIZUEs*. To reduce the computation time, we propose a two-step heuristic algorithm. In step one (called as hDPRA), we efficiently choose the potential D2D based relay pairs and allocate radio resources to them. In step two (called as hDPA), an *LP* model is formulated for power control of D2D links. We have conducted extensive evaluations to show that our proposed D2D heuristic algorithm is very close to the D2D MILP model.

3. Proposed LTE HetNet system with D2D relays

In this section, we present architecture of LTE HetNet system with D2D relays, system model, building model and channel model.

3.1. HetNet architecture with D2D relays

In traditional cellular networks, UEs communicate with each other only through BSs (e.g., Macros, Picos, and Femtos). But in D2D [18], UEs communicate directly with each other for exchanging data traffic (D-plane) and the serving BS only assists in the establishment and maintenance of D2D links as shown in Fig. 2. In our HetNet architecture with D2D relays, Femtos make use of free/idle *IUEs* (*FIUEs*) in their cells as UE-relays for forwarding downlink data traffic (D-plane) of *HIZUEs* by setting up D2D links (i.e., *FIUE* → *HIZUE*). Hence, *HIZUEs* are going to be served in downlink by one of Femtos deployed inside the building by using *FIUEs* (typically located at Femto cell-edge regions) as relay nodes. However, *HIZUEs* always communicate with MBS for their uplink communication. The control traffic (C-plane) for the *HIZUEs* is still delivered by the MBS [15] for better reliability and reducing the number of handovers for *HIZUEs* which are typically more mobile than indoor UEs.

The architecture of proposed HetNet system with D2D based relays is shown in Fig. 3. The data traffic (D-plane) for the *HIZUEs*

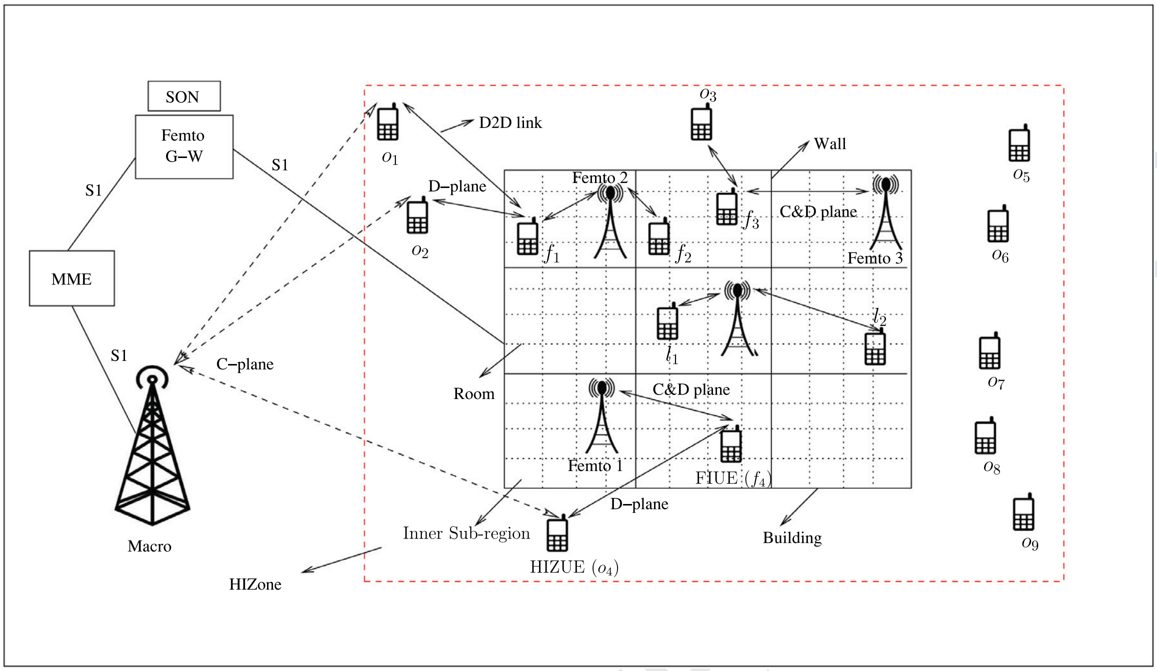

Fig. 3. Architecture of proposed HetNet system with D2D based relays.

is first sent to *FIUEs* from the Femto by normal cellular communications. The *FIUEs* act as UE-relays and forward the data traffic to the *HIZUEs*. All the Femtos are connected to a Femto-Gateway (F-GW) over S1 interface. Self Organization Network (SON) features (e.g., optimally choosing D2D links and tuning their transmit power levels) can be integrated into the F-GW to automate the network operation. Broadly there are two approaches for choosing D2D links and fine tuning of their transmit power levels: distributed one which could be implemented at *FIUEs* and centralized one which could be implemented at the F-GW/SON. Both these approaches require the knowledge of distance/channel state information between *FIUEs* and *HIZUEs* for establishing D2D links with the required transmit power. But, it is very challenging and costly to acquire this information at *FIUEs* and choose D2D links by themselves in a distributed manner. Hence, in our work, we consider the centralized approach (i.e., Network assisted mode [34,35]) by implementing the proposed D2D heuristic algorithm at the F-GW/SON. MBS periodically provides the list of potential *HIZUEs* (through C-plane messages) to the F-GW/SON. Femtos also provide the list of potential *FIUEs* to the F-GW/SON periodically (e.g., 10 ms which is equal to one LTE frame duration). The downlink channel (from *FIUEs* to *HIZUES*) quality can be estimated at *HIZUEs* by overhearing the uplink sounding reference signals (SRSs [16,36–38]) of the *FIUEs*. Note that SRSs are sent periodically by *FIUEs* in the uplink to the serving Femtos for estimating uplink channel state. *HIZUEs* listening to these SRSs could estimate their downlink channel state and convey the same to F-GW/SON via MBS. If *FIUEs* are configured not to send SRSs, then the F-GW/SON needs to go for default power setting for D2D links. The D2D heuristic algorithm which is implemented at the F-GW/SON determines D2D links and their respective transmit power levels for communicating the same to respective *FIUEs* via their respective serving Femtos.

The D2D connection setup process involves choosing one of the *FIUEs* as UE-relay through *D2D candidate indication* message sent from the corresponding Femto via F-GW (refer Fig. 4). Similarly the same *D2D candidate indication* message sent from MBS via F-GW informs the corresponding *HIZUE*. The *FIUE* and *HIZUE* then initiate the *D2D connection setup* procedure [39,40] by sending ACK from *FIUE* to F-GW via Femto. Similarly, once the ACK sent from *HIZUE* to F-GW via MBS. After *D2D connection setup* is established, *D2D data transfer* (D-Plane) procedure will take place.

3.2. System model

In this work, we consider an LTE HetNet system of MBSs in outdoor environment, to which the *OUEs* are associated, and Femtos inside an enterprise office building as shown in Fig. 3. We have considered the case where Femtos and MBSs operate on the same frequency band (i.e., reuse of one) to improve system's capacity. But, this can lead to high co-channel interference and affect *HIZUEs*′ performance. We also assume that Femtos are all configured in open access i.e., UEs are authorized to connect with any of the Femtos of an operator. *IUEs* are connected to one of the Femtos deployed inside the building. There are two types of *IUEs*: legacy *IUEs* (*LIUEs*) represented by $l_1, l_2, l_3, \ldots, l_m$ and free/idle *IUEs* (*FIUEs*) represented by $f_1, f_2, f_3, \ldots, f_n$ as shown in Fig. 3. *HIZUEs* are represented by $o_1, o_2, o_3, \ldots, o_p$. *LIUEs* are *IUEs* who send/receive data to/from a Femto at a particular Transmission Time Interval (TTI) for their own communication. *FIUEs* are *IUEs* who can act as UE-relays between their respective serving Femtos and one of *HIZUEs*. *FIUEs* can either be idle UEs or the UEs who are not going to be scheduled to receive any downlink data of their own from their serving Femtos for some TTIs. We assume that list of *FIUEs* is available at the F-GW/SON and it is updated dynamically.

The default scheduling algorithm is assumed to be running at each Femto for serving IUEs. The scheduling for downlink data of *HIZUEs* connected using D2D relays is also done at the Femtos. The D2D pairs are chosen such that they could be held for quiet sometime, so they will not be changing in every TTI. This can be assured if appropriate D2D Device Discovery mechanism [41] is used for choosing the *FIUEs*. We assume that the transmission power across resource blocks (RBs) for the Femtos are equal whereas for that of the *FIUEs* the power is varied accordingly to each RB. The D2D based relays (*FIUEs*) do not face severe battery issues because the *FIUEs* transmit at lower power. The *FIUEs* can also be provided with incentives by the operator for acting as D2D based UE-relays.

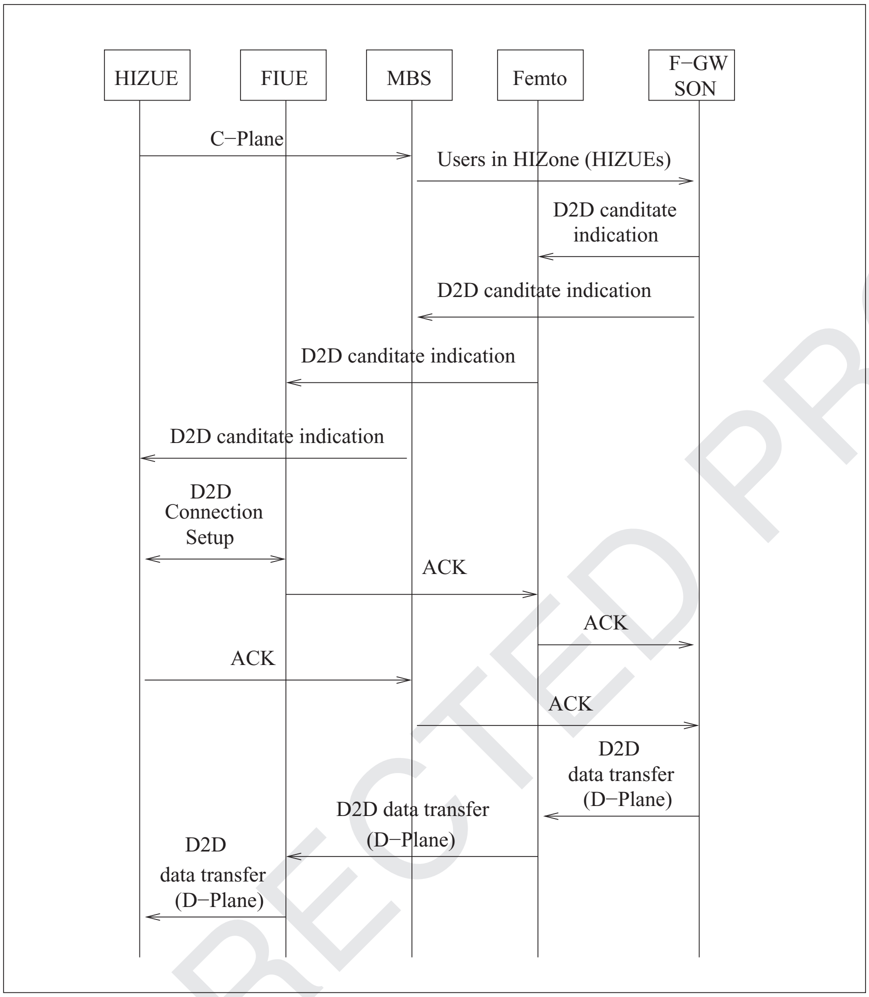

Fig. 4. Call flow diagram for D2D based communication in proposed HetNet system.

A variety of scenarios can co-exist in this HetNet system model for the D2D links as shown in Fig. 3. A D2D link can be established by an *FIUE* to serve one or more *HIZUEs*. A single *FIUE* can also serve multiple *HIZUEs* using D2D links. In the worst case, when it is impossible to establish any D2D link due to high load at the Femto or lack of *FIUEs*, the F-GW/SON can opt for *dynamic Femto power* (OptFP) model [1] in order to reduce interference to *HIZUEs* from the Femtos (explained later in Section 4.4).

3.3. Building model

Consider the dimensions of a building to be $L \times W \times H$, where L, W and H are respectively the length, width and height. Each floor is divided by walls into several rooms as shown in Fig. 3. Each room is further logically divided into smaller inner sub-regions, S_is. For example, a building which is divided logically into $(I_1, I_2, \ldots, I_{144})$ is shown in Fig. 5. The thick lines represent the walls of the rooms and the small squares are the sub-regions. Similarly, the HIZone region outside the building is divided into outer sub-regions, S_os. In the example, they are $O_1, O_2, \ldots, O_{52}$. As the size of sub-region is much smaller compared to the building/room size, we can safely assume that within every sub-region, the average SINR value is almost constant.

3.4. Channel model

The Path Loss (PL) between MBS and *IUEs* or *HIZUEs* is given by [12]:

$$PL_{macro} = 40\log_{10}\frac{d}{1000} + 30\log_{10} f + 49 + n\phi \qquad (1)$$

where, d is the distance of the *IUE*/*HIZUE* from MBS in meters, n is the number of walls in between MBS and *IUE*/*HIZUE*, f is the center frequency of MBS and ϕ is the penetration loss of a wall. To account for the fact that Femtos are placed in a multi-story building, PL between Femto and *IUE*/*HIZUE* is given by:

$$PL_{femto/D2D} = 37 + 30\log_{10} d + 18.3\nu^{\frac{(\nu+2)}{(\nu+1)}-0.46} + n\phi \qquad (2)$$

where ν is the number of floors in between Femto and *IUE*/*HIZUE*. We assume that PL model for D2D links is same as that of between Femto and IUE/HIZUE. We also assumed that the antenna gain for Macros and Femtos are 20 dBi and 2 dBi, respectively. We calculate the channel gain between UEs and various BSs using the PL models given above and antenna gains [42].

4. Femto placement and D2D pair selection models in LTE HetNets

In this section, we first present Minimize the Number of Femtos (MinNF) MILP model for determining the number of Femtos to be deployed in LTE HetNet system. Then we formulate D2D MILP model which establishes D2D based relay pairs between *FIUEs* and *HIZUEs* and also guarantees certain SINR threshold ($SINR_{th}$) for both *IUEs* and *HIZUEs*. As D2D MILP model takes more computation time, it is not usable in real-world deployments for establishing D2D pairs dynamically. To address this issue, we propose a two-step heuristic algorithm for establishing D2D pairs.

Please cite this article as: V. Sathya et al., On improving SINR in LTE HetNets with D2D relays, Computer Communications (2016), http://dx.doi.org/10.1016/j.comcom.2015.12.004

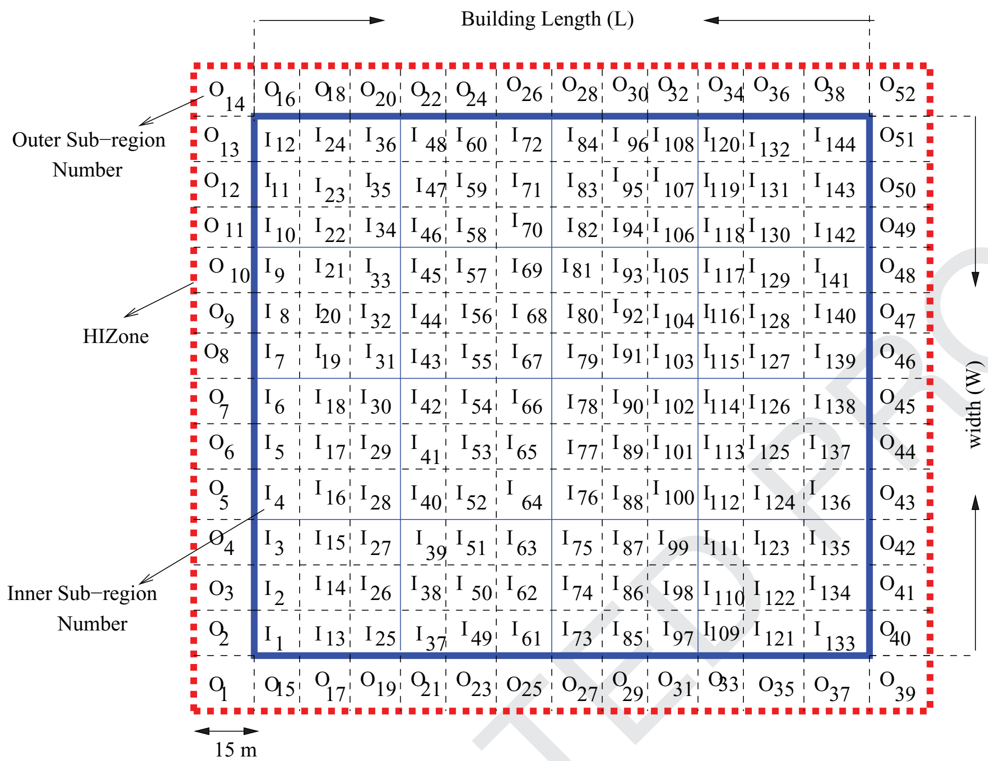

Fig. 5. Bird-eye view of floor area inside and outside a single-floor building.

Table 2
Glossary of MinNF MILP Model.

Notation	Definition
S_i	Set of all inner sub-regions
S_o	Set of all outer sub-regions
w_a	1 if Femto is placed at inner sub-region a, zero otherwise
y_{ja}	1 if jth inner sub-region of the building is associated with the Femto located at inner sub-region a, zero otherwise
G_{ja}	Channel gain between inner sub-regions j and a
M	Set of all MBSs

4.1. Femto placement: minimize the number of Femtos (MinNF) MILP model

In MinNF model, the minimum number of Femtos required for placement inside a building to provide a threshold SINR ($SINR_{th}$) to every inner sub-region is estimated. The aim is to boost the average SINR for all the IUEs by deploying optimal number of Femtos and maintain a minimum $SINR_{th}$ in all the inner sub-regions. To boost the data rate for IUEs, the Femtos that transmit at the peak power must be placed optimally inside the building without any coverage holes. The objectives of the MinNF model are given below:

- Minimize the number of Femtos, NF_{min}, needed for maintaining certain $SINR_{th}$ in each inner sub-region of the building.
- Determine the optimal locations for placement of NF_{min} Femtos inside the building.
- Identify the Femtos in NF_{min} to which the IUEs have to be associated.

The MinNF method has been described below and Table 2 shows the notation used in MinNF model. In order to provide a good SINR to IUEs, every Femto operates at its peak transmit power (P^f_{max}). The goal is to minimize the total number of Femtos deployed, expressed by Eq. (3).

$$min \sum_{a \in S_i} w_a \tag{3}$$

Every sub-region (i.e., all *IUEs* present in a sub-region) is allowed to associate with only one Femto BS (refer Eqs. (4) and (5)) inside the building.

$$\sum_{a \in S_i} y_{ja} = 1 \qquad \forall j \in S_i \tag{4}$$

$$y_{ja} - w_a \le 0 \qquad \forall j, a \in S_i \tag{5}$$

MinNF model needs to guarantee a certain minimum $SINR_{th}$ for all *IUEs* present in every sub-region of the building. The L.H.S. of the Eq. (6) is the SINR received by a particular inner sub-region j from the Femto located at sub-region a based on the worst case assumption of using all the resource blocks by all Femtos and MBS in the HetNet system. To ensure good coverage, the SINR received in each of inner sub-regions must be maintained above the predefined threshold λ (which is the $SINR_{th}$), given by:

$$\frac{Inf * (1 - y_{ja}) + G_{ja} P^f_{max} w_a}{N_o + \sum_{b \in S_i \backslash a} G_{jb} P^f_{max} w_b + \sum_{e \in M} G_{je} P_{macro}} \ge \lambda \quad \forall j, a \in S_i \tag{6}$$

The above Eq. (6) can be rewritten as,

$$Inf * (1 - y_{ja}) + G_{ja} P^f_{max} w_a \ge \left(\lambda N_o + \sum_{b \in S_i \backslash a} G_{jb} P^f_{max} w_b \lambda + \sum_{e \in M} G_{je} P_{macro} \lambda \right) \quad \forall j, a \in S_i \tag{7}$$

G_{je} and G_{ja} are the channel gain from Macro and Femto calculated using Eqs. (1) and (2), respectively, N_0 is the system noise and P_{macro} is the Macro BS's transmission power. In Eq. (6), *Inf* is a virtually infinite value (a very large value like 10^6). The reason for using $Inf * (1 - y_{ja})$ is that if $y_{ja} = 0$ then $Inf * (1 - y_{ja})$ becomes a large value and the expression can be ignored safely. Without

Table 3
Glossary of D2D MILP Model.

Notation	Definition
K	Set of all resource blocks (RBs)
F	Set of all Free Indoor UEs (*FIUEs*)
L	Set of all Legacy Indoor UEs (*LIUEs*)
O	Set of all Outdoor UEs in HIZone (*HIZUEs*)
M	Set of all MBSs
D_{fo}	A binary variable whose value is 1 if f is connected to o for D2D else 0, where f ϵ F, o ϵ O
C^k_{fo}	A binary variable whose value is 1 if f is connected to o for D2D using RB k else 0, where f ϵ F, o ϵ O, k ϵ K
h^k_f	A binary variable whose value is 1 if f is using RB k for D2D link else 0, where f ϵ F, k ϵ K
G_{xy}	Channel gain between two nodes x and y, where nodes can be *IUEs*, *HIZUEs*, MBSs or Femtos
p^k_f	Normalized power emitted by f in RB k, $0 \leq p^k_f \leq 1$, where f ϵ F, k ϵ K

the virtual infinite value, Eq. (6) ensures that all the Femtos provide a minimum $SINR_{th}$ to a particular sub-region. But just a single Femto is necessary to give $SINR_{th}$ for any given inner sub-region. The proposed MILP model will always be infeasible if we do not use the virtual infinite value as not all Femtos can meet $SINR_{th}$ in each inner sub-region. Finally, the MinNF model is formulated as follows,

$$min \sum_{a \in S_i} w_a \quad \text{s.t, (4), (5), (7).}$$

As shown later in Section 5, the proposed MinNF model guarantees that with minimum number of Femtos, all users inside the building get a certain $SINR_{th}$ (λ). It is a reasonable approach to boost the indoor SINR as the Femtos transmit at their maximum transmission power. Since Femtos and Macros operate on the same spectrum band, interference can occur between the Femtos and Macro users and it in turn would degrade the signal strength of the HIZUEs in HIZone. To avoid the degradation of HIZUEs and to guarantee certain minimum SINR for both *IUEs* and *HIZUEs*, we propose another optimization model, in next section, that optimally selects D2D links between *FIUEs* and *HIZUEs* to maintain $SINR_{th}$ for both *IUEs* and *HIZUEs*.

4.2. D2D MILP model

In order to achieve the required $SINR_{th}$ for both *IUEs* and *HIZUEs* in the HetNet system, we need to optimally choose D2D links, effectively allocate the RBs to the D2D links and adjust power for these links. We formulate a MILP model to address this problem. The notations used in this model are listed in Table 3.

In order to minimize battery drain of *FIUEs*, one of the main objectives[1] is to minimize the overall power consumed by the D2D links as expressed in Eq. (8):

$$min \sum_{f \in F} \sum_{k \in K} p^k_f \tag{8}$$

Eq. (9) sets an upper bound on the number of *HIZUEs* that can be served by each *FIUE*. Similarly, Eq. (10) restricts the number of *FIUEs* serving each *HIZUE*.

$$\sum_{o \in O} D_{fo} \leq \alpha \quad \forall f \epsilon F \tag{9}$$

$$\sum_{f \in F} D_{fo} \leq \beta \quad \forall o \epsilon O \tag{10}$$

[1] Another alternate optimization goal can be minimization of the maximum power ($min(max(p^k_f))$) consumed by D2D links where all the constraints are identical to the proposed D2D MILP model.

$$\sum_{f \in F} \sum_{o \in O} D_{fo} = \psi \quad \forall o \epsilon O \tag{11}$$

In order to limit the total number of D2D links that would be established in a TTI, we introduce Eq. (11). The values of α, β and ψ can be fine tuned as per the requirements of the operator. The binary variable C^k_{fo} is 1 when *FIUE* f and *HIZUE* o are communicating by using RB k. Hence, C^k_{fo} can never be 1 when there is no D2D link between f and o. This is ensured by Eq. (12). Here, η represents the maximum number of RBs that can be assigned to each D2D link.

$$\sum_{k \in K} C^k_{fo} \leq \eta \times D_{fo} \quad \forall f \epsilon F, o \epsilon O \tag{12}$$

Eq. (13) ensures that the maximum number of times a particular RB k can be reused by an *FIUE* f is 1.

$$\sum_{o \in O} C^k_{fo} \leq 1 \quad \forall f \epsilon F, k \epsilon K \tag{13}$$

h^k_f is set to be 1 if *FIUE* f is using the RB k. This is ensured by Eq. (14).

$$h^k_f = C^k_{fo} \quad \forall f \epsilon F, o \epsilon O, k \epsilon K \tag{14}$$

The constraint in Eq. (15) ensures that the normalized power emitted by *FIUE* f in a particular RB k is 0 when it is not used by f.

$$p^k_f \leq h^k_f \quad \forall f \epsilon F, k \epsilon K \tag{15}$$

The P^d_{max} is the maximum power of a D2D link. Once the MILP model is solved, transmission power of an *FIUE* f in a RB k is calculated as $p^k_f \times P^d_{max}$. G_{fl} gives the gain from the *FIUE* f to the *LIUE* l. S^k_l is an input parameter whose value is 1 when l is connected to its serving Femto (downlink) using RB k, else 0. The constraint in Eq. (16) ensures that the maximum interference power that is received by l is less than the allowed threshold value (I_l). I_l is computed for a given value of $SINR_{th}$ of *IUEs*.

$$\sum_{f \in F} (G_{fl} \times S^k_l \times p^k_f \times P^d_{max}) \leq I_l \quad \forall l \epsilon L, k \epsilon K \tag{16}$$

The L.H.S. of Eq. (17) is the SINR received by *HIZUE* o from *FIUE* f. To ensure good connection, the SINR of each D2D link is maintained above a predefined threshold λ_o which could vary across *HIZUEs*.

$$\frac{Inf * (1 - C^k_{fo}) + G_{fo} p^k_f P^d_{max}}{N_o + \sum_{m \in M} G_{mo} P_{macro} + \sum_{a \in B_k} G_{ao} P^f_{max} + \sum_{f' \in F \setminus f} G_{f'_o} p^k_{f'} P^d_{max}} \geq \lambda_o \quad \forall f \epsilon F, o \epsilon O, k \epsilon K \tag{17}$$

Here, B_k is the set of all Femtos using the RB k in a given TTI. Similarly, G_{ao} is the channel gain from Femto a to o, G_{fo} is the channel gain from f to o and G_{mo} is the channel gain from MBS m to o, calculated by using Eq. (1) or Eq. (2). The need to use $Inf * (1 - C^k_{fo})$ is that if $C^k_{fo} = 0$ then $Inf * (1 - C^k_{fo})$ becomes a large value and the expression can be ignored safely. Without the virtual infinite value, Eq. (17), ensures that all the *FIUEs* provide a minimum $SINR_{th}$ to a particular *HIZUE*. The MILP will always be infeasible if we do not use the virtual infinite value, as not all *FIUEs* can maintain a $SINR_{th}$ (λ_o) for an *HIZUE*. The Eq. (17) can be rewritten as follows,

$$Inf * (1 - C^k_{fo}) + G_{fo} p^k_f P^d_{max} \geq \Bigg\{ \Bigg(\lambda_o N_o + \lambda_o \sum_{m \in M} G_{mo} P_{macro} + \lambda_o \sum_{a \in B_k} G_{ao} P^f_{max} + \lambda_o \sum_{f' \in F \setminus f} G_{f'_o} p^k_{f'} P^d_{max} \Bigg) \Bigg\} \forall f \epsilon F, o \epsilon O, k \epsilon K \tag{18}$$

Please cite this article as: V. Sathya et al., On improving SINR in LTE HetNets with D2D relays, Computer Communications (2016), http://dx.doi.org/10.1016/j.comcom.2015.12.004

Finally, the D2D MILP model is formulated as follows,

$$min \sum_{f\epsilon F} \sum_{k\epsilon K} p_f^k s.t,$$

(9), (10), (11), (12), (13), (14), (15), (16), (18).

By solving this MILP model, we achieve the following:

- Get best *FIUEs* as relays for establishing D2D links
- Assign RBs to each of the D2D links established
- Adjust the transmit power for each of the D2D links and minimize the overall power emitted by guaranteeing $SINR_{th}$ for *LIUEs* and *HIZUEs* served by *FIUEs*.

As shown later in Section 5, the above D2D MILP model ensures fairness for both indoor and outdoor users by assuring certain minimum *SINR* for all *IUEs* and *HIZUEs*. But the computation time of this D2D MILP model is high so the solution will not converge in real-time for any practical usage by Femto cells. To overcome this shortcoming, we propose a two-step D2D heuristic algorithm in the next sub-section.

4.3. D2D heuristic algorithm

D2D heuristic algorithm has two steps: one step for selecting D2D pairs and allocating RBs, and other step for setting the powers of D2D pairs. Below we present these two steps.

Step 1: Heuristic D2D pair and resource allocation (hDPRA)

Proposed hDPRA (refer Algorithm 1) checks whether a particular *FIUE f* can connect to an *HIZUE o* using an RB *k*. For this we define a parameter, Win-to-Loss (W2L) Ratio (γ) for all possible (*f*, *o*, *k*) combinations, as expressed in Eq. (19).

$$\gamma_{fo}^k = \frac{G_{fo}}{\sum_{o'\epsilon O_k} G_{fo'} + \sum_{l'\epsilon L_k} G_{fl'} + \sum_{f'\epsilon F_k} G_{f'o}} \tag{19}$$

Here, O_k ($\subset O$) represents the set of *HIZUEs* receiving data using the RB *k*, $L_k(\subset L)$ represents the set of *LIUEs* receiving data from Femto using the RB *k* and $F_k(\subset F)$ represents the set of *FIUEs* transmitting data to *HIZUEs* using the RB *k*. The numerator in the R.H.S. of Eq. (19) represents the gain between *f* and *o*, so it acts as an approximate measure (since the transmission power is not considered) for signal strength. The values $G_{fo'}$, $G_{fl'}$ and $G_{f'o}$, in the denominator represent the channel gain between *f* and o', *f* and l', and f' and *o*, respectively and they act as an approximate measure of the interference caused by the interfering links. The numerator and denominator are two opposing parameters to the W2L ratio. Hence, larger the value of γ_{fo}^k, higher the possibility of the particular combination (*f*, *o*) to have a D2D link using RB *k*. W2L ratio will be higher in case RB *k* is not used by some Femtos for serving their UEs in a given TTI i.e., the value of $\sum_{l'\epsilon L_k} G_{fl'}$ will reduce in Eq. (19).

σ^* is the set that contains the triplet (f^*, o^*, k^*) if f^* and o^* are having a D2D link using RB k^*. Every element in σ^* should have its W2L ratio greater than $\overline{\gamma}$, an operator defined parameter which gives control over the number of D2D links that can be formed. Initially σ^* is a null set. We start by computing the W2L ratio for each (*f*, *o*) pair for all possible RBs and store them in the γ matrix. From this set, the maximum W2L ratio is found and this gives the corresponding triplet (f_{max}, o_{max}, k_{max}). On adding this particular triplet to σ^*, there will be additional interference ($G_{f_{max}o^*}$) to the existing (f^*, o^*) pairs who are using RB k_{max} for their data transmissions. Hence, $\gamma_{f^*o^*}^{k_{max}}$ values have to be recalculated and checked whether they remain greater than $\overline{\gamma}$. If all of these values remain greater than $\overline{\gamma}$, the triplet (f_{max}, o_{max}, k_{max}) is added to σ^* and the recalculated $\gamma_{f^*o^*}^{k_{max}}$ values are stored in the γ matrix, otherwise triplet (f_{max}, o_{max}, k_{max}) is not added to σ^*. In case triplet (f_{max}, o_{max}, k_{max}) is added to σ^*, the $\alpha_{f_{max}}$ and $\beta_{o_{max}}$ values are incremented, where $\alpha_{f_{max}}$ is the count for the number of *HIZUEs* connected to *FIUE* f_{max} and $\beta_{o_{max}}$ is the number of *FIUEs* connected to *HIZUE* o_{max}. If $\alpha_{f_{max}}$ value reaches the maximum limit α, then all the γ_{fo}^k values for *FIUE* f_{max} are removed from the γ matrix. Similarly if $\beta_{o_{max}}$ reaches the maximum limit of β, then all the γ_{fo}^k values for *HIZUE* o_{max} are removed from the γ matrix. W2L ratio in the γ matrix is updated $\forall$ *f*, *o* which are using RB k_{max}. If any of the updated $\gamma_{fo}^{k_{max}}$ is lesser than $\overline{\gamma}$, then that value is removed from the γ matrix and is not considered during the next iteration. Finally, it removes $\gamma_{f^*_{max}o^*_{max}}^{k_{max}}$ from the γ matrix and continues to the next iteration until all the entries are removed from the γ matrix.

Algorithm 1 Heuristic D2D pair and resource allocation (hDPRA) algorithm.

Input 1 : *F*, *O*, *L*
Input 2 : *Optimal Femto Locations (Obtained by solving MinNF model)*
Input 3 : $\overline{\gamma}$, α *and* β *values*
Output : D_{fo}, C_{fo}^k, h_f^k

Initialization ();

$D_{fo} \leftarrow 0 \quad \forall\ f\epsilon F,\ o\epsilon O$
$C_{fo}^k \leftarrow 0 \quad \forall\ f\epsilon F,\ o\epsilon O,\ k\epsilon K$
Compute $\gamma_{fo}^k\ \forall f\epsilon F, o\epsilon O, k\epsilon K$ and store in γ matrix
$\alpha_f \leftarrow 0 \quad \forall$ f $\in F$ { Count for number of *HIZUEs* connected to each *FIUE* }
$\beta_o \leftarrow 0 \quad \forall$ o $\in O$ { Count for number of *FIUEs* serving each *HIZUE* }
$\sigma^* \leftarrow \{\ \}$
while size(γ) $\neq 0$ **do**
  (f_{max}, o_{max}, k_{max}) $\leftarrow$ max(γ);
  if Updated W2L values of entries in $\sigma^* > \overline{\gamma}$ **then**
    $D_{f_{max}o_{max}} \leftarrow 1$
    $C_{f_{max}o_{max}}^{k_{max}} \leftarrow 1$
    $\alpha_{f_{max}} + +$
    $\beta_{o_{max}} + +$
    if $\alpha_{f_{max}} == \alpha$ **then**
      Remove $\gamma_{f_{max}o}^k \quad \forall\ o\epsilon O, k\epsilon K$
    end if
    if $\beta_{o_{max}} == \beta$ **then**
      Remove $\gamma_{fo_{max}}^k \quad \forall\ f\epsilon F, k\epsilon K$
    end if
    Remove $\gamma_{f_{max}o_{max}}^{k_{max}}$
    if Updated $\gamma_{fo}^{k_{max}} < \overline{\gamma}$ **then**
      Remove $\gamma_{fo}^{k_{max}}${Removes all *f* and *o* pairs using RB k_{max} from γ matrix }
    end if
    $\sigma^* \leftarrow \sigma^*\ U$ (f_{max}, o_{max}, k_{max})
  else
    Remove $\gamma_{f_{max}o_{max}}^{k_{max}}$
  end if
end while

Step 2: Heuristic D2D power allocation (hDPA)

Using outputs of the hDPRA from the Step 1, namely D_{fo}, C_{fo}^k, h_f^k, as the input in the Step 2 we solve an LP model which adjusts the power for each of the D2D links. The LP model is formulated similar to D2D MILP model presented earlier but with fewer constraints as given below.

$$min \sum_{f\epsilon F} \sum_{k\epsilon K} p^k_f \tag{20}$$

$$p^k_f \leq h^k_f \qquad \forall f\epsilon F, k\epsilon K \tag{21}$$

$$\sum_{f\epsilon F} (G_{fl} \times S_{lk} \times p^k_f \times P^d_{max}) \leq I_l \qquad \forall l\epsilon L, k\epsilon K \tag{22}$$

$$Inf * (1 - C^k_{fo}) + G_{fo} p^k_f P^d_{max} \geq \left\{ \left(\lambda_o N_o + \lambda_o \sum_{m\epsilon M} G_{mo} P_{macro} + \lambda_o \sum_{a\epsilon B_k} G_{ao} P^{fem}_a + \lambda_o \sum_{f'\epsilon F \setminus f} G_{f'_o} p^k_{f'} P^d_{max} \right) \right\} \quad \forall f\epsilon F, o\epsilon O, k\epsilon K \tag{23}$$

Finally, the LP model for D2D power control is formulated as follows,

$$min \sum_{f\epsilon F} \sum_{k\epsilon K} p^k_f s.t,$$

(21),(22), (23).

As shown later in Section 5, the proposed two-step D2D heuristic algorithm is fair to both the *IUEs* and *HIZUEs* by choosing the D2D links, allocating resources to the D2D links and adjusting their transmission power levels. It runs in polynomial time (refer Appendix A) and its low running time makes it usable at F-GW/SON.

4.4. Optimal Femto transmission power (OptFP) MILP model

Under some circumstances, when it is not possible to establish D2D links due to lack of *FIUEs* (for example: if we observe Fig. 3, there are no *FIUEs* present in east side of the building to establish D2D link with HIZUEs (o_5, o_6, o_7 and o_8)), the F-GW/SON can be directed to reduce the Femto transmission power, thereby reducing the interference to *HIZUEs* from it. The arbitrary tuning of Femto transmit power may degrade the performance of total *IUEs* connected to that Femto and also cause coverage issues. We propose a means to optimally control the Femto transmit power whenever there are HIZUEs present outside the building but no FIUE is inside, thereby guaranteeing a minimum $SINR_{th}$ for *IUEs* and reduce the interference to *HIZUEs*. The corresponding *HIZUE* can then connect with *MBS* for D-plane communication. We formulated this as OptFP MILP model in [1] and by solving it we can,

- Determine the optimal power required by each Femto for maintaining the $SINR_{th}$ in each of the inner sub-regions and maintain the SINR degradation at less than 2 dB for HIZUEs.
- Determine the Femto to which the users in any given inner sub-region have to be associated with.

4.5. Joint D2D heuristic and OptFP (JDHO) algorithm

In most of the cases, the S-GW/SON might not be able to establish D2D links in all sides of the building. It is also equally probable that D2D links are established more readily in some sides of the building and not in the other sides due to lack of *FIUEs* (for example, east and west sides of the building given in Fig. 3). Hence, the S-GW/SON has to reduce the transmit power of Femtos optimally so as to allow the *HIZUEs* to connect with one of MBSs. This can be achieved by the combinatorial utilization of both D2D heuristic algorithm and OptFP model (called as JDHO algorithm), that would allow some HIZUEs which do not have any FIUE to get connected to one of MBSs and the remaining HIZUEs through D2D links. The proposed JDHO algorithm is given in Algorithm 2.

Algorithm 2 Joint D2D Heuristic and OptFP (JDHO) algorithm.

Input 1 : *Set of all inner and outer sub-regions*
Input 2 : *Potential HIZUEs in HIZone*

All Femtos are configured to transmit at their peak power by default.
All HIZUEs (O) are connected to one of MBSs for their C-Plane.
Find the set of all *HIZUEs*, O', for whom it is not possible to establish *D2D based relays* by using *FIUEs*. $O' \subset O$.
Find the set of Femtos, B', who are causing interference to O' HIZUEs. $B' \subset$ B.
Apply the OptFP model [1] on B' to reduce their transmit powers so that interference to O' is reduced.
The O' HIZUEs are then allowed to connect to one of MBSs even for their D-plane (i.e., no D2D links, it is the traditional cellular communication).
Apply *D2D Heuristic Algorithm* (Algorithm 1) on $(O - O')$ HIZUEs to establish D2D based relays by using FIUEs

4.6. Cost analysis

In our system model, two-hop communication cost is essentially the additional resources incurred by the proposed system over the existing traditional system. It can be classified as resource utilization, energy consumption and additional interference due to the reuse of spectrum.

1. *Resource utilization:* In the first-hop communication (Femto to LIUEs/FIUEs), the radio resources (RBs) allocated for the data demanded by HIZUEs are the additional cost incurred by the proposed system. If the downlink scheduler at the Femto has excess resources (even after fulfilling the demand of the IUEs in a TTI) then the additional cost incurred is zero. But, if the Femto lacks excess resources, then the cost to the system is the resources allocated to the FIUEs to receive *HIZUEs* data from the Femto. These resources could have otherwise been scheduled to the LIUEs. In the second-hop (FIUE to HIZUE (D2D link)), there is reuse of radio resources which increases the interference (explained in next paragraph). Hence, the cost can be expressed as given in Eq. (24), when the downlink scheduler at Femto does not have excess resources.

$$\textit{Radio Resource Cost} = \sum_{i=1}^{N} \textit{No of RBs allocated to } FIUE_i \textit{ by Femto}. \tag{24}$$

Where N is the number of *FIUEs* participating as *D2D based relays* for Femto to *HIZUE* communication.
2. *Interference:* In the first-hop there is no new interference source introduced to the traditional system, whereas in the second-hop (due to reuse of Femto RBs by D2D links) there is additional interference for the IUEs present in the system. This could degrade SINR of *IUEs* and this reduction in SINR is the additional cost incurred in the proposed system.
3. *Energy consumption:* In our work, the transmission power of the Femto (first-hop communication) is kept as P^f_{max} (0.1 W) to study the system performance in the worst case scenario. In second-hop communication, the power consumed for the transmission from *FIUE* to *HIZUE*, which varies based on distance between *HIZUE* and *FIUE*, is the cost to the system.

5. Performance results

The system model described in Section 4 has been simulated using MATLAB. The simulation parameters are given in Table 5. We

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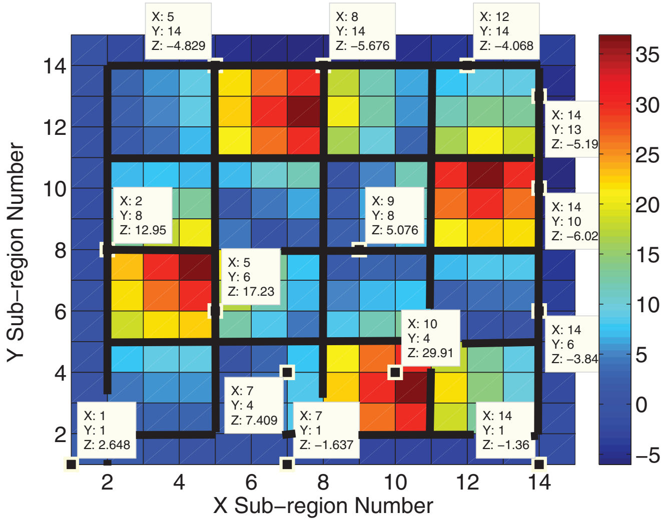

Fig. 6. REM plot of sub-regions inside building after placing Femtos by using MinNF. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

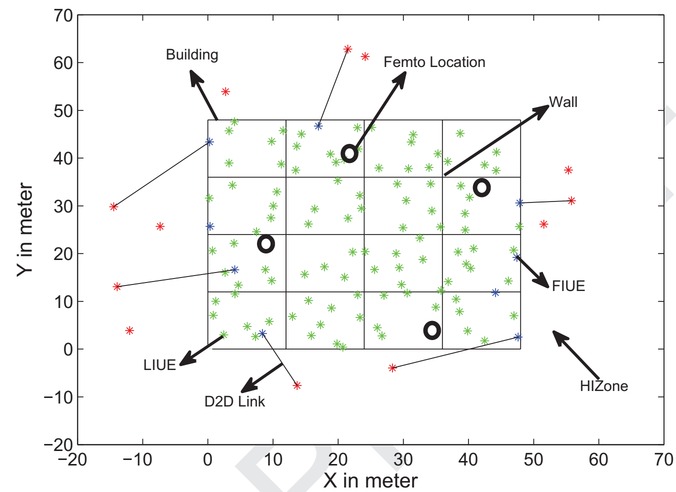

Fig. 7. *hDPRA* D2D links in instance #1. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

considered a single-floor building with a single MBS placed at a distance of 350 m from the south west side of the building. Further, we considered the scenario where all Femtos and MBS are configured to use the same 5 MHz channel (i.e., 25 RBs). Femtos are allowed to be attached only to the ceiling of the building and we did not consider the user mobility in our simulation experiments as we focused only on indoor scenarios. We show the performance of the LTE HetNet system in the worst case scenario where all RBs of all Femtos are in use in every TTI. Also we assume that channel state information of links between *FIUEs* and *HIZUEs* is available at the F-GW/SON for the fine tuning of D2D link transmission power. For the performance evaluation, we generate different topologies by varying number of UEs (i.e., *IUEs* and *HIZUEs*) and their positions in such a way that in each of the topologies that we considered there always exist one or more *FIUEs* for forming D2D links for each of the *HIZUEs*.

5.1. MinNF model: performance results

The four Femtos with their optimal coordinates are obtained by solving MinNF MILP problem with GAMS CPLEX solver [43]. The GAMS CPLEX solver is a high-level modeling system for optimization and utilizes branch and bound framework for solving MILP based optimization problems. This MILP optimizer has the capability to solve large and numerically difficult MILP models with features including settable priorities on integer variables, choice of different branching, and node selection strategies. The Femtos are placed in dark brown regions inside the building at sub-regions I_{30}, I_{71}, I_{98}, I_{129} (refer Fig. 5 for numbering of sub-regions) as shown in Fig. 6. All the Femtos transmit at their peak power (0.1 W). Fig. 6 also shows SINR distribution for inner and outer sub-regions. For example, UEs in the sub-region I_{98} get SINR of 29.9 dB as the Femto (F3) is very close to it. Similarly, the sub-regions I_6, I_{29}, I_{79}, and I_{51} inside the building have relatively good SINR values 12.9, 17.2, 5.0, 7.4 dB, respectively. But if we consider *Macro only scenario*, where there are no Femtos inside the building like in Fig. 1, the sub-regions I_6, I_{29}, I_{79}, and I_{51} inside the building have relatively less SNR values of −8.2, −8.3, −9.2, −8.3 dB, respectively due to poor indoor signal strength.

Due to addition of Femtos, the UEs present inside the building get improved SINR up to 35 dB (refer Fig. 6). But in this case, the outer sub-regions (e.g., O_{48}), get SINR as low as −6.0 dB. This is a consequence of Femtos being closer to the corners of the building and hence there being a high power leakage (interference) in HIZone.

5.2. D2D based relays: performance results

In this section, we compare the performance of proposed D2D MILP model and D2D heuristic algorithm with the following three different schemes.

- *Macro only:* No Femtos are placed inside the building. No HIZone exists around the building, but the MBS has to serve even *IUEs* with poor signal quality.
- *Full Power Femto:* Femtos are optimally placed inside the building by MinNF method, but Femtos are configured to emit at their full transmission power. In this scheme, HIZone exists around the building and therefore affects performance of *HIZUEs*.
- *Optimal Femto Power* (OptFP): Femtos are optimally placed inside the building by MinNF method, but transmission power of *all* the Femtos are reduced by OptFP method to decrease the interference to *HIZUEs*. Since such reduction at all the Femtos is not needed, this scheme affects performance of *IUEs*.

5.2.1. D2D heuristic algorithm: performance results

In this section, we show the formation of efficient D2D links and SINR CDF of UEs. Also, we studied the effect of $SINR_{th}$ on SINR of *IUEs* and effect of *IUE* density on *FIUEs* transmission power. Finally, we have shown the average performance of *D2D heuristic algorithm* by considering 500 different combinations of *IUEs* and *HIZUEs* location.

5.2.1.1. Formation of D2D links and their effects on SINR of UEs. In this section, we describe the hDPRA which efficiently chooses the potential D2D based relay pairs and allocates radio resources to them. Then we discuss about the performance of hDPA for power control of D2D links.

(a) hDPRA results:

The optimal Femto locations given by the MinNF model are shown as the circled regions in Fig. 7. The red, green and blue marked locations are the positions of the deployed *HIZUEs*, *LIUEs* and *FIUEs*, respectively in this topology # 1. These UEs locations at a particular instance (TTI) along with other parameters are given as input to the proposed heuristic algorithm. In Fig. 7, D2D connectivity diagram shows the number of D2D links in the instance #1. On

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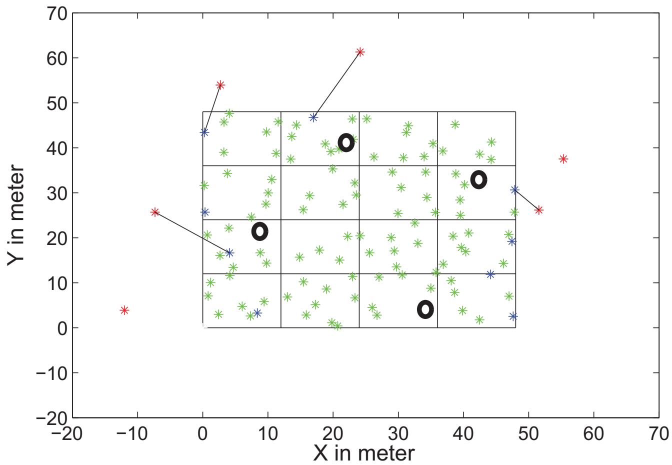

Fig. 8. *hDPRA* D2D links in instance #2.

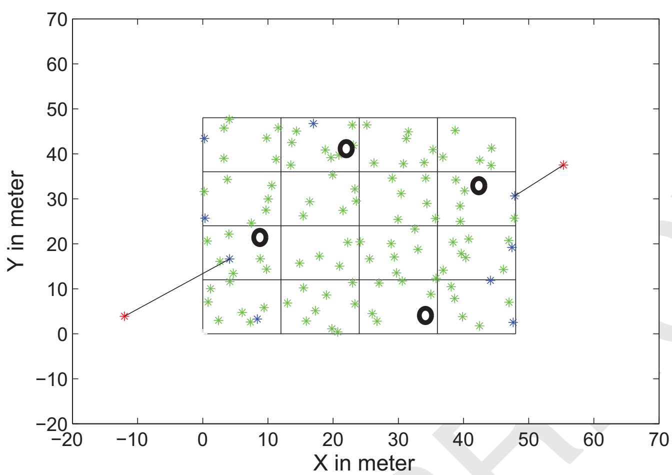

Fig. 9. *hDPRA* D2D links in instance #3.

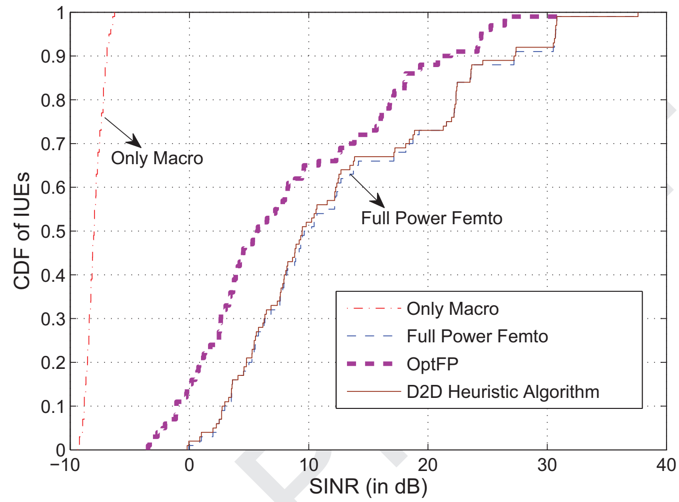

Fig. 10. SINR CDF of *IUEs* using heuristic algorithm. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

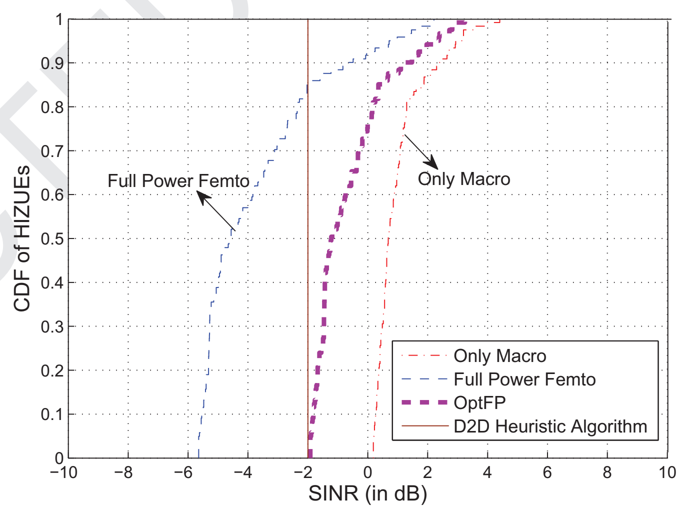

Fig. 11. SINR CDF of *HIZUEs* using heuristic algorithm. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

one hand, there are relatively less number of *HIZUEs* at the south side of the building, but on the other hand, at the east, west and north sides of the building, there are some *HIZUEs* not served by *FIUE* in a particular TTI. It has to be kept in mind that a *HIZUE* can connect to only one *FIUE* in a given TTI as shown in all sides of the building. The reason for the other *HIZUE* to not connect is that even when there are certain free RBs that are not used by other D2D links, there is a possible interference between the *LIUEs* or the possibility of guaranteeing an SINR threshold only by increasing the transmission power for D2D links above the 3GPP standards [22,44]. Hence, the *HIZUE* that does not get paired in the given TTI, get paired in subsequent TTIs. Figs. 8 and 9 show the pending D2D link connections to be made in subsequent instances. The output from hDPRA is given as the input to GAMS CPLEX solver [43] through an interface between MATLAB and GAMS to solve the hDPA LP model. Solving the hDPA model yields the transmission power for the D2D links.

(b) hDPA results:

Figs. 10 and 11 show the SINR CDF of *HIZUEs* and *IUEs*, respectively. In *Only Macro* scheme (shown by red curve) the *HIZUEs* receive good SINR values but the *IUEs* receive very less SINR values, less than -5 dB which is due to the signal degradation caused by the walls. In our evaluation, we considered the worst case scenario where the *Full Power Femto* scheme (shown by blue curve) has increased SINR for the *IUEs* but at the cost of the SINR of *HIZUEs*. To overcome this issue, Femtos are made to transmit at lower power in the *OptFP* [1] i.e., OptFP scheme (shown by purple curve) thus alleviating the interference issues of *HIZUEs*, although this declines the SINR value of *IUEs*. However in *D2D heuristic algorithm* scheme (shown by brown curve) *HIZUEs* receive good SINR values and the *IUEs* also receive SINR values close to that of *Full Power Femto* scheme (worst case scenario). The straight line in Fig. 11 represents the SINR value of *HIZUEs* using *D2D heuristic algorithm* maintained at −2 dB constraint (to ensure basic voice call communication for all suffering *HIZUEs*) of outdoor (HIZone) region. This is achieved by minimizing total transmit power of *FIUEs*, and thus the minimum power required to guarantee $SINR_{th}$ ensures that all the *HIZUEs* achieve $SINR_{th}$. The small deviation in the *IUEs* SINR values is because of the interference caused by the D2D pairs. The overall degradation in SINR for *IUEs* is 2% in the *D2D heuristic algorithm* as compared to the *Full Power Femto* scheme. But in comparison to the *OptFP* [1] scheme the SINR of *IUEs* improves by 39% for the *D2D heuristic algorithm*. Thus *D2D heuristic algorithm* is able to provide a good signal strength to the *HIZUEs* without affecting the *IUE* performance.

5.2.1.2. Effect of $\mathrm{SINR_{th}}$ *on SINR of* IUEs. We studied the variation in SINR of *IUEs* by varying $SINR_{th}$ values. We also measured the

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Table 4
Simulation parameters.

Parameter	Value
Building dimensions	48 m × 48 m × 3 m
Number of rooms	16
Room dimensions	12 m × 12 m × 3 m
Number of inner sub-regions	144
Number of outer sub-regions	52
Inner sub-region dimension	4 m × 4m × 3m
$SINR_{Th}$ for *IUEs* (MinNF method)	0 dB
Number of floor	One
Floor and wall loss	10 and 8 dB
Macro transmit power (P_{macro})	46 dBm (39.8 W)
Femto transmit power (P^f_{max})	20 dBm (0.1 W)
Macro BS height	30 m
D2D Max transmit power (P^d_{max})	20 dBm (0.1 W)
Number of *IUEs*	109
HIZUE $SINR_{Th}$	−2 dB
α (*FIUE* D2D links limit)	1
β (*HIZUE* D2D links limit)	1
$\overline{\gamma}$ (W2L Threshold)	5

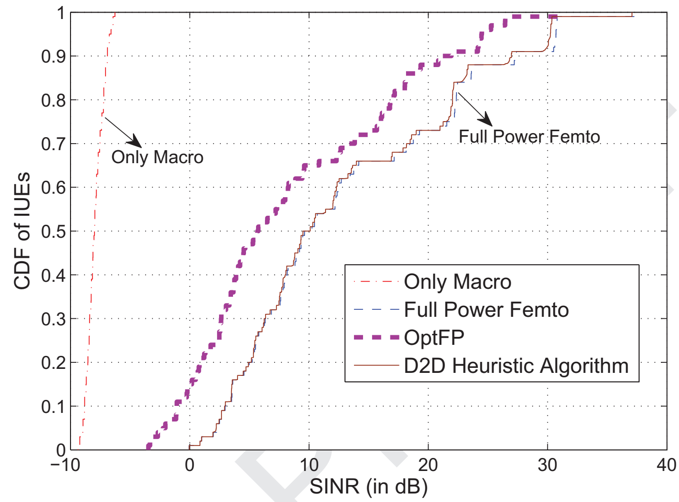

Fig. 12. Average SINR CDF of *IUEs* for various schemes in 500 topologies.

variation in average D2D transmission power for topology # 1. As shown in Table 4, the average transmit power of D2D links increases gradually with increasing $SINR_{th}$. This increases the interference to the IUEs and hence causes a fall in average *IUE* SINR with increase in $SINR_{th}$ of *HIZUEs*. We note that even with changes in $SINR_{th}$ the degradation of *IUEs* SINR is not very significant. This validates the efficiency of our *D2D heuristic algorithm*.

5.2.1.3. Effect of IUE *density on* FIUEs *transmission power.* In our work, we studied the variation in D2D transmission power. Here we consider topology # 1 as above but vary the number of *FIUEs* for a fixed *HIZUE* location (shown in Fig. 7). Initially, the total number of *IUEs* is 110 (i.e., *LIUEs* = 100 (constant) and *FIUEs* = 10) and we gradually increase only the *FIUEs* count to 15, 20, 25, 30 and 35. Table 6 shows that as the number of *FIUEs* increases, the average transmit power of *FIUEs* decreases. This is due to the increased possibility of forming shorter *D2D based relay* links with increasing *FIUE* density levels. Once the *FIUEs* density level is very high, the transmission power of the *FIUEs* will get saturated due to marginal decrease in D2D relay link distance.

5.2.1.4. Average performance of D2D heuristic algorithm. In order to obtain average performance of proposed *D2D heuristic algorithm*, we have evaluated its performance for 500 different topologies by varying the number of *IUEs* in the range of 110 to 135 and *HIZUEs* in the range of 1 to 30 and measured the SINR of *IUEs* and *HIZUEs*. Fig. 12 shows SINR CDF of *IUEs* over various scenarios for different schemes. When compared to the *Optimal Femto Power* scheme, *D2D heuristic algorithm* improves the SINR of *IUEs* by 40% as shown in Fig. 12. However, the degradation in SINR of *IUEs* is only 1.6% when compared to the *Full Power Femto* scheme. Similarly, Fig. 13 shows average CDFs of *HIZUEs* over various scenarios for different schemes. If we observe Fig. 13, the minimum $SINR_{th} = -2$ dB is maintained for all *HIZUEs* in the *HIZone*.

5.2.2. D2D MILP model: performance analysis

In the proposed D2D heuristic algorithm, we cannot set the number of D2D links in each TTI. To make a fair comparison with the D2D MILP model, we have given the number of D2D links obtained from the D2D heuristic algorithm in each instance as an input for the D2D MILP model. For example, for the instance #1 shown in Fig. 7 the number of D2D links given by the heuristic algorithm is six. Hence in the D2D MILP model the number of D2D

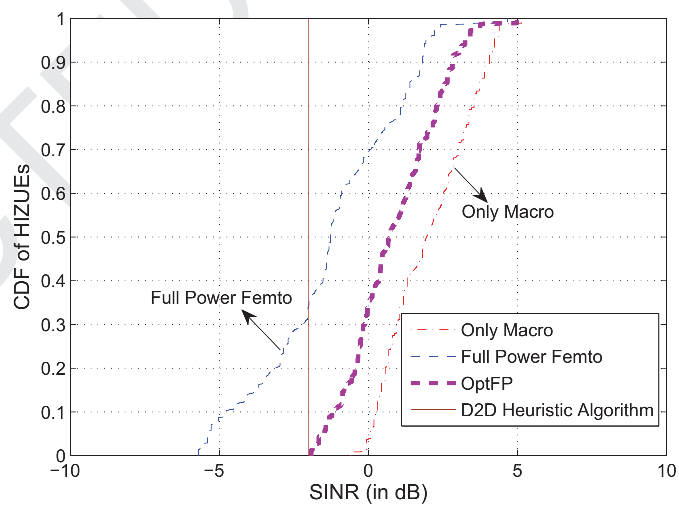

Fig. 13. Average SINR CDF of *HIZUEs* for various schemes in 500 topologies.

Table 6
Number of *FIUEs* vs. average D2D transmission power.

S.no.	No. of *FIUEs*	Average D2D transmission power (W)
1	10	0.061
2	15	0.054
3	20	0.051
4	25	0.043
5	30	0.042
6	35	0.041

Table 5
$SINR_{th}$ vs. *IUEs* SINR.

Metric	$SINR_{th} = -3$ dB	$SINR_{th} = -2$ dB	$SINR_{th} = -1$ dB	$SINR_{th} = 0$ dB
Average transmission power of D2D links (W)	0.03	0.04	0.05	0.06
Average *IUEs* SINR (dB)	12.78	12.75	12.72	12.68

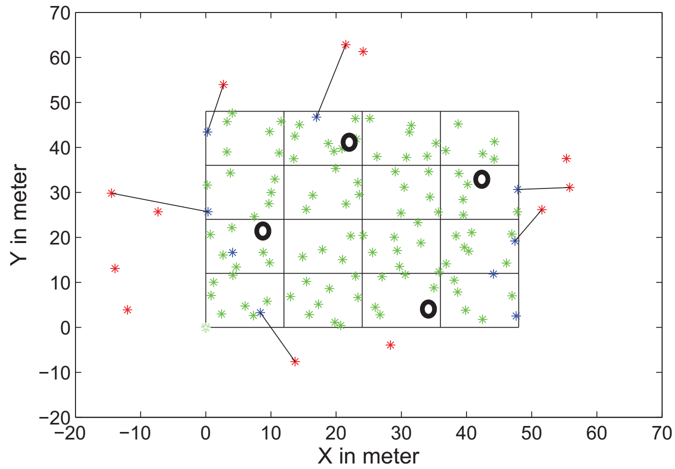

Fig. 14. MILP D2D links in instance #1.

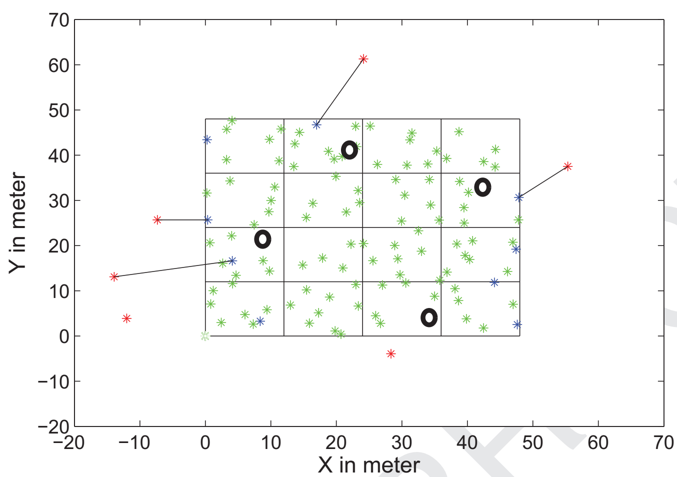

Fig. 15. MILP D2D links in instance #2.

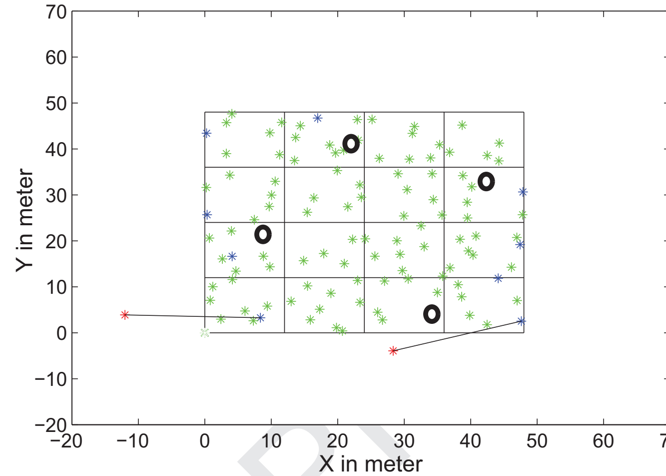

Fig. 16. MILP D2D links in instance #3.

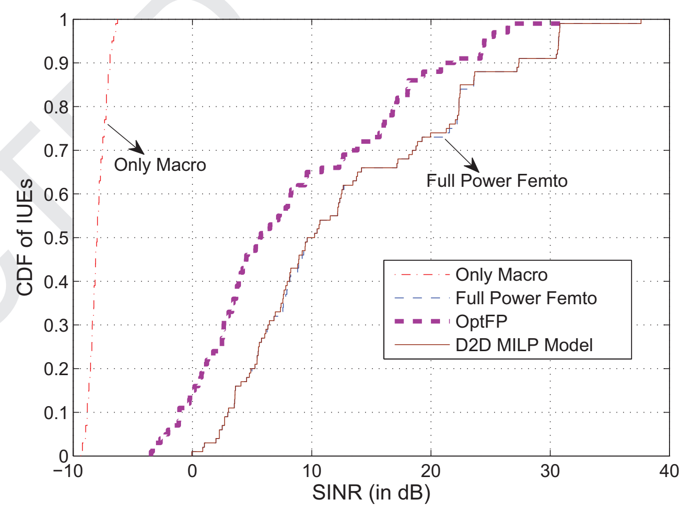

Fig. 17. SINR CDF of *IUEs* using MILP model.

links that have to be formed at the instance #1 is fixed to be six, i.e., $\psi = 6$.

In Fig. 14, D2D connectivity diagram shows the number of D2D links in the instance #1. As in the heuristic algorithm, there are some *HIZUEs* which are not served by *FIUEs* in a particular TTI. The pending *HIZUEs* served by *FIUEs* based on the D2D MILP model are shown in Figs. 15 and 16. In the instance #1, the algorithm mostly tries to form all D2D links with the closer *HIZUEs* to minimize the total D2D transmission power. In the next TTI, it tries to form the remaining D2D links with the farther *HIZUEs*. Hence the *FIUE* needs to transmit high transmission power to maintain these D2D links, which increases the possibility of interference between *LIUEs* and *HIZUEs*. Fig. 17 shows the SINR CDF of *IUEs*. The advantage of forming optimal D2D link is that *D2D MILP model* achieves SINR close to that of *Full Power Femto* because the power value is optimal. Similarly, the SINR CDF of *HIZUEs* in optimal approach (D2D MILP) is also maintained $SINR_{th} = -2$ dB as in the heuristic approach (Fig. 11). The SINR CDF of *HIZUEs* using MILP model will be same as that of the heuristic algorithm (Fig. 11) because the same $SINR_{th}$ is maintained in both D2D heuristic algorithm and D2D MILP model. The overall degradation in SINR for *IUEs* is 0.5% in the *D2D MILP model* compared to the *Full Power Femto* scheme. On the other hand, when compared to *OptFP* [1] scheme the SINR of *IUEs* improves by 52% in the *D2D MILP model*. Thus *D2D MILP model* is able to provide lesser degradation in signal strength to the *IUEs* than the *D2D heuristic algorithm* with the cost of more running time (explained further in Section 5.3.2).

5.3. Comparison between D2D MILP model and D2D heuristic algorithm

To compare D2D MILP model and D2D heuristic algorithm, we have taken the seven different topologies, where the *HIZUE* placement and the number of *HIZUEs* vary as shown in Figs. 18–24. Table 7 shows indices of outer sub-regions having HIZUEs in these seven topologies.

5.3.1. SINR of IUEs

In MILP model, the average power transmitted by the D2D links is lower than that in the heuristic algorithm. This helps to reduce the interference to *IUEs*. Fig. 25 shows the average SINR achieved by *IUEs* in different topologies. The average SINR achieved in the heuristic algorithm is very close to that in the D2D MILP model.

5.3.2. Running time

Fig. 26 shows the average running times of D2D MILP model and D2D heuristic algorithm for different topologies. These run times are obtained on a workstation having the following configuration: 12 GB RAM, eight Cores of 2.40 GHz each. We observe

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Table 7
Topologies having varying distribution of *HIZUEs* in HIZone.

Topology	No. of HIZUEs	Indices of outer sub-regions having HIZone UEs
1	12	(O_5, O_9, O_{15}, O_{21}, O_{27}, O_{28}, O_{29}, O_{30}, O_{34}, O_{40}, O_{45}, O_{46})
2	15	(O_3, O_5, O_{10}, O_{12}, O_{14}, O_{18}, O_{23}, O_{25}, O_{30}, O_{32}, O_{41}, O_{44} ,O_{45}, O_{46}, O_{48})
3	7	(O_1, O_6, O_{13}, O_{27}, O_{35}, O_{43}, O_{45})
4	10	(O_{17}, O_{23}, O_{29}, O_6, O_9, O_{13}, O_{22}, O_{26}, O_{35}, O_{46})
5	10	(O_1, O_{21}, O_{31}, O_{37}, O_{10}, O_{13}, O_{22}, O_{26}, O_{45}, O_5)
6	13	(O_{15}, O_{21}, O_{31}, O_{41}, O_{45}, O_8, O_{10}, O_{14}, O_{20}, O_{22}, O_{26}, O_5)
7	9	(O_9, O_{23}, O_{35}, O_{45}, O_{13}, O_{20}, O_{24}, O_{26}, O_4)

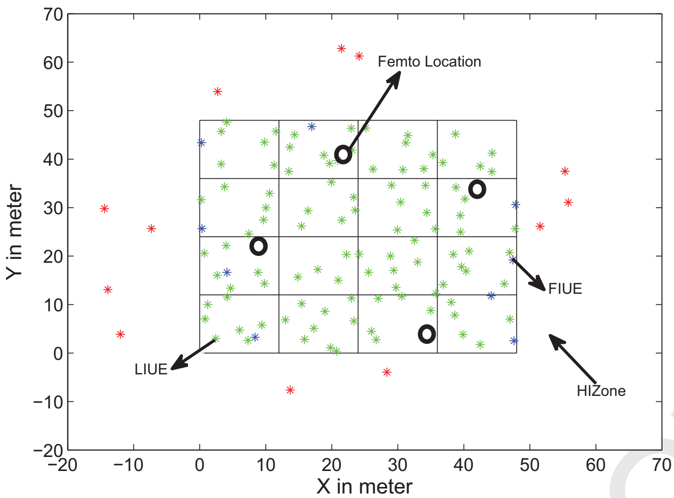

Fig. 18. UE distribution in Topology 1.

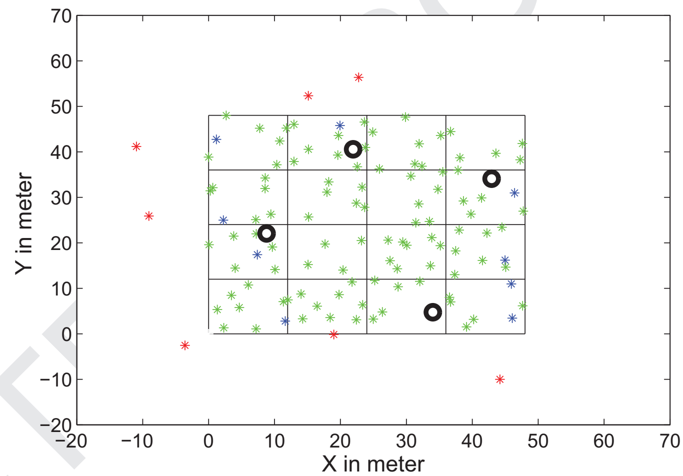

Fig. 20. UE distribution in Topology 3.

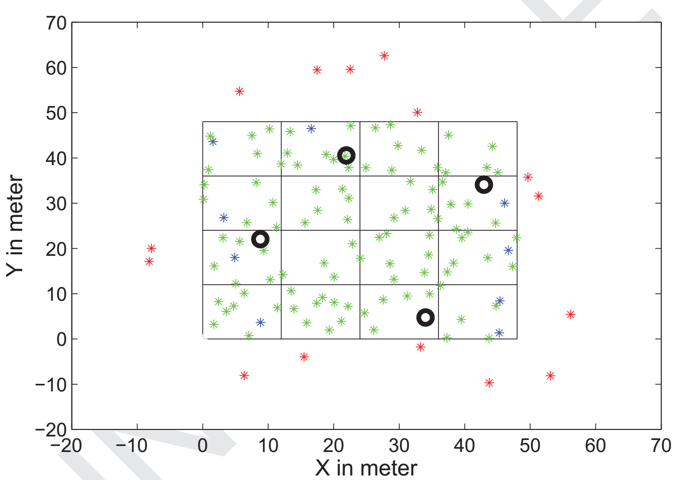

Fig. 19. UE distribution in Topology 2.

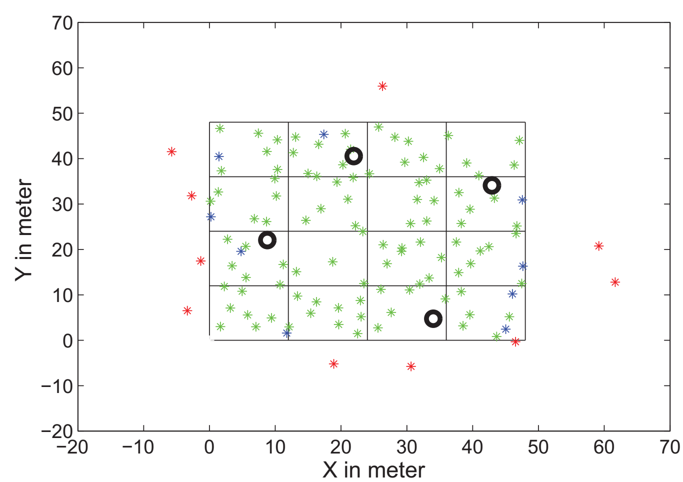

Fig. 21. UE distribution in Topology 4.

that the running time for *D2D heuristic algorithm* showed an average decrease of up to 87% when compared to *D2D MILP model* in different topologies of *HIZUE* placement. In each topology, depending on the position of the HIZUEs, the running time of GAMS optimization solver changed. For example, when *HIZUEs* are very close to each other it demands efficient spectrum allocation and power control between *FIUE* and *HIZUE* in all instances without creating interference to *IUEs*. Therefore, on a few occasions many D2D links may not be possible within the *HIZone* at a particular TTI instance which indirectly increases the average running time. As we discussed earlier in the system model, the D2D heuristic algorithm will be running at the F-GW/SON which will have abundant computing resources to handle the load of so many Femtos [45,46]. Therefore, the run time of *D2D heuristic algorithm* is only a few ms and usable in practical deployments of Femtos.

5.3.3. Energy consumption

Fig. 27 shows the average power transmitted by the D2D links for different topologies with the $SINR_{th}= -2$ dB. The average power transmitted by the D2D links (for example, it is 0.043 W and 0.047 W in *D2D MILP model* and *D2D heuristic algorithm*, respectively) are lower than the maximum allowed D2D link power of 0.1 W. We can clearly observe that the average transmission power of the D2D links in the heuristic algorithm is close to that in the MILP model and the difference between them is marginal.

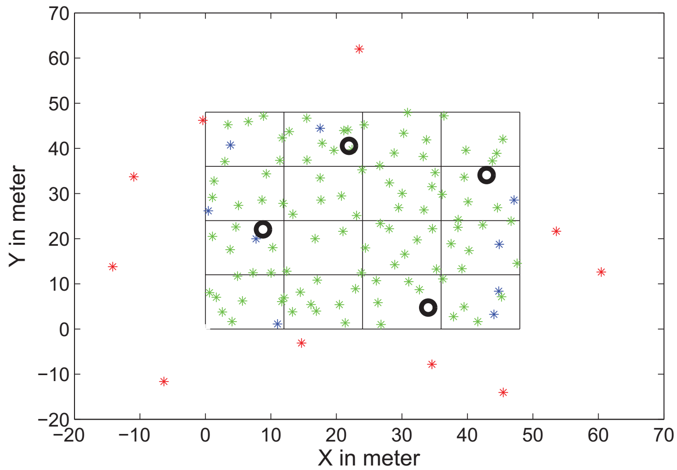

Fig. 22. UE distribution in Topology 5.

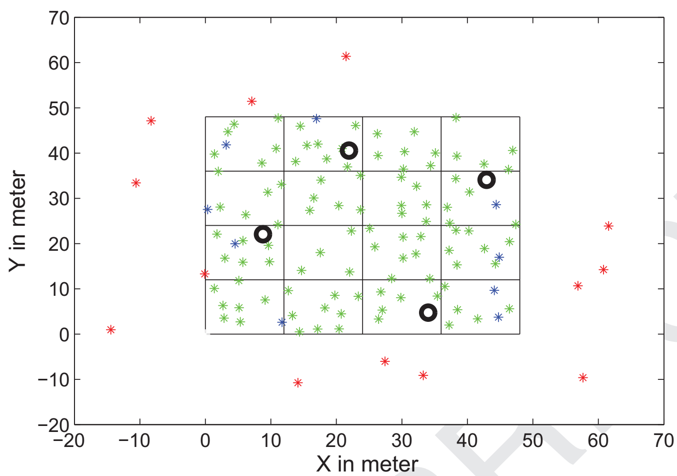

Fig. 23. UE distribution in Topology 6.

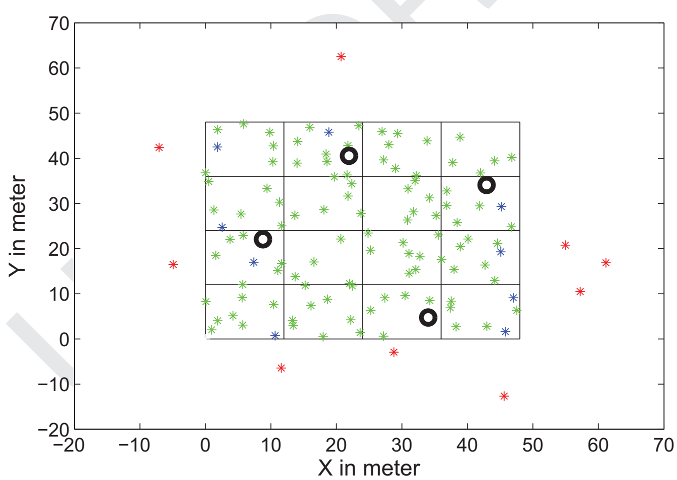

Fig. 24. UE distribution in Topology 7.

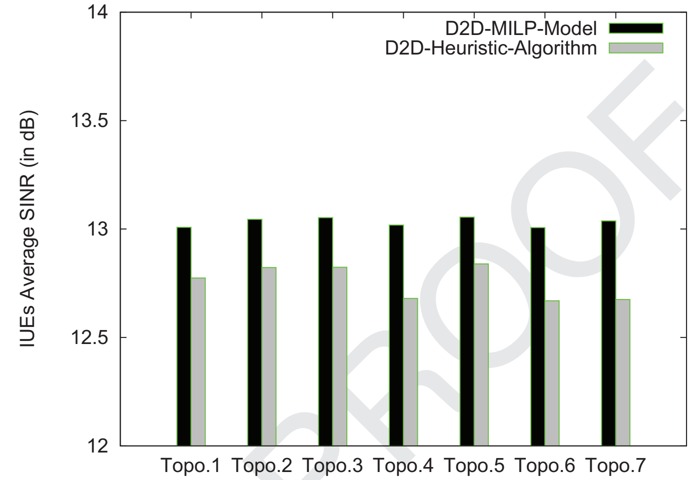

Fig. 25. Average SINR of *IUEs*.

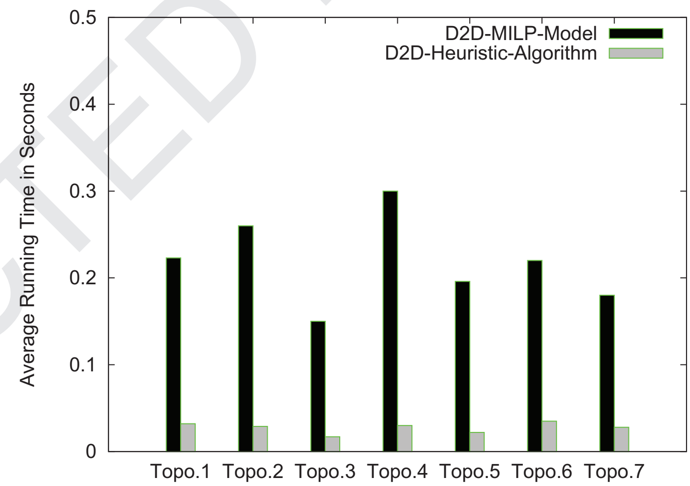

Fig. 26. Running time of D2D MILP and heuristic algorithm.

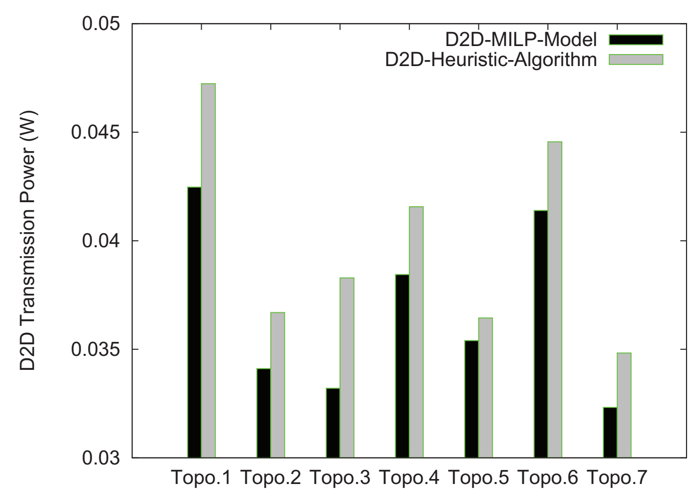

Fig. 27. D2D average transmission power.

5.4. Cost analysis

In our work we assumed that the downlink scheduling algorithm [47] (e.g., proportional fair or priority set scheduler) will allocate only one resource block to the selected Femto to *FIUE* links or *FIUE* to *HIZUE* links in every TTI. Using this, we have simulated 500 different possible combinations for *IUEs* and *HIZUEs* locations and observed that an average of 5 D2D links are formed in a TTI. Hence, five resource blocks will be used for the first-hop i.e., Femto to FIUE link to get the data for *HIZUEs*. This means that these five resource blocks are the *radio resource* cost.

The *D2D based relay* links will reuse these five Femto RBs in the second-hop transmission (*FIUE* to *HIZUE*) [48–50]. The interference introduced in the system by these *D2D based relay* links leads

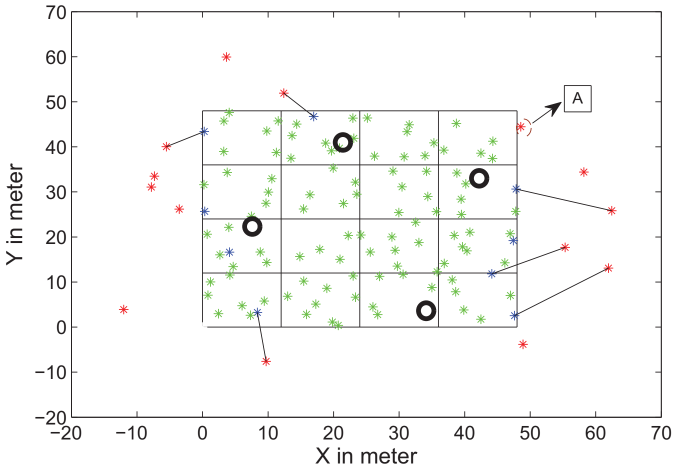

Fig. 28. *hDPRA* D2D links in instance #1.

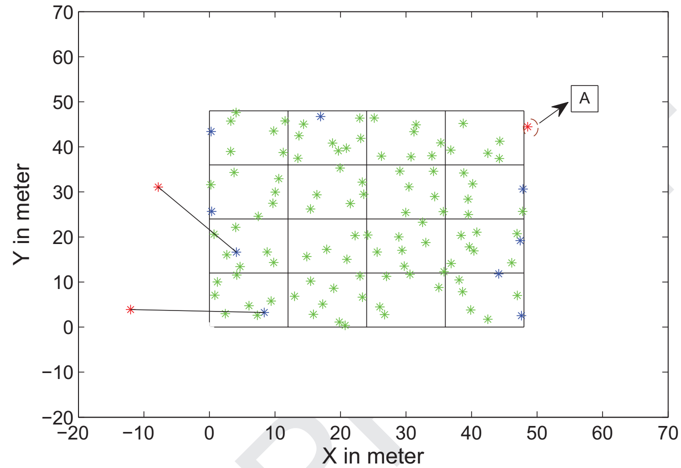

Fig. 30. *hDPRA* D2D links in instance #3.

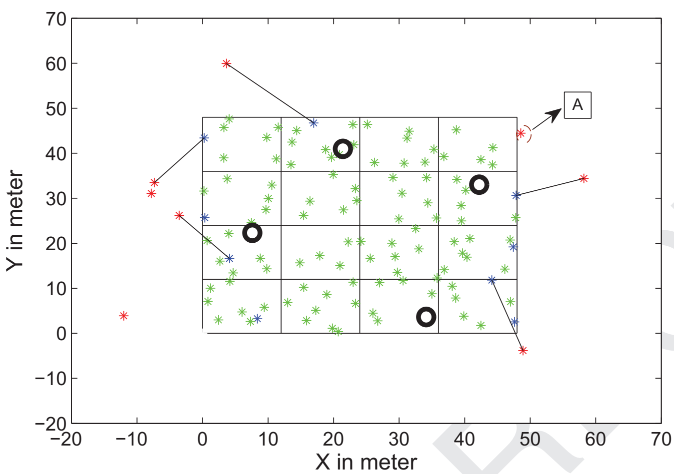

Fig. 29. *hDPRA* D2D links in instance #2.

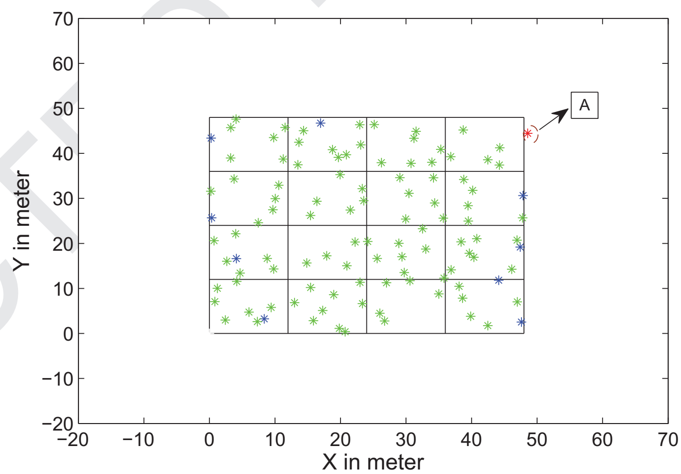

Fig. 31. *hDPRA* D2D links in instance #4.

to decrease in the SINR of IUEs by 1.6% (averaged over 500 scenarios). This is the cost of using the proposed system in terms of interference.

As shown in Fig. 27, the transmission power of the D2D links is adjusted in order to maintain the $SINR_{th}$ of −2 dB for *HIZUEs*. Because of power adjustment, D2D links are able to reuse the same RBs and thereby improve the spectral efficiency of the HetNet system. Hence, the total energy consumption [51] in the two-hop communication is 0.1 W + *D2D based relay* transmission power.

5.5. JDHO performance analysis

Unlike the previous section, here we study the performance of JDHO algorithm by considering a topology where some of the *HIZUEs* could not able to make D2D links due to lack of *FIUEs*. As seen in Algorithm 2 (Step 6), these O' *HIZUEs* connect to the MBS for their D-plane communication. The remaining *HIZUEs* (i.e., $(O - O')$) form D2D links with *FIUEs* by using proposed *D2D heuristic algorithm*. Consider the topology shown in Fig. 28, where one can see that there are no *FIUEs* in the vicinity of *HIZUE A*. *D2D heuristic algorithm* which is running at F-GW cannot able to form any D2D link for serving the *HIZUE* A. In order to reduce interference at this *HIZUE* in the HIZone, JDHO algorithm controls the transmit power of the Femto which is serving the parts of the building closest to this region. By doing so, the *HIZUE A* can maintain a minimum $SINR_{th}$ in *HIZone*. Figs. 29–31 show the pending D2D links established in the subsequent instances. When com-

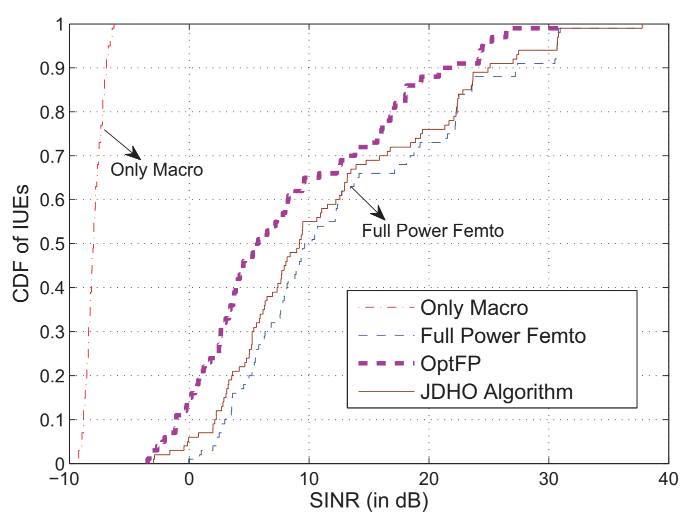

Fig. 32. SINR CDF of *IUEs* using JDHO algorithm.

pared to *Full Power Femto* scheme where the degradation of *IUEs* SINR is found to be 2% as obtained in the previous case (shown in Fig. 10), in the current *JDHO algorithm* scenario as shown in Fig. 32 the degradation of *IUEs* SINR was found to be 9%. This is because, to maintain the communication (D-Plane) for *HIZUE A* from MBS, the corresponding/particular Femto has to optimally

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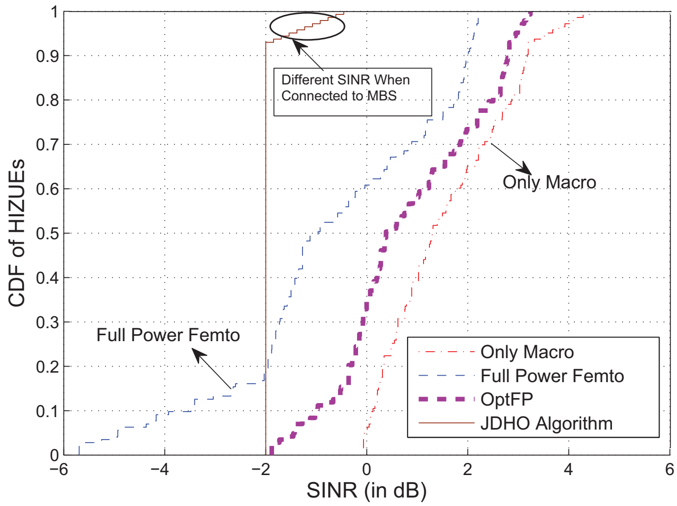

Fig. 33. SINR CDF of *HIZUEs* using JDHO algorithm.

decrease its transmission power further to reduce the SINR of *IUEs*. Fig. 33 shows that *HIZUEs* maintained $SINR_{th}$ when *JDHO algorithm* is used. In previous scenario (shown in Fig. 11) we maintained a constant $SINR_{th}$ to all HIZUEs. But in the present scenario, in JDHO algorithm by using the OptFP model, the $SINR_{th}$ for *HIZUE A* is maintained at more than −2 dB (as shown in circle region).

6. Conclusions and future work

In this paper, we showed that D2D technology when adopted to LTE HetNets increases the spectrum efficiency by guaranteeing good $SINR_{th}$ for all the users even when the Femtos are transmitting at their full power. By introducing Femtos, a fair distribution for both *IUEs* and *HIZUEs* with minimal interference can be observed. Additionally, an increase in SINR values of *IUEs* by 40% compared to the *OptFP* [1] scheme was noted in *D2D heuristic algorithm*. On the other hand, the decrease in the SINR of *IUEs* compared to the *Full Power Femto* scheme is only 1.6%. We also observed that the average running time of the proposed *D2D heuristic algorithm* was 87% lesser when compared to *D2D MILP model*.

Future work includes design of an efficient scheduling algorithm that considers fair allocation of radio resources for both *IUEs* and *HIZUEs* and also study the additional signaling overhead caused by the D2D links in the proposed system. Optimization of the size of HIZone based on the D2D standards (i.e., maximum D2D link distance and transmit power) is also a future task.

Acknowledgment

This work was supported by the Deity, Govt of India (grant no. 13(6)/2010CC&BT).

Appendix A

Running time complexity

The proposed D2D MILP model takes more computation time. To reduce the running time complexity, we have proposed a two-step D2D heuristic algorithm. The running time complexity for hD-PRA (step 1 of D2D heuristic algorithm) is shown below,

The time taken to compute maximum value in the γ matrix is $O(f * o * k)$

The running time for the while loop is $O(f * o * k)$

The total running time is $O(f^2 * o^2 * k^2)$

Since the step 2 of D2D heuristic algorithm (hDPA, an LP model) has a polynomial running time algorithm [52], our proposed D2D heuristic algorithm runs in polynomial time.

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Please cite this article as: V. Sathya et al., On improving SINR in LTE HetNets with D2D relays, Computer Communications (2016), http://dx.doi.org/10.1016/j.comcom.2015.12.004

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Please cite this article as: V. Sathya et al., On improving SINR in LTE HetNets with D2D relays, Computer Communications (2016), http://dx.doi.org/10.1016/j.comcom.2015.12.004