A Novel Resource Allocation and Power Control Mechanism for Hybrid Access Femtocells

Shrestha Ghosh, Vanlin Sathya, Arun Ramamurthy, Akilesh B, Bheemarjuna Reddy Tamma

PII: S0140-3664(16)30450-9
DOI: 10.1016/j.comcom.2017.05.007
Reference: COMCOM 5502

To appear in: *Computer Communications*

Received date: 18 October 2016
Revised date: 14 March 2017
Accepted date: 13 May 2017

A Novel Resource Allocation and Power Control Mechanism for Hybrid Access Femtocells

Shrestha Ghosh[*], Vanlin Sathya[†], Arun Ramamurthy[•], Akilesh B[†], and Bheemarjuna Reddy Tamma[†]

[*]Department of Computer Science and Technology, Indian Institute of Engineering Science and Technology, Shibpur, India
[†]Department of Computer Science and Engineering, Indian Institute of Technology Hyderabad, India
[•]Department of Industrial Engineering and Operational Research, Indian Institute of Technology Bombay, India

Abstract

LTE Small cells like Femto cells are being deployed in enterprises and residential buildings to improve data rates of indoor users who experience low Signal-to-Interference plus Noise Ratio (SINR) from Macro Base Stations (MBSs). Deployment of Femto cells inside a building can lead to signal leakage at the edges/corners of the buildings. This causes cross-tier interference and degrades the performance of users in High Interference Zone (HIZone) around the building area, who are connected to one of the MBSs in LTE Heterogeneous Networks (HetNets). Hybrid Access Femto cells (HAFs) can ensure QoS for paid Subscriber Group (SG) users by giving them preferential access to resource blocks over non-SG (NSG) users and also improve the throughput of LTE HetNet system by serving nearby NSG users. In this work, we address various challenges involved in deployment and operation of HAFs in indoor environments by proposing an *Optimal Placement of Femto cell (OPF)* model, a dynamic *Bandwidth Allocation (BWA)* mechanism for splitting resource blocks between SG and NSG users, a dynamic *power control* mechanism to mitigate co-tier and cross-tier interference in HetNets and an *Enhanced Priority (EP)* scheduling mechanism to give more priority to SG users over NSG users.

During peak traffic load scenarios, HAFs may not be able to guarantee QoS of both indoor and HIZone users connected to them. As HAFs are primarily meant for indoor users, HAFs employ an Optimal Power Control (OPC) mechanism to tune their transmit powers so that HIZone users are offloaded to near-by MBSs. Since the OPC is a Mixed Integer Non-linear Programming (MINLP) problem, we put forth a Sub-Optimal Power Control (SOPC) mechanism. The SOPC mechanism boosts the throughput of MBSs by almost 62% over the traditional 3GPP proposed enhanced Inter-Cell Interference Co-ordination (eICIC) mechanism for 300 users in the HetNet system. Also, the proposed EP scheduling mechanism maintains Jain's fairness index of 0.99 for both SG and NSG users while providing a 40% higher per user throughput than that obtained with the legacy *proportional fair* and *Priority Set* schedulers.

Keywords: Hybrid access femtocells, resource splitting, optimization, power control and dynamic scheduling.

1. Introduction

Cellular networks are under constant pressure to meet the ever increasing traffic demand from the users. The global mobile data traffic reached 2.5 exabytes per month by the end of the year 2014 and is expected to increase at least ten-folds by 2020. According to [1], the indoor users are the largest consumers of mobile data. But, due to the path loss and many obstacles in indoors, the signal strength received from outdoor Macro Base Station (MBS) by an

[1]Email: ghosh_shrestha@yahoo.co.in (Shrestha Ghosh), cs11p1003@iith.ac.in (Vanlin Sathya), 163190013@iitb.ac.in (Arun Ramamurthy), cs13b1042@iith.ac.in (Akilesh B), tbr@iith.ac.in (Bheemarjuna Reddy Tamma).

indoor user is typically not sufficient to provide higher data rates. The recent trend has been to deploy cost-effective and low-power base stations (aka small cells such as Femtos) like Femto cells on top of the existing cellular network infrastructure of Macro cells so that the network capacity is improved significantly. On the face of it, Femto cells are believed to increase overall network capacity by handling offloaded traffic from MBSs. But, this requires usage of efficient mechanisms for mitigating co-tier interference between neighboring Femtos and cross-tier interference between Femtos and MBSs due to *frequency reuse one* employed in LTE/LTE-A HetNets.

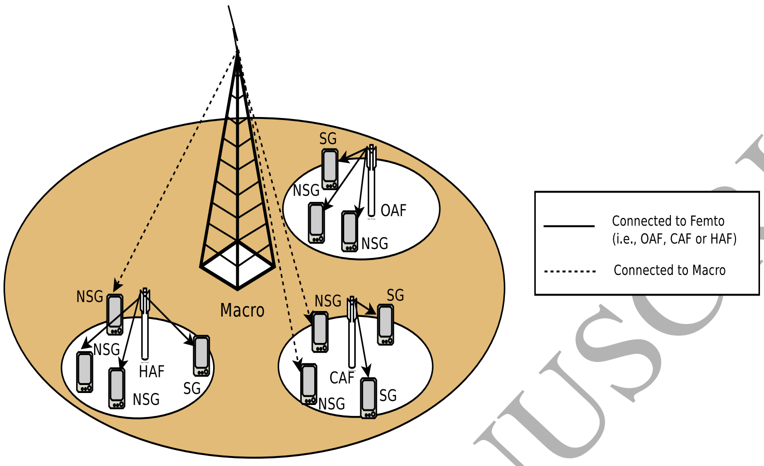

Figure 1: An example of LTE HetNet with MBS, OAF, CAF, and HAF Cells

Since Femtos are deployed for offering high data rate services to indoor (paid) users in enterprise and residential buildings, each Femto is configured with a list of subscribers called Subscriber Group (SG) so that only the users in the SG can access them. The users not belonging to this list are called Non-SG (NSG) and they are served by MBSs deployed in outdoor environments even when they are in close proximity to a Femto deployed in indoors. This type of restricted access is called the closed access [1], [2] and [3]. Unlike Closed Access Femtos (CAFs), Femtos configured in open access do not distinguish between SG and NSG users and serve all users like the way MBSs serve them. Open Access Femtos (OAFs) are typically deployed in public hotspots like airports and shopping malls. If this access mechanism is employed in enterprise and residential buildings, QoS of SG users is affected as the number of NSG users increases in indoors. Hybrid access mechanism integrates the principles of both closed and open access mechanisms. It lets some of NSG users in indoors to connect with Hybrid Access Femto cells (HAFs) and share its resource blocks along with SG users. This mechanism provides a trade-off between maximizing overall HetNet capacity and maximizing the throughput of SG users. Fig. 1 shows an LTE HetNet system comprising of one Macro cell and three Femto cells: one OAF, one CAF and one HAF. Here, the OAF is serving both SG and NSG users located in its coverage area. But, in CAF case all of the NSG users located in the CAF's coverage area are forced to connect with the MBS. As a compromise, HAF serves two of NSG users along with its SG users and the rest of NSG users are served by the MBS.

More importantly, Hybrid Access Femto cells (HAFs) provide service to NSG users when they are inside the building where they experience low signal from MBSs. And, because OAFs are not a favorite in large private buildings, HAFs are a welcome relief to the NSG users who would otherwise be deprived of even basic data rates when they are indoors in CAFs. Hybrid access mechanism needs to be effectively promoted as the SG users are usually reluctant to share resources they have paid for, with unknown NSG users who visit their buildings. This mechanism can be made attractive by rewarding the SG users for sharing their resources with the NSG users [4],[5].

Optimal arrangement of Femtos with minimum overlapping regions is necessitated by the need to save the cost of deploying Femtos and reduce co-tier interference due to frequency reuse one in LTE HetNets. In enterprises and campus environments, placement of Femtos play an important role in assuring good signal strength unlike in small areas like homes where controlling the placement of Femtos is not realistic. If enterprises allow planned Femto deployment, unnecessary co-tier interference and load imbalance can be avoided. [6] deals with the optimal placement of CAFs with minimum overlapping areas and reduced co-tier interference. Optimal placement of Femtos operating in hybrid access allows users in the high interference zone (HIZone) surrounding the building to connect to one of the HAFs instead of the MBS. Thus, HIZone users who earlier experienced high cross-tier interference from HAFs while connecting to the MBS, enjoy better services from a near-by HAF.

Care needs to be taken to ensure QoS of SG users by dynamically splitting resource blocks between SG and NSG users. When a near-by HAF is not able to maintain the minimum QoS requirement for its users, it reduces its transmit power allowing the HIZone users to connect to one of the MBSs with lower SINR degradation. The reduction in transmit power may affect the indoor users who now get reduced signal strength but the HAF can use the additional resources, previously reserved for the HIZone users, to serve the indoor users. A dynamic power control mechanism also adds advantage to the indoor users at times when there are no users in the HIZone, especially at nights. During such times, HAFs may be tuned to operate at the maximum transmit power thereby serving the indoor users with high data rates.

The rest of this paper is organized as follows. Related work and our contributions are given in Section 2. Section 3 introduces the system model and enumerates the assumptions made in this work. We elaborate the proposed work in Section 4. This section describes the optimal placement of the HAFs, the Bandwidth Allocation (BWA) and the optimal and the sub-optimal power control mechanisms. This is followed by Section 5 where we present the simulation results and then provide insights into the working of proposed mechanism. Finally, Section 6 summarizes and concludes the work.

2. Related Work

Large-scale deployment of Femtos can severely affect the performance of MBS cells under which the Femtos are deployed, especially if they are configured to operate on the same channel due to frequency reuse one in LTE HetNets. This section presents some important related works in the area of resource management and scheduling of Femtos. Besides scheduling, optimal placement and power control techniques also help to improve overall network performance [7, 8, 9].

Optimal placement of and dynamic power control by CAFs in a two-tier LTE network overcome co-tier and cross-tier interference at the cost of reduced CAF transmit power to the SG users [6]. In order to assure minimum degradation to NSG users in outdoors, SG users suffer from lower throughput values. SG users are affected by the presence of even a single NSG user in the HIZone since the Femtos lower their transmit power to reduce cross-tier interference. [7] studies the effect of the user-deployed co-channel Femtos on the call drop probability of the Macro users in residential areas. The results show that the use of co-channel Femtos is efficient but to make it financially viable the Femtos should have auto-configuration abilities. The main aspect of this auto-configuration is tuning the Femto transmit power to reduce the number of dropped calls of NSG user due to interference. The authors of [8] provide an analysis of the co-tier interference in CAFs. They point out that coverage holes appear in the downlink of MBS cells in the vicinity of CAFs. Results show some improvement when Femtos employ a transmit power adjustment mechanism and operate on an different adjacent channel. The survey on transmit power control techniques in Femto networks presented in [9] discusses and compares several power control techniques focusing mainly on distributed transmit power control techniques due to decentralized nature of Femtos.

Optimization plays an important part in dynamic systems where the state of the system changes over time. A dynamic spectrum allocation method for the hybrid access cognitive femtocell is proposed in [10]. The authors of [10] formulated the resource allocation problem as a sum-utility maximization problem and proposed an optimization method to solve it via the dual decomposition method. In [11], the authors proposed a dynamic resource management scheme for hybrid architectures. The proposed scheme uses an optimal greedy algorithm to classify and perform lexicographic admission control on the incoming traffic data flows. In order to maximize the weighted sum of data rates of each femtocell, a suboptimal delay-bounded packet scheduling algorithm and a dual decomposition-based power allocation algorithm are developed subject to bound packet delays and power constraints.

The key features and challenges for designing a scheduler and comparison of existing popular schemes have been detailed in [12]. The main objective of a scheduler should be to achieve a good trade-o between spectral eciency and user throughput. Scheduling resource blocks between SG and NSG in the downlink shared access Femtos is addressed in [2] where, home users associate with either a Femto or MBS depending on the signal strength. Cellular users associate with a nearby Femto only when it near cell edge. In a particular hybrid spectrum management and interference mitigation scheme [13], the CAFs closer to the MBS operate in dedicated-channel and CAFs farther away from the MBS operate in co-channel spectrum. The outer CAFs (situated closer to cell edge) use the entire spectrum, the MBS operates on one part of the spectrum and the inner Femtos (closer to the MBS) operate on the remaining part. The interference from the CAFs experienced by the NSG users closer to the cell edge is severe and of particular concern. In [14], resource blocks are allocated in hybrid environment where each Femto independently selects a mutually exclusive subset of resource blocks. This decentralized mechanism which aims to reduce the cross-tier interference is not scalable. The number of resource blocks that a Femto can select keeps decreasing as the Femtos count increases. Another solution to resource block management in hybrid access is presented in [4]. The authors propose a four-stage resource block management mechanism where base stations perform access control, resource block allocation, channel allocation and the users perform power control. Interference mitigation is performed by assigning dedicated channels per each Femto based on minimum QoS requirement of users and additional channels as an incentive to serve cellular users. The drawback of the proposal is that the authors consider a system with one MBS and one Femto. Since, the MBS and the Femto operate on dierent channels to avoid co-channel interference for the NSG, channel allocation becomes a problem in practical situations where multiple Femtos need to be deployed.

Newer solutions focus on communication between proximity devices, high frequency transmission and inter-cell interference co-ordination (ICIC) to increase network capacity. To address the dominant interference scenarios where NSG users come close to a building having Femtos, enhanced ICIC (eICIC) mechanism is introduced by 3GPP [15]. In time domain eICIC mechanism, MBS periodically blanks some of its sub-frames so that the interference to the co-channel Femtos is lower. In frequency domain eICIC mechanism, the C-plane messages of the Femtos are scheduled in reduced bandwidth so that the control information transmission of the Femtos is orthogonal to one another. Power control techniques in eICIC allow the MBS as well as the Femtos to operate all times but the Femtos operate at reduced transmit power levels when they interfere with the nearby NSG users.

Rewarding extra resource blocks to Femtos deployed extensively under a MBS, for serving NSG users is a new solution for improving the network performance. [16] proposes an economic solution for mobile operators and SG users based on game theory by analyzing the existence of the Nash Equilibrium of the game. They use the concept of revenue sharing to provide a positive cycle to sustain the Femto service by maximizing operator's benefits and satisfying the users' service requirements. [17] motivates the MBSs to lease a part of their spectrum to the Femtos and the Femtos to open a part of the above obtained spectrum to serve the NSG users. The authors of [18] have proposed an optimal as well as a sub-optimal mechanisms to implement a reverse auction framework for a fair and ecient access permission transaction. This work further motivates SG to use HAFs. Most recent work in the area of cross-tier and co-tier interference mitigation when both CAFs and MBS operate in the same frequency is [19]. The authors adopt static allocation of resource blocks and power control is done for each resource block in a CAF located at the cell edge. Therefore, an interfering CAF may serve a subscriber with a resource block R_i at higher transmit power while serving another subscriber at a lower transmit power with a resource block R_j if MBS serves a nearby NSG user with R_j. But, there is no provision for NSG users inside the building.

2.1. Our Contributions

Our contributions in this paper are enumerated as follows:

- An *optimal placement of Femtos (OPF)* mechanism which is used for optimally placing Hybrid Access Femtos (HAFs) inside enterprise buildings to mitigate co-tier interference and provide good connectivity in the HIZone of buildings. The objective of OPF is to reduce the number of HAFs needed for deployment inside a building without leading to any coverage holes. OPF provides a trade-o between co-tier interference between HAFs and coverage holes introduced due to insucient number of HAFs.

- A decentralized *dynamic bandwidth allocation (BWA)* mechanism which prioritizes subscribed group (SG) users over non-subscribed (NSG) users by restricting bandwidth used by the NSG users. BWA is necessary to maintain priority of the SG over the NSG who are given limited access due to their inability to establish strong connection with any of the outside Macro Base Stations (MBSs). By allowing NSG users to use at most some fixed number of resource blocks, the SG users are always given preferential treatment while NSG users are guaranteed connectivity at otherwise high-interference zones (HIZones) in and around the building.

- The idea behind configuring Femtos in hybrid access mode is to reap in the advantages of both open access and closed access Femtos. The HAFs balance between maximizing the network performance and maximizing the closed subscribed users' throughput. Dynamic power control of HAFs relives the HAFs of the obligation to always serve the HIZone users at the cost of degraded indoor users throughput. Hence, if an HAF is unable to serve all of its connected users, it o□oads a few HIZone users to an MBS by reducing the transmit power and only serves users who are much closer to it. The Optimal Power Control (OPC) and Sub-Optimal Power Control (SOPC) mechanisms are formulated keeping this motivation in mind.

- An enhanced priority (EP) scheduling mechanism employs two schedulers which are implemented using proportional fair (PF) algorithm. While one scheduler maintains fairness among the SG users, the other fairly schedules resource blocks among the users of NSG. Our EP scheduling mechanism works better than the legacy PF scheduler as well as the legacy Priority Set (PS) scheduler by prioritizing SG users over NSG users and maintaining fairness within both user groups.

3. Preliminaries and Assumptions

We describe the system model considered in this work. The building and channel models along with the associated assumptions necessary for the system setup are also detailed.

3.1. System Model

The system is modeled on downlink LTE HetNet consisting of MBSs in the outdoor environment and HAFs inside an enterprise building which is located in the cell edge of an MBS as shown in Fig. 2. Frequency reuse one is employed in HetNet to improve the capacity of the system. HAFs are connected to Femto-Gateway (F-GW) over S1 interface. The F-GW has Self Organizing Network (SON) feature which makes the system self-configurable, self-optimizing and self-healing. SON helps HAFs to dynamically adjust the power.

Here we assume that the resource block requirement of SG users, R_S, can always be satisfied by the available resource blocks in the HAF before the power control. Otherwise, the HAF will be unable to maintain a baseline throughput for SG users at full transmit power even in the absence of NSG users. The HAF giving the strongest signal to each user in each sub-region (indoor or HIZone) is identified so that a user in that sub-region may connect to it with minimum cross-tier interference. We classify the users on two parameters - priority and location. The user groups formed on basis of priority are SG and NSG where the former gets higher priority than NSG when connected to HAFs. Indoor users and HIZone users are determined by their locations by using Position Reference Signal (PRS) [20, 21, 22]. At any time a user is served by either the MBS or an HAF.

The HAFs send downlink control/data plane (C/D plane) to the NSG users in the HIZone. At each periodic time interval T (comprising of a number of transmission time intervals (TTIs)), the HAFs split their resource blocks between the NSG users and SG users before running the EP scheduler. When an HAF operates in full transmit power and the number of resource blocks required to serve all the HIZone and indoor users at the minimum QoS exceeds the available resource blocks, the F-GW tunes the HAF's transmit power. Hence, the HIZone users previously connected to the HAF are now connected to the MBS above a threshold SINR, $SINR_{Th}^{PC}$. The transmit power is tuned so that these HIZone users can connect to the MBS with minimum cross-tier interference.

For example, if HAF_1 transmits at full transmit power, there are not enough resource blocks to serve all the users (both SG and NSG) with some guaranteed baseline throughput. Hence, the HAF_1 reduces its transmit power to allow

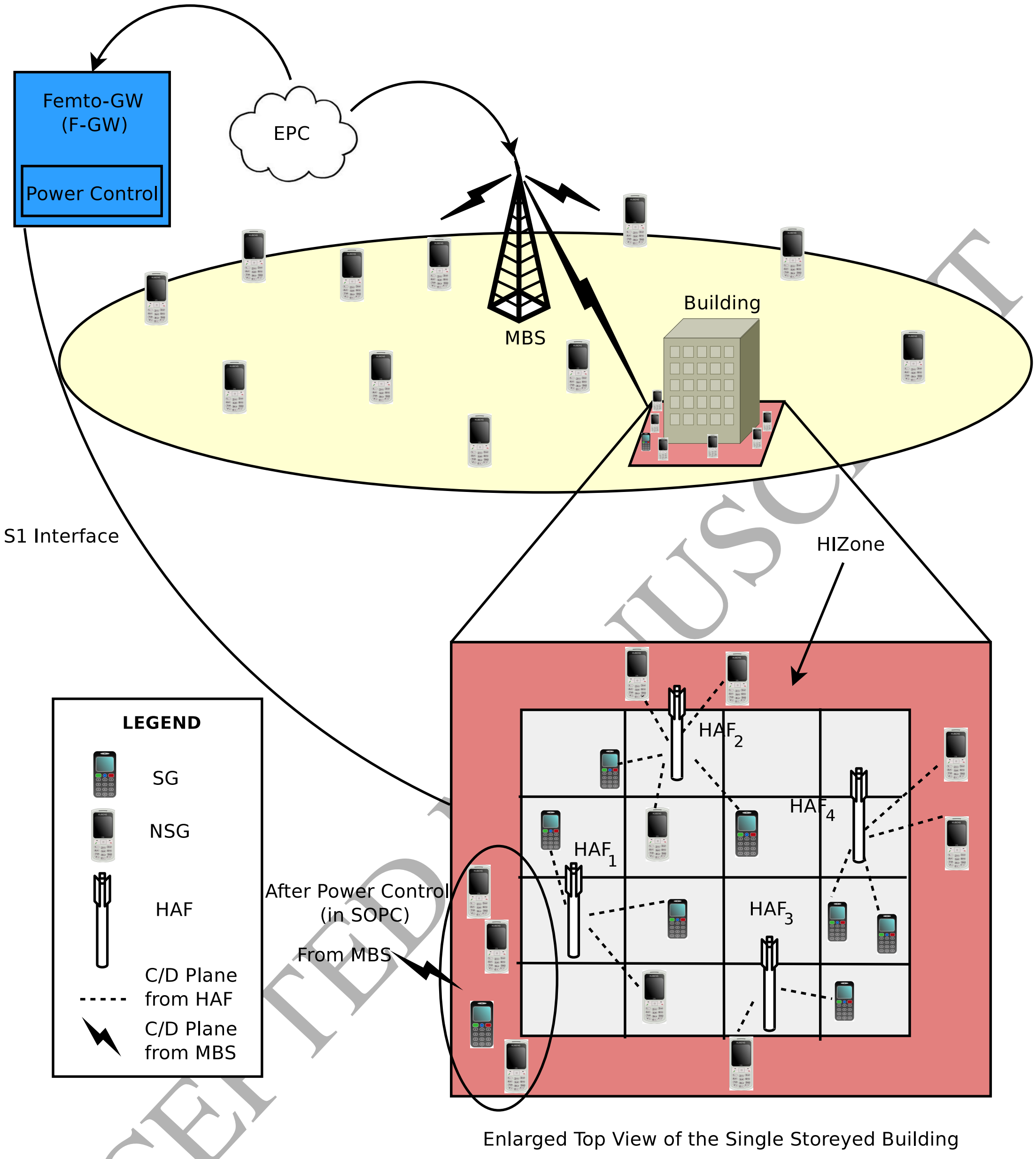

Figure 2: HAF based LTE HetNet System Model

the users in the HIZone to get their D-plane and C-plane from the MBS with better SINR. The resource blocks of HAF_1 can then be exclusively used to serve the indoor users. Since the BWA is done between the two user groups, priority of the SG users is not compromised. Similarly, the SG users in the HIZone experiences better throughput when connected to the MBS than when connected to HAF_1 which has insu□cient resource blocks for serving both indoor and HIZone users.

3.2. Building Model

The building has dimensions $l \times b \times h$ where l, b and h are the length, breadth and height, respectively. There are g floors of equal height and each floor is divided into equal sized rooms. Each room is further divided into $m \times$

n logical sub-regions which is the level of granularity in our placement model. The division into sub-regions in each room ensures that the SINR remains more or less constant within each sub-region.

A list of notations used in this paper is presented in Table 1. We have also provided an illustrative example of the notations in Fig. 3 so that the formulations can be easily visualized. In the illustration, we have shown how the variables used in the formulations behave for a sample HAF ($f = 3$) placed on the ceiling of an indoor sub-region (denoted by i, $i = 61$). $s_{j,61} = 1$ and $x_{j,3} = 1$ when signal strength from HAF_3 is greater than or equal to the threshold SINR, where, $s_{j,i} = x_{j,f} = 1$ denotes connectivity of indoor sub-region j to HAF f located in indoor sub-region i. Similarly, $t_{j,i}$ and $y_{j,f}$ denote HIZone sub-region connectivity to HAF f located at indoor sub-region i. When an HIZone sub-region, say j, is connected to an HAF, then $z_j = 1$. But if j is connected to an MBS, $z_j = 0$. $q_i = 1$ whenever a user occupies indoor sub-region i. $q_h = 1$ when a user occupies an HIZone sub-region h.

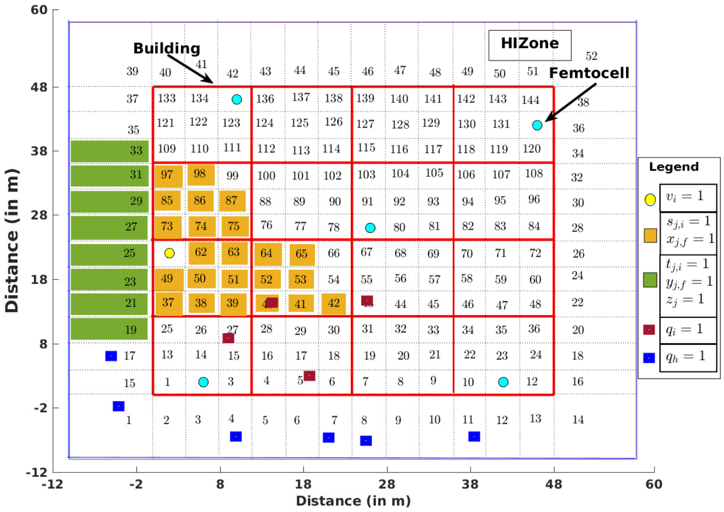

Figure 3: Illustrative example of some notations used in formulation when $i = 61$ and $f = 3$

3.3. Channel Model

The path loss (PL) from the MBS to an indoor user occupying any of the indoor sub-regions and HIZone user occupying any HIZone sub-region is given by Eqn. (1) [23].

$$PL_{MBS} = 40\log_{10}(\frac{d}{1000}) + 30\log_{10} f + 49 + w\eta \quad (1)$$

where, d is the distance of the sub-region of indoor/HIZone user from MBS in meters, w is the number of walls that a signal needs to pass through while traveling from its origin (the MBS or an HAF) to the user, f is the center frequency of MBS in MHz and η is the penetration loss. The PL from HAF to indoor/HIZone user is given by Eqn. (2) [23]:

$$PL_{HAF} = 37 + 30\log_{10} d + 18.3G^{\frac{(G+2)}{(G+1)-0.46}} + w\eta \quad (2)$$

where, G is the number of floors. In our system model, we assumed the antenna gain of the MBS and the HAFs to be 20 dBi and 2 dBi, respectively [24]. The channel gain between users and various base stations is determined from antenna gains and the PL models given above.

Table 1: List of notations used in the problem formulations

Notation	Definition
F	Set of all HAFs inside a building
M	A set of MBSs
H	Set of all HIZone sub-regions
I	Set of all indoor sub-regions
T	Periodic time interval of duration equal to n TTIs
R	Number of resource blocks available in a HAF in a single TTI
R_S	Number of resource blocks required by SG from a HAF in a single TTI
R_{NS}	Number of resource blocks required by NSG from a HAF in a single TTI
P_f	Transmitting power of a HAF, f
P_{max}	Maximum transmitting power of HAF
P_M	Transmitting power of MBS, M
N_o	System Noise
$SINR^{P}_{Th}$	Threshold SINR to be maintained in all indoor and HIZone sub-regions during placement of HAFs inside the building
$SINR^{PC}_{Th}$	Threshold SINR to be maintained in all indoor and HIZone sub-regions during the power control of HAFs in SOPC mechanism
v_i	1 if HAF is placed in indoor sub-region i, 0 otherwise
s_{ji}	1 if indoor sub-region j is connected to HAF located in indoor sub-region i, 0 otherwise
t_{ji}	1 if HIZone sub-region j is connected to HAF located in indoor sub-region i, 0 otherwise
g'_{ja}/g''_{ja}	Channel gain between indoor sub-region or HIZone sub-region j and indoor sub-region a
g_{if}/g_{iM}	Channel gain of indoor sub-region i from HAF f or MBS M
g_{hf}/g_{hM}	Channel gain of HIZone sub-region h from HAF f or MBS M
d_i/d_h	Demand of user in indoor sub-region i or HIZone sub-region h for time interval T
$mcs(sinr_{if})$ or $mcs(sinr_{hf})$	Amount of data transmitted in one resource block based on the MCS value of indoor sub-region i or HIZone sub-region h (a function of the sub-region's SINR value from HAF f)
x_{if}	1 if indoor sub-region i is connected to HAF f, 0 otherwise
y_{hf}	1 if HIZone sub-region h is connected to HAF f, 0 otherwise
z_h	1 if HIZone sub-region h is connected to a HAF, 0 if it is connected to MBS M
q_i/q_h	1 if indoor sub-region i or HIZone sub-region h is occupied by a user, 0 otherwise

4. Proposed Work

In this section, we will describe in detail the optimization problems and propose a sub-optimal mechanism which runs in polynomial time and is appropriate for dynamic scheduling. Initially, the HAFs are placed inside the building by using an optimal placement model. This is a one time process after which the SOPC mechanism handles the SG and NSG user connections by a power control model. The set ISR has the list of all the HAFs for which the relation $R_S + R_{NS} \leq R$, *i.e.*, the sum of resource block demand by the SG and NSG being less than the available resource blocks, does not hold. In a situation where $ISR \neq NULL$, a new set $OCCU$ is formed which consists of all the HIZone users (SG and NSG) under the coverage of HAFs in the ISR. EP scheduler then schedules the resource blocks among all the users in each group. We describe each of the above steps, in detail, in the following subsections.

4.1. Optimal Placement of Femtos (OPF)

The first step deals with efficient placement of HAFs inside the building. Our objective is to ensure optimal placement of the HAFs, operating at their maximum transmit power P_{max}, inside the building so that a user situated anywhere in the building or in the HIZone (who is connected to the HAF giving highest SINR), is ensured certain minimum SINR, $SINR_{Th}$, from the HAF. The number of HAFs provides a trade-off between coverage holes and co-tier interference as the co-tier interference is directly proportional to the number of HAFs.

The OPF model is formulated with the objective to minimize the number of HAFs deployed in the building, as expressed in Eqn. (3), such that the HAFs operate at P_{max} to provide good SINR to all indoor and HIZone users, *i.e.*, there are no coverage holes. The optimization model uses the channel gains as discussed in the channel model to estimate the SINR.

$$min \sum_{i \in I} v_i \tag{3}$$

Eqn. (3) is subject to the following constraints. Since we want each indoor and HIZone sub-region to associate with only one HAF, we ensure it by adding constraints given by Eqns. (4), (5), (6), and (7).

$$\sum_{i \in I} s_{ji} = 1 \quad \forall j \in I \tag{4}$$

$$\sum_{i \in I} t_{ji} = 1 \quad \forall j \in H \tag{5}$$

$$s_{ji} - v_i \leq 0 \quad \forall j, i \in I \tag{6}$$

$$t_{ji} - v_i \leq 0 \quad \forall i \in I, j \in H \tag{7}$$

The following constraints fulfill our requirement that every indoor and HIZone sub-region should have SINR above the pre-defined threshold of $SINR^P_{Th}$. The $SINR^P_{Th}$ is set as λ_i and λ_h for indoor and HIZone sub-regions, respectively, to ensure good coverage. The L.H.S. of Eqn. (8) and Eqn. (9) are the SINR values of indoor and HIZone sub-regions, respectively, obtained from HAF located at indoor sub-region, a.

$$\frac{Inf * (1 - s_{ja}) + g'_{ja} P_{max} v_a}{N_o + \sum_{b \in I \setminus a} g'_{jb} P_{max} v_b + g'_{jM} P_M} \geq \lambda_i \quad \forall j, a \in I \tag{8}$$

$$\frac{Inf * (1 - t_{ja}) + g''_{ja} P_{max} v_a}{N_o + \sum_{b \in I \setminus a} g''_{jb} P_{max} v_b + g''_{jM} P_M} \geq \lambda_h \quad \forall a \in I, j \in H \tag{9}$$

g'_{ja} and g'_{jM} are the channel gains from HAF and MBS to indoor sub-region j, respectively. Similarly, g''_{ja} and g''_{jM} are the channel gain from HAF and MBS to HIZone sub-region j, respectively. If there are multiple Macro cells, then summation of the channel gains from all MBSs gives the total interference. N_o is the thermal noise. Inf is a virtually infinite value (a large value like 10^6) used to ensure that the every indoor/HIZone sub-region gets at least $SINR^P_{Th}$ (λ_i for indoor sub-regions and λ_h for HIZone sub-regions), from only one HAF. Otherwise, all HAFs would try to assure the $SINR^P_{Th}$ to every sub-region and render the optimization problem infeasible.

By minimizing the number of HAFs needed for the deployment, the problem of co-tier interference which invariably arises when subscribers themselves deploy HAFs is mitigated to a large extent. The placement guarantees that every sub-region has at least $SINR^P_{Th}$, which implies that, if the cell-edge sub-regions have exact $SINR^P_{Th}$, then the sub-regions closer to the HAFs get higher SINRs. Thus if all cell-edge sub-regions have at least $SINR^P_{Th}$ (by solving OPF formulation), then we can say that when a neighboring HAF does transmit power control then the cell-edge shifts towards the HAF with reduced transmit power. The previous cell-edge users will now receive better SINR from the HAF which has still retained its transmit power due to decreased co-tier interference as a result of the power control by other HAFs. The re-adjusted transmit powers therefore guarantee the optimization obtained at OPF.

4.2. Optimal Power Control (OPC)

After placement of the HAFs, each HAF allocates its resource blocks to every active user connected to it in every periodic time interval, T. If the resource block demand is greater than the available resource blocks R, the F-GW performs OPC to tune the transmit powers of HAFs. The objective of OPC model is to maximize the sum of transmit powers of all HAFs so that resource demand at each HAF from its connected users can be satisfied. It chooses HIZone users (SG and NSG) who will be served by the MBS when the transmit powers of the HAFs, to whom they are connected currently, are reduced from P_{max}. In such a case, the selected HIZone users must be ensured at least a $SINR_{Th}^{PC}$ from the MBS in order to be served by it.

OPC Formulation: F is used to denote the set of all HAFs in the building and M is the set of MBSs. All the sub-regions in the HIZone and indoor form the sets H and I, respectively. D_i and D_h are the demands of i^{th} indoor user and h^{th} HIZone user, respectively, in T time interval. P_M denotes the transmit power of the MBS. We use the following variables to determine the connectivity of each sub-region to an HAF and to determine whether a sub-region is occupied.

- Indoor HAF connectivity variable $x = \{x_{if} | x_{if} = \{0, 1\}; i \in I; f \in F\}$, *i.e.*, $x_{if} = 1$ if indoor sub-region i is connected to HAF f, 0 otherwise.
- HIZone HAF connectivity variable $y = \{y_{hf} | y_{hf} = \{0, 1\}; h \in H; f \in F\}$, *i.e.*, $y_{hf} = 1$ if HIZone sub-region h is connected to HAF f, 0 otherwise.
- HIZone Macro connectivity variable $z = \{z_h | z_h = \{0, 1\}; h \in H\}$, *i.e.*, $z_h = 1$ if HIZone sub-region h is connected to a HAF f, 0 if connected to M.
- Indoor sub-region occupancy $op_i = \{q_i | q_i = \{0, 1\}; i \in I\}$, *i.e.*, $q_i = 1$ if indoor sub-region i is occupied by a user, 0 otherwise.
- HIZone sub-region occupancy $op_h = \{q_h | q_h = \{0, 1\}; h \in H\}$, *i.e.*, $q_h = 1$ if HIZone sub-region h is occupied by a user, 0 otherwise.

To ensure that every HAF can serve the users connected to it with minimum number of resource blocks, the OPC maximizes the total transmit power of all the HAFs, that is,

$$max \sum_{f \in F} P_f \tag{10}$$

The OPC maximizing the sum of transmit powers of HAFs as an objective function instead of minimizing it is considered in this work. This is because if minimization is considered some HAFs may shut down in order to reduce interference thereby reducing the number of resource blocks that might be available for scheduling if they are still operating. Whereas, by maximizing the transmit power and also guaranteeing a minimum SINR to all sub-regions, we make sure that adequate resource blocks are available for the SG and NSG users.

To ensure that every indoor sub-region, i, is connected to exactly one HAF and that any HIZone sub-region, h, if not connected to an MBS is associated with only a single HAF, Eqn. (10) is subject to the connectivity constraints (11) and (12).

$$\sum_{f \in F} x_{if} = 1 \qquad \forall i \in I \tag{11}$$

$$\sum_{f \in F} y_{hf} = z_h \qquad \forall h \in H \tag{12}$$

We use the SINR constraint given in Eqn. (13) to make sure that all the indoor sub-regions, which are connected to HAF, f, get at least $SINR_{Th}^{PC}$ which is equal to λ_i for indoor sub-regions.

$$\frac{Inf \cdot (1 - x_{if}) + g_{if} P_f}{N_o + \sum_{f' \in F \setminus f} g_{if'} P_{f'} + \sum_{m \in M} g_{im} P_m} \geq \lambda_i \quad \forall i \in I, f \in F \tag{13}$$

In order to ensure $SINR_{Th}^{PC}$ which is equal to λ_h for HIZone sub-regions from their respective HAFs, constraint given in Eqn. (14) is used.

$$\frac{Inf \cdot (1 - y_{hf}) + g_{hf} P_f}{N_o + \sum_{f' \in F \setminus f} g_{hf'} P_{f'} + \sum_{m \in M} g_{hm} P_m} \geq \lambda_h \quad \forall h \in H, f \in F \tag{14}$$

where, g_{hf} and g_{hm} are the gains from HAF, f, and MBS, m, to the HIZone sub-region h, respectively. For a HAF f, Eqn. (14) uses Inf to filter the HIZone sub-regions not connected to f to prevent the problem from becoming infeasible. The constraint given in Eqn. (15) is used to make sure that HIZone sub-regions connected to an MBS, $m' \in M$ get SINR greater than λ_h.

$$\frac{Inf \cdot z_h + g_{hm'} P_M}{N_o + \sum_{f \in F} g_{hf} P_f + \sum_{m \in M \setminus m'} g_{hm} P_m} \geq \lambda_h \quad \forall h \in H \tag{15}$$

Like earlier, Inf filters the HIZone sub-regions not connected to the MBS.

The constraint (16) gives an upper bound of nR to the net required resource blocks for the time interval T.

$$\sum_{i \in I} \left\lceil \frac{d_i q_i}{mcs(sinr_{if})} \right\rceil x_{if} + \sum_{h \in H} \left\lceil \frac{d_h q_h}{mcs(sinr_{hf})} \right\rceil y_{hf} \leq nR \quad \forall f \in F \tag{16}$$

where, R is the number of resource blocks available per TTI and n is the number of TTIs in the time interval T.

The first summation in Eqn. (16) determines the maximum number of resource blocks required by the indoor users connected to HAF f which depends on the individual user's data requirement d_i for the time interval T and their Modulation and Coding Scheme (MCS) values. Mapping of SINR values to MCS values is given in [25]. Similarly, the second term is the summation of the maximum number of resource blocks required by the HIZone users connected to f. nR is the upper bound to the net required resource blocks obtained from both the summation terms of the constraint (16) for the time interval T.

Thus, the OPC takes care of BWA for any combination of SG and NSG user locations by tuning the transmit power of HAFs whenever the demand in a HAF exceeds R. The demand from the indoor users (SG and NSG) itself can exceed R in a HAF operating at P_{max} due to presence of large number of indoor NSG users. Then the BWA is in proportion of the resource block demand between the SG and NSG (refer Eqn. (17) and Eqn. (18)) as the OPC is not feasible in such a situation.

$$R'_S = \frac{R_S}{R_S + R_{NS}} R \tag{17}$$

$$R'_{NS} = \frac{R_{NS}}{R_S + R_{NS}} R \tag{18}$$

The OPC problem (refer Eqn. 10) is a Mixed Integer Non-linear Programming (MINLP) problem and is very hard to solve in polynomial time [26]. Hence, we propose an efficient heuristic power control mechanism to solve the above power control problem in polynomial time.

4.3. Sub-Optimal Power Control (SOPC) Mechanism

The flowchart in Fig. 4 provides a basic idea of our proposed SOPC mechanism. In this section, we shall explain how the SOPC mechanism works. We shall also discuss the time complexity of SOPC mechanism. The SOPC mechanism comprises of two algorithms which are executed in each time interval T and are outlined as follows:

- Algorithm 1: It computes resource block demand of HAFs at P_{max}.

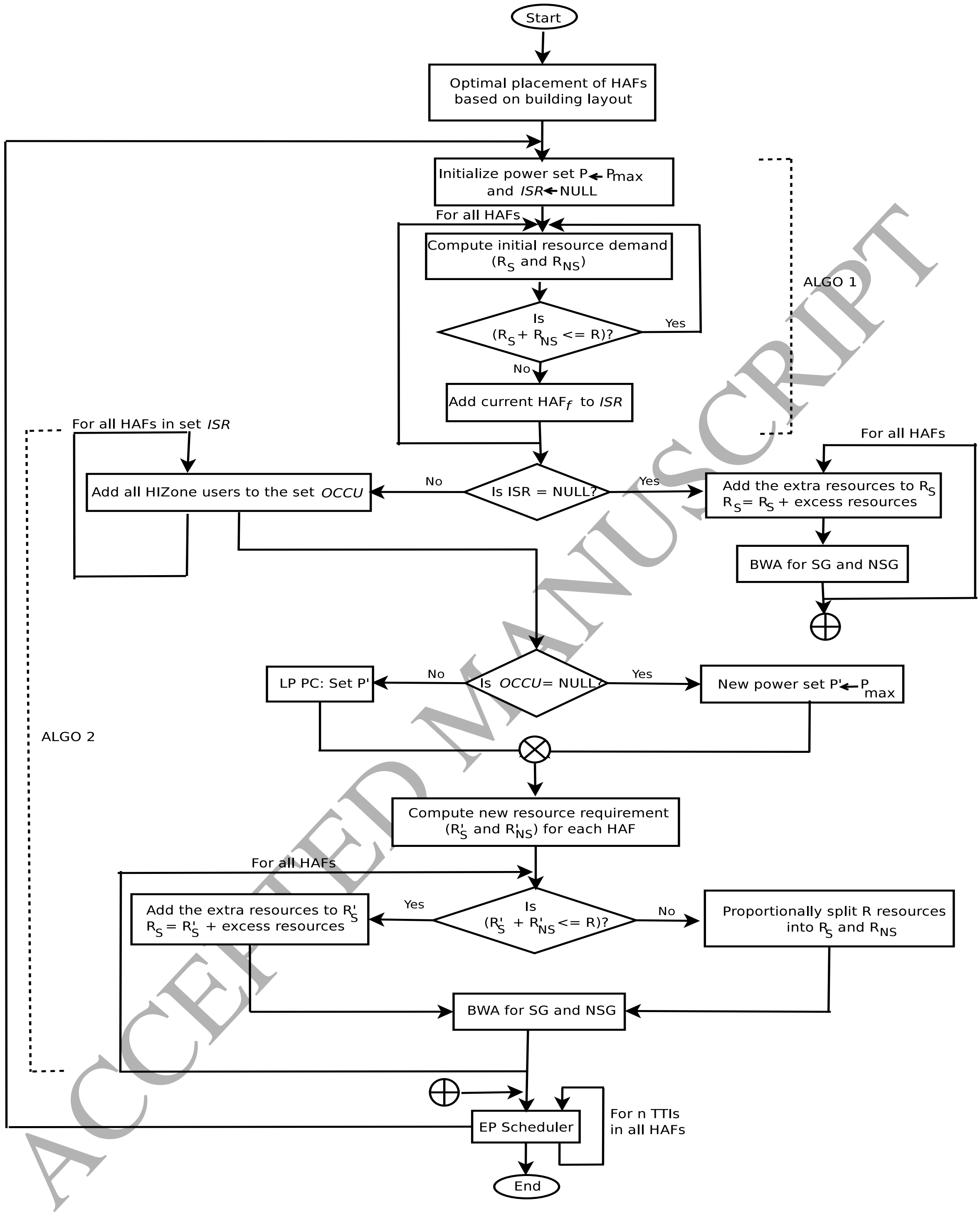

Figure 4: Flowchart of the proposed SOPC mechanism

- Algorithm 2: It performs BWA when HAFs can satisfy the user demand with R resource blocks available at each HAF and also when the resource block demand by users exceeds the resource blocks available at HAF.

Starting from the optimal placement of the HAFs to the iterative resource computation and scheduling, the SOPC mechanism proceeds as discussed below.

4.3.1. Placement

The first step is the optimal placement of the HAFs which takes as input the layout of the building and gives the co-ordinates where the HAFs are to be placed by using the OPF mechanism. This is one-time task executed during the deployment of the HAFs.

4.3.2. Initial resource computation

At the beginning of each time interval, T, the set of active users is determined by the PRS and fed as input to Algorithm 1. This algorithm then computes the resource block demand of SG and NSG users under each HAF operating at P_{max}. The resource blocks are split between the two user groups, SG and NSG, as denoted by R_S and R_{NS}, respectively. A set ISR is maintained which lists all the HAFs for which the constraint $R_S + R_{NS} \leq R$ does not hold. If for a HAF_f, the total resource blocks required by SG and NSG in a TTI exceeds R, then f is added to the set ISR. The output of this algorithm is the set ISR which forms the input of Algorithm 2.

When $R_S + R_{NS} \leq R$ *i.e.*, when $ISR = NULL$, the excess resource blocks are used by the SG users to further improve their throughputs (refer Algorithm 2). In this case, the BWA is performed immediately for all HAFs by dividing the available bandwidth between the two groups (SG and NSG) in proportion of R_S and R_{NS}. The Algorithm 2 performs BWA when $ISR \neq NULL$ only after doing resource re-computation for each HAF.

4.3.3. Power control and resource re-computation

When one or more HAFs have insufficient radio resources to meet the baseline throughput requirements of all connected users *i.e.*, when $ISR \neq NULL$, a new set $OCCU$ is formed. $OCCU$ comprises all the HIZone users (SG and NSG) connected to HAFs belonging to the set ISR (refer Algorithm 2). If the insufficiency in bandwidth is due to the presence of at least one HIZone user, that is, if $OCCU \neq NULL$, then the power control (PC) is performed at the F-GW.

This PC has the following objectives:

- To maximize the total transmit power of all HAFs
- To maintain $SINR^{PC}_{Th}$ for HIZone users in the set $OCCU$ who are connected to the MBS

The PC in SOPC mechanism maximizes the sum of transmit powers of all HAFs given by Eqn. (19).

$$max \sum_{f \in F} P_f \tag{19}$$

where, P_f is the transmit power of HAF, f, such that constraint given in Eqn. (20) is satisfied.

$$\frac{Inf \cdot z_h + g_{hM} P_M}{N_o + \sum_{f \in F} g_{hf} P_f} \geq \lambda_h \quad \forall h \in H \tag{20}$$

This constraint maximizes the total transmit power by selecting only those HIZone users to be connected to the MBS who if connected to a HAF increase the resource block demand to greater than the available resource blocks, that is, $z_h = 0$ for all HIZone sub-regions to which the SG and NSG in $OCCU$ belong.

The values P_f obtained by solving the optimization problem given in Eqn. (19) form the set P^{*}. As is evident from the constraint given in Eqn. (20), the transmit power maximization problem falls in the class of linear optimization (or LP). An LP optimization problem is solvable in polynomial time and is supported by [27] where the authors proposed a polynomial-time algorithm for solving LP optimization problems.

The F-GW tunes the transmit power of the HAFs such that the total transmit power is maximized. Hence, the HIZone users in the set $OCCU$ connect to the MBS which offers SINR greater than or equal to the $SINR_{Th}^{PC}$. With the new transmit power values P^{*}, the SINR of each sub-region also changes. We visualize this change with the help of SINR Radio Environment Maps (REM) and connectivity maps. The resource block requirement of SG, (R_S^{*}), and NSG, (R_{NS}^{*}), are computed with the new SINR values. If the new resource block demand of SG and NSG connected to a HAF can be satisfied by R, the process similar to the case where $ISR = NULL$ is performed. After the power control, co-tier interference from neighboring HAFs reduces allowing the HAF edge users to receive better signal thereby requiring lesser resource blocks. The demand for resource blocks for the users situated closer to a HAF increases when its transmit power is reduced. However, after the power control, the HAF allocates the resource blocks previously reserved for the HIZone users, to the indoor users. Thus, the total demand from the HAF is still satisfiable even if the HAF reduces its transmit power. The power control may not necessarily reduce the demand for resource blocks. There may arise a situation where on reducing the transmit power of a HAF, a significant number of the HAF cell edge users shift their connectivity to a neighboring HAF. If this increase is such that the resource block demand from the neighboring HAF exceeds R, Algorithm 2 divides R between SG and NSG so that the allotted resource blocks are in proportion to the actual requirement. Thereafter, the BWA is performed where the entire bandwidth is divided between SG and NSG users in each HAF in proportion to R_S and R_{NS}.

If there are no HIZone users then the insufficiency is due to crowding of SG and NSG users inside the building itself. In such a case all HAFs continue operating at P_{max} and the resource block requirement remains same for SG and NSG. The BWA is done by proportionally splitting the spectrum with respect to the resource block demands of SG and NSG users in the building.

4.3.4. Scheduling

At the end of running Algorithm 2, the bandwidth allocation for the two groups (SG and NSG) is completed. The Enhanced Priority (EP) scheduler then schedules resource blocks among all the users in each group such that the SG and NSG users have R_S and R_{NS} resource blocks, respectively. We now justify the need for EP scheduler. A legacy PF scheduler maintains fairness among all users in the network. The scheduler dynamically selects the active users in the current time interval of T with priority based on traffic. The PF scheduler cannot distinguish between SG and NSG users which may be unacceptable to the SG. A legacy PS scheduler might serve as an alternative, but, the PS scheduler gives the NSG users extra resource blocks which ought to be given to the SG. We make use of two PF schedulers to serve the SG and NSG jointly by dividing the resource blocks between the two groups. The schedulers maintain the pre-determined baseline throughput for both groups when available resources in a HAF are sufficient to satisfy the total resource block demand of all users of the HAF. The throughput of the SG users is maximized by allocating NSG users with the exact resource blocks needed to meet their baseline throughput demands and using the rest for the SG users. We name this two-scheduler mechanism as Enhanced Priority scheduling mechanism since it enhances the priority of the SG over NSG at the same time maintaining fairness among users of the individual groups.

4.4. Time Complexity of the SOPC mechanism

We now analyze the time complexity of the SOPC mechanism. In Algorithm 1, the resource block requirement of every SG and NSG user is calculated and is added to R_S and R_{NS}, respectively. This process is repeated for all HAFs. If the total number of SG users and NSG users are s and ns, then the resource block computation takes $(O(s) + O(ns))$ time. The ISR is formed in $O(|f|)$ time, where $|f|$ is the cardinality of the set of HAFs. Since $|f|$ is very less compared

Algorithm 1 Resource Block Demand Computation at P_{max}

Input: SG & NSG users in each HAF, list of indoor and HIZone users.
Output: R_S and R_{NS} for each HAF before the power control.

```
Initialize ISR ← NULL { ISR : set of all HAFs with insufficient resource blocks. }
for each HAF f ∈ F do
    Compute R_S { R_S : resource blocks required by SG users connected to HAF f at P_max for the current time interval T }
    Compute R_NS {R_NS : resource blocks required by NSG users connected to HAF f at P_max for the current time interval T }
    if R_S + R_NS > R then
        ISR ← ISR ∪ f
    end if
end for
```

to s and ns, the time complexity of Algorithm 1 is dominated by the time taken for resource block computation, that is, $(O(s) + O(ns))$.

If Step 1 (if $ISR = NULL$) of Algorithm 2 is true, the R_S and R_{NS} for each HAF is recomputed by adding extra resource blocks to R_S. The resource blocks required by individual user, however, need not be recomputed. Hence, the time complexity of computing the new values of R_S and R_{NS} is $O(|f|)$.

If Step 1 of Algorithm 2 is false, to form the $OCCU$ set, the for loop takes $(O(s)+O(ns))$ time to check every SG and NSG user. The power control is a LP optimization problem which will take $O(n^{3.5}L)$ time, where n is the number of variables (here, $|f|$) and L is the number of bits needed to store the input. The resource block computation from the new SINR values will take $(O(s)+O(ns))$ time. The final resource block computation runs once for each HAF thereby taking $O(|f|)$ time. Thus, the total running time of Algorithm 2 is $(O(s) + O(ns) + O(n^{3.5}L))$.

Thus, summing up, the total running time of the SOPC is:

- $O(s) + O(ns)$ if Algorithm 1 and Step 1 of Algorithm 2 are true.
- $O(s) + O(ns) + O(n^{3.5}L)$ if Algorithm 1 and Step 1 of Algorithm 2 are false and PC is performed to assign new transmit powers to HAFs.
- $O(s) + O(ns)$ if Algorithm 1 and Step 1 of Algorithm 2 are false and PC is not performed.

4.5. Analysis of Occupant Locations

The different combinations of occupant locations are given in Table 2, where, PC is the power control optimization adopted in Algorithm 2 of the SOPC mechanism. An entry with value 1 in Table 2 represents the scenario where SG/NSG users are present in Indoor/*HIZone*. The first four row entries are the scenarios without any HIZone users. These scenarios occur in reality especially during the night time. The indoor users can take benefit of HAFs operating at P_{max} by being served at higher data rates. Here the power control is not required since there are no HIZone users. Even if there is a spike in the resource block demand from the indoor users, the HAF continues to operate at P_{max} but the indoor users are served at a lower data rate. This may occur in three cases. First, when the building is occupied by NSG users only (refer to the second entry of Table 2) and say, everyone is simultaneously making a voice call or downloading a video. Since NSG users are not subscribed, the HAFs may be designed to either provide no service at all or provide best-effort service. Second case is when the building has only SG users. As mentioned in the system model, we assumed that the HAFs can handle all types of demands from indoor SG users. If however, the demand shoots up, it can be taken care of by load balancing between HAFs as has been done in [28, 29] to solve localized congestion problems or by device-to-device (D2D) communication where devices use lower resource blocks in direct communication [30]. The third case is when the indoor demand increases due to increase in demand of both SG and NSG users. This may also be solved by load balancing or D2D communication.

Algorithm 2 : BWA Algorithm

Input: ISR, initial R_S and R_{NS} for each HAF obtained from Algorithm 1
Let P' be the set of new transmit powers of HAFs
Let $OCCU$ be the set of HIZone users connected to the MBS
Output: Final R_S and R_{NS} for each HAF

if $ISR = NULL$ **then**
  for each HAF $f \in F$ **do**
    $R_S \leftarrow R_S + (R - R_S - R_{NS})$ {*The leftover resource blocks are given to the SG users*}
    Perform Bandwidth Allocation (BWA) for f
  end for
else{$ISR \neq NULL$}
  $OCCU \leftarrow NULL$
  for each HAF $f \in ISR$ **do**
    for each NSG user in f **do**
      if NSG user is in HIZone **then**
        $OCCU \leftarrow OCCU \cup NSG$
      end if
    end for
    for each SG user in f **do**
      if a SG user is in HIZone **then**
        $OCCU \leftarrow OCCU \cup SG$
      end if
    end for
  end for
  if $OCCU \neq NULL$ **then** {There is at least one HIZone user}
    Initiate PC *i.e.,* Eqn (19)) and obtain new power values, P' {*PC problem is solvable in polynomial time*}
    Compute new SINR REM and connectivity map
    for each HAF $f \in F$ **do**
      Compute R'_S and R'_{NS} {*with the new SINR values*}
    end for
  else
    $P' \leftarrow P_{max}$ {*New transmit power values remain same as maximum values*}
    $R'_S \leftarrow R_S$
    $R'_{NS} \leftarrow R_{NS}$ {*Resource block count is same as that obtained at P_{max}*}
  end if
  for each HAF $f \in F$ **do**
    if $R'_S + R'_{NS} \leq R$ **then**
      $R_S \leftarrow R'_S + (R - R'_S - R'_{NS})$ {*The leftover resource blocks are given to the SG users of f*}
      $R_{NS} \leftarrow R'_{NS}$
    else
      Compute resource block requirement at reduced transmit power by proportional split
      $R'_{S_{reduced}} \leftarrow \left\lfloor \frac{R'_S}{R'_S + R'_{NS}} R \right\rfloor$ {*Take floor so that at least one resource block is given to the NSG*}
      $R_S \leftarrow R'_{S_{reduced}}$
      $R_{NS} \leftarrow R - R_S$
      Perform Bandwidth Allocation (BWA) for f
    end if
  end for
end if
Goto EP Scheduler

Table 2: Truth table showing di erent combinations of user locations and need for Power Control at HAFs

	HIZone		Indoor	
	SG	NSG	SG	NSG
PC not required	0	0	0	0
	0	0	0	1
	0	0	1	0
	0	0	1	1
PC may be required	0	1	0	0
	0	1	0	1
	0	1	1	0
	0	1	1	1
	1	0	0	0
	1	0	0	1
	1	0	1	0
	1	0	1	1
	1	1	0	0
	1	1	0	1
	1	1	1	0
	1	1	1	1

Power control may be required however in the next 12 scenarios when the resource block requirement in a HAF exceeds R and the HAF tunes its transmit power in order to revoke the resource blocks initially set aside for the HIZone users and use them to serve the indoor users. This ensures that the HIZone users can get service at least from the MBS while the HAFs serve the indoor users. In worst cases, for example, where the indoor resource block requirement itself exceeds R, then, even after the power control and shifting of HIZone users to the MBS, the SG users will not achieve their baseline throughput even after the power control. Here, the HAFs may be allowed to operate at P_{max} by proportionally splitting the resource blocks between the SG and NSG if the SG get more resource blocks than they get when the HAFs operate at reduced transmit power.

5. Simulation Setup and Performance Results

The system model described in Section 3 is simulated using MATLAB. First, we describe the simulation parameters used for setting up the HetNet environment. Then we present the performance of proposed SOPC mechanism under di erent scenarios.

5.1. Simulation Setup

The HetNet topology considered in our simulation experiment consists of a single MBS and several HAFs that are deployed inside a building. Dimensions of the building and other simulation parameters are listed out in Table 3. The lower leftmost indoor sub-region of the building is at a distance of 350m from the MBS. The HIZone around the building is chosen to be 10 m wide. The SG and NSG users are placed statically in and around the building in arbitrary manner. The power control optimization problem (refer Eqn (19)) is solved using the GAMS CPLEX solver. For simplicity, we have considered the baseline throughput requirements to be same for all the users in SG and NSG, *i.e.*, 400 Kbps for per SG user and 200 Kbps per NSG user. All the users are assumed to have infinite tra c demand (*i.e.*, saturated scenario) and the HAFs with R resource blocks try to guarantee at least the above mentioned data rates to SG and NSG users in the network. For the user locations in indoor and HIZone sub-regions, we have considered one user in each sub-region.

Table 3: Simulation Parameters

Parameter	Value
Building dimensions	$48m \times 48m \times 3m$
Number of rooms	16
Room dimensions	$12m \times 12m \times 3m$
Indoor sub-region dimensions	$4m \times 4m \times 3m$
Number of indoor sub-regions	144
HIZone width	10 m
Number of HIZone sub-regions	52
Number of floors	One
$SINR^{P}_{Th}$	-2 dB
$SINR^{PC}_{Th}$	-4 dB
Floor and wall loss	8 and 10 dB
HAF transmit power (P_{max})	23 dBm
Macro transmit power (P_M)	46 dBm
MBS height	30m
Transmission time interval (TTI)	1 ms
Simulation time (T)	100s
Number of RBs (R)	25
Baseline throughput of SG user	400 Kbps
Baseline throughput of NSG user	200 Kbps

5.2. Performance Analysis

We provide a detailed assessment of the SOPC mechanism and how it handles different situations with the help of two scenarios. Initially, the HAF co-ordinates are obtained from OPF for the selected building layout. Next, the user occupant scenarios are selected from Table 2. At first, a simple scenario is considered where the SG users are indoors and the NSG users are in the HIZone (seventh entry in Table 2). Another scenario is where the SG and NSG users occupy both indoor and HIZone (the last entry in Table 2). Our objective is to study how the SOPC works in different scenarios. We discuss performance of OPF in comparison with non-optimal and intuitive placement of HAFs particularly after the SOPC is applied. The fate of the HIZone users who connect to the MBS after the power control is also discussed.

5.2.1. Femto co-ordinates from OPF

The number of HAFs and their co-ordinates inside the building are determined by the OPF model (refer Eqn (3)) solved using GAMS CPLEX solver [31]. CPLEX is a mathematical optimization software accessible through high-level modeling systems like GAMS. The GAMS CPLEX is capable of modeling and solving linear, non-linear and mixed-integer optimization problems. All the HAFs are placed on the ceiling of the building. The minimum number of HAFs required and their optimal locations inside the building when all the HAFs are operating at P_{max} as obtained from the OPF model are depicted in Fig. 5. The dark red colored indoor sub-regions which are encircled and marked are the sub-regions where the HAFs are positioned on the ceiling. The co-ordinates of the HAFs are the centers of the encircled sub-regions. This placement ensures that every indoor and HIZone sub-region gets SINR above $SINR^{P}_{Th}$. As can be seen from the figure, the weakest signal received by a sub-region is above -2 dB. Here, sub-regions, like sub-regions at co-ordinates (3,2) and (2,7) named $SR_{(3,2)}$ and $SR_{(2,7)}$, are lighter than the others like $SR_{(12,2)}$, $SR_{(8,8)}$, $SR_{(4,13)}$ and $SR_{(13,12)}$ because these sub-regions with lighter shade experience greater co-tier interference than the others.

The connectivity map in Fig. 6 shows the coverage area of each HAF inside the building and in the HIZone when operated at P_{max}. The sub-regions in the cell edge of the HAFs are the ones which receive lower SINR values. This occurrence can be observed by comparing an indoor sub-region $SR_{(2,8)}$ and HIZone sub-regions $SR_{(2,14)}$ and $SR_{(5,14)}$ in Fig. 5. Sub-regions which receive direct interference from the MBS *i.e.*, those situated outside the building have lower SINR values than those inside the building. This is illustrated as follows. The signal from HAF_3 has to cross just one wall to reach the sub-region $SR_{(2,8)}$. The same holds for the signal coming from HAF_6 to the sub-regions $SR_{(2,14)}$ and $SR_{(5,14)}$. However, the cross-tier interference from the MBS to the sub-region $SR_{(2,8)}$ is lower when compared to the sub-regions $SR_{(2,14)}$ and $SR_{(5,14)}$. This is because the signal from the MBS has to penetrate through the building wall to reach sub-region $SR_{(2,8)}$. The sub-region $SR_{(4,13)}$, above which HAF_6 is located is darker compared to $SR_{(2,7)}$ above which HAF_3 is located, that is, sub-regions close to HAF_6 experience lower co-tier interference than the ones near to HAF_3. But, still, the SINR of $SR_{(2,8)}$ is higher than that of both $SR_{(2,14)}$ and $SR_{(5,14)}$. This shows that the cross-tier interference is dominant over co-tier interference outside the building yet, the $SINR^P_{Th}$ is maintained in indoor and HIZone which reinforces the need for using OPF model for placement of HAFs.

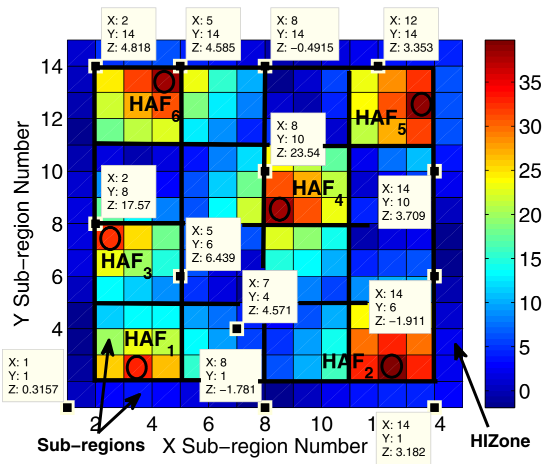

Figure 5: REM of sub-regions for six optimally placed HAFs at P_{max}

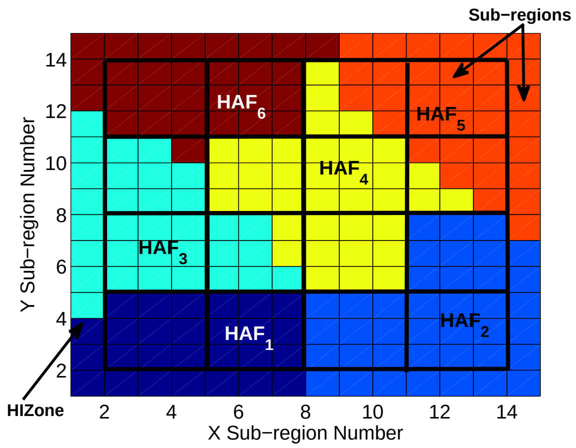

Figure 6: Connectivity of sub-regions to six optimally placed HAFs, where same colored sub-regions are connected to a single HAF, HAF_i

The importance of OPF model gets highlighted when we observe how intuitive centre-placement fares. In the absence of OPF model, the problem is how to decide number of HAFs required to ensure connectivity throughout the building. For example, initially 5 HAFs are deployed in the building (refer Figs. 7 and 8) by some rough calculation. Only after the users actually start accessing the HAFs, the coverage holes, if any, are discovered. Hence, an extra HAF may be added to address the issue of very bad or no signal strength in some parts of the building (refer Figs. 9 and 10). This may continue till an acceptable coverage is obtained. A situation may also arise where the problem of coverage holes is never solved because increasing HAFs unconditionally increases co-tier interference as in Figs. 11 and 12. This requires shifting locations of already deployed HAFs in an iterative manner till proper coverage is achieved. But frequent changes to HAF placement in part defeats the purpose of small cells. From Figs. 7, 9 and 11, it can be observed that there are sub-regions inside the building which receive low SINR due to cross-tier interference. As a result, a user located there will require higher number of resource blocks to achieve the baseline data rate requirement. Such sub-regions occur at HAF cell edges which are not considered while deploying the HAFs. HAFs deployed non-optimally are mostly intuition based and therefore only users at close vicinity to the HAFs enjoy high-speed data rates. In non-optimal HAF placement scenario, SINR changes very rapidly across sub-regions once SOPC is applied. We present the e□ect of SOPC in non-optimal HAF placement in the following section.

5.2.2. Issues with non-optimal HAF placement

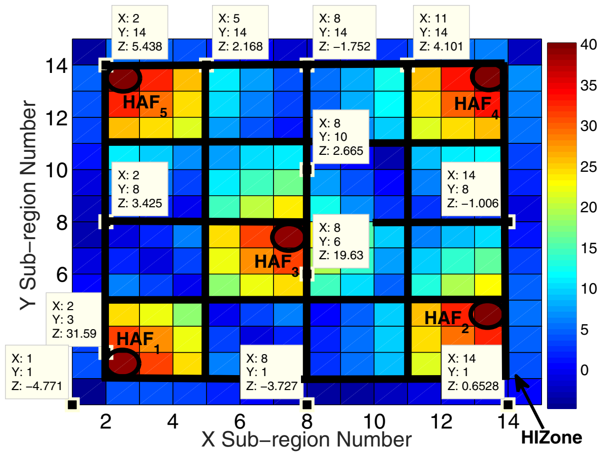

Figure 7: REM of sub-regions for five non-optimally placed HAFs at P_{max}

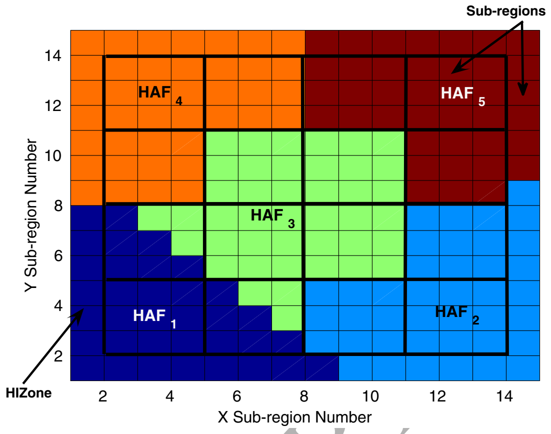

Figure 8: Connectivity of sub-regions to five non-optimally HAFs, where same colored sub-regions are connected to a single HAF, HAF_i

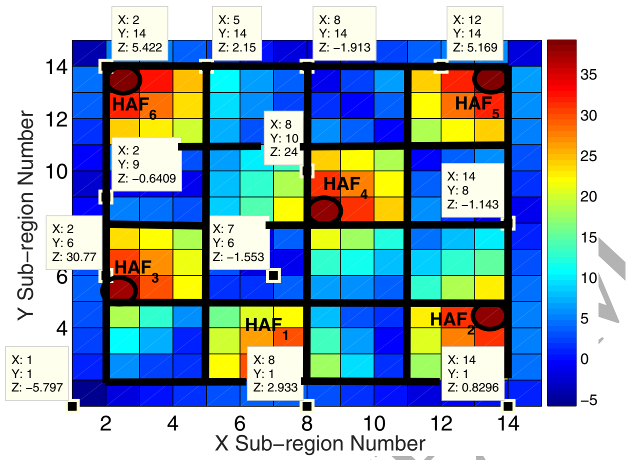

Figure 9: REM of sub-regions for six non-optimally placed HAFs at P_{max}

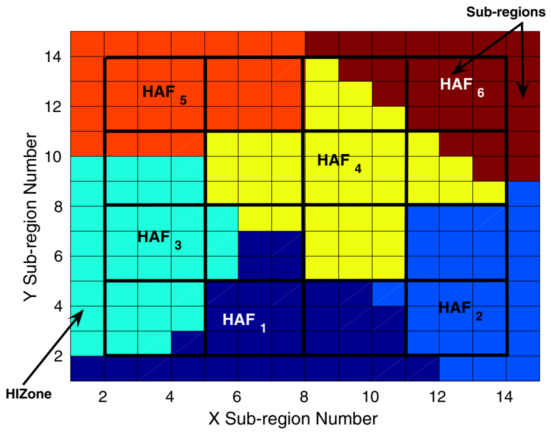

Figure 10: Connectivity of sub-regions to six non-optimally HAFs, where same colored sub-regions are connected to a single HAF, HAF_i

This section deals with how SOPC works for non-optimal placement of HAFs considered in Figs. 7, 9 and 11. The analysis is done for 41 indoor SG users, 10 indoor NSG users, 5 HIZone SG users and 17 HIZone NSG users. The user positions can be referred in Fig. 13 which has the same user occupancy for six optimally placed HAFs. Tables 4, 5 and 6 show the resource block requirement of SG and NSG users before and after the power control. The resource block requirement shown in the tables is averaged over a time interval T where 25 resource blocks are available in each TTI (R = 25). One thing that stands out in all the three tables is the extremely high resource block requirement of some of the HAFs which is reaching the order of a few thousands in one TTI while each of the HAFs have only 25 resource blocks. It can be observed from Figs. 14, 15 and 16, SINR changes very rapidly from one sub-region to another with quite a few indoor sub-regions below -2dB. In the indoor sub-region $SR_{(9,2)}$ for the five non-optimally placed HAFs (refer Fig. 14), it receives SINR lower than the set threshold of -4 dB. This implies that merely applying SOPC without optimal HAF placement (OPF model) may not always give best results. Though -4 dB is taken as the SINR threshold for the power control, it is observed that indoor sub-regions have SINR well above -2 dB even after the power control if the OPF model is applied at the deployment stage for choosing locations for HAF placement. If the indoor SINR itself drops to such low levels, changing very rapidly within a room (refer sub-regions $SR_{(5,5)}$, $SR_{(6,6)}$

Table 4: Resource block requirements of five HAFs (non-optimal placement) before and after the power control

# SG users, Resource block demand R_S before power control	**# SG users, Resource block demand R_S after power control**	**# NSG users, Resource block demand R_{NS} before power control**	**# NSG users, Resource block demand R_{NS} after power control**	**New transmit powers of HAFs**
8, 13	7, 8019	4, 2009	0, 0	0.1025W
8, 37	5, 7	8, 17	2, 16	0.0128W
13, 44	13, 34	1, 2	4, 4	0.2W
7, 13	7, 44	5, 11	6, 4013	0.2W
10, 33	10, 49	9, 311	6, 2038	0.1036W

The resource block demand shown is for 1 TTI averaged over $T = 100sec$

Table 5: Resource block requirements of 6 HAFs (non-optimal placement) before and after the power control

# SG users, Resource block demand R_S before power control	**# SG users, Resource block demand R_S after power control**	**# NSG users, Resource block demand R_{NS} before power control**	**# NSG users, Resource block demand R_{NS} after power control**	**New transmit powers of HAFs**
5, 24	3, 31	5, 2010	3, 4009	0.0875W
7, 17	5, 4018	8, 20	3, 6013	0.0333W
10, 25	10, 20	2, 11	0, 0	0.1180W
9, 14	12, 30	1, 4	3, 12	0.2W
7, 21	4, 4005	4, 11	0, 0	0.0213W
8, 28	7, 61	7, 18	1, 4022	0.0374W

The resource block demand shown is for 1 TTI averaged over $T = 100sec$

Table 6: Resource block requirements of 7 HAFs (non-optimal placement) before and after the power control

# SG users, Resource block demand R_S before power control	**# SG users, Resource block demand R_S after power control**	**# NSG users, Resource block demand R_{NS} before power control**	**# NSG users, Resource block demand R_{NS} after power control**	**New transmit powers of HAFs**
5, 23	2, 23	5, 2010	2, 2005	0.0829W
7, 16	5, 4019	7, 20	2, 4007	0.0321W
8, 20	9, 22	0, 0	0, 0	0.2W
8, 14	8, 13	0, 0	2, 10	0.2W
8, 17	8, 17	5, 15	5, 2015	0.2W
6, 9	5, 38	4, 12	0, 0	0.0238W
4, 5	4, 4	6, 15	7, 15	0.2W

The resource block demand is shown per TTI averaged over $T = 100sec$

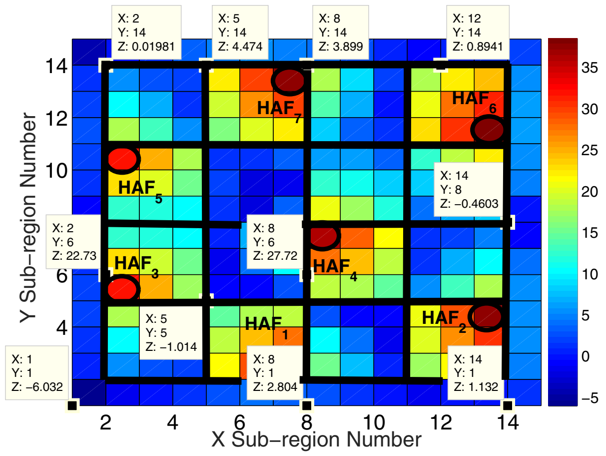

Figure 11: REM of sub-regions for seven non-optimally placed HAFs at P_{max}

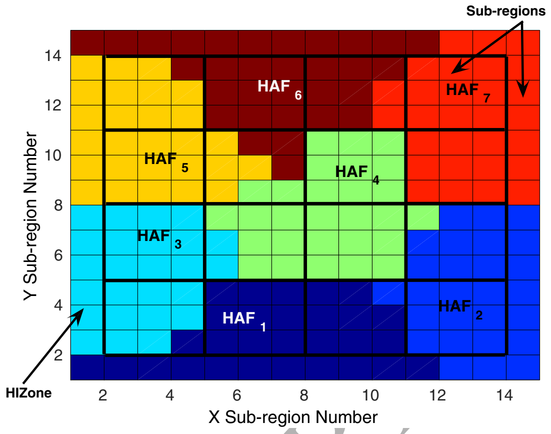

Figure 12: Connectivity of sub-regions to seven non-optimally HAFs, where same colored sub-regions are connected to a single HAF, HAF_i

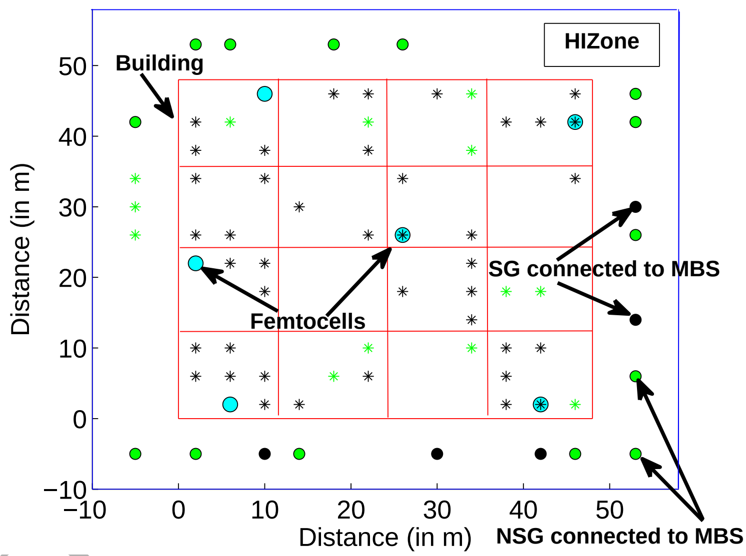

Figure 13: Scenario II: Building with SG and NSG users at both indoors and HIZone

and $SR_{(7,7)}$ in Fig 15), the resource block requirement shoots up.

The reason for high demand of resource blocks also becomes apparent on closer inspection of the connectivity maps (refer Figs. 17, 18 and 19) and the building layouts (refer Figs. 20, 21 and 22). Once the power control takes place, the SINR in the HIZone becomes very low. If the SINR drops below -4 dB, the users in such HIZone sub-regions get connected to the MBS. In the connectivity maps, the HIZone sub-regions occupied by the o□oaded users are denoted in brown color. Those HIZone users which are still connected to the HAFs receive very low SINR (refer HIZone along $Y = 14$ axis in Fig. 14 with five HAFs) and high cross-tier interference from the MBS. Such users are therefore in need of a large number of resource blocks to satisfy their baseline data rate requirement. Even for the non-optimal placement of seven HAFs, the HAFs require a large number of resource blocks to satisfy the users demand. Moreover, for the scenarios with five and seven HAFs, the HAFs are not only operating at reduced transmit power levels but they are also serving almost 40% of the HIZone users along with the indoor users. Serving HIZone

HAF_4. In order to serve these new users, the HAF experience an insuﬃciency in resource blocks and is therefore unable to maintain the baseline throughput for the users connected to it. Henceforth, it may be possible that a HAF initially having suﬃcient resource blocks before the power control has insuﬃcient resource blocks after it. This may be because the HAF now has to accommodate some cell edge users of neighboring HAFs or because the HAF which reduced its power has all or most of its users near its cell edge. If in an extreme case we find that even after the power control the insuﬃciency in most of the HAFs is increasing, we may allow the HAFs to operate at P_{max} if that provides the SG users with greater number of resource blocks.

5.2.11. Analysis of throughput of Macro users

In the previous sections we have shown the fate of the users connected to HAFs. Here, we provide an analysis of the throughput of the Macro users, that is, any SG or NSG user connected to the MBS from outside the building (including the HIZone). The number of Macro users in the system having a video session (which requires a baseline throughput of 50 Kbps) is varied from 10 to 100. The performance of Macro users making a voice call (which requires a baseline throughput of 10 kbps) is also captured for a range of 10 to 300 users. The baseline throughputs for video and audio sessions have been set as recommended in [33]. The average throughput curves obtained are for the following four cases:

- $Case_1$: When the HIZone users are connected to the MBS and there are no HAFs. All the users in the system connect to the MBS.
- $Case_2$: When the HIZone users are connected to HAFs operating at P_{max} (fixed transmit power). The MBS provides service to all the outdoor users in the cell except those in the HIZone and inside the building.
- $Case_3$: When the HIZone users may/ may not connect to HAFs (transmit power is controlled using SOPC mechanism). Here the MBS may also serve some users in the HIZone, that is, those HIZone users who cannot be served by the nearest HAF.
- $Case_4$: When the HIZone users connect to the MBS with the HAFs operating at P_{max}. The HAFs act as closed access points for the HIZone users.
- $Case_5$: When time domain eICIC technique based on Almost Blank Subframe (Almost Blank Subframe (ABS)) is used. Here, the HAFs mute their transmissions for 1/8 of each time interval, T (simulation time), so that the MBS can schedule the HIZone users experiencing strong interference from HAFs.

In Fig. 33, $Case_2$ apparently seems the best choice as all the HIZone users are always served by the HAFs which transmit at P_{max} such that the number of users that the MBS has to serve goes down and their throughput is boosted. A point worth noting is that though the Macro users enjoy high throughput values, the throughput of the HIZone users connected to the HAFs degrades since, the baseline data requirements are not met. The performance of the Macro users under the proposed SOPC mechanism is recorded in $Case_3$. The curve in $Case_4$ also shows a better performance than the SOPC mechanism. But, in $Case_4$ there may be few HIZone users whose SINR does not cross the $SINR_{Th}^{PC}$ resulting in zero throughput. Such HIZone users get no service from MBS due to high cross-tier interference from the HAFs operating at P_{max}. Almost 40% of the sub-regions cannot connect to the MBS due to the received SINR being lower than $SINR_{Th}$.

$Case_3$ provides a trade-oﬀ between the $Case_4$ and $Case_2$. In $Case_3$, if all the HAFs are able to meet the minimum user data rate, then the MBS does not have to serve the HIZone users. If, however, any HAF is unable to meet the minimum data rate, the power control allows the HIZone users of these HAFs to be served by the MBS. As a result, all users are served at all times without greatly aﬀecting any particular group of users. The curve obtained for $Case_1$ is lower than the one obtained from the SOPC mechanism, $Case_3$, because, in the former, the MBS has to serve all the users irrespective of their locations. $Case_3$ improves over $Case_1$ by almost 30% when there are 50 Macro users and 61% in case of 100 Macro users in the system.

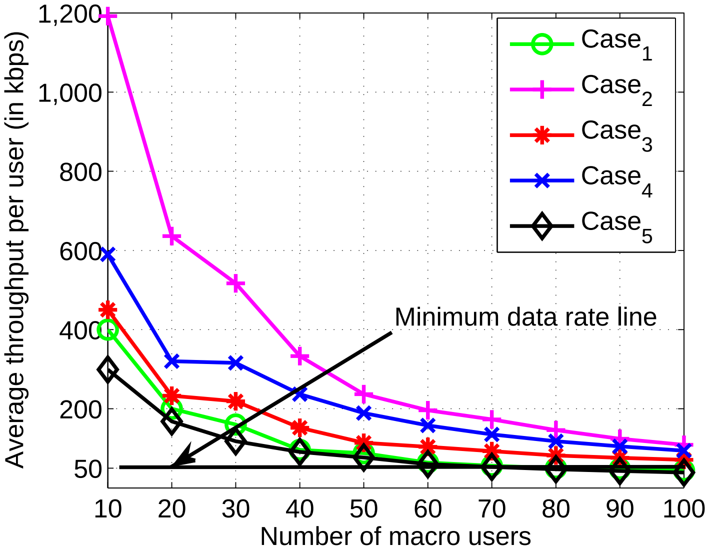

Figure 33: Average throughput of users connected to the MBS for video sessions

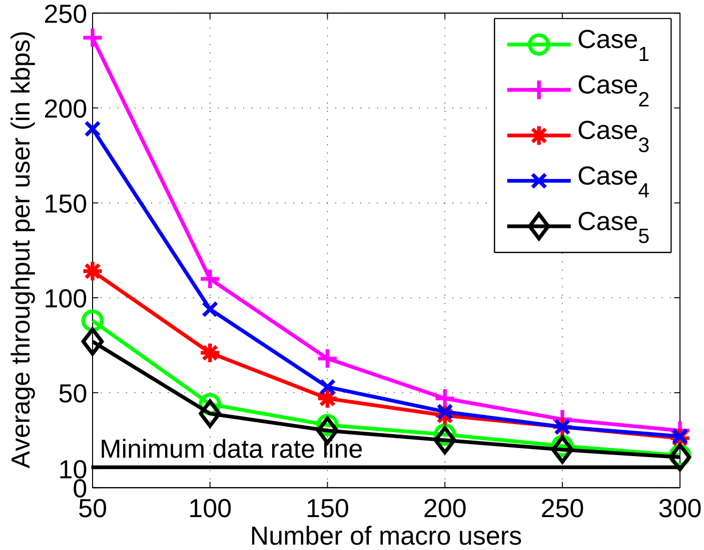

Figure 34: Average throughput of users connected to the MBS for voice sessions

The curve in $Case_5$ shows the average throughput per user when eICIC is used. Our SOPC mechanism performs better than eICIC o ering a gain of almost 48% and 82% in case of 50 and 100 Macro users, respectively. The curve obtained in the SOPC mechanism provides a per user average throughput greater than 50 Kbps with 100 Macro users and can therefore support flows requiring higher guaranteed data rates. The curves become flatter and come closer to each other as the number of users increase because the user density served by the Macro increases at a much faster rate than the user density in the HIZone.

Table 10: Resource block requirements of 6 HAFs before and after the power control

# SG users, Resource block demand R_S before power control	# SG users, Resource block demand R_S after power control	# NSG users, Resource block demand R_{NS} before power control	# NSG users, Resource block demand R_{NS} after power control	New transmit powers of HAFs
9, 25	8, 22	5, 10	2, 3	0.0838W
8, 37	5, 8	7, 10	3, 8	0.0321W
6, 16	7, 16	3, 9	3, 6	0.2W
9, 21	11, 37	0, 0	2, 5	0.2W
7, 28	5, 12	5, 10	1, 3	0.0435W
7, 27	5, 23	7, 12	2, 4	0.0243W

The resource block demand shown is for 1 TTI averaged over $T = 100sec$, baseline throughput of SG is 600 Kbps and NSG is 150 Kbps

As voice calls can be made with low data rate requirements, in Fig. 34 we vary the number of Macro users till 300. The average throughput per user obtained in our SOPC mechanism in $Case_3$ is at an acceptable data rate of 26 Kbps, which is almost 62% greater than that obtained in eICIC mechanism in $Case_5$.

5.2.12. E ect of network parameters

In this section, we explore the performance of six HAFs which are placed optimally when they are provided with greater number of resource blocks and baseline throughputs of the users are increased. The user locations are kept same as before (Scenario II).

If the baseline throughput of the SG is increased by keeping the number of resource blocks available as constant, then the SOPC works well only till a certain data rate. As the baseline throughput increases, more resource blocks are required to fulfil the resource demands. We ran simulations by increasing the baseline throughput of SG users from 400 Kbps to 600 Kbps. As expected, the resource demand for maintaining the new baseline throughput increased (refer Table 10). Fig. 37 shows the average throughput of users where the baseline throughput of SG users is 600 Kbps and that of NSG users is 150 Kbps. It can be observed that though SOPC brings down the resource block demand, there is a trade-o between transmit power and resource block demand. Even if the SINR threshold is maintained after the power control, the demand for resource blocks by users does increase due to low transmit power. For example, for HAF_4 the new demand increases to 39 resource blocks per TTI against the available 25 because of the migration of 2 edge users of SG and NSG groups each. Refer Fig. 35 which gives the user locations and the building layout. The o oaded users include 5 SG and 14 NSG users of the HIZone. The connectivity plot in Fig. 36 gives an idea on the connectivity of users so that the number of cell edge users each HAF supports can be visualized. As the number of cell edge users increases, the resource block demand also increases after the power control. The baseline throughput of the NSG users is reduced to 150 Kbps because SOPC could not guarantee high baseline throughput for both SG and NSG with only 25 resource blocks even after the power control. For 25 resource blocks, HAFs can support a maximum data rate of 600 Kbps for SG users when the total SG users are about 40. Lesser number of users will allow an HAF to ensure higher average throughput to its users.

Since increasing the baseline throughput alone does not guarantee high throughputs, the number of available resource blocks (R) in each HAF is increased from 25 to 50. Fig. 38 shows the average throughput per user when 50 resource blocks are available. The power control is not required because as seen in Table 11, the total demand for resource blocks in each HAF is less than 50, *i.e.*,, $R_S + R_{NS} \leq 50$. Thus all users remain connected to the HAFs and

Table 11: Resource block requirements of 6 HAFs when $R = 50$

# SG users, Resource block demand R_S before power control	# NSG users, Resource block demand R_{NS} before power control	Total demand
9, 17	5, 13	30
8, 25	7, 13	38
6, 11	3, 12	23
9, 14	0, 0	14
7, 19	5, 13	32
7, 18	7, 16	34

The resource block demand shown is for 1 TTI averaged over $T = 100sec$

Table 12: Resource block requirements of 6 HAFs before and after the power control

# SG users, Resource block demand R_S before power control	# NSG users, Resource block demand R_{NS} before power control	Total demand
9, 17	5, 13	30
8, 25	7, 13	38
6, 11	3, 12	23
9, 14	0, 0	14
7, 19	5, 13	32
7, 18	7, 16	34

The resource block demand shown is for 1 TTI averaged over $T = 100sec$, baseline throughput of SG is 600 Kbps and NSG is 200 Kbps

Table 13: Resource block requirements of 6 HAFs before and after the power control

# SG users, Resource block demand R_S before power control	# SG users, Resource block demand R_S after power control	# NSG users, Resource block demand R_{NS} before power control	# NSG users, Resource block demand R_{NS} after power control	New transmit powers of HAFs
9, 25	9, 34	5, 15	5, 27	0.0854W
8, 37	5, 8	7, 15	3, 18	0.0262W
6, 16	6, 16	3, 15	3, 13	0.2W
9, 21	9, 18	0, 0	1, 5	0.2W
7, 28	7, 28	5, 15	5, 13	0.2W
7, 27	7, 27	7, 19	7, 19	0.2W

The resource block demand shown is for 1 TTI averaged over $T = 100sec$, baseline throughput of SG is 600 Kbps and NSG is 240 Kbps

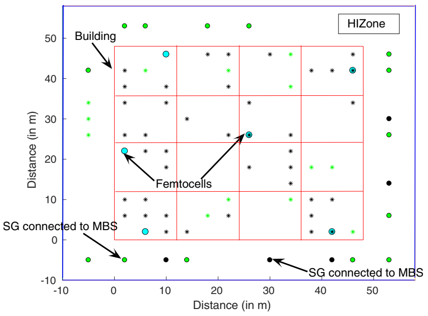

Figure 35: User connectivity to MBS and HAFs after the power control

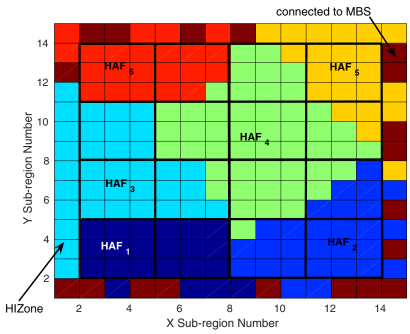

Figure 36: Sub-region connectivity to HAFs after the power control

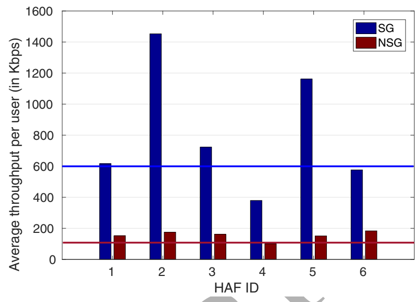

Figure 37: Average throughput per user in each HAF after the power control in SOPC mechanism

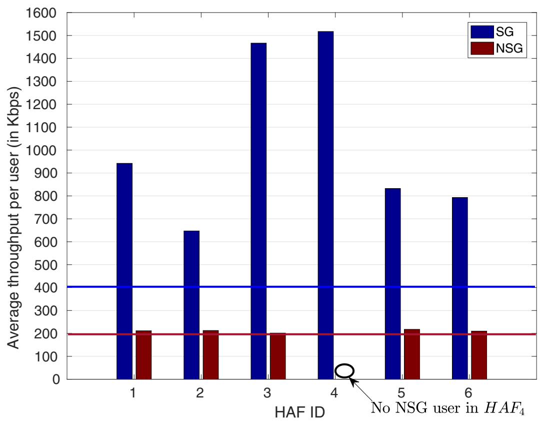

Figure 38: Average throughput per user in each HAF when baseline throughput of SG is 400 Kbps and NSG is 200 Kbps and $R = 50$

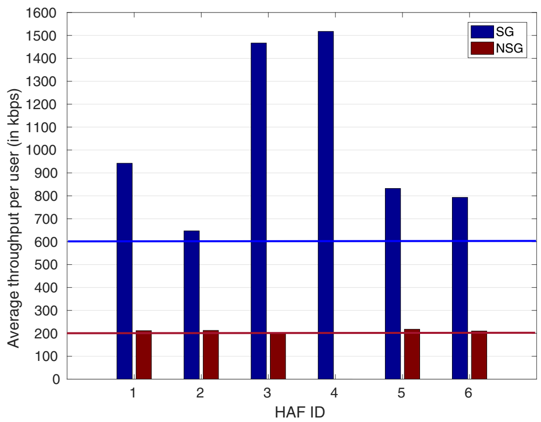

Figure 39: Average throughput per user in each HAF when baseline throughput of SG is 600 Kbps and NSG is 200 Kbps

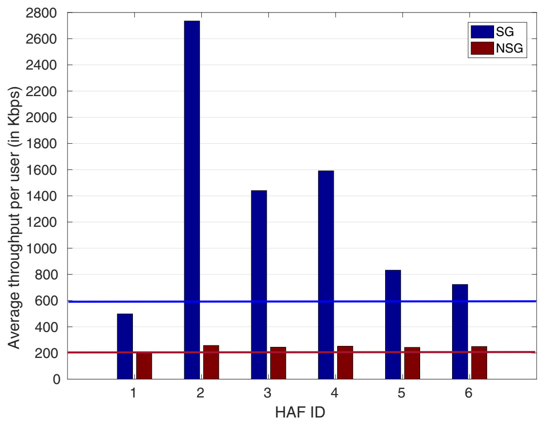

Figure 40: Average throughput per user in each HAF when baseline throughput of SG is 600 Kbps and NSG is 240 Kbps

all HAFs operate at P_{max} transmit power.

We now estimate the maximum baseline throughput that can be guaranteed to the users with 50 resource blocks. At a baseline throughput of 600 Kbps for the SG users and 240 Kbps for the NSG users, the HAFs cannot always guarantee the baseline throughputs. However, if the baseline throughput of the NSG is fixed at 200 Kbps, then baseline throughputs are maintained for all users. Refer Figs. 39 and 40 which show the average throughput for each user for NSG baseline throughputs 240 Kbps and 200 Kbps, respectively. From Table 12, it can be observed that the resource demand for the SG before the power control is within 50 resource blocks per TTI. As the baseline throughput of the NSG is increased to 240 Kbps, the resource demand for HAF_2 crosses 50 resource blocks per TTI (refer Table 13). The resource block requirement shoots up because of the HAFs now try to guarantee the baseline throughput for all NSG users connected to it.

When the baseline throughput of the SG users is increased to 800 Kbps, the NSG users can be guaranteed a baseline throughput of only 24 Kbps. Beyond that the resource demand of HAFs shoots up and SOPC does not help much because at low transmit power, the demand of the indoor cell edge users increases which cannot be satisfied any more.

6. Conclusions

In this work, we motivated hybrid access mode in Femtos so that non-subscribed users can get certain minimum guaranteed service from HAFs when they are inside a building or in the HIZone of the building. We proposed an optimal HAF placement model and a sub-optimal power control (SOPC) mechanism that adjust transmit power of the HAFs whenever the available resource blocks are insu□cient to serve all the connected Femto users. Simulation results showed that the power control and EP scheduler improved the throughput of the subscribed users. The proposed SOPC mechanism provides a gain of almost 82% over the eICIC mechanism when there are 100 Macro users in a LTE HetNet system with one Macro cell and several indoor Femtos.

References

[1] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, M. C. Reed, Femtocells: Past, present, and future, Selected Areas in Communications, IEEE Journal on 30 (3) (2012) 497–508.
[2] H.-S. Jo, P. Xia, J. G. Andrews, Open, closed, and shared access femtocells in the downlink, EURASIP Journal on Wireless Communications and Networking 2012 (1) (2012) 1–16.
[3] G. De La Roche, A. Valcarce, D. López-Pérez, J. Zhang, Access control mechanisms for femtocells, Communications Magazine, IEEE 48 (1) (2010) 33–39.
[4] B. Niu, V. W. Wong, The design of resource management mechanism with hybrid access in a macro-femto system, in: Globecom Workshops (GC Wkshps), 2013 IEEE, IEEE, 2013, pp. 4679–4685.
[5] N. Zhang, N. Cheng, A. T. Gamage, K. Zhang, J. W. Mark, X. Shen, Cloud assisted hetnets toward 5g wireless networks, IEEE Communications Magazine 53 (6) (2015) 59–65.
[6] V. Sathya, A. Ramamurthy, B. R. Tamma, On placement and dynamic power control of femtocells in lte hetnets, in: Global Communications Conference (GLOBECOM), 2014 IEEE, IEEE, 2014, pp. 4394–4399.
[7] L. T. Ho, H. Claussen, E□ects of user-deployed, co-channel femtocells on the call drop probability in a residential scenario, in: Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on, IEEE, 2007, pp. 1–5.
[8] J. Espino, J. Markendahl, Analysis of macroâĂŤfemtocell interference and implications for spectrum allocation, in: Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on, IEEE, 2009, pp. 2208–2212.
[9] S. A. Saad, M. Ismail, R. Nordin, A survey on power control techniques in femtocell networks., JCM 8 (12) (2013) 845–854.
[10] L. Zhang, T. Jiang, K. Luo, Dynamic spectrum allocation for the downlink of ofdma-based hybrid-access cognitive femtocell networks, IEEE Transactions on Vehicular Technology 65 (3) (2016) 1772–1781.
[11] Y. L. Lee, J. Loo, T. C. Chuah, Dynamic resource management for lte-based hybrid access femtocell systems, IEEE Systems Journal.
[12] F. Capozzi, G. Piro, L. A. Grieco, G. Boggia, P. Camarda, Downlink packet scheduling in lte cellular networks: Key design issues and a survey, Communications Surveys & Tutorials, IEEE 15 (2) (2013) 678–700.
[13] Y. Bai, L. Chen, Hybrid spectrum arrangement and interference mitigation for coexistence between lte macrocellular and femtocell networks, EURASIP Journal on Wireless Communications and Networking 2013 (1) (2013) 1–15.
[14] X. Chu, Y. Wu, L. Benmesbah, W.-K. Ling, Resource allocation in hybrid macro/femto networks, in: Wireless Communications and Networking Conference Workshops (WCNCW), 2010 IEEE, IEEE, 2010, pp. 1–5.
[15] 3GPP, "3GPP TSGSA: Feasibilty Study for Proximity Services (ProSe) (Release 12), 3GPP, Tech.Rep. TR 22.803. Aug 2013.
[16] Y.-Y. Shih, A.-C. Pang, M.-H. Tsai, C.-H. Chai, A rewarding framework for network resource sharing in co-channel hybrid access femtocell networks, IEEE Transactions on Computers 64 (11) (2015) 3079–3090.

[17] Y. Yi, J. Zhang, Q. Zhang, T. Jiang, Spectrum leasing to femto service provider with hybrid access, in: INFOCOM, 2012 Proceedings IEEE, IEEE, 2012, pp. 1215–1223.
[18] Y. Chen, J. Zhang, Q. Zhang, J. Jia, A reverse auction framework for access permission transaction to promote hybrid access in femtocell network, in: INFOCOM, 2012 Proceedings IEEE, IEEE, 2012, pp. 2761–2765.
[19] R. Kurda, L. Boukhatem, M. Kaneko, Femtocell power control methods based on usersâĂŹ context information in two-tier heterogeneous networks, EURASIP Journal on Wireless Communications and Networking 2015 (1) (2015) 1–17.
[20] S. Fischer, Observed time di erence of arrival (otdoa) positioning in 3gpp lte, Qualcomm White Pap.
[21] C. Gentner, E. Muñoz, M. Khider, E. Staudinger, S. Sand, A. Dammann, Particle filter based positioning with 3gpp-lte in indoor environments, in: Position Location and Navigation Symposium (PLANS), 2012 IEEE/ION, IEEE, 2012, pp. 301–308.
[22] I. Sharp, K. Yu, Enhanced least-squares positioning algorithm for indoor positioning, Mobile Computing, IEEE Transactions on 12 (8) (2013) 1640–1650.
[23] K. Han, Y. Choi, D. Kim, M. Na, S. Choi, K. Han, Optimization of femtocell network configuration under interference constraints, in: Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, 2009. WiOPT 2009. 7th International Symposium on, IEEE, 2009, pp. 1–7.
[24] A. Hameed, A. Oudah, Interference in wireless networks: Causes, analyses and practical mitigating techniques, Modern Applied Science 8 (5) (2014) p56.
[25] 3GPP, "3GPP: Technical Specification Group Radio Access Network: E-UTRA Physical Layer Procedures (Release 9), 3GPP, Tech.Rep. TS 36.213. Aug 2010.
[26] P. Belotti, C. Kirches, S. Ley er, J. Linderoth, J. Luedtke, A. Mahajan, Mixed-integer nonlinear optimization, Acta Numerica 22 (2013) 1–131.
[27] N. Karmarkar, A new polynomial-time algorithm for linear programming, in: Proceedings of the sixteenth annual ACM symposium on Theory of computing, ACM, 1984, pp. 302–311.
[28] J. M. R. Avilés, S. Luna-Ramirez, M. Toril, F. Ruiz, I. De la Bandera-Cascales, P. Munoz-Luengo, Analysis of load sharing techniques in enterprise lte femtocells, in: Wireless Advanced (WiAd), 2011, IEEE, 2011, pp. 195–200.
[29] Z. Liu, P. Hong, K. Xue, M. Peng, Conflict avoidance between mobility robustness optimization and mobility load balancing, in: Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE, IEEE, 2010, pp. 1–5.
[30] P. Phunchongharn, E. Hossain, D. I. Kim, Resource allocation for device-to-device communications underlaying lte-advanced networks, IEEE Wireless Communications 20 (4) (2013) 91–100.
[31] GAMS, http://www.gams.com/.
[32] R. Jain, D. Chiu, W. Hawe, A quantitative measure of fairness and discrimination for resource allocation in shared computer systems, CoRR cs.NI/9809099.
[33] Live dynamic streaming, http://www.adobe.com/devnet/adobe-media-server/articles/dynstream_live.html (2009).