On improving SINR in LTE HetNets with D2D relays

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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 ($\text{SINR}_{\text{th}}$) 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 $\text{SINR}_{\text{th}}$ 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.

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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 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 (SINR) 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., $-8\, \text{dB}$, $-9\, \text{dB}$) compared to OUEs (e.g., $4$, $2$, $0$, $-1\, \text{dB}$).

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
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 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], 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 $\text{SINR}_{th}$ 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 $\text{SINR}_{th}$ inside the building by considering co-tier interference, cross-tier interference and impedance caused by walls. We also varied the $\text{SINR}_{th}$ depending on average user density in each region inside the building. This resulted in improving spectral efficiency of Femtos deployed in indoors. However, $\text{HIZUES}$ 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 deployed.
and their respective coordinates to guarantee a minimum $\text{SINR}_{\text{th}}$ of 0 dB for all indoor regions, assuming full transmission power of the Femtos. Configuration of Femtos at the full transmission power degrades $\text{SINR}$ values of HIZUEs. To address this issue, OptFP model is used to find the optimal power of the Femtos to reduce degradation in $\text{SINR}$ for the HIZUEs. The maximum fall in $\text{SINR}$ for HIZUEs is limited to 2 dB after the deployment of Femtos. Since Femto power is reduced, $\text{SINR}_{\text{th}}$ 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 $\text{SINR}$ 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.

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 $\text{SINR}_{\text{th}}$ 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 $\text{SINR}_{\text{th}}$ 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 hDPRB), 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., $\text{FIUE} \rightarrow \text{HIZUE}$). 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...
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 (SRs [16,36–38]) of the FIUEs. Note that SRs are sent periodically by FIUEs in the uplink to the serving Femtos for estimating uplink channel state. HIZUEs listening to these SRs could estimate their downlink channel state and convey the same to F-GW/SON via MBS. If FIUEs are configured not to send SRs, 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 $l_1, l_2, l_3, \ldots, l_n$ and free/idle IUEs (FI-UEs) 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 and FIUEs send/receive data to/from a Femto at a particular Transmission Time Interval (TTI) for their own communication. FIUEs are IUEs who act as UE-relays between their respective serving Femtos and one of the Femtos. 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 TTI. 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 LIUEs. 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.

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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 opting 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, $S_i$s. 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, $S_o$s. 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]:

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

$$PL_{\text{femto/D2D}} = 37 + 30\log_{10} d + 18.3v\frac{10^{2v+1}}{10^{2v+3}} + n\phi$$ (2)

where $v$ 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.

![Call flow diagram for D2D based communication in proposed HetNet system.](image-url)
power (a good SINR to IUEs, every Femto operates at its peak transmit coverage holes. The objectives of the MinNF model are given be- to associate with only one Femto BS (refer Eqs. (4) and (5)) inside the building.

\[ \sum_{a} y_{ja} = 1 \quad \forall j \in S_i \]  

\[ y_{ja} - w_a \leq 0 \quad \forall j, a \in S_i \]  

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 \( \lambda \) (which is the SINR_{th}), given by:

\[ \text{Inf} f \ast (1 - y_{ja}) + G_{ja}P_{macro}w_a - \sum_{a} G_{ja}P_{macro} \lambda \geq \lambda \quad \forall j, a \in S_i \]  

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

\[ \text{Inf} f \ast (1 - y_{ja}) + G_{ja}P_{macro}w_a \geq \lambda \quad \forall j, a \in S_i \]  

G_{ja} and C_{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), \( \text{Inf} f \ast (1 - y_{ja}) \) is a virtually infinite value (a very large value like 10^6). The reason for using \( \text{Inf} f \ast (1 - y_{ja}) \) is that if \( y_{ja} = 0 \) then \( \text{Inf} f \ast (1 - y_{ja}) \) becomes a large value and the expression can be ignored safely. Without

### Table 2
Glossary of MinNF MILP Model.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_i )</td>
<td>Set of all inner sub-regions</td>
</tr>
<tr>
<td>( S_o )</td>
<td>Set of all outer sub-regions</td>
</tr>
<tr>
<td>( w_a )</td>
<td>1 if Femto is placed at inner sub-region ( a ), zero otherwise</td>
</tr>
<tr>
<td>( y_{ja} )</td>
<td>1 if ( j )th inner sub-region of the building is associated with the Femto located at inner sub-region ( a ), zero otherwise</td>
</tr>
<tr>
<td>( G_{ja} )</td>
<td>Channel gain between inner sub-regions ( j ) and ( a )</td>
</tr>
<tr>
<td>( M )</td>
<td>Set of all MBSs</td>
</tr>
</tbody>
</table>

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 (\( P_{max} \)). The goal is to minimize the total number of Femtos deployed, expressed by Eq. (3).

\[ \min \sum_{a} w_a \]  

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.

\[ y_{ja} - w_a \leq 0 \quad \forall j, a \in S_i \]  

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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,

\[ \min \sum_{o \in O} w_o \quad \text{s.t.} \ (4), (5), (7). \]

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} (\lambda). 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 Macros, 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 IUEs 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 IUEs, one of the main objectives is to minimize the overall power consumed by the D2D links as expressed in Eq. (8):

\[ \min \sum_{f \in F} \sum_{k \in K} p_{fk} \quad (8) \]

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

\[ \sum_{o \in O} D_{fo} \leq \alpha \quad \forall f \in F \]

(9)

\[ \sum_{f \in F} D_{fo} \leq \beta \quad \forall o \in O \]

(10)

Another alternate optimization goal can be minimization of the maximum power (\min(max(p_{fk})) consumed by D2D links where all the constraints are identical to the proposed D2D MILP model.

\[ \sum_{f \in F} \sum_{k \in K} D_{fo} = \psi \quad \forall o \in O \]

(11)

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

\[ \sum_{k \in K} C_{fo} \leq \eta \times D_{fo} \quad \forall f \in F, o \in O \]

(12)

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

\[ \sum_{o \in O} C_{fo} \leq 1 \quad \forall f \in F, k \in K \]

(13)

\[ h_{o}^{f} \]

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

\[ h_{o}^{f} = C_{fo} \quad \forall f \in F, o \in O, k \in K \]

(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.

\[ p_{fk} \leq h_{o}^{f} \quad \forall f \in F, k \in K \]

(15)

The power constraint 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 \( p_{fk}^* \). \( P_{f}^* \) gives the gain from the FIUE f to the LIUE o

\[ I_{o} \]

is an input parameter whose value is 1 when \( I_{o} \) 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 \( I_{o} \) is less than the allowed threshold value \( I_{o} \). \( I_{o} \) is computed for a given value of SINR_{th} of IUEs.

\[ \sum_{f \in F} \sum_{k \in K} (G_{f} \times S_{k} \times p_{fk}^*) \leq I_{o} \quad \forall o \in O, k \in K \]

(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 \( \lambda_{o} \) which could vary across HIZUEs.

\[ \frac{G_{f} \times S_{k} \times p_{fk}^*}{\sum_{m \in M} G_{m} \times P_{m}^{\max} + \sum_{o \in O} G_{o} \times P_{o}^{\max} + \sum_{f \in F} \sum_{k \in K} G_{f} \times P_{f}^{\max} \} \geq \lambda_{o} \quad \forall f \in F, o \in O, k \in K \]

(17)

Here, \( G_{f} \) is the set of all Femtos using the RB k in a given TTL. Similarly, \( G_{o} \) is the channel gain from Femto a to o, \( G_{m} \) is the channel gain from f to o and \( G_{m} \) is the channel gain from \( G_{o} \) to Femto b. Calculated by using Eq. (1) or Eq. (2). The need to use \( \lambda_{o} \) is that if \( C_{fo} = 0 \) then \( \lambda_{o} \) 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 minimum SINR_{th} for an HIZUE. The Eq. (17) can be rewritten as follows,

\[ \text{Inf}_{f} = (1 - C_{fo}) + G_{f} \times P_{f}^{\max} \geq \left( \lambda_{o} \times N_{o} + \lambda_{o} \sum_{m \in M} G_{m} \times P_{m}^{\max} \right) \times \left( \lambda_{o} \sum_{f \in F} \sum_{k \in K} G_{f} \times P_{f}^{\max} \right) \quad \forall f \in F, o \in O, k \in K \]

(18)
Finally, the D2D MILP model is formulated as follows,

\[
\min \sum_{f \in F} \sum_{k \in K} \rho_f^k \text{s.t.} \quad (9), (10), (11), (12), (13), (14), (15), (16), (18).
\]

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 LIUEs 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 \( \gamma \) for all possible \((f, o, k)\) combinations, as expressed in Eq. (19).

\[
\gamma_f^k = \frac{C_{fo}^k}{\sum_{f' \in K} G_{fo}^{f'} + \sum_{f' \in K} L_{fo}^{f'} + \sum_{f' \in K} L_{k}^{f'}}
\] (19)

Here, \( C_{fo}^k \) represents the set of HIZUEs receiving data using the RB \( k \), \( L_{fo}^k \) represents the set of FIUEs receiving data from Femto using the RB \( k \) and \( L_{k}^o \) represents the number of FIUEs transmitting data to HIZUE 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 \( G_{fo}^f \), \( G_{fo}^{f'} \) and \( L_{fo}^f \), \( L_{fo}^{f'} \) and \( G_{fo}^k \) represent the channel gain between \( f \) and \( o \), \( f' \) and \( f' \), 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. Initially \( \gamma_f^k \) 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 \( \gamma \) 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 \( \gamma^* \), there will be additional interference \((G_{fo}^{f'})\) to the existing \((f', o')\) pairs who are using RB \( k_{max} \) for their UEs transmissions. Hence, \( \gamma_f^k \) values have to be recalculated and checked whether they remain greater than \( \gamma \). If all of these values remain greater than \( \gamma \), the triplet \((f_{max}, o_{max}, k_{max})\) is added to \( \gamma^* \) and the recalculated \( \gamma_{f_{max}}^{k_{max}} \) values are stored in the \( \gamma \) matrix, otherwise triplet \((f_{max}, o_{max}, k_{max})\) is not added to \( \gamma^* \). In case triplet \((f_{max}, o_{max}, k_{max})\) is added to \( \gamma^* \), the \( \alpha_{max} \) and \( \beta_{max} \) values are incremented, where \( \alpha_{max} \) is the count for the number of HIZUEs connected to FIUE \( f_{max} \) and \( \beta_{max} \) is the number of FIUEs connected to HIZUE \( o_{max} \). If \( \alpha_{max} \) value reaches the maximum limit \( \alpha \), then all the \( \gamma_f^k \) values for FIUE \( f_{max} \) are removed from the \( \gamma \) matrix. Similarly if \( \beta_{max} \) reaches the maximum limit of \( \beta \), then all the \( \gamma_f^k \) values for HIZUE \( o_{max} \) are removed from the \( \gamma \) matrix. W2L ratio in the \( \gamma \) matrix is updated \( \forall f, o \) which are using RB \( k_{max} \). If any of the updated \( \gamma_f^k \) is lesser than \( \gamma \), then that value is removed from the \( \gamma \) matrix and is not considered during the next iteration. Finally, it removes \( \gamma_{max}^{k_{max}} \) from the \( \gamma \) matrix and continues to the next iteration until all the entries are removed from the \( \gamma \) matrix.

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

\begin{enumerate}
\item \( D_{f_{max}} \rightarrow \forall f \in F, o \in O \)
\item \( C_f^k \rightarrow \forall f \in F, o \in O, k \in K \)
\item Compute \( \gamma_f^k \) \( \forall f \in F, o \in O, k \in K \) and store in \( \gamma \) matrix
\item \( \alpha_f \rightarrow \forall f \in F \) \{Count for number of HIZUEs connected to each FIUE\}
\item \( \beta_o \rightarrow \forall o \in O \) \{Count for number of FIUEs serving each HIZUE\}
\item \( \alpha^* \rightarrow \{\} \)
\item while \( \text{size} (\gamma) \neq 0 \) do
\item Compute \( \alpha_{max}^{f_{max}} \) and \( \beta_{max}^{o_{max}} \) \( \forall f_{max}, o_{max}, k_{max} \)
\item if \( \text{Updated } \gamma_{fo}^{k_{max}} \) values for entries in \( \gamma^* \) \( \gamma \) then
\item \( D_{f_{max}} \rightarrow 1 \)
\item \( C_f^k \rightarrow 1 \)
\item \( G_{fo}^k \rightarrow 1 \)
\item \( \alpha_f = \alpha + 1 \)
\item \( \beta_o = \beta + 1 \)
\item remove \( \gamma_{fo}^{k_{max}} \) \( \forall f, o, k \in K \)
\item end if
\item end if
\item if \( \gamma_{fo}^{k_{max}} < \gamma \) then
\item Remove \( \gamma_{fo}^{k_{max}} \) \( \forall f, o, k \in K \)
\item end if
\item end if
\item end while
\end{enumerate}

Step 2: Heuristic D2D power allocation (hDPA)

Using outputs of the hDPRA from the Step 1, namely \( D_{f_{max}} \), \( C_f^k \), \( G_{fo}^k \), and is the input in the Step 2 we solve an LP model which adjusts the powers 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.

\[
\min \sum_{j \in F} \sum_{k \in K} p_{fj}^k \quad (20)
\]

\[
p_{fj}^k \leq h_{fj}^k \quad \forall f \in F, k \in K
\]

\[
\sum_{j \in F} (G_{fl} \times S_{fl} \times p_{fj}^k \times p_{max}^k) \leq h_l \quad \forall l \in L, k \in K
\]

\[
\ln f \times \left(1 - \frac{C_{fl}^k}{C_{f}}\right) + G_{fl}p_{fj}^k \cdot p_{max}^k \geq \left(\lambda_o N_o + \lambda_o \sum_{m \in M} G_{mo}p_{macro} + \lambda_o \sum_{a \in A} G_{ao}p_{lim} + \lambda_o \sum_{f \in F} G_{fo}p_{max}^k\right) \quad \forall f \in F, o \in O, k \in K
\]

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

\[
\min \sum_{f \in F} \sum_{k \in K} p_{fj}^k s.t.
\]

(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 (0.3, 0.3, 0.7 and 0.9)), 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 for IUEs and reduce the interference to HIZUEs.

The corresponding OptFP can then connect with MBS for D-plane communication. We formulated this as OptFP MILP model [1] and by solving it we can,

- Determine the optimal power required by each Femto for maintaining the SINR 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

1. All Femtos are configured to transmit at their peak power by default.
2. All HIZUEs (0) are connected to one of MBSs for their C-Plane.
3. Find the set of all HIZUEs, O’, for whom it is not possible to establish D2D based relays by using FIUEs, O < O.
4. Find the set of Femtos, B’, who are causing interference to O’ HIZUEs, B’ < B.
5. Apply the OptFP model [1] on B’ to reduce their transmit powers so that interference to O’ is reduced.
6. 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).
7. 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.

Radio Resource Cost

\[
\sum_{i=1}^{K} \text{No of RBs allocated to FIUE by Femto}.
\]

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 \( P_{\text{max}} \) (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
considered a single-floor building with a single MBS placed at a
distance of 350 m from the south west side of the building. Fur-
ther, we considered the scenario where all Femtos and MBS are
configured to use the same 5 MHz channel (i.e., 25 RBs). Fem-
tos are allowed to be attached only to the ceiling of the building
and we did not consider the user mobility in our simulation ex-
periments 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 trans-
mission power. For the performance evaluation, we generate differ-
ent 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 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 optimiza-
tion and utilizes branch and bound framework for solving MILP
based optimization problems. This MILP optimizer has the capa-
bility 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}, and I_{29} (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_{50}, I_{29},
I_{79}, and I_{31} 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_{7}, I_{8}, and I_{31} inside the building have
relatively less SINR 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 build-
ning 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 build-
  ing by MinNF method, but Femtos are configured to emit at their full
  transmission power. In this scheme, HIZone exists around the build-
  ing 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 $\text{SINR}_I$ on SINR
of IUEs and effect of IUE density on FIUEs transmission power. Fi-
nally, 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 hDPRA 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, IUEs
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 connectiv-
ity diagram shows the number of D2D links in the instance #1.

![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 re-
ferred to the web version of this article.)](image)

![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.)](image)
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 LI-UEs 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 ensures that all the HIZUEs achieve SINRth. 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 SINRth on SINR of IUEs. We studied the variation in SINR of IUEs by varying SINRth values. We also measured the...
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 $\text{SINR}_{\text{th}}$. This increases the interference to the IUEs and hence causes a fall in average IUE $\text{SINR}$. With increase in $\text{SINR}_{\text{th}}$ of HIZUES. We note that even with changes in $\text{SINR}_{\text{th}}$ the degradation of IUEs $\text{SINR}$ 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., IUES = 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 $\text{SINR}$ of IUEs and HIZUES. Fig. 12 shows $\text{CDF}$ of IUEs over various scenarios for different schemes. When compared to the Optimal Femto Power scheme, D2D heuristic algorithm improves the $\text{SINR}$ of IUEs by 40% as shown in Fig. 12. However, the degradation in $\text{SINR}$ of IUEs is only 1.6% when compared to the Full Power Femto scheme. Similarly, Fig. 13 shows average $\text{CDF}$s of HIZUES over various scenarios for different schemes. If we observe Fig. 13, the minimum $\text{SINR}_{\text{th}} = -2$ 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 links limited to 1.
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.

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 IUEs 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 $\text{SINR}_{\text{th}} = -2 \text{ dB}$ 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 $\text{SINR}_{\text{th}}$ 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...
Table 7
Topologies having varying distribution of HIZUEs in HIZone.

<table>
<thead>
<tr>
<th>Topology</th>
<th>No. of HIZUEs</th>
<th>Indices of outer sub-regions having HIZone UEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>(O_5, O_9, O_{11}, O_{15}, O_{21}, O_{27}, O_{34}, O_{40}, O_{45}, O_{46})</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>(O_1, O_5, O_{10}, O_{14}, O_{21}, O_{31}, O_{35}, O_{45}, O_{46}, O_{48})</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>(O_1, O_5, O_{10}, O_{14}, O_{21}, O_{31}, O_{35}, O_{45}, O_{46}, O_{48})</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>(O_{17}, O_{23}, O_{25}, O_{30}, O_{32}, O_{35}, O_{41}, O_{44}, O_{45}, O_{46})</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>(O_1, O_{21}, O_{27}, O_{31}, O_{35}, O_{45}, O_{46})</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>(O_{15}, O_{21}, O_{27}, O_{35}, O_{41}, O_{45}, O_{46}, O_{48}, O_{50}, O_{52}, O_{53})</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>(O_1, O_{23}, O_{31}, O_{45}, O_{51}, O_{52}, O_{54}, O_{56}, O_{58})</td>
</tr>
</tbody>
</table>

Fig. 18. UE distribution in Topology 1.

Fig. 19. UE distribution in Topology 2.

Fig. 20. UE distribution in Topology 3.

Fig. 21. UE distribution in Topology 4.

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.

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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...
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 $0.1 \text{ W} + D2D$ 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 HZone, 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 HZone. Figs. 29–31 show the pending D2D links established in the subsequent instances. When compared 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...
decrease its transmission power further to reduce the SINR of IUEs. Fig. 33 shows that HIZUEs maintained SINR\(_d\) when JDHO algorithm is used. In previous scenario (shown in Fig. 11) we maintained a constant SINR\(_d\) to all HIZUEs. But in the present scenario, in JDHO algorithm by using the OptFP model, the SINR\(_d\) 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\(_d\) for all 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 1.8%. 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.

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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 hDPPRA (step 1 of D2D heuristic algorithm) is shown below.

The time taken to compute maximum value in the γ matrix is \(O(\gamma^2)\).

The running time of the for loop is \(O(\gamma^2)\).

The total running time is \(O(\gamma^2)\).

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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