A novel cluster based resource sharing model for femtocell networks

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ABSTRACT

Femtocells have been deployed to enhance indoor coverage, improve the system capacity of cellular networks, and increase the spectrum efficiency by means of full subcarrier reuse among macrocell and femtocells. Nevertheless, the introduction of hybrid access mode imposes new challenges for the resource sharing model in the femtocell networks such as: (1) granting access to public users while guaranteeing QoS of subscriber transmissions, (2) trade-off between level of offloaded traffic from macrocell and bandwidth allocated to femto-tier and (3) appropriate power settings that finds a compromise between the overall system performance and the bandwidth allocated to femtocells. In this paper, we propose a novel cluster formation technique together with a resource sharing model based on Particle swarm optimization technique. Our algorithm aims at maximization of the network throughput and determines the serving base station and the amount of resources per user taking into account user locations, demands, femtocell proximity and traffic load in existing clusters. Simulations are conducted to show the performance of the proposed model contrasted with a benchmark model based on known Weighted Water Filling resource allocation algorithm and known cluster formation technique.

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1. Introduction

Femtocells have been incorporated to traditional wireless networks as a promising solution to increase their current capacity and to improve indoor coverage without any investment in the cellular infrastructure. A femtocell (FC) is established by a low-cost end-user base station (BS) with short-range that is connected to the cellular network through a fixed public broadband backhaul. FC deployment brings several benefits such as extended coverage, offloading traffic from macrocell, enhanced spectral efficiency and prolonged battery life of the mobile equipment. Despite all these benefits, there are still some challenges that need to be addressed such as resource management, interference mitigation, mobility management, access control and time synchronization [1].

Since femtocells can operate in the same licensed spectrum as the overlaid macrocell, the spectrum allocation as well as the interference mitigation have attracted attention of many researchers. The spectrum allocation can be classified into two categories: spectrum partitioning or spectrum sharing. In the spectrum partition-

ing approach, dedicated number of subcarriers is assigned to each tier [2] while in the spectrum sharing approach, subcarriers are shared among the two tiers [3]. The former approach has been used for non-dense FC deployment whereas the latter is recommended for dense deployments but requires interference management schemes to uphold Quality of Service (QoS) of transmissions and to enhance the network throughput. In this paper we consider the spectrum partitioning approach between the two tiers. Also we focus on resource allocation for the downlink (DL) transmission that is usually the bottleneck of the cellular systems.

There are several research works related to spectrum partitioning that are focused on different issues, such as: power control [4,5], fractional frequency reuse [6], soft frequency reuse [7], full frequency reuse in femto tier [8], improving the spatial reuse [9] and the use of cognitive radios [10]. Another group of studies is focused on determining interference models to represent the femtocell interference signal in outdoor environments, e.g. [11].

The interference between femtocells and the macrocell depends on the spectrum allocation approach and FC access control mechanism. Some spectrum allocation approaches can be applied only to uplink (UL) [12,13] or downlink (DL) transmissions [2,8] since their air interface technology is different. For instance, OFDMA technology is used for DL transmission while SC-FDMA for UL

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transmission in LTE. In this paper, we focus on the resource allocation for DL transmission.

The access control mechanism determines whether a public user can have access to a nearby FC or not. There are three access control categories: closed access, open access and hybrid access [1]. In closed access, public users cannot use FCs and the FC subscribers get full benefit of their own FC but this approach limits the network capacity and increases the interference to nearby macro users, which is known as a dead-zone problem. Open access mechanism allows any users to use FCs. However, this approach requires tight coordination between FCs and their macrocell that may result in traffic congestion over the backhaul connections. In hybrid access, public users can access FCs but some FC capacity is reserved for FC subscribers. Hence, this approach can combine the benefits and overcome the limitations of the two previous access control categories. Due to this potential, in this paper we focus on hybrid access FCs.

The introduction of hybrid access femtocells imposes several technical challenges for resource allocation and clustering techniques due to contrasting factors that affect the overall system performance, such as: (*i*) access to public users, satisfaction of own FC subscribers and mechanisms to motivate FCs to grant access to public users, (*ii*) level of offloaded traffic from the macrocell and dedicated bandwidth allocated to femto tier, (*iii*) bandwidth reuse at femto tier, power adaptation and interference, and (*iv*) handover and users mobility.

Several FC cluster formation schemes have been investigated to reduce the complexity of resource allocation models. The main objective is to group FC into clusters in such way that the resource allocation algorithm can be locally executed in each FC cluster for a specific bandwidth allocated to the femto tier. The clustering schemes aim at several objectives such as: maximization of FC subscribers data rate while minimizing the co-tier interference among the clusters [14], upholding QoS of subscriber transmissions [15,16], and minimization of the co-tier interference among the clusters [17] or interference alignment within the cluster [18]. For FC networks with hybrid access, few cluster based resource allocation approaches has been investigated such as they perform universal subcarrier reuse at femto tier, e.g. [8], but they do not determine the optimal cluster size and do not adapt the allocated bandwidth per tier taking into account the satisfied demand of public users granted by FCs.

To the best of our knowledge, the resource allocation has not been addressed together with the clustering formation and the base station selection taking into account hybrid access femtocell networks. There are several important aspects that should to be addressed to solve the clustering and resource allocation together. First, femtocells should be encouraged to choose the hybrid access mechanism to become member of a cluster if the QoS of their own subscriber transmissions is guaranteed. Second, the spectrum partitioning approach can avoid the inter-tier interference among the tiers but the required channels for the femto tier is determined by the cluster size and its traffic load. Finally, resource sharing can be allowed among FCs belonging to different clusters, but this might increase the inter-cluster interference and deprive the femto user transmissions.

Accordingly, the limitations of previous works can be summarized as:

1. QoS of subscriber transmissions is not guaranteed when granting access to public users through FCs.
2. Limited mechanisms that motivate FCs to grant access to nearby public users and to become a member of a cluster.
3. Lack of appropriate mechanisms that adapt the bandwidth allocated per tier taking into account the satisfied demand of public users granted by FCs.

4. Lack of adaptive power control that finds a trade-off between overall system performance and resources used by public users in FC.

To overcome above limitations, we propose a model to perform cluster formation, BS selection and resource allocation for OFDMA femtocell networks aiming at the maximization of the network throughput. Since the targeted problem has to be solved in short time due to the time duration of the resource block in OFDMA technology [19], our resource sharing model is based on Particle swarm optimization (PSO). PSO is a good candidate to speed up the optimization process and obtain a satisfying near-optimal solution [20] and it has has been investigated to solve the subcarrier allocation for OFDMA macrocell systems in [21] and for LTE systems in [22]. These prior works show that PSO can reduce complexity compared to linear search and sorted list approaches. In our previous work [23], we showed that PSO indeed enhances the network throughput in comparison with the Weighted Water Filling algorithm, [2], for a given BS selection.

Our previous works presented in [24,25] addressed the resource optimization problem using Linear Programming to solve the BS selection together with the resource allocation taking into account the spectrum partitioning and spectrum sharing respectively. Their disadvantage is high complexity and long running times. Then, we proposed to use alternate optimization tools such as Genetic Algorithm [26] and PSO [23] to solve the resource allocation problem for a given BS selection. These two optimization techniques find a satisfying near-to-optimal solution in a shorter running time than the optimal resource allocation solution [24]. Both approaches also improve the results obtained by the Weighted Water Filling algorithm from [2]. In [27], we proposed a clustering technique that keeps the traffic load balanced among the established clusters together with a distributed Weighted Water Filling based resource allocation algorithm. It was shown that the load balanced clustering outperforms the clustering based on the interference levels.

In this paper, we present a novel cluster formation framework that consists of three stages: (1) a BS selection algorithm that balances the traffic load of public users among the clusters, (2) a cluster formation algorithm that takes into account the cluster size, load and remaining resources, and (3) a resource allocation algorithm based on PSO that determines the required number of subcarriers in femto tier. Besides the novelty of the three-stage structure itself, each stage has novel elements compared to our previous works. In the BS selection procedure, the novelty is related to the fact that the potential serving femtocells are sorted according to three parameters: link rate, cluster size, and their remaining capacity (in terms of the number of users) unlike the majority of the related work where decision is based on the link rate only. Thus, the algorithm prefers to allocate public users to small-size clusters instead of large-size clusters if the considered FCs have the same capacity. In this way, the number of public users is fairly distributed among the established clusters and the bandwidth starvation is avoided within the clusters. The novelty of the cluster formation algorithm lies in that it utilizes the cluster size, load and remaining resources to select the best cluster to join for stand-alone femtocells, unlike our prior clustering scheme that considered the cluster load and interference. Finally, the novelty of the PSO based resource allocation model is related to the fact that it aims at maximizing the femto tier throughput (i.e. the sum of the cluster throughput) with inter-cluster interference and bandwidth constraints unlike our prior PSO based solution that maximizes the network throughput for a given BS selection without considering any clustering among femtocells. In particular, our contribution is a model that provides:

- Bandwidth adaptation per tier based on average satisfied demand of public users through FCs,

- BS selection based on user demands, user locations, FC proximity, cluster load and cluster size,
- Enhanced power distribution over active bandwidth in each BS (macrocell or femtocell),
- Universal subcarrier reuse at femto tier,
- Reduction of inter-cluster interference and running time.

A performance comparison among the proposed PSO based resource allocation algorithm and an Integer Linear Programming (ILP) model for a non-dense femtocell network is presented to show that the proposed model finds a satisfying near-to-optimal solution. Moreover, we propose to use the Weighted Water Filling (WWF) based resource allocation algorithm [2] and the clustering technique based on the perceived interference levels and FC bandwidth reduction [8] to evaluate the performance of the proposed PSO based model. First, we evaluate the performance of the clustering techniques using the WWF based resource allocation algorithm. Then, we evaluate the PSO based and WWF based resource allocation algorithms that use the proposed clustering technique. Finally, the proposed clustering technique, together with the PSO based model, is analyzed for scenarios with increasing FC numbers.

The remainder of the paper is organized as follows: Section 2 describes the targeted problem and presents the problem formulation. Section 3 presents the load balanced clustering scheme and PSO based resource sharing model. Section 4 briefly describes the benchmark models with their modifications to cope with the same constrains as the proposed model. Section 5 presents the performance metrics. Section 6 shows the numerical results obtained for the proposed model contrasted with the optimal solution and the benchmark model. Finally, Section 7 concludes the paper.

2. Problem statement

We consider a macrocell with a set of underlaid femtocells as illustrated in Fig. 1. We focus on downlink (DL) transmissions. Both the macrocell (MC) and the femtocells (FCs) are assumed to operate using OFDMA technology. According to [19], each mobile device can identify FCs that could potentially provide service and notify this info to the serving macro BS. Thus, the macrocell is able to determine which public users can be connected to FCs as well as which FCs can be grouped into clusters that can serve more public users and increase the network throughput.

The cross-tier interference can be avoided by using spectrum partitioning approach among the two tiers (i.e. dedicated subcarriers per tier) while the co-tier interference between neighboring femtocells can be mitigated by cooperative resource allocation among the femtocells (e.g., based on clustering of femtocells). The idea behind clustering is to allow the resource sharing among femtocells belonging to different clusters. The femtocell network can be divided into disjoint clusters, where its corresponding set of subcarriers is available to each cluster. However two femtocells in the same cluster are not allowed to transmit using the same set of subcarriers. In this regard, the cluster size is an important parameter that affects the achievable throughput per cluster and the macrocell throughput owing to the fact that the subcarriers are dedicated for each tier. Therefore, femtocells are encouraged to form clusters by granting access to public users and getting some extra resources from the macrocell. Femtocells in small-size clusters can have higher share in the available spectrum with higher inter-cluster interference from neighboring clusters but the small-size clusters require less bandwidth for the femto tier. On the contrary, femtocells in high-size clusters can have lower share in the available spectrum with lower inter-cluster interference but the high-size clusters require more bandwidth for the femto tier. This suggests that the cluster size should be determined in order to re-

duce inter-cluster interference, to maximize the share of the available spectrum for each femtocell and to minimize the bandwidth required for femto tier.

2.1. Illustrative example

Let us assume that 10 channels, each with bandwidth of B_c units, are available in the overlaid MC. These 10 channels should be allocated among FCs and MC in a way that maximizes the network throughput and minimizes the blocking ratio. The mobile users ($U_1,...U_{13}$, $S_1,...S_7$) can be allocated to macrocell or femtocell depending on the femtocell access mechanism.

To facilitate understanding of the illustrative example, we assume that only one channel can be allocated to each mobile user and one user can be served by only one BS. Thus, the network throughput is estimated as the sum of user data rates. Each user data rate is equal to the spectral efficiency of the serving BS multiplied by the channel bandwidth (B_c). The spectrum efficiency is assumed to be 2 bps/Hz in macrocell and 6 bps/Hz in each femtocell. Hence, the user data rate is equal to $2 \times B_c$ or $6 \times B_c$ for users served by macrocell or femtocell, respectively. Finally, the blocking ratio is calculated as the number of users without allocated channels divided by the total number of users in the network.

To understand better the network example from Fig. 1, let us analyze the following four scenarios that combine FC access mechanism, spectrum usage in femto tier and cluster formation technique.

1. *Spectrum partitioning in FC tier and closed access policy. In this case maximizing number of users allocated to femtocells maximizes the network throughput. According to Fig. 1, maximum of six FC subscribers can be served by FCs that also gives four users served by macrocell. Therefore, the network throughput is 44 B_c and blocking ratio is 0.5. Note that this approach prioritizes the subscriber transmissions leading to bandwidth starvation in the macrocell.*
2. *Spectrum sharing in FC tier (the channel reuse is allowed between FCs) and closed access policy. Since in our example each femtocell has at most one subscriber under its coverage, only one channel needs be allocated to femto tier but the interference will be present among neighboring FCs, which leads to a spectrum efficiency reduction in femtocells. Assuming that in our example the spectrum efficiency is reduced to 4 bps/Hz, the throughput is 42 B_c and the blocking ratio is 0.25.*
3. *Spectrum sharing in FC tier, closed access policy and cluster formation (used to avoid the co-tier interference within each cluster). In this case, the maximum number of channels required is given by the cluster with most subscribers in its coverage, which is cluster Cluster3 in Fig. 1. Thus, 3 and 7 channels can be orthogonally allocated to the femto tier and macro tier, respectively, leading to the blocking ratio of 0.35 and the throughput of 50 B_c. The latter shows that clustering indeed reduces the co-tier interference and increases the network throughput at expenses of increasing the blocking ratio.*
4. *Spectrum sharing, hybrid access policy and cluster formation. In this case, the cluster that can potentially serve most users is used to determine the maximum number of channels required at femto tier. In Fig. 1, Cluster$_1$ has five potential users, which means that five channels should be allocated to each cluster. In this case, the throughput is increased to approximately 76 B_c and the blocking ratio is reduced to 0.2.*

The last scenario is best from the operator's perspective. However, from FC owners' point of view, FCs belonging to the clusters that serves more public users have no incentive to grant access to public users while FCs belonging to the other clusters get extra resources that can be allocated to their own subscribers. Therefore a
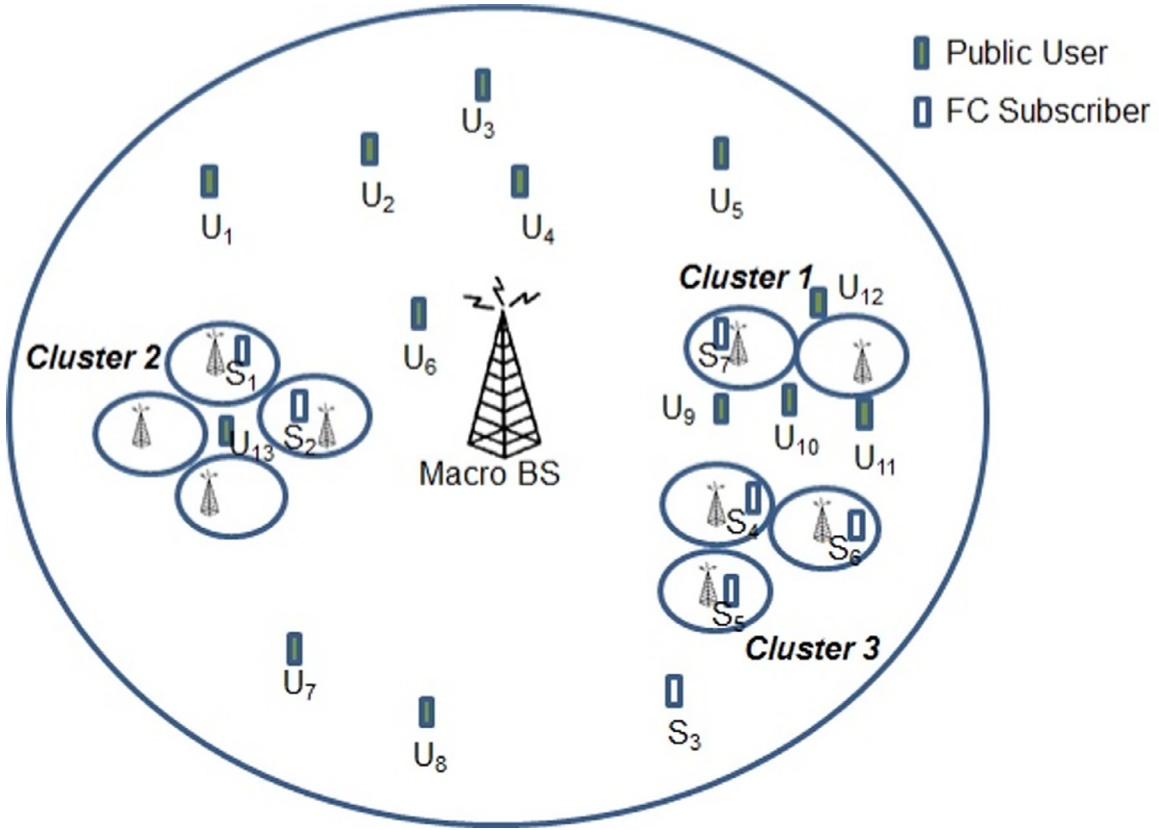
Fig. 1. Network example with three FC clusters. S_i and U_i represents FC subscribers and public user respectively.

smart motivation mechanism is needed to give all FCs incentives to grant access to public users.

Also note that while cluster formation avoids the interference among cluster members through the orthogonal subcarrier assignment, there is still the inter-cluster interference that affects FC on the cluster edge (FC close to other clusters in the network, such as some FCs in *Cluster*1 and *Cluster*3 in Fig. 1).

In summary, when using clustering technique, a compromise between maximizing network throughput, power control and FCs incentives should be determined.

2.2. Problem formulation

The proposed cluster based resource allocation model is presented in this section. This model aims at the maximization of the two-tier network throughput defined as the sum of achievable user data rates in the overlaid macrocell and FCs being grouped into disjoint clusters. Using Shannon's Law, our objective function can be formulated as:

$$\max_{\mathbf{FCM},\mathbf{A},\mathbf{b},\mathbf{P}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} A_i^m b_i^s log_2(1 + SINR_i^{m,s}) +$$

$$\sum_{c\in\{C\}} \sum_{i\in\{MS\}} \sum_{j\in\{m,FC^c\}} \sum_{s\in\{SC\}} FCM_j^c A_i^j b_i^s log_2(1 + SINR_i^{s,j}), \quad (1)$$

where vectors **FCM**, **A**, **b** and **P** correspond to femtocell-cluster membership, user-base station association, bandwidth and power assignment for each user. FC, MS, SC, C represent to the sets of femtocells, mobile stations, subcarriers and clusters. First term of (1) corresponds to the MC throughput and the second term is the sum of data rate in femto tier. C is the set of disjoint FC clusters and FCM_j^c is a binary variable that indicates the jth FC membership in cluster c. A_i^j is binary variables that determines if the BS j

is selected for user i. The vector **b** consists of real variables, b_i^s, indicating that subcarrier s is allocated to user i. $SINR_i^{s,j}$ is the signal to interference plus noise ratio perceived by the mobile user over the subcarrier s and is given by:

$$SINR_i^{s,j} = \frac{P_i^{s,j}}{PL_i^{s,j} \times (N_0 + I_i^{s,FC})}, \qquad j \in FC, i \in MS, s \in SC. \quad (2)$$

where $P_i^{s,j}$ is the transmitted power from BS j to user i in the subcarrier s and $PL_i^{s,j}$ is the path loss due to the channel propagation models for outdoor and indoor environment [28] and is given by:

$$PL_i^{s,j}(dB) = \begin{cases} 10log_{10}(d_{im}^{\alpha_m}) + 30log_{10}(f_c) + 49, & \text{for outdoor} \\ 10log_{10}(d_{if}^{\alpha_f}) + 37, & \text{for indoor} \end{cases} \quad (3)$$

where d_{im} is the distance from the user i to the MC base station (given in kilometers) and d_{if} is the distance from the user i to the fth FC base station (given in meters).

Note that since we are considering orthogonal subcarrier assignment between the two tiers and among the members of a cluster, the co-tier interference comes from clusters sharing the same set of subcarriers. Thus, the co-tier interference can be expressed by:

$$I_i^{s,FC} = \sum_{k\in C\backslash c} \sum_{f\in FC} \sum_{h\in\{MS\backslash i\}} FCM_f^k A_h^f \frac{P_h^{s,f}}{PL_i^{s,f}} \quad (4)$$

2.2.0.1. Objective function modification. Our problem is NP-hard since Eq. (1) is a non-linear function. This means that there is no polynomial-time algorithm that can obtain the optimal solution for

Table 1
Model parameters.

System parameters	
Name	**Description**
N_s	Number of available subcarriers
B^{SC}	Bandwidth per subcarrier
P_k^{Total}	Maximum transmitted power in BS k
$P_k^{max,s}$	Maximum transmitted power per subcarrier in BS k
R_m, R_f	Radii in macrocell and FCs
D^{max}	Maximum capacity per user per MC zone
γ_f, γ_m	Attenuation factor of indoor and outdoor environments
l_m^{mod}	Number of bits of modulation in MC
l_f^{mod}	Number of bits of modulation in FC f
N_0	Average thermal noise power
N	Number of mobile users in the network
N^f	Maximum number of users at the femtocell
Input parameters	
D_i	Requested demand of mobile user i
d_{if}	Distance from FBS f to the mobile user i
d_{im}	Distance from MBS to the mobile user i
Output parameters	
FCM_j^c	Femtocell membership of cluster c
$b_i^{s,j}$	Subcarrier allocated to user i in BS j
$P_i^{s,j}$	Transmitted power for DL between BS j and user i
A_i^j	User i is assigned to BS j

clustering together with BS selection and bandwidth and power allocation. For this reason, we modify (1) into:

$$\max_{\mathbf{b},\mathbf{P}} \sum_{i \in \{MS\}} \sum_{s \in \{SC\}} A_i^m b_i^s l_m^{mod} + \sum_{c \in C} \sum_{i \in \{MS\}} \sum_{f \in FC} \sum_{s \in \{SC\}} FCM_j^c A_i^j b_i^s l_j^{mod} \qquad (5)$$

in such way we aim at the maximization of the sum of the lower bound of achievable user data rates assuming that the log term should be at least equal to the spectral efficiency required in the MC, l_m^{mod}, or FC, l_f^{mod}. Then we propose a Mixed Integer Linear Program (MILP) model to jointly solve the clustering and resource allocation in a two-tier network taking into account user locations, demands and FC locations. As we did in our previous work in [24], a piece wise segment linear approximation can be used to replace the log term in (10) and to solve the resource allocation problem using Linear Programming. In the following, we present the model parameters and constraints of the optimization problem.

2.2.0.2. Model parameters. The parameters used in the proposed model are described in Table 1. They are classified as system, input, and output parameters. The system parameters represent the network features, such as available bandwidth, maximum power per user, maximum transmitted power in macrocell, attenuation factors, carrier frequency, average noise. The input parameters specify the requirements of the mobile users and femtocells, such as their demands and locations. The output parameters are the ILP model variables.

2.2.0.3. Model constraints. The objective function (5) is subject to the following constraints:

- Upper bound for the allocated bandwidth per user to satisfy his demand

$$\sum_{s \in \{SC\}} b_i^s \leq A_i^m \frac{\min (D_i, D^{max})}{l_f^{mod}} + \sum_{j \in \{FC\}} A_i^j \frac{D_i}{l_f^{mod}}; \quad i \in MS, \qquad (6)$$

- Upper bound for allocated bandwidth to macro and femto tiers

$$\sum_{i \in \{MS\}} A_i^m \sum_{s \in \{SC\}} b_i^s < B_m, \qquad (7)$$

$$\sum_{i \in \{MS\}} \sum_{j \in \{FC^c\}} A_i^j \sum_{s \in \{SC\}} b_i^s \leq B - B_m; \quad c \in \{C\}, \qquad (8)$$

where B_m is a variable that determines the bandwidth allocated to macro tier.

- Upper bound for transmitted power per BS

$$\sum_{i \in \{N\}} \sum_{s \in \{SC\}} A_i^j P_i^{s,j} \leq P_j^{Total} \qquad (9)$$

- Lower bound for the spectrum efficiency per BS

$$log_2 \left(1 + \frac{P_i^{s,j}}{PL_i^{s,j} \times (N_0 + I_i^{s,FC})}\right) \geq l_j^{mod} A_i^j; \quad i \in MS, j \in \{m, FC\}, s \in SC \qquad (10)$$

- Upper bound of the cluster

$$\sum_{j \in \{FC\}} FCM_j^c \leq N_{bs}^c; \quad c \in C \qquad (11)$$

- One FC can only be assigned to one cluster

$$\sum_{c \in \{C\}} FCM_j^c \leq 1 \qquad j \in FC \qquad (12)$$

To find the optimal cluster configuration, an exhaustive search could be applied. This means performing the joint BS selection and resource allocation over all possible given cluster configuration. The total number of possible ways of grouping a set of FCs into disjoint clusters can be derived using the Stirling Partition number [29] and is given by

$$C_{conf}^{Total} = \sum_{j=1}^{|FC|} \frac{1}{j!} \sum_{i=0}^{j} (-1)^{j-i} \binom{j}{i} i^{|FC|} \qquad (13)$$

Thus, an exhaustive search would require long running times since the number of possible cluster configuration increases exponentially with the number of femtocells. This model is more time consuming than our previous work [24] due to the new variables representing FC cluster membership. Therefore, we propose the use of cluster formation technique in order to reduce the complexity of the resource allocation for macro-femtocell networks as in [8]. Thus, we propose a heuristic framework that consists of three main components: a BS selection procedure, a PSO based resource allocation algorithm and a novel clustering scheme.

3. Cluster based resource sharing model

In this section we present the three-stage resource sharing model that performs: (1) BS selection procedure to balance the public users traffic load among the existing clusters, (2) resource allocation for the macro-femtocell network that mitigates the inter-cluster interference, maximizes the network throughput while guaranteeing QoS subscribers connections and adaptively determines the allocated bandwidth for both tiers, and (3) cluster formation based on the cluster size and its available capacity in terms of number of connected users and allocated resources. Fig. 2 presents the connection among the three stages of the model. Note that the clustering algorithm is triggered only when a stand-alone FC perceives interference level higher than a given threshold so the proposed framework will attempt to combine such FCs with current clusters.

In the following we describe algorithms related to each of these tasks.

3.1. BS selection per user

The objective is to balance the traffic load of public users among the given clusters while guaranteeing the QoS of FC subscriber transmissions. First, the mobile users are sorted according to their type (i.e. FC subscriber transmission should have priority inside their own FC) and weighted demand. Second, for each user,
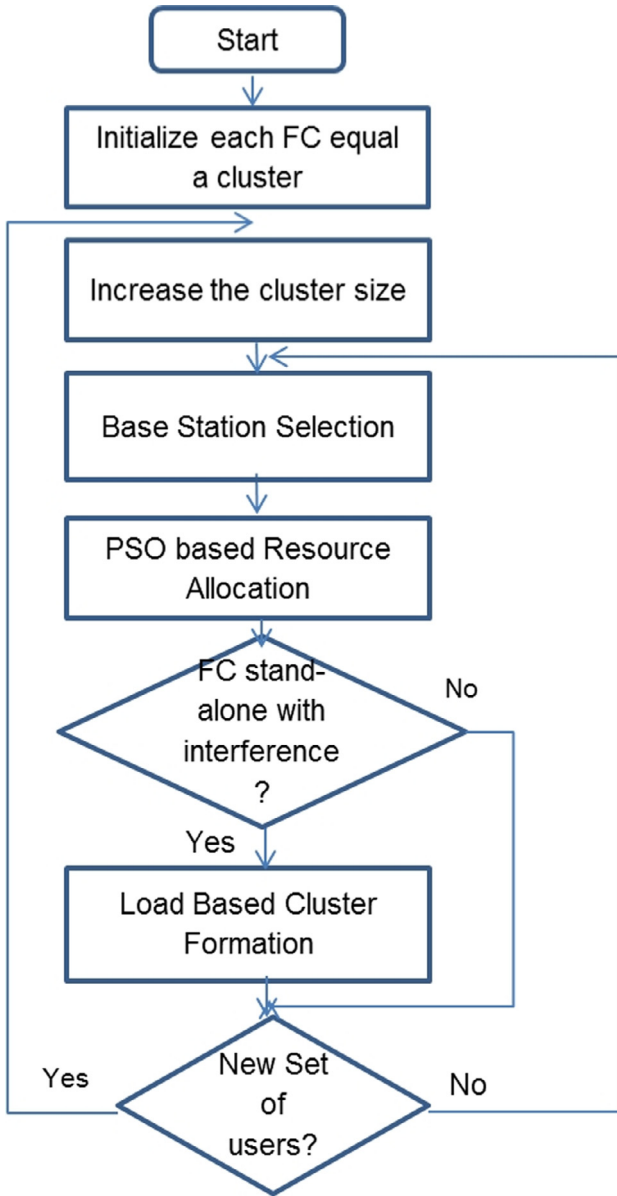
Fig. 2. Three-stage model flowchart.

Algorithm 1: BS selection.

Data: *MS* Set of users, *FC* Set of Femtocell, m represents Macrocell,
     User Locations (X_i, Y_i), FC Locations (X_f, Y_f), Demands (D_i)

Result: (A_i^j) BS selection

begin

   Sort set *MS* in decreasing order by their type of user (T_u) and weighted demand (D_u);

   for *each* $u \in MS$ **do**

     Determine the FC_{user} with higher link rate than the MC and available capacity in terms of users.

     if $FC_{user}\, ! = 0$ **then**

       Sort this FC set in decreasing order by: link rate, available capacity, available resource in its cluster, available number of FC to be connected to the cluster.

       Assign user to the first FC in the ordered list.

       $A_u^j \leftarrow 1$;

       Increase the number of femto or macrousers on FCs depending on its type.

       if $T_u = 2$ **then**

         $N_{SU}^j \leftarrow N_{SU}^j + 1$;

       else

         $N_{PU}^j \leftarrow N_{PU}^j + 1$;

       Reduce the available capacity of femtocell j.

     else

       Assign user to the macrocell.

       $A_u^m \leftarrow 1$;

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the algorithm chooses FCs with better link rate conditions than the macrocell. Then, for each user, FCs are sorted according to their link rate, available capacity (in terms of the number of users that can be connected to FC), cluster size, cluster load, and available number of FCs to be connected to the cluster. Then, our BS selection procedure allocates public users to FC with the highest available capacity that is located in the cluster with the lowest number of members. By doing that we want to keep cluster with almost the same number of members and balanced traffic load. If the selected FC set is empty, the public user is allocated to MC. This procedure is repeated until all users are allocated either to one FC or the macrocell. Algorithm 1 presents the BS selection procedure.

Our BS selection procedure allocates users to FC with higher available capacity and member of cluster with lower number of FC. Doing so, we avoid having FC cluster with higher load than any other cluster in the network.

3.2. Particle swarm optimization based resource allocation model

Particle swarm optimization is a population-based search approach that requires information sharing among the population members to enhance the search process using a combination of deterministic and probabilistic rules. PSO has been proven to yield the same effectiveness as the evolutionary algorithms but it requires less number of function evaluations [20]. The PSO algorithm uses two vectors that determine the position and velocity of each particle n at each iteration k. These two vectors are updated based on the memory gained by each particle. The position x_n^{k+1} and velocity v_n^{k+1} of particle n at each iteration k are updated as follows:

$$x_n^{k+1} = x_n^k + \delta_t v_n^k, \tag{14}$$

$$v_n^{k+1} = \omega v_n^k + c_1 r_1 (p_k^{local} - x_n^k) + c_2 r_2 (p_k^{global} - x_n^k), \tag{15}$$

where δ_t is the time step value typically considered as unity [30], p_k^{local} and p_k^{global} are the best ever position of particle n and the best global position of the entire swarm of particles so far (current iteration k), and r_1 and r_2 represent random numbers from interval [0,1]. Parameters ω, c_1 and c_2 are the configuration parameters that determine the PSO convergence behavior. The first term in (15) corresponds to the inertia of particle i which is used to control the exploration abilities of the swarm. Large inertia produce higher velocity updates allowing the algorithm to explore the search space globally while small inertia values force the velocity to concentrate in a local region of the search space. Second and third term are associated with cognitive knowledge that each particle has experienced and the social interactions among particles respectively. Parameters c_1 and c_2 are known as the cognitive scaling and social scaling factors [20].

According to [30], the convergence of PSO is guaranteed if the following two conditions are met:

$$0 \leq (c_1 + c_2) \leq 4, \tag{16}$$

and

$$\frac{c_1 + c_2}{2} - 1 \le \omega \le 1. \tag{17}$$

In our resource allocation algorithm, two vectors $(\mathbf{b}, \mathbf{P})$ are used to define the location of each particle n in the search space, where b and P represents allocated bandwidth per user and transmitted power per user respectively. We also keep two different velocity vectors $(\mathbf{v_b}, \mathbf{v_P})$ to update the particle location in each iteration using (15). We define a bandwidth step increase as δ_b, which can be the subcarrier bandwidth. In addition, we propose to use a discrete number of power levels to reduce the search space.

One classic way to accommodate constraints is to add penalties proportional to the degree of constraint infeasibility. The main concern with this method is that the quality of the solution depends directly on the value of the specified scaling parameters. For that reason, we use a parameter-less scheme, where penalties are based on the average of the objective function and the level of violation of each constraint during each iteration [30]. Thus, the penalty coefficients are determined by

$$cp_l = |\bar{f}(x)| \frac{\overline{g_l}(x)}{\sum_{j=1}^{C} [\bar{g}(x)]^2}, \tag{18}$$

where $\bar{f}(x)$ is the average objective function, $\bar{g}(x)$ is the average level of l_{th} constraint violation over the current population and C is the number of constraints [30]. Then, our fitness function is defined by

$$f'(x) = \begin{cases} f(x_n^k), & \text{if } x_n^k \text{ is feasible} \\ f(x_n^k) + \sum_{l=1}^{C} cp_l\widehat{g}(x_n^k), & \text{otherwise} \end{cases}. \tag{19}$$

and $\widehat{g}(x_n^k)$ is determined as follows:

$$\widehat{g}(x_n^k) = \max\left(0, [g_j(x_n^k)]\right). \tag{20}$$

Accordingly, the average of the fitness function for any population is approximately equal to $\bar{f}(x) + |\bar{f}(x)|$.

Since our objective function is to maximize the network throughput and PSO is defined to solve a minimization problem, we modify our objective function from (5) to

$$f(\mathbf{b}, \mathbf{P}) = Q - \sum_{i \in \{MS\}} \sum_{j \in \{m, FC\}} A_i^j b_i log_2(1 + SNR_i^j) \tag{21}$$

where Q is a large number (at least twice of the maximum throughput that can be achieved). In such way, we convert our maximization problem into a minimization problem. The parameter A_i^j is the user-base station association and is equal to 1 if $bs_n(i)$ is equal to j and 0 otherwise as it was described in Section 3.1. Our fitness function is given by

$$f'(x) = \begin{cases} f(\mathbf{b}, \mathbf{P}), & \text{for feasible solutions} \\ f(\mathbf{b}, \mathbf{P}) + \sum_{l=1}^{C} k_l\widehat{g}(\mathbf{b}, \mathbf{P}), & \text{otherwise} \end{cases}. \tag{22}$$

where constraints (6–10) defined in Section 2.2 are included in $\sum_{l=1}^{C} k_l\widehat{g}(\mathbf{b}, \mathbf{P})$ to penalize unfeasible solutions. Algorithm 2 (also referred to as PSO algorithm) presents the PSO based resource allocation for given user-BS allocation. Vectors $\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}, \mathbf{r_4}$ are composed of random numbers between 0 and 1 with the same cardinality as vector $\mathbf{b}$ and $\mathbf{P}$, which is equal to the cardinality of the user set.

We also analyze the effectiveness for the proposed PSO based resource allocation algorithm for different values of cognition and social behavior factors (c_1, c_2). Fig. 3 shows the throughput convergence for different setting of parameters c_1, c_2 and ω.

Algorithm 2: PSO based resource allocation algorithm

Data: MS User Locations (x_i, y_i), FC Locations (x_f, y_f), Users Demands (D_i)
and BS selection per user (bs_i).
Result: Bandwidth and power allocation per user (b_i, P_i).
begin
  for *each* $i \in MS$ **do**
    if $bs_i = m$ **then**
      $b_i^{max} \leftarrow \frac{D_i}{I_{mod}^m}$;
      $P_i^{max} \leftarrow \min(P_z^{max}, SNR_k^{max} \times N_O \times PL_i^m)$;
    else
      $b_i^{max} \leftarrow \frac{D_i}{I_{mod}^f}$;
      $P_i^{max} \leftarrow \min(P_f^{max}, SINR_k^{max} \times (N_O + I_{th}) \times PL_i^f)$;
  Generate initial swarm with the particle positions and velocities as follows;
  $\mathbf{b} \leftarrow \mathbf{r_1}.\mathbf{b^{max}}$;
  $\mathbf{P} \leftarrow \mathbf{P^{min}} + \mathbf{r_2}.(\mathbf{P^{max}} - \mathbf{P^{min}})$;
  $\mathbf{v_b} \leftarrow \mathbf{r_3}.\mathbf{b^{max}}$;
  $\mathbf{v_P} \leftarrow \mathbf{P^{min}} + \mathbf{r_4}.(\mathbf{P^{max}} - \mathbf{P^{min}})$;
  Evaluate Fitness Function;
  Determine first global best of the swarm;
  while $k \le MaxIteration$ **do**
    Update Position;
    Evaluate Fitness Function;
    Determine best local for each particle;
    Determine best global in the swarm and update the best global;
    Update velocity;

The PSO based resource allocation algorithm requires between 100 to 1000 iterations to converge as shown in Fig. 3. It can be noticed that the maximum throughput value for the proposed model is reached with $c_1 = 2.5$, $c_2 = 1.5$ and ω in the interval of [0.2, 0.9]. An adaptive PSO approach that changes the inertia factor in each iteration as follows:

$$\omega_k = \omega_{max} - (\omega_{max} - \omega_{min}) \times \frac{k}{k_{max}} \tag{23}$$

has been proven to reduce the convergence time in other optimization problems [31]. Therefore, we propose to use this variation with $\omega_{min} = 0.2$ and $\omega_{max} = 0.9$. The number of iterations required to converge lies in the interval [100,500], which corresponds to running times between 5 and 10 sec.

3.3. Load balanced based cluster formation algorithm (LBC)

We propose a heuristic cluster algorithm to balance traffic load among the clusters so they would have the same size (if possible), allocated resources and allocated public users. Initially, each FC is considered as a cluster. Thus, the cluster number, $|C|$, is equal to the femtocell number in the network, $|FC|$. Once BS selection is performed, the resources are allocated to each cluster taking into account the average bandwidth required by FCs. Then, the resource allocation is carried out by means of orthogonal subcarrier allocation within a cluster and FC power control is performed to mitigate interference and to achieve target SINR.

The resource manager entity can identify the interfering FC set by means of the measurement reports delivered by mobile users. The proposed clustering scheme pursues to merge stand-alone (SA) FCs that perceives interference from the clusters with available
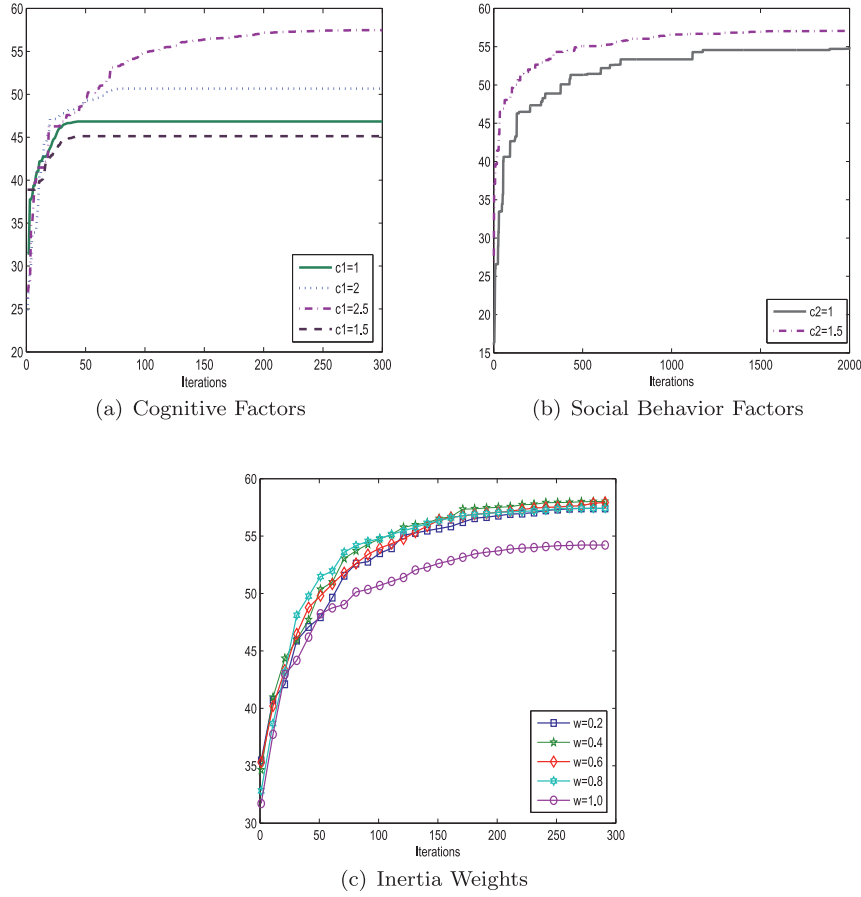
(a) Cognitive Factors

(b) Social Behavior Factors

(c) Inertia Weights

Fig. 3. Analysis of particle swarm optimization model for BS selection and resource allocation problem (a) $c_2 = 1$, $\omega = 0.7$, (b) $c_1 = 2.5$, $\omega = 0.7$, (c) $c_1 = 2.5$, $c_2 = 1$.

capacity in terms of available subcarriers without exceeding the maximum cluster size allowed in each iteration. The cluster formation procedure is presented in Algorithm 3.

Algorithm 3: Clustering algorithm

Data: *FC* Set of Femtocell
Result: (X_j^c) Cluster Configuration
begin
  Initialization
  Each FC j is a cluster initially, so there are totally $|FC|$ clusters
  for *each FC i without cluster* **do**
    Determine the set of interfering Clusters, $Cluster_{Int}^i$ of Cluster i
    for *each element j of $Cluster_{Int}^i$* **do**
      Calculate the merging metric for the interfering clusters
    Sort the cluster j in descending order of the metric
    Select the first cluster (j)
    for *each element j of $Cluster_{Int}^i$* **do**
      if $|FC^j| + 1 \leq N_C^{MAX}$ **then**
        Add FC i to the femtocells set belonging to cluster j, FC^j;
        break;
      else
        Select the next cluster in $Cluster_{Int}^i$

The key element of this algorithm is the proposed merging metric that attempts to group stand-alone FCs to form clusters with almost the same traffic load and size. This is controlled by setting a maximum cluster size, in each iteration, which is one unit higher than the maximum size of the cluster in the prior iteration. The proposed metric also takes into account other two important factors: the available capacity (i.e. number of public users that can be connected) and available subcarriers in a cluster. Thus, our merging metric is defined as:

$$METRIC_{cl}^j = \max\left(0, 1 - \frac{|FC_j|}{N_C^{FC}}\right) * \max\left(0, 1 - \frac{|SC^{SU,j}|}{SC^j}\right)$$
$$* \max\left(0, 1 - \frac{SC^j}{SC^{FT}}\right) \tag{24}$$

where $SC^{SU,j}$ represents the number of subcarriers required by the subscribers in cluster j and SC^j is the number of subcarriers allocated to cluster j, which should be less or equal to the number of subcarriers allocated to femto tier for a given of mobile users, SC^{FT}. N_C^{FC} is the maximum cluster size. Our metric consists of three components: (1) number of FC that can be added to a cluster j without trespassing the maximum cluster size, (2) the available capacity (i.e. number of users that can be connected to the cluster j), and (3) the available resources (number of subcarriers or subchannels). For this reason, we named our clustering scheme as Load Balanced Clustering scheme (LBC). In the case when two or more clusters have the same metric value, the algorithm selects the highest interfering cluster to merge with the stand-alone FC.

4. Benchmark models

The benchmark models use the same BS selection procedure as the proposed model but they combine a modified version of the resource allocation algorithm based on WWF algorithm [2] or our proposed PSO based algorithm and the clustering technique based on interference mitigation and bandwidth reduction (IMBR) [8]. The comparison of our model with the original models from [2] or [8] would not be fair since the scope of proposed model is wider than these two previous approaches. In fact, [2] addressed only the bandwidth allocation for macro-femtocell networks while [8] addressed the clustering formation. In the following, we describe the WWF Algorithm and the IMBR clustering technique.

4.1. Weighted water filling based resource allocation algorithm

We select the resource allocation algorithm presented in [2] since it pursues the same objective as in our PSO based resource allocation algorithm (i.e. maximization of the network throughput while guaranteeing the user satisfaction in both tiers). In their work, bandwidth allocation is performed using WWF algorithm taking into account pre-fixed user selection per BS and no power limitation. The latter means that the bandwidth is assigned assuming that user data rates can be provided without limitation of maximum transmitted power per BS. We modified this algorithm to satisfy the SINR target as long as the sum of the allocated power do not trespass the maximum transmitted power per BS. Algorithms 4 and 5 presents the modified version of WWF for macrocell and femtocells   respectively.

Algorithm 4: MC weighted water filling algorithm.

Data: Available bandwidth **B**, Available power **P**,
  Demand D_i, given BS selection **BS** per user
Result: Bandwidth and power allocation per user and FC
begin

 $U \leftarrow \{F, MS^m\}$;
 Compute $w_i^m, b_i^{required}$ as follows;
 for each $f \in FC$ **do**

  for $i \in MS^f$ **do**

   $w_i^f \leftarrow \sqrt{\frac{1}{r_i^f}}; b_{i,f}^{req} \leftarrow \frac{D_i}{l_{mod}^f}$;

 if User i is FC **then**

  $w_i^m \leftarrow \sum_{j \in MSf} w_j^f; b_{i,f}^{req} \leftarrow \sum_{j \in \{MSf\}} b_{j,f}^{req}$;

 else

  $w_i^m \leftarrow \sqrt{\frac{1}{r_i^m}}; b_{i,m}^{req} \leftarrow \frac{D_i}{l_{mod}^m}$;

 Sort U according to the bandwidth required divided by the weight;
 while $i \in U$ **do**

  $b_i^{wwf} \leftarrow \min\left(\frac{b_i^{required}-b_i^{k-1}}{w_i^m}, \frac{B-\sum_{k=1}^{i-1}\sum_{j=k}^{MS^m+FC} b_j}{\sum_{j=i}^{MS^m+FC} w_j^m}\right)$;

  for $j = i \rightarrow |U|$ **do**

   while b_i is not satisfied and B and P_m^{Total} are not exhausted **do**

    $b_j^k \leftarrow b_j^{k-1} + w_j^m b_i^{wwf}$;

  if user i is MS **then**

   $p_i^m \leftarrow \min\left(SNR_{th}^m N_0 PL_i^m, \min(P_m^{max}, P_m^{res})\right)$;

Algorithm 5: FC weighted water filling algorithm

Data: Bandwidth assigned to FC (B_f^m), Set of weights (w_i^f).
  Set of users assigned to femtocell f (MS_f)
Result: Resources allocation per user (B_{MS}^f, P_{MS}^f).
begin

 Sort MS^f according to the bandwidth required divided by the weight;
 while $i \in MS^f$ **do**

  $b_i^{wwf} \leftarrow \min\left(\frac{b_i^{required}-b_i^{k-1}}{w_i^f}, \frac{B_f^m-\sum_{k=1}^{i-1}\sum_{j=k}^{MS^f} b_j}{\sum_{j=i}^{MS^f} w_j^f}\right)$;

  for $j = i \rightarrow |MS^f|$ **do**

   while b_i is not satisfied and B_f and P^f are not exhausted **do**

    $b_j^k \leftarrow b_j^{k-1} + w_j^f b_i^{wwf}$;

  $p_i^f \leftarrow \min\left(SNR_{th}^f N_0 PL_i^f, \min(P_f^{max}, P_f^{res})\right)$;

4.2. Interference mitigation and bandwidth reduction based clustering technique

The clustering technique in [8] reduces the complexity of exhaustive search for the joint clustering and resource allocation. In this case, the interfering femtocells are motivated to form clusters through the co-tier interference avoidance (i.e. orthogonal subchannel allocation among femtocells belonging to the same cluster). On the other hand, femtocells are also penalized due to the bandwidth reduction that they might cause to the cluster members because the available number of subchannels per cluster should be redistributed among more FCs. Their merging metric is given as:

$$METRIC_{cl}^j = \frac{I_f^j}{\sum_{k \in C} I_f^k} \times \max\left(0, \frac{\max(SC_{req}^j, SC^{FT}) - SC_{req}^f}{\max(SC_{req}^j, SC^{FT}) + SC_{req}^f}\right) \quad (25)$$

where the first term corresponds to the motivation to avoid co-tier interference among a cluster and a stand-alone FC and the second term is penalty due to the reduction of the cluster member bandwidth due to the new femtocell f. SC_{req}^j and SC_{req}^f are the number of subcarriers required by the cluster j and the femtocell f, respectively. We named this clustering scheme as interference mitigation and bandwidth reduction based clustering scheme.

5. Performance metrics

To evaluate the models' performance, we use the following metrics:

1. *Throughput:* The achievable network throughput is calculated based on Shannon's Law Capacity:

$$T = \sum_{i \in \{MS\}} \sum_{j \in \{m, FC\}} A_i^j b_i \log_2(1 + SNR_i^j). \quad (26)$$

2. *Subscriber satisfaction:* Subscriber satisfaction is defined as the ratio between the sum of assigned subscriber data rates and the sum of subscriber demands:

$$S = \frac{\sum_{i \in \{SU\}} \sum_{j \in \{m, FC\}} A_i^j b_i l_j^{mod}}{\sum_{i \in \{SU\}} D_i}. \quad (27)$$

3. *Power consumption:* The total power consumed in the network is the total transmitted power by macro BS and femto BSs:

$$P^{Total} = \sum_{i \in \{MS\}} \sum_{j \in \{m, FC\}} A_i^j P_i. \quad (28)$$

Table 2
System parameters.

Name	Description
B	50 MHz
P_m^{Total}, P_f^{Total}	(50 dBm, 10 dBm)
R_m, R_f	500 m, 20 m
γ_f, γ_m	3, 3.7
I_m^{mod}, I_f^{mod}	(2, 6)
W_l	−3 dB
N_0	−174 dBm/Hz
f_c	2.3 MHz
N^f	4
D^i	128 Kbps to 1 Mbps

Table 3
OFDMA physical layer assumptions.

Zone	Modulation	Bits/Sym	SNR Target (dB)	Surface[%]
Z_1	64-QAM	6	22.4	2.64
Z_2	16-QAM	4	16.24	9.21
Z_3	QPSK	2	9.4	48.75
Z_4	BPSK	1	6	39.4

4. *Bandwidth usage:* The bandwidth usage is the sum of bandwidth assigned in both tiers:

$$BW^{Total} = \sum_{i \in \{MS\}} A_i^m b_i + \max_c \left(\sum_{i \in \{MS\}} \sum_{j \in \{FC^c\}} A_i^k b_i \right), \quad (29)$$

where FC^c is the FC set of the cluster C.

5. *Jain's fairness index :* This index measures the fairness of a set of values where there are n users with different allocated throughput and is given by

$$JF = \frac{\left(\sum_{i \in \{MS\}} Th_i \right)^2}{\left(|MS| \times \sum_{i \in \{MS\}} Th_i^2 \right)} \quad (30)$$

where Th_i is the achieved throughput for users i estimated as

$$Th_i = \sum_{j \in \{FC\}} \sum_{s \in \{SC\}} A_i^j b_i log_2 (1 + SNR_i^j) \quad (31)$$

The index ranges from $\frac{1}{n}$ for the worst case to 1 for the best case. Its maximum is obtained when all users receive the same allocation [32].

6. Simulation results

In this section we present the main assumptions and the system configuration. Table 2 presents the system parameters used for the simulations.

Table 3 depicts the OFDMA physical layer assumptions [33]. In particular, the number of bits used for modulating the signal is 6, 4, 2, 1 for users in Z_1, Z_2, Z_3, Z_4, respectively.

First, we compare the PSO based resource allocation algorithm and the optimal one [24] (ILP) for a given cluster configuration under an incremental traffic scenario. Then, the proposed three-stage model is compared with the benchmark models under two scenarios:

1. Incremental PU number: Number of public users is increasing from 10 to 60 with five users increment. 10 FCs are deployed within area of 60 × 80 m as illustrated in Fig. 4. Public users are randomly located within FC vicinity. In this scenario, we analyze the following cases: one subscriber per FC with fixed demand (512 bps) or variable demand (128 bps–1 Mbps), variable subscriber number per FC with variable demand (128 bps–1 Mbps).

2. Incremental FC number: FC number changes from 10 to 50 with 5 FCs increment and high density of public users close to FCs is considered.

In the reminder of this section we present performance comparisons between: (1) the proposed resource allocation algorithm the ILP Model, (2) the LBC clustering scheme and IMBR based Clustering scheme using the WWF based resource allocation algorithm for both clustering schemes, (3) the LBC clustering scheme combined with the PSO based resource allocation (LBC-PSO) and the LBC clustering scheme combined with WWF based resource allocation (LBC-WWF), and (4) the LBC-PSO and IMBR-PSO models.

6.1. Comparison with integer linear programming model

Here, we use the scenario with only five FC deployed in one cluster in such a way that the optimization problem is reduced to the base station selection and resource allocation optimization problem which can be solved using our prior work in [24]. Thus, we present a comparison between the PSO based resource allocation model and the optimal ILP based resource allocation model [24] for a given cluster configuration using an incremental traffic scenario. This means that no clustering algorithm is employed for ILP model and it is assumed that all FCs belong to the cluster. The total number of users is increasing from 10 to 60 users with increment of five users with 10% of the total users are the FC subscribers and 30% corresponds to public users close to FCs.

The performance metrics for both models (ILP, PSO) are shown in Fig. 5. Fig. 5(a) indicates that both models present similar throughput values however the power consumption for the PSO model is between 1 and 3 dB higher than for the ILP model as shown in Fig. 5(d). Fig. 5(b) shows that the ILP model gives higher user satisfaction compared to the PSO model for the cases with less than 30 users. Figure 5(c) shows the bandwidth usage per tier, the solid lines represent the bandwidth used in macro tier (MT) and the dotted lines correspond to bandwidth used in femto tier. It can be noticed that bandwidth used in macro tier by PSO model is higher than the obtained using ILP model.

In general, both models provide similar values of network throughput for less than 50 mobile users. The main differences are in the power consumption and bandwidth usage, which are higher for PSO model. Since the complexity of the ILP model increases exponentially with the number of FC, the PSO based resource allocation model is a practical solution that finds a satisfying near to optimal solution.

6.2. Clustering schemes comparison

In this section, the performance of both clustering schemes (LBC, IMBR) is analyzed using the WWF based resource allocation model under the incremental PU number scenario. Fig. 6(a) shows the network throughput for the cases with one subscriber and variable number of subscribers per FC. Moreover, the FC subscriber demands are fixed or randomly generated (shown as F. Dem and R. Dem in the figures). As expected, both clustering approaches present similar network throughput values (dotted lines) when the requested demand per subscriber is fixed (512 kbps per subscriber). In particular, the LBC-WWF model using the proposed clustering technique (LBC) reaches the highest throughput for both scenarios with less than 50 users in the network. Both models (LBC-WWF, IMBR-WWF) reach maximum throughput values for less than 50 users in both random demand scenarios. These maximum values indicate that it is not possible to assign more public users to the current cluster configuration that would allow FCs to obtain extra resources or enhance SINR for their own subscribers.
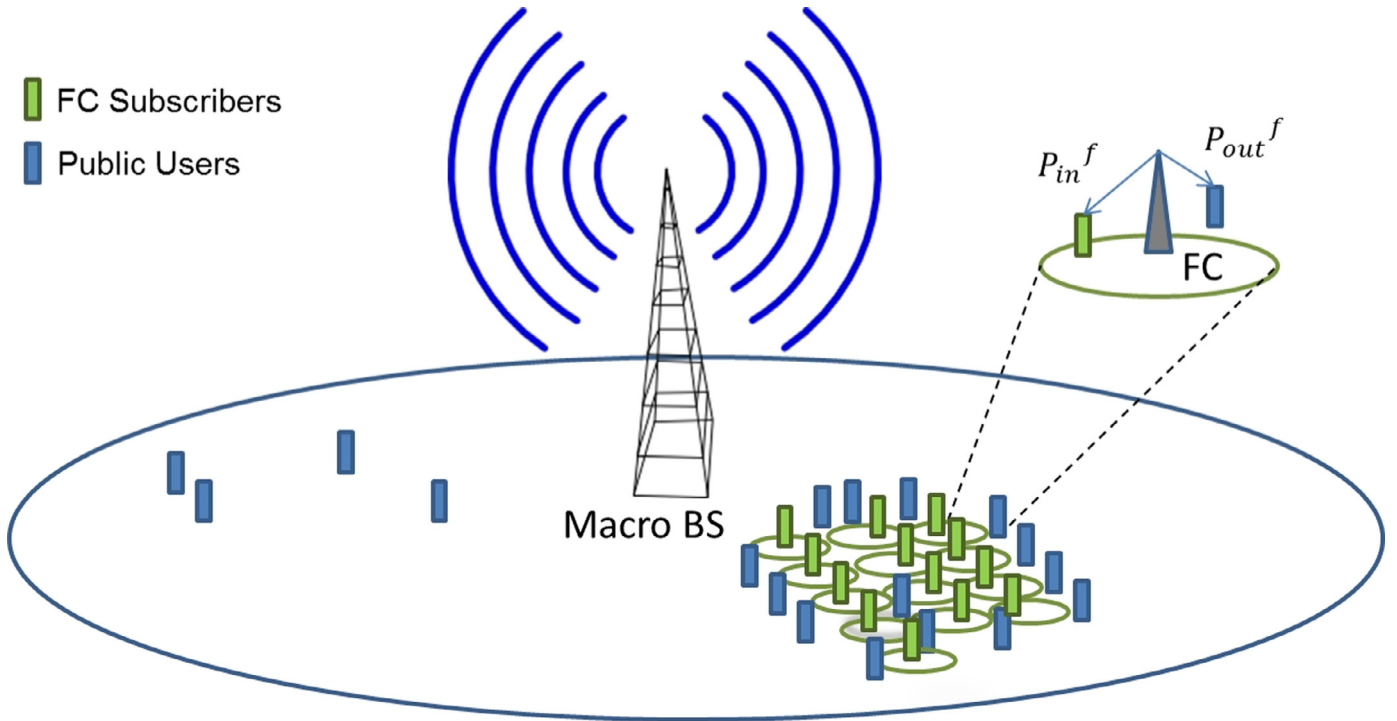
Fig. 4. Network example: ten femtocells are deployed within an area of 80 × 60 m, and the majority of the mobile users are close to the FC neighbor (PU and SU stand for Public Users and FC Subscribers respectively.
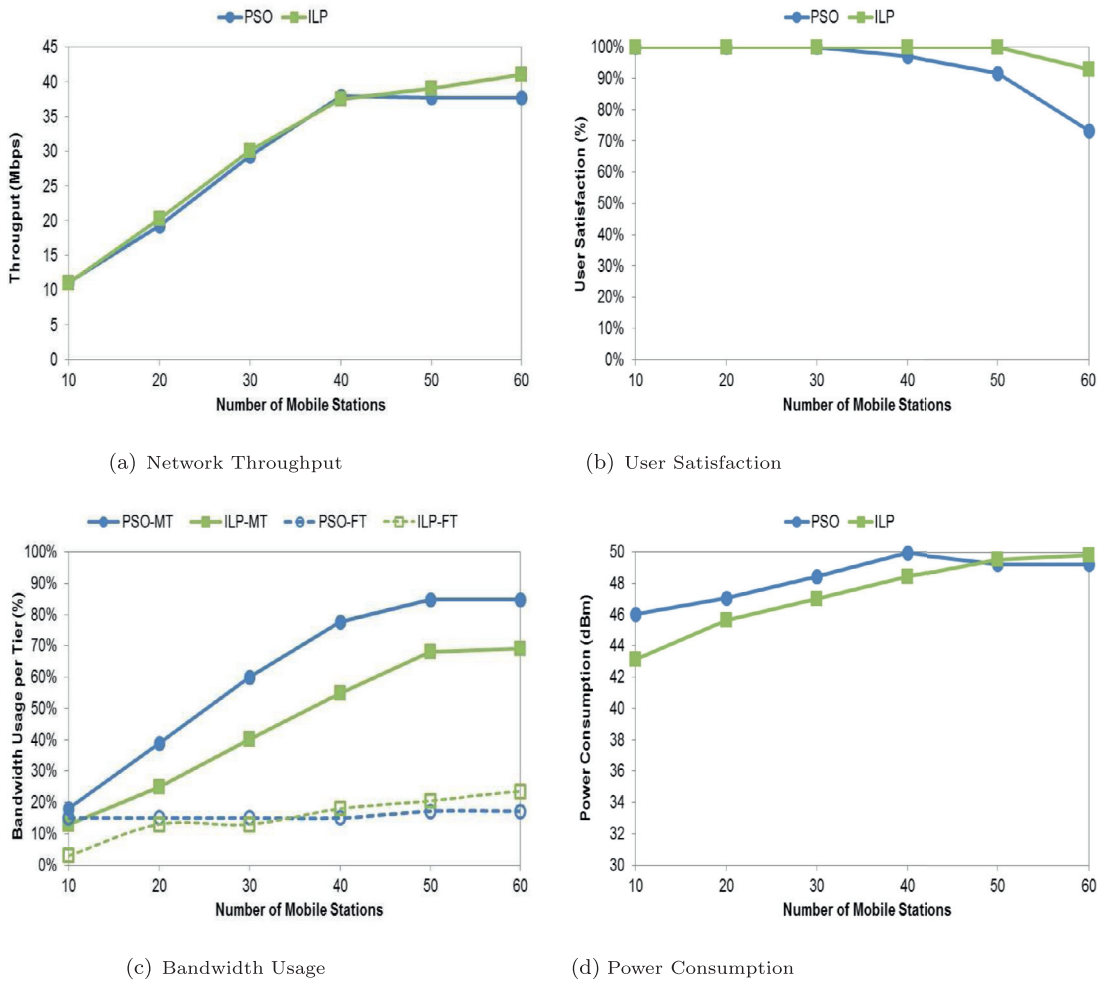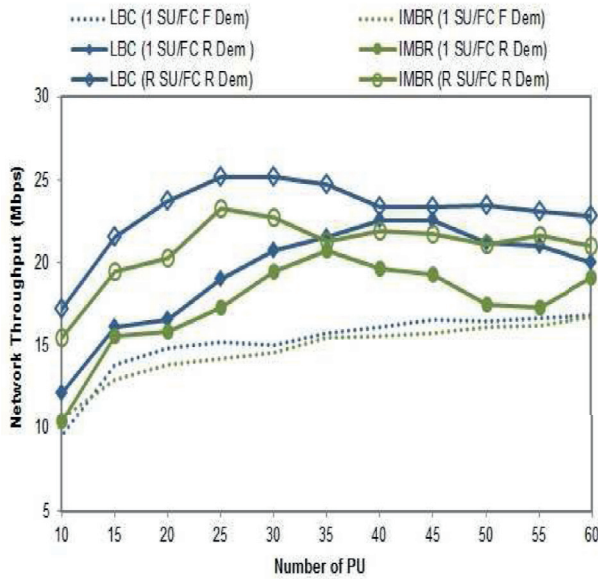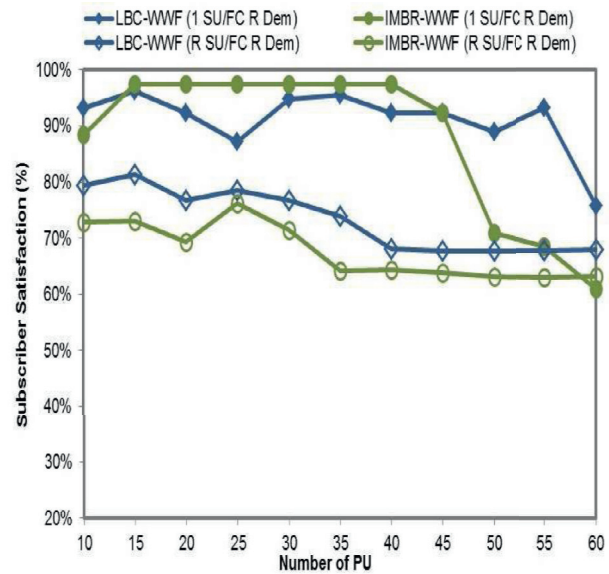

(a) Network Throughput

(b) User Satisfaction

(c) Bandwidth Usage

(d) Power Consumption

Fig. 5. Performance analysis of PSO and ILP models.

(a) Network throughput

(b) Subscriber Satisfaction

Fig. 6. Performance metrics under the incremental PU number scenario. Dotted lines corresponds to the scenario with 1 SU per FC with fixed demand equal to 512 kbps. Solid lines with filled markers correspond to the scenario with one SU per FC with random demand. Solid lines and markers with no fill represents the scenario with random subscriber number and random demand. The circle and diamond markers identify the IMBR and LBC model respectively.

From Fig. 6(b), it can be observed that the LBC-WWF model presents higher subscriber satisfaction than IMBR-WWF model in the case with variable number of subscribers per FC with random demand. Also, in general, the subscriber satisfaction is higher for both models in the scenario with one subscriber than in the scenario with several subscribers per FC except for IMBR-WWF model with high number of PUs The last feature is related to the fact that in the IMBR-WWF model the subscriber satisfaction decreases rapidly when number of PU exceeds 45. This can be explained by the fact that FCs with one subscriber can obtain more extra resources than FCs with higher subscriber number, since the former are able to grant access to more public users. Then, as femtocells become member of a cluster, they share the extra resources among all subscribers within the cluster. Thus, when the clusters are already established and FCs have more allocated public users, the subscriber satisfaction is negatively affected by the inter-cluster interference because the extra resources are shared with public users from the neighbor clusters. Therefore, the subscriber satisfaction can be reduced by two factors: the extra resource sharing and the inter-cluster interference. Note that the LBC model handles this issue better since the reduction of satisfaction for this model arrives only for more than 55 PU users.

Table 4 presents the public users distribution among the tiers for the cases with one subscriber per FC with random demand and variable subscriber number with random demand. As our LBC clustering model attempts to balance the traffic load of public users among the existing clusters taking into account their availability, it results in increased number of connected users, including public users, when compared with the IMBR clustering technique. Therefore, our clustering scheme reduces the blocking ratio in the network. In the particular case with one subscriber per FC and 60 public users within the FCs vicinities, it can be observed that for LBC the number of connected users is equal to 59, which corresponds to blocking ratio around 2%, while in case of IMBR only 53 users can be connected which corresponds to blocking ratio around 9%.

To demonstrate the efficiency of the proposed clustering technique LBC, Table 5 presents spectral efficiency (γ_{SU}) per subscriber

Table 4
Public users distribution per tier.

MS	LBC-WWF		IMBR-WWF	
	FT	MT	FT	MT
1 SU per FC with random demand				
10	7	3	9	1
20	11	9	16	4
30	20	10	21	9
40	24	16	22	18
50	25	25	23	24
60	26	33	21	32
Variable SU per FC with random demand				
10	5	5	8	2
20	10	10	11	9
30	13	17	15	15
40	15	25	11	29
50	13	37	11	38
60	13	47	12	46

in cluster member and stand-alone (SA) femtocells, the average gain in terms of subcarriers obtained for subscribers transmissions if FCs belong to a cluster, and the average number of subcarriers allocated per user in each tier. Both clustering schemes (LBC, IMBR) achieve the target SINR for subscribers in FCs belonging to clusters. It can be observed that the number of additional subcarriers for subscribers transmissions in our model is greater than the one obtained using IMBR clustering scheme (shown in the columns of Extra SC). Finally, the LBC clustering scheme gives higher number of allocated subcarriers per user at femto tier when compared with the IMBR scheme.

In summary, the proposed clustering technique (LBC) achieves better throughput than the interference mitigation and bandwidth reduction based clustering scheme. This is owing to the fact that our objective is to balance the traffic load from public users in order to get a cluster configuration that allows FC to get extra resources for their own subscribers.

Table 5
QoS guarantee and extra resources for subscribers in Femto tier.

PU umber	γ_{SU} in cluster		γ_{SU} in SA FC		Extra SC		SC/User in MT		SC/User in FT	
	LBC-WWF	IMBR-WWF	LBC-WWF	IMBR-WWF	LBC-WWF	IMBR-WWF	LBC-WWF	IMBR-WWF	LBC-WWF	IMBR-WWF
10	7.31	7.26	6.73	6.04	4	2	17	17	4	3
20	7.30	7.05	5.11	4.41	1	1	15	14	3	2
30	7.30	7.12	4.47	0	1	1	11	10	3	2
40	7.27	7.09	4.97	0	2	1	9	10	2	1
50	7.06	7.12	5.08	0	1	1	7	7	2	1
60	7.06	7.17	5.08	0	1	1	6	6	2	1

(a) Network Throughput   (b) Subscribers Satisfaction
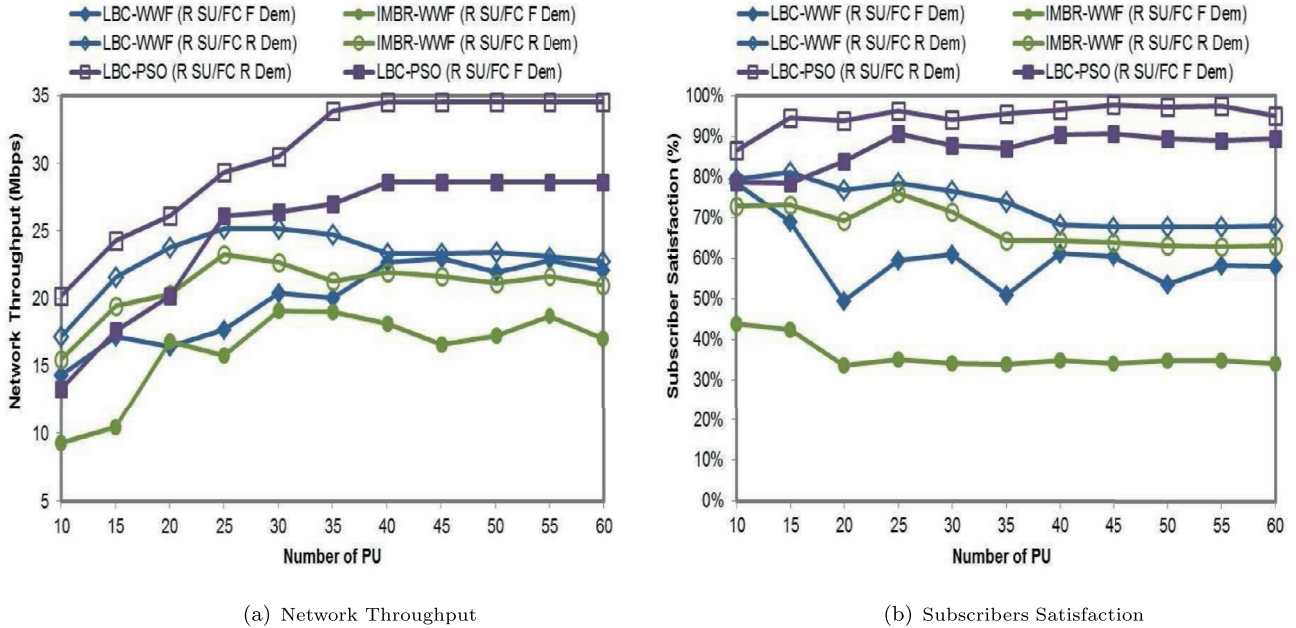
Fig. 7. Performance metrics for the incremental PU number scenario. The circle, diamond, square markers identify the IMBR-WWF, LBC-WWF and LBC-PSO models respectively. Filled markers correspond to the scenario with random number of subscribers per FC with fixed demand. Markers with no fill represent the scenario with random subscriber number and random demand.

6.3. Resource allocation algorithms comparison

In this section, we compare our three-stage model (LBC-PSO) with the WWF based resource allocation algorithm using both clustering schemes(LBC, IMBR). By doing so, we want to show the advantages of using PSO instead of WWF.

6.3.1. Network throughput and subscriber satisfaction

Fig. 7 shows the network throughput and the subscribers satisfaction for the scenarios with random number of subscribers SU per FC with a fixed demand of 512 kbps (R SU/FC F Dem)and variable demand between 128 kbps and 1 Mbps (R SU/FC R Dem). In the case of fixed demand, LBC-PSO presents a throughput gain of around 28% compared to LBC-WWF, which is due to the power distribution enhancement over the active bandwidth used to tackle the interference in femto tier. At the same time we can observe in Fig. 7(a) that the LBC-PSO model gives gain in the subscriber satisfaction between 30% and 40% when compared with the WWF model for any of the clustering schemes (i.e. LBC-WWF and IMBR-WWF). This is owing mainly to the fact that the WWF algorithm does not perform power control to mitigate the inter-cluster interference since the resources are independently allocated in each cluster. Unlike WWF, PSO algorithm is centralized and includes a constraint to reduce the inter-cluster interference level.
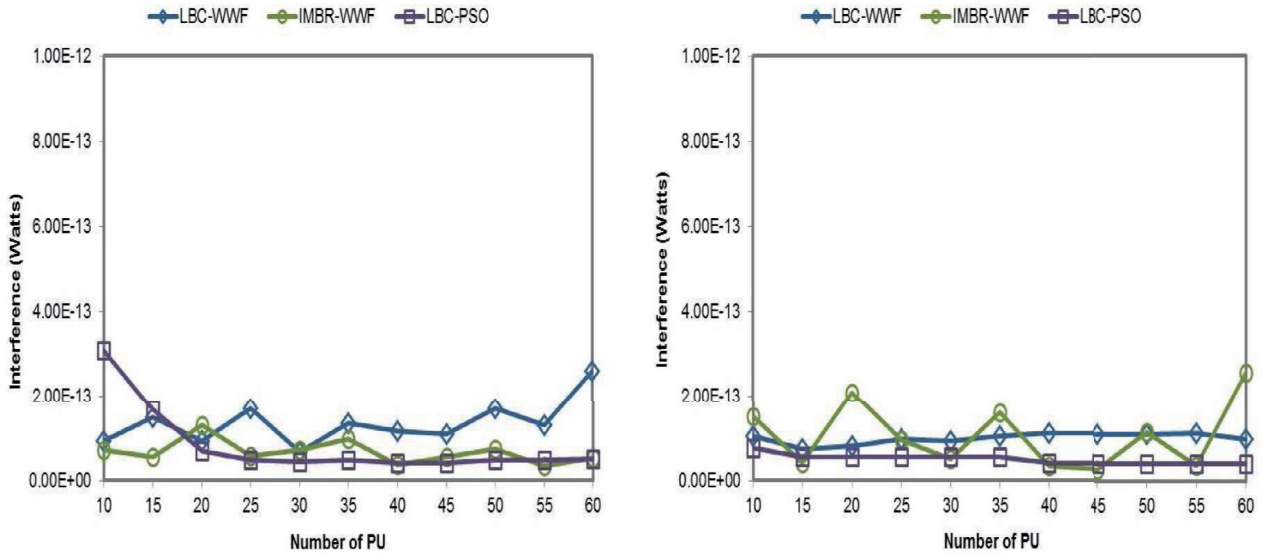
Fig. 8 shows the average interference per subcarrier for the LBC-PSO, LBC-WWF and IMBR-WWF models. Our proposed clustering technique (LBC) with WWF algorithm does not reduce the aver-

age interference level but if applied together with Particle swarm optimization it reduces the interference level below the values obtained by the IMBR-WWF model for most of the points.

6.3.2. Resource and user distribution

Table 6 presents the power consumption and bandwidth usage per tier for different number of public users for the case with random subscriber number per FC and variable demand. It also includes the number of blocked users. One can observe that the LBC-PSO model increases the total power consumption by around 6 dB at the femto tier while the MC power consumption is reduced by 3 dB compared to the LBC-WWF model. For the scenario with more than 40 public users, both models start blocking some public users. The main difference is that the LBC-WWF model rejects public users due to the power starvation at the macro tier without exhausting the total bandwidth while the proposed model starts blocking public users because the bandwidth is exhausted. This can be observe in Table 7 where the public users distribution among the tiers is presented.

Fig. 9 depicts the average power allocated per subcarrier in each tier. In the particular case of the macro tier, LBC-PSO requires between 30% and 66 % less power than the LBC-WWF model (see Fig. 9(a)). From Fig. 9(b), it can be observed that LBC-PSO model presents higher the transmitted power than the LBC-WWF model for more than 30 users in the femto tier, which is owing to the fact that the LBC-WWF model fails to allocate public users to femtocells when the inter-cluster interference increases and reallocates

(a) Scenario with Fixed Demand/SU   (b) Scenario with Random Demand/SU

Fig. 8. Average interference per subcarrier for scenarios with random number of subscribers per FC.
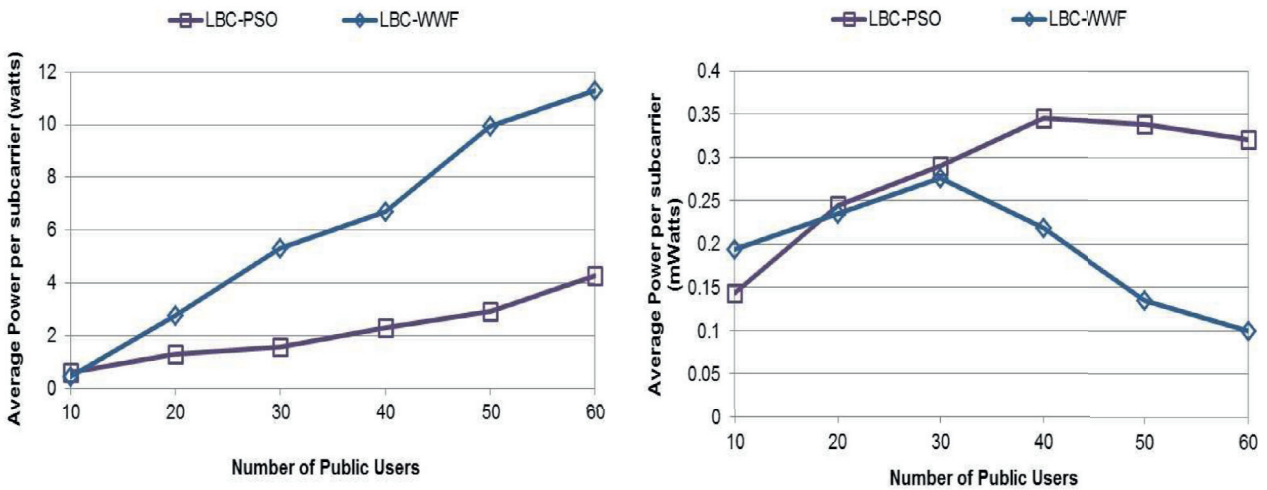

(a) Macro Tier   (b) Femto Tier

Fig. 9. Transmitted power per subcarrier.

Table 6
Power consumption and bandwidth usage (scenario with random number of SU per FC with variable demand).

PU number	Power consumption (dBm)				Bandwidth usage FT (%)				Blocking ratio	
	LBC-PSO		LBC-WWF		LBC-PSO		LBC-WWF		LBC	LBC
	FT	MT	FT	MT	FT	MT	FT	MT	PSO	WWF
10	13.80	51.43	13.06	51.35	20	32	19	14	0	0
20	16.27	55.70	13.13	56.38	26	59	15	48	0	0
30	17.49	56.71	13.68	57.83	27	73	14	64	0	0
40	18.82	56.81	12.02	59.03	29	71	11	75	0	2
50	18.82	56.81	12.48	59.03	29	71	11	77	8	12
60	18.82	56.81	12.48	59.03	29	71	11	80	17	15
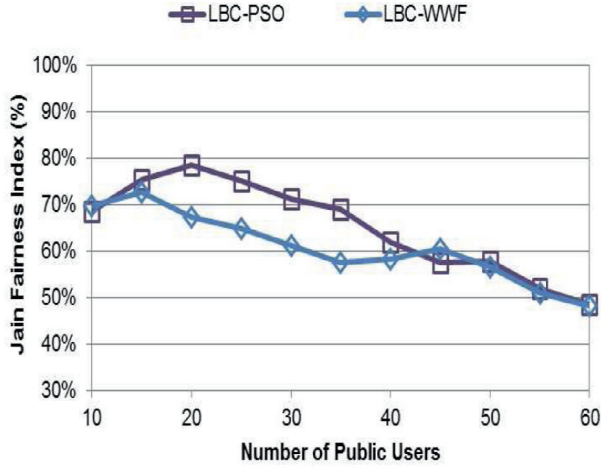
(a) Jain's Fairness Index for all users in network
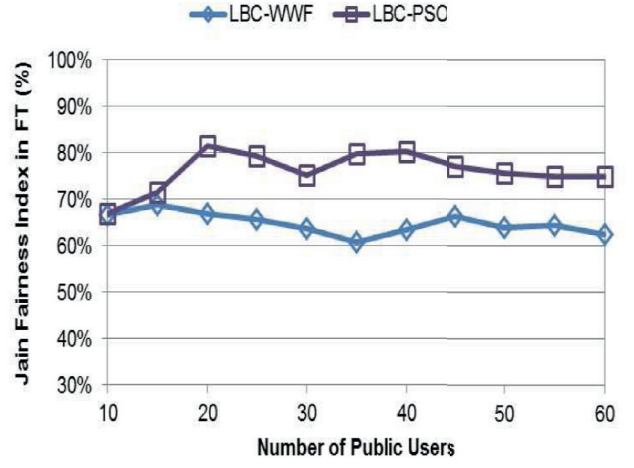
(b) Jain's Fairness Index for users associated to FCs

Fig. 10. Jain's fairness index.

Table 7
User distribution (%).

PU	LBC-PSO		LBC-WWF	
	FT	MT	FT	MT
10	50	50	60	40
20	40	60	30	70
30	40	60	20	80
40	45	55	20	78
50	38	54	18	70
60	32	51	17	68

them to be served by the macroell. Therefore, the LBC-WWF model increases the total transmitted power and bandwidth in the macrocell as it can be appreciated in Table 6.

6.3.3. QoS guarantee for subscribers

Table 8 presents the QoS guarantee and extra resources allocated to FC subscribers. In comparison with LBC-WWF, LBC-PSO is able to achieve higher spectral efficiency (γ_{SU}) and higher number of additional (extra) subcarriers for own FC subscribers while the values of average number of subcarrier per users in both tiers are similar to LBC-WWF.

6.3.4. Jain's fairness

In Fig. 10, we present the numerical results for the fairness among all users in the entire network as well as the fairness for the users associated with the femto tier. The fairness is measured using the Jain's Fairness index described in Section 5. From Fig. 10(a) it can be observed that LBC-PSO model increases the Jain's fairness index for all users in the network for cases with 40 public users or less. For more than 40 public users, both models present almost the same fairness value. Moreover, the fairness among the users associated with the femto tier is always guaranteed as shown in Fig. 10(b). In particular, our model enhances the fairness index by 10% to 20% for more than 20 public users when compared with the benchmark model.

In summary, the proposed PSO based resource allocation approach together with the proposed LBC clustering scheme provides several advantages such as: improved throughput, enhanced power distribution, lower interference levels, improved subscribers satis-

faction, and larger number of additional subcarriers allocated for subscriber transmissions.

6.4. FC density and cluster size

In this section, we analyze the performance of the proposed model (LBC-PSO) for dense femtocell networks. Unlike the majority of previous resource allocation approaches that analyze dense FC networks with a high number of femtocells located far away from each other (i.e. co-tier interference is negligible), we analyze a dense FC network, where FCs are close to each other such (as in [34–36]). In the tested scenarios, the FC density is changing by placing 10 to 50 FC (with interval of 10) in the area illustrated in Fig. 4 and keeping the distance of 2 FC coverage radiuses between FCs. In addition, a high density of public users is generated in the FCs vicinity (i.e. the total number of user that FCs might potentially serve) and each FC has one connected subscriber.

Fig. 11 shows the network throughput and subscriber satisfaction as a function of the number of FCs.

Fig. 11 (a) demonstrates that both models (LBC-PSO, IMBR-PSO) enhance the throughput as the number of FC increases. However, the LBC-PSO model obtains throughput gain between 4 and 11% in comparison with the IMBR-PSO model. The subscriber satisfaction is also improved by the LBC-PSO model with values between 85% and 90% as shown in Fig. 11(b), while IMBR-PSO model gives subscriber satisfaction values between 75% and 90%. This is owing to the fact that our model aims at guaranteeing the target SINR of subscriber transmissions as well as the compensation with extra subcarriers allocated for the own FC subscriber transmissions.

Table 9 presents the subscriber QoS guarantees in terms of spectral efficiency (γ_{SU}), the average of extra resources allocated to FC members of a cluster and the mean and standard deviation of cluster size for both clustering schemes with PSO based resource allocation algorithm. Both models are able to achieve the target spectral efficiency (i.e. $\gamma_{SU}=6$ bit/symbol) but the LBC-PSO model allocates higher number of extra subcarriers for FC subscribers when it is possible.

It can be observed that both models (LBC-PSO, IMBR-PSO) reduce the average number of allocated subcarriers per user in macro tier as the number of public users that are close to FC increases. This is owing to the fact that some users, being denied

Table 8
QoS guarantee and extra subcarriers for subscribers at Femto tier.

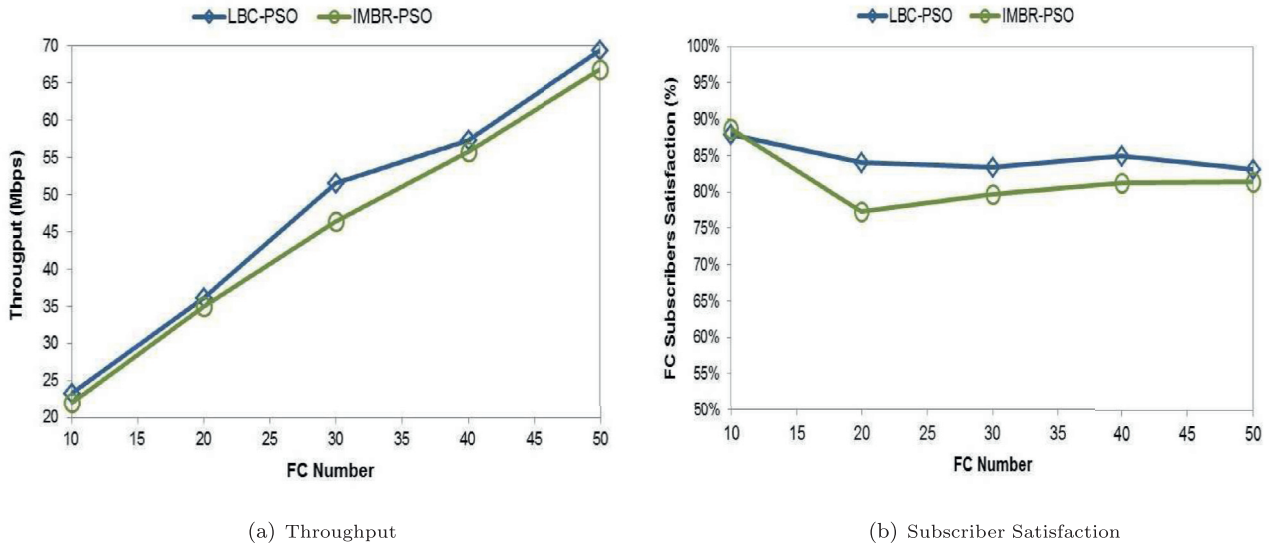| PU	Spectral efficiency γ_{SU} in cluster		Extra subcarrier		Macro tier SC per user		Femto tier SC per user	
number	LBC-PSO	LBC-WWF	LBC-PSO	LBC-WWF	LBC-PSO	LBC-WWF	LBC-PSO	LBC-WWF
10	7.80	6.62	1.67	1.00	16	16	5	5
20	8.05	7.05	3.67	3.25	12	14	5	5
30	8.16	7.23	4.17	3.50	10	11	5	5
40	8.21	6.70	3.33	1.00	7	7	5	4
50	8.21	6.93	3.33	1.25	7	7	5	4
60	8.21	6.68	3.33	1.00	7	5	5	4

(a) Throughput

(b) Subscriber Satisfaction

Fig. 11. Performance metrics for incremental FC number scenario.

Table 9
QoS guarantee and extra resources for subscribers at Femto tier.

FC	γ_{SU} in cluster		Extra SC	
number	LBC-PSO	IMBR-PSO	LBC-PSO	IMBR-PSO
10	6.84	7.03	0.5	0.4
20	7.39	7.05	0.8	0.4
30	7.13	7.15	1.0	0.0
40	6.98	7.11	0.4	0.24
FC	Avg. SC per User in MT		Avg. SC per User in FT	
Number	LBC-PSO	IMBR-PSO	LBC-PSO	IMBR-PSO
10	10	9	5	5
20	4	5	5	5
30	3	4	5	4
40	3	3	4	4
FC	Cluster size mean		Cluster size std. dev.	
Number	LBC-PSO	IMBR-PSO	LBC-PSO	IMBR-PSO
10	1.42	1.42	0.53	0.53
20	1.33	1.17	0.48	0.39
30	1.76	1.30	0.83	0.47
40	1.73	1.37	0.75	0.49

in macro tier should be at least equal to the average number of subcarriers allocated per user in femto tier. However, we do not consider such modification in this paper.

It is also worth noticing that the LBC-PSO model has higher cluster size mean than the IMBR-PSO model, which means that the femto tier will obtain more resources from the macrocell because more public users can be connected to the FC clusters. For the LBC-PSO model, the standard deviations values indicate that there are clusters with size between 1 and 3 for LBC-PSO and between 1 and 2 for IMBR-PSO.

6.5. Complexity and running time

The complexity of the proposed three-stage model depends on the number of subcarriers, the number of users, FC number and the number of clusters. In the tested scenarios, the PSO algorithm requires between 5 and 10 s to converge to a solution for the resource allocation problem with given cluster configuration and BS selection. However, the clustering scheme requires long running times as FC number increases especially under the worst case scenario, which is high density of public users. In Table 10 we present the running times for different FC and PU numbers. It can be noticed that our model requires longer running times in comparison with LBC-WWF model. These times can be reduced by using other PSO variants that can be addressed in a future research work.

Also note that in our LBC cluster formation scheme, once the current clusters are established, the algorithm takes into account the stand-alone FCs that can be merged with current clusters if the resources are exhausted for every cluster or if it is not possible to allocate public users to any cluster without depriving FC

service at lower tier, need to be served by the macrocell. Since our PSO based macrocell resource allocation model aims at the fair subcarriers distribution among the allocated users, the average number of allocated subcarrier per user is indeed reduced as the number of macro users increases. In order to avoid the reduction of average number of subcarrier allocated per user in macrocell, the PSO based algorithm should be modified to take into account the fact that the average number of allocated subcarriers per user

Table 10
Running time.

FC number	PU number	BS selection time	PSO RA time	Total time	
				LBC-PSO	LBC-WWF
10	30	0.15	2.50	8	1
20	60	0.35	7.79	42	3
30	90	0.81	13.14	103	8
40	120	2.10	23.04	189	43
50	150	4.08	35.15	305	89

subscriber transmissions. Therefore, the two-tier network should keep low number of stand-alone FCs to reduce the running times of the clustering mechanism since formation of new cluster configurations will be less likely to occur. In other words, the running time of the three-stage framework is reduced to the running time of the centralized PSO resource allocation algorithm, which is in the worst case scenario determined by the maximum number of iterations (i.e. 500 iterations from the converge analysis in Section 3.2).

It is worth noticing that a way to reduce the total running times shown in Table 10 is to find out first all possible cluster configurations from the current one. Then, several instances of the PSO based resource allocation run in parallel for each cluster configuration. Thus, the running time can be reduced. Moreover, there are some PSO variants that can be implemented to further reduce the running time of the PSO based resource allocation, such as Multi-swarm PSO [37,38] or the resource allocation algorithm can be performed locally within each cluster. However, these two strategies are out of the scope of the paper since our main goal is to get some insight results that can lead us to simpler heuristics when the three components of the framework can be carried out in a distributed fashion

7. Conclusion

In this paper we proposed a novel cluster based resource sharing model for OFDMA femtocell networks. The model consists of the Particle swarm optimization based resource allocation algorithm and the load balanced clustering scheme. The proposed model is able to determine the best serving BS and the bandwidth and power allocation for each user taking into account its demand, location, FC proximity and current cluster configuration. Our solution was tested under the incremental public user number scenario and compared with the benchmark model based on Weighted Water Filling resource allocation algorithm and the interference mitigation and bandwidth reduction based clustering scheme. We demonstrated that the proposed approach indeed improves the overall network throughput without depriving subscribers satisfaction by means of rewarding the femtocells with extra resources for their own transmission. Moreover, in the tested scenarios, the macrocell power consumption is reduced by 3 dB since the femtocells grant access to public users. By means of the femtocell power control, the proposed solution reduces the inter-cluster interference and allows the efficient bandwidth usage. The main disadvantage of the benchmark resource allocation algorithm lies in the lack of femtocell power control which increases the inter-cluster interference level and therefore degrades the QoS of femtocell subscribers transmissions. The proposed model has the drawback of high complexity and therefore long running times. In future works, we will investigate the PSO variants for the resource allocation, study further the cluster formation mechanism and its possibility to convert our model into a distributed model, and analyze the performance of the proposed framework using other channel propagation models that include the shadowing and fading effects.

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