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# Stable femtocells cluster formation and resource allocation based on cooperative game theory

Katty Rohoden [a,d,*], Rebeca Estrada [b,d], Hadi Otrok [c,d], Zbigniew Dziong [d]

[a] Department of Computer Science and Electronic, Universidad Técnica Particular de Loja, Loja, Ecuador
[b] Escuela Superior Politécnica del Litoral, Information Technology Center & ReDIT, Guayaquil, Ecuador
[c] Department of ECE, Khalifa University, Abu Dhabi, United Arab Emirates
[d] Department of Electrical Engineering, Université du Québec, École de Technologie Supérieure, Montréal, QC, Canada

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ABSTRACT

In this paper, we address the problem of forming stable groups of femtocells that can reduce the complexity of the resource management and enhance the subscribers' satisfaction while guaranteeing the service to nearby public users. In a macro-femtocell network, the resource management becomes a very challenging task as the number of deployed femtocells increases. Several strategies of clustering have been proposed to allocate resources in a distributed manner. However, forming stable clusters of femtocells is yet to be addressed. We propose a distributed cluster-based resource allocation framework that consists of three components: (1) a base station selection algorithm for public users that guarantees them a high data rate, (2) a coalition game, where femtocells are grouped into stable clusters to reduce the resource allocation complexity, and (3) a fair resource allocation using the Shapley value to compute the payoff of each cluster member based on Particle Swarm Optimization algorithm. The $\epsilon$-core concept from game theory is used as the stability criteria to form the clusters. A performance comparison is carried out between the proposed solution and two benchmark models: a centralized approach and a distributed approach with non-stable group formation. Simulation results show that our framework indeed increases the network throughput, provides higher subscribers satisfaction, and higher Jain fairness index for the distribution of resources among the existing users in the femto-tier.

## 1. Introduction

According to [1], global mobile data traffic will increase approximately sevenfold between 2016 and 2021. One promising solution for achieving this goal is network densification. Accordingly, the mobile broadband network has introduced a heterogeneous network model, which consists of macrocells and femtocells (also known as small cells). In fact, it is expected that the next generation of wireless networks will be dominated by densely deployed femtocell networks, also referred to as ultra-dense femtocell networks (UDFNs). Femtocells (FCs) are home base stations that are deployed inside the coverage area of a macrocell (MC). Their purpose is to increase the coverage in dead zones for indoor environments and provide better system capacity. It should be noticed that femtocells are mostly deployed by end users without prior planning. As a result, interference can increase dramatically if the resources are not adequately managed among neighboring femtocells. In addition, interference depends on the access control mechanisms for femtocells.

Access control mechanisms are used to determine if public users are allowed to access a nearby femtocell or not. There are three access control categories: closed access, open access and hybrid access [2]. In the closed access case, the public users cannot access the nearby FCs and the FC subscribers get full benefit of their own FC but this approach limits the network bandwidth utilization and increases the interference to nearby public users, which is known as a dead-zone problem. The open access category allows any user to benefit from FCs services. However, this approach requires tight coordination between FCs and their macrocell that may result in traffic congestion over the backhaul connections. In the hybrid access case, a public user can access a nearby FC but some capacity of this FC is reserved for this FC subscriber. 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 the hybrid access control.

A macro-femtocell network can be implemented using spectrum partitioning [3] or spectrum sharing [4] between tiers. Spectrum sharing approaches allow femtocells to share the same set of subcarriers with the macrocell. On the other hand, spectrum partitioning approaches divide the set of subcarriers into two disjoint sets to be used by the macro-tier and the femto-tier. Nevertheless, the resource allocation problem is a

* Corresponding author at: Department of Electrical Engineering, Université du Québec, École de Technologie Supérieure, Montréal, QC, Canada.
*E-mail addresses:* karohoden@utpl.edu.ec (K. Rohoden), restrada@espol.edu.ec (R. Estrada), hadi.otrok@ku.ac.ae (H. Otrok), Zbigniew.Dziong@etsmtl.ca (Z. Dziong).

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very challenging task for dense femtocell networks. Currently, several approaches have been proposed to solve the clustering together with the resource allocation such as [5,6]. In [5], interfering femtocells are grouped into clusters while the subchannel allocation is performed by a cluster head, the femtocell with the highest degree of interfering neighbors. In [6], the clustering is performed based on femtocells positions. Specifically, the K-means algorithm executes an iterative, data-partitioning algorithm based on a given cluster size and cluster number. Then, the resource allocation takes into account QoS requirements and cross-tier interference.

The majority of the previous cluster-based resource allocation approaches do not consider neither the stability of the clusters nor the fair allocation of resources. The cluster stability assures that the cluster configuration is not constantly changing over the time. Thus, the number of unnecessary handovers of public users changing their serving femtocell can be reduced. Moreover, there is no need to perform a constant resource reallocation due to the cluster configuration changes.

The main limitations of the prior related work can be summarized as follows:

1. The majority of approaches focus on clustering schemes for femtocells that work in closed access mode [7,6]. Those approaches are not suitable for femtocells working in hybrid access mode and thus the access to nearby public users would not be guaranteed.
2. Lack of cluster formation methods that ensure the formation of stable clusters. Cluster stability is important since it prevents the femtocells from abruptly changing the existing cluster for another one, which leads to an unstable network.
3. Most of the resource management approaches do not ensure a fair allocation of resources [8,9]. A fair resource allocation allows for the cooperative femtocells to receive a higher number of subcarriers in comparison with the non-cooperative femtocells.
4. Lack of rewarding methods that consider resources as a payment from the macrocell to encourage femtocells to form clusters and grant service to public users.

To overcome the above limitations, we propose a distributed resource allocation framework that maximizes the femto-tier throughput while enhancing the satisfaction of femtocell subscribers. The proposed solution focuses on the fairness of the resource distribution among all femtocells by means of the Shapley value and the cluster stability by applying the e-core concept of the game theory. Previously, we addressed a resource distribution in [10] using an equal distribution of the resources among FCs within a cluster. However, this method does not guarantee the same subscriber satisfaction for the cooperative femtocells. The main differences between the current work and our prior work [10] are the methods used to reward the cooperative femtocells and in the applied stability criteria.

The proposed solution comprises three stages. In the first stage, a Base Station (BS) selection algorithm is used to assign public users to BSs that provide them with high data rates. The second stage executes a cluster formation, in which a coalitional game is carried out to group femtocells into stable clusters. This stage includes the cluster head selection. Finally, in the third stage, a resource allocation algorithm based on the Shapley value and Particle Swarm Optimization (PSO) is implemented. In this stage, the cluster heads run locally the resource allocation algorithm within their respective clusters.

In brief, the main contribution of this paper is a framework that is able to:

- Form stable clusters while enhancing the subscriber's satisfaction using the $\varepsilon$-core concept of game theory.
- Allocate resources fairly among the cluster members using the Shapley value and PSO algorithm.

The remainder of this paper is organized as follows. Section 2 presents the related work where clustering for macro-femtocell networks is emphasized. Section 3 describes the system model, problem formulation and model parameters. Section 4 explains the components of the proposed model for clustering and resource allocation. This section also covers the performance metrics and the benchmark models. Section 6 provides simulation results. Finally, conclusions are drawn in Section 7.

## 2. Related work

This section presents the latest studies that address the resource allocation problem in femtocell networks. Specifically, works based on game theory and clustering techniques are presented. In general, the resource allocation problem for heterogeneous cellular networks has been widely investigated. For instance, authors in [8] proposed a centralized resource allocation framework. The aim was to maximize the system capacity for dense indoor mobile communication systems by jointly allocating power and subchannels. A physical resource block (PRB) allocation with improved QoS (Quality of Service) by avoiding co-channel and co-tiered interference is proposed in [11]. [7] analyzes an optimal decentralized spectrum allocation policy for two-tier networks. The approach is optimal in terms of area spectral efficiency while guaranteeing that MC and FC users obtain a prescribed data rate. A framework to allocate differentiated resources to users was developed in [12] by considering different users' requirements.

Game theory has been considered to solve the problem of resource allocation in a macro-femtocell network. In [13], an evolutionary game is proposed to adjust the FC transmitted power to mitigate the cross-tier interference by means of FC cooperation with the MC. Thus, FCs are allowed to reuse the less interfered MC channels although their subscribers' satisfaction is not guaranteed. In [9], the MC and the FCs maximize their capacity by playing a multiple-leader multiple-follower Stackelberg game under a distributed algorithm for downlink power allocation. In [14] a distributed algorithm for the formation of stable femtocells coalitions is proposed to suppress intratier interference using interference alignment. Power control in a two-tier Orthogonal Frequency Division Multiple Access (OFDMA) femtocell network is proposed in [15] to mitigate the co-tier and cross-tier interference. Further, an auction game is formulated between the MC and the FC users in order to minimize the total power radiated by the FC base station.

Recently, cluster-based approaches have been studied to solve the complexity of resource allocation and interference management in densely deployed femtocells. In [6], a semi-centralized scheme based on clustering for joint power control and resource allocation is proposed, the problem of cross-tier and co-tier interference is tackled based on a closed access mode scenario. A centralized meta-heuristic model and a semi-distributed interference management scheme are proposed in [16] and [17], respectively, to address the problem of joint clustering and resource allocation. In [18], a resource allocation algorithm is proposed based on FCs clustering and a femto user mobility model to guarantee the mobile service quality. [19] presents a power control scheme for co-channel deployment of cluster of femtocells in the macrocell area. [5] presents a hierarchical resource allocation framework for small cell networks. Their proposal is comprised of small cells clustering, a cluster head election to carry out intra-cluster subchannels allocation, and a distributed learning-base coordination mechanism to tackle the inter-cluster interference.

Table 1 summarizes the relevant prior approaches that focus on clustering and game theory for resource allocation in macro-femtocell networks.

## 3. System model

We consider a macro-femtocell network with several femtocells, FCs, deployed under the coverage area of a macrocell, MC, as illustrated in Fig. 1. Let $F = \{f_1, f_2, \ldots, f_{N_f}\}$ be the set of FCs where the $f_i$ is the $i$th femtocell of the considered macrocell and $|F| = N_f$. The set of available subcarriers is denoted as $SC = \{s_1, s_2, \ldots, s_{N_s}\}$ where $s_i$

**Table 1**
Literature review summary of the resource allocation in macro-femtocell networks.

| Techniques | Scheme | Advantages | Shortcomings |
|---|---|---|---|
| Resource allocation | • decentralized [7] | • Optimal in terms of Area Spectral Efficiency, considers QoS requirements. | • FCs operate in closed access mode. |
| | • decentralized [9] | • Considers Stackelberg equilibrium, reduces algorithm costs. | • Prioritizes MC over FCs. |
| | • decentralized [10] | • Cluster-based, increases SUs satisfaction, guarantees service to PUs, manages stability. | • Fairness not considered, high clustering computation time. |
| | • decentralized [20] | • Finds the top-coalition formed by femtocells and macrocell, PSO-based resource allocation. | • Fairness not considered. |
| | • centralized [16] | • Uses PSO, manages hybrid access mode, serving BS selection. | • No cluster stability, high complexity. |
| Power control | • decentralized [13] | • FC cooperation with MC, reuse MC channels. | • FC subscriber satisfaction not guaranteed, FC access policy not defined. |
| | • hybrid scheme [19] | • Minimizes FC power consumption, guarantees user's QoS. | • Manages CSG, no cluster stability. |
| Interference management | • centralized [11] | • Considers QoS, manages co-channel and co-tiered interference, improves resource efficiency. | • Manages closed subscriber group. |
| | • decentralized [14] | • Interference alignment technique, stability based on recursive core. | • Wired backhaul constraints. |
| Joint schemes | • centralized [8] | • Allocating power and subchannel, maximizes the system capacity. | • Poor power allocation, additional complexity, problem of fairness. |
| | • decentralized [15] | • Guarantees FC throughput requirements, low computational complexity. | • Low femtocell density, no incentives to FC users. |
| | • semi-centralized [6] | • Considers cluster members' QoS requirements, alleviates cross-tier interference. | • No resource allocation for MC users, closed FC access, no cluster stability. |
| | • partially-distributed [5] | • Mitigates co-tier interference, reduce network complexity, manages graph coloring. | • Manages CSG, no cluster stability, no incentive to FCs. |

denotes a subcarrier. Furthermore, $SC$ is partitioned into two disjoint sets, $SC_{macro}$ and $SC_{femto}$, in such a way that their intersection is the empty set and their union is $SC$. These two disjoint sets represent the set of subcarriers for the macro-tier and the femto-tier, respectively. Each subcarrier, $s_i$, has a bandwidth denoted by $B_s$.

We assume that each femtocell can grant service to one subscriber since in this case FCs are more likely to obtain more resources than in the case of FCs having multiple subscribers, as it was demonstrated in our prior work [16]. It is assumed that femtocells work in the hybrid access mode allowing to grant service to nearby public users as well as their own subscribers. The demanded data rate for subscribers and public users is assumed to be random.

The resource allocation complexity in the considered macro-femtocell network is addressed by grouping femtocells into clusters. For example, in Fig. 1, the femtocells $f_5, f_6, f_7$ and $f_8$ are forming a cluster. Within this cluster, the interference among FCs is controlled by allocating resources in an orthogonal fashion. However, in the same figure, there are some femtocells that do not belong to any cluster, i.e. $f_1, f_2, f_3, f_4, f_8$ and $f_{10}$. Since these femtocells use the same set of subcarriers, it can cause interference among them, for example, $FC_1$ causes interference to $f_3$'s subscriber, $SU_3$. This interference can be avoided if femtocells form clusters and a designated femtocell, within each cluster, coordinates the allocation of resources, e.g. a cluster head.

Our model proposes an algorithm for the formation of femtocell clusters and the allocation of resources locally within each cluster. The set of clusters is defined as $C = \{c_1, c_2, \dots, c_{N_c}\}$. The total amount of clusters $|C| = N_c$.

### 3.1. Problem formulation

Our goal is to maximize the femto-tier throughput, estimated as the sum of the achievable data rates of the users served by the femtocells forming clusters in the network. The objective function is defined as:

$$\max_{\epsilon,\alpha,\beta,\mathbf{P},\mathbf{C}} \sum_{c\in\{C\}} \sum_{f\in\{F\}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \epsilon_f^c \alpha_i^f \beta_i^{s,f} log_2(1 + SINR_i^{s,f}) \tag{1}$$

where $P$ consists of power allocations $P_i^{s,f}$ per user $i$ served by femtocell $f$ in the frequency $s$. $MS$, $SC$ and $C$ are the sets of mobile stations, subcarriers, and clusters, respectively, $F$ is the set of femtocells, $\epsilon$ is the vector of binary variables, $\epsilon_f^c$, that defines membership of femtocell $f$ in cluster $c$. $\alpha$ and $\beta$ are the vectors that represent user base station association and bandwidth allocation per user, respectively. These two parameters are indicator functions and their values are either 1 or 0. In other words, $\alpha$ is composed of binary variables, $\alpha_i^f$, that determines if user $i$ is served by femtocell $f$ while $\beta$ comprises binary variables $\beta_i^{s,f}$, that indicates if subcarrier $s$ is allocated to user $i$ in femtocell $f$. $SINR$ perceived by mobile user $i$ being served by femtocell $f$ in subcarrier $s$ is assumed to be given by

$$SINR_i^{s,f} = \frac{\alpha_i^f P_i^{s,f}}{PL_i^{s,f} \times (N_0 + \sum_{h\in\{C\setminus c\}} \sum_{f\in\{F^h\}} I_i^{s,f})};$$
$$c \in C, f \in F^c, i \in MS \tag{2}$$

where $P_i^{s,f}$ is the transmitted power from serving BS $f$ to user $i$ in subcarrier $s$, $PL_i^{s,f}$ is the path loss due to the channel propagation models for indoor environment, and $I_i^{s,f}$ represents the co-tier interference. In our model, the interference source for the femto-tier is the inter-cluster interference that is represented by the second term of the denominator in Eq. (2). The propagation model used to estimate the SINR ratio is similar to the one presented in our previous work [21], and is given by:

$$PL_i^{s,k}(dB) = 10log_{10}(d_{ik}^{\omega_f}) + 37, k \in F \tag{3}$$

where $d_{ik}$ is the distance from BS $k$ to user $i$ (that should be given in meters) and $\omega_f$ is the indoor attenuation factor assumed to be equal to 3, in accordance with the carrier frequency used for femtocells [22].

Eq. (1) formulates the maximization of the femto-tier throughput in a centralized manner that creates a Mixed Integer Nonlinear Programming (MINLP) problem with continuous and discrete variables and nonlinear functions. This problem was proved to be intractable in [17] owing to the fact that the computational complexity increases as the FC number increases. In addition, the computational complexity is a function of the number of possible cluster configurations that can be formed. In [17], the authors determined that the potential number of cluster configurations is given by the Stirling number of the second kind (Bell number), which grows exponentially with the number of femtocells and the complexity is given as $\mathcal{O}(f^f)$. Therefore, in order to reduce the complexity, we propose to decompose the maximization problem into two sub-problems: the clustering sub-problem that forms the clusters and the resource allocation within each cluster sub-problem that maximizes each cluster throughput. It is important to underline that our approach finds a satisfying near-to-optimal solution within each cluster.

The clustering sub-problem is solved by using a coalitional game in partition form where femtocells are considered the players of the

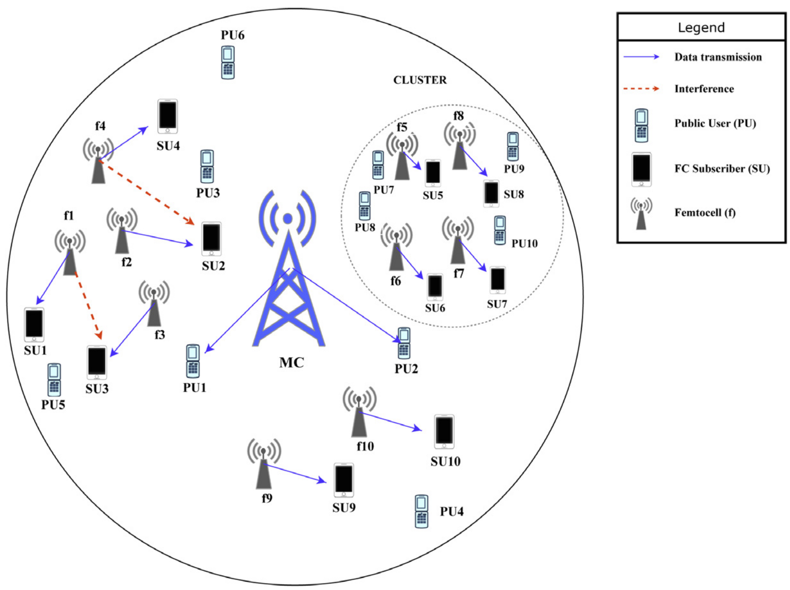



**Fig. 1.** Topology of the macro-femtocell network.

game. In this game, femtocells are divided into disjoint clusters using Algorithm 2. The goal of the clustering is to distribute the resource allocation per cluster and improve femtocells' performance. In particular, the femtocells cooperate in the formation of clusters to increase their data rate and reduce the co-tier interference. In addition, every cooperative femtocell will grant service to nearby public users. As a consequence, cooperative femtocells receive extra-subcarriers for their subscribers which in turn increase the throughput of the cluster. Thus, the increase of the networks' throughput is guaranteed by the increase of every cluster's throughput. In addition, our solution focuses on forming stable clusters. To tackle this task, we use a stability criterion based on the e-core concept of game theory. Thus, when stability is maintained, the solution that maximizes the throughput of each cluster is equivalent to maximizing the sum of the throughputs of all clusters, since the clusters do not change constantly.

On the other hand, the resource allocation-subproblem, that maximizes the throughput within a cluster, is solved for every user within a cluster using Algorithm 3 that is based on PSO. In this case, within each cluster, the femtocell with highest number of neighbors is elected as the cluster head. The cluster head is responsible for the resource allocation among all the members of the cluster and the objective function of the resource allocation sub-problem is formulated as follows:

$$\max_{\boldsymbol{\alpha},\boldsymbol{\beta},\mathbf{P}} \sum_{f\in\{F^c\}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \alpha_i^f \beta_i^{s,f} log_2(1+SINR_i^{s,f}) \tag{4}$$

### 3.1.1. Model constraints

Our objective function (4) is subject to the following constraints:

- Constraint (5) is used to avoid the cross-tier interference, which means that a subcarrier being used in the macro-tier is not used by any cluster in the femto-tier. Furthermore, subcarriers cannot be reused within a cluster but they can be reused in different clusters.

$$\sum_{k\in\{MC,F^c\}} \sum_{s\in\{SC\}} \beta_i^{s,k} \le 1 \quad ;i\in MS \tag{5}$$

- Upper bound for the allocated subcarriers to the cluster $c$ (i.e. femto-tier).

$$\sum_{f\in\{F^c\}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \alpha_i^f \beta_i^{s,f} \le N_s - \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \alpha_i^{MC} \beta_i^{s,MC} \tag{6}$$

- Spectral efficiency achieved by mobile user $i$ within a cluster is higher or equal to a target spectral efficiency. Here, $\gamma_f$ represents the target spectral efficiency in FC $f$.

$$log_2\left(1+SINR_i^{s,f}\right) \ge \alpha_i^f \beta_i^{s,f} \gamma_f \quad ;i\in MS, f\in\{F^c\}, s\in\{SC\}, \tag{7}$$

- One user can be assigned to only one base station.

$$\sum_{k\in\{MC,F^c\}} \alpha_i^k \le 1 \quad ;i\in MS \tag{8}$$

- Lower bound for minimum data rate for public users, which is equal to the data rate that macrocell can offer to the user at a given instant.

$$B_s \times \sum_{s\in\{SC\}} \beta_i^{s,k} \gamma_k^s \ge \alpha_i^k \times D_i \quad ;i\in MS \tag{9}$$

### 3.1.2. Model parameters

The parameters of the proposed model are detailed in Table 2. These parameters are classified into: system, input, and output parameters. The system parameters describe the network features while the input parameters specify the users' requirements and locations. Output parameters are the set of stable clusters, the set of femtocell-cluster membership, and the bandwidth and power resources allocated to all users.

The proposed solution consists of three stages: (1) a BS selection for PUs, (2) a cluster formation based on a coalitional game, and (3) a distributed fair resource allocation algorithm.

## 4. Stable cluster formation and resource allocation framework

In this section, we describe the proposed framework that performs: (1) a BS selection for PUs based on their requested data rate and their proximity towards the FCs, (2) a cluster formation algorithm based on a coalitional game where cooperative FCs are rewarded with extra-subcarriers and the clusters stability is analyzed using the $\epsilon$-core concept, and (3) a fair resource allocation within each cluster based on the Shapley value and the PSO algorithm.

In the following sections we describe the algorithms used to implement the three stages of the proposed framework.

**Table 2**
Model parameters.

| Name | Description |
|---|---|
| System parameters | |
| $C$ | Set of clusters |
| $c_{max}$ | Maximum size achieved by a cluster |
| $SC$ | Set of available subcarriers |
| $MS$ | Set of mobile users |
| $F$ | Set of deployed femtocells |
| $F^c$ | Set of FCs per cluster $c$ or $h$ |
| $B_s$ | Bandwidth per subcarrier |
| $BW_c$ | Bandwidth reserved for the clusters formation |
| $N_f$ | Number of femtocells |
| $N_c$ | Number of clusters |
| $N_s$ | Number of subcarriers |
| $N_s^f$ | Average number of subcarriers required per femtocells |
| $N_{s-extra}^{f,c}$ | Number of extra-subcarriers received by FC $f$ in the cluster $c$ |
| $P_k^{Total}$ | Total transmitted power in BS $k$ |
| $P_k^{max,s}$ | Maximum transmitted power per subcarrier in BS $k$ |
| $P_f^{max}$ | Total transmitted power in femtocells |
| $r_{MC}, r_f$ | Radii in macrocell and femtocells |
| $\theta_f, \theta_{MC}$ | Attenuation factor of indoor and outdoor environments |
| $\gamma_{MC}^s, \gamma_f^s$ | Subcarrier $s$ spectral efficiency in MC and in FC $f$, respectively |
| $\gamma_{MC}, \gamma_f$ | Target subcarrier spectral efficiency in MC and in FC $f$, respectively |
| $\omega_k$ | Outdoor/indoor attenuation factor $k \in MC, FC$ |
| $f_c$ | Carrier frequency adopted by the MC (in MHz) |
| $N_0$ | Average Thermal Noise Power |
| $v(c)$ | Value of the cluster $c$ in terms of subcarriers |
| $x_{f,c}$ | Individual payoff of FC $f$ in cluster $c$ |
| Input parameters | |
| $R_{SU}^f$ | Subscriber data rate demands in FC $f$ |
| $R_{PU}^f$ | PU data rate demands in FC $f$ |
| $D_i$ | Requested data rate demand of mobile user $i$ |
| $D_c$ | Requested data rate demand of cluster $c$ |
| $D^{f,c}$ | Requested data rate demand of femtocell $f$ in cluster $c$ |
| $d_{if}$ | Distance from FC $f$ to the mobile user $i$ |
| $d_{iMC}$ | Distance from MC to the mobile user $i$ |
| Output parameters | |
| $\alpha_i^k$ | User $i$ is assigned to BS $k$ |
| $\epsilon_f^c$ | Femtocell membership of the cluster $c$ |
| $\beta_i^{s,k}$ | Subcarrier allocated to user $i$ in BS $k$ |
| $P_i^{s,k}$ | Transmitted Power in DL transmission between BS $k$ and the user $i$ |
| $Ra_{SU}^{f,c}$ | Data rate allocated to femtocell $f$ in cluster $c$ to serve SUs |
| $Ra_{PU}^{f,c}$ | Data rate allocated to femtocell $f$ in cluster $c$ to serve PUs |

### 4.1. Base station selection for public users

The objective of the base station selection procedure is to select the femtocell that can grant service to nearby public users. For this, the public users are sorted in a descending manner by their demanded data rate and in ascending manner by their distance towards FCs, considering that each FC can be a cluster or belongs to a cluster. In this approach, the resource allocation uses two algorithms, the WWF algorithm and the PSO algorithm. The WWF algorithm [10] is used to determine the possible offered data rate for every public user in the base station selection stage, while the PSO algorithm is used in the final allocation of resources per cluster. While PSO could be also used in the base station selection stage, we opted for the WWF algorithm since it reduces the computation times as was demonstrated in [16]. Each public user is assigned to the femtocell that provides higher data rate than the macrocell with available capacity. Then, the femtocell updates its capacity for the next public user in the list. Otherwise, the public user is assigned to the macrocell. The base station selection procedure is repeated until all PUs are assigned to base stations. The base station selection for public users is described in Algorithm 1.

### 4.2. Clustering

In this section, the clustering stage is presented. Clustering techniques allow reducing the resource allocation complexity of a dense femtocell network. In addition, the co-tier interference is avoided since the set of subcarriers allocated to FCs in a cluster is managed by a cluster head. That is, the cluster head allocates different subcarriers to all FCs within a cluster. The clusters created by the proposed algorithm are stable, i.e., no FCs would gain from changing the cluster allocation. The stability conditions for each possible cluster are presented in Section 4.2.2.

**Algorithm 1:** BS selection for public users

```
Data: Set of users MS,
      Cluster set C
      User Locations (X_i, Y_i), FC Locations (X_f, Y_f), Demands(D_i)
Result: α_i^k BS selection, MS^c Set of users for each cluster
begin
   Sort set MS in decreasing order by demanded data rate (D_u);
   for each u ∈ MS do
      Determine the set of clusters that can possibly serve the public users Cluster_i.
      for each c ∈ Cluster_i do
         Determine the possible offered data rate using WWF based resource allocation
         algorithm.
      end
      Select the set of Cluster that satisfied the data rate higher than the macrocell,
      Cluster_i^*
      Sort the Cluster set, Cluster_i^*, in decreasing order by offered data rate
      for each c ∈ Cluster_i^* do
         if Femtocell f belonging to cluster c has capacity then
            Assign the user to the femtocell in the cluster in the ordered list, α_i^f = 1.
            Increase the number of femto or public users served by FCs depending on
            its type.
            Reduce the available capacity of femtocell f.
            Break
         end
      end
      if user u was not assigned to any cluster then
         Assign user to the macrocell, α_i^MC = 1.
      end
   end
end
```

#### 4.2.1. Coalition formation game fundamentals

In order to solve the clustering problem, we propose a coalitional game with Transferable Utility (TU) where FCs are the players. In the proposed coalitional game, FCs are encouraged to cooperate in the formation of clusters while improving their own performance by increasing their SUs satisfaction and granting service to some nearby PUs. From now on the groups of FCs are named as clusters or coalitions interchangeably.

**Definition 1** (*Game*)**.** A coalitional game with transferable utility is defined as the pair $(\mathcal{N}, v)$ where $\mathcal{N} = \{F\}$ is the set of players that includes the subset of available FCs, and function $v$ is defined for each coalition $c \subseteq \mathcal{N}, v(c)$ as a real number representing the utility that coalition $c$ receives, also known as the value of a coalition. This utility can be distributed in any arbitrary way among the FCs belonging to the coalition. The proposed coalitional game is in partition form as $v(c)$ depends on how the FCs are organized outside $c$ since FCs in a coalition experience interference from FCs outside the coalition $c$.

Note that in our approach we assume that each femtocell is able to collect the needed information about the corresponding data rate demand of nearby public users and neighboring femtocells. For example, this can be done by means of the cognitive pilot channel (CPC) mechanism [23].

**Definition 2** (*Preference Relation*)**.** The preference relation is a standard way to model player preferences. Let $X$ be the set of outcomes elements with common elements $x, y, z$. The relation on $X$ represents the relative merits of any two outcomes for the player with respect to some criterion. The following notations denote strict and weak preferences. We denote $x \succ y$ whenever $x$ is strictly preferred to $y$ and $x \succeq y$ whenever $x$ is weakly preferred to $y$. The indifference relation is denoted by $x \sim y$ which means that the player is indifferent between $x$ and $y$ [24].

**Definition 3** (*Shapley Value*). Given a coalitional game $(\mathcal{N}, v)$, a coalition $c$, a set of players $\mathcal{N}$, a value of coalition $v(c)$, the Shapley value of player $i$ is given by

$$\phi_i = \sum_{c \subseteq \mathcal{N} \setminus i} \frac{|c|!(|\mathcal{N}| - |c| - 1)!}{|\mathcal{N}|!} [v(c \cup i) - v(c)] \tag{10}$$

**Definition 4** (*Stability*). A set of actions is considered stable when no set of players would change their action given the opportunity. In fact, a coalitional structure is said to be stable if it satisfies two conditions, namely, internal and external stabilities. In the internal stability case, no player in a coalition has an incentive to leave its coalition and acts as a singleton since the payoff received by any player in the coalition is higher than the one received acting alone. In the external stability case, in a given partition, no player can improve its payoff by leaving its current coalition and joining another one [25].

**Definition 5** (*Core*). The core of a game is the set of all stable allocations. A vector $x \in \mathbb{R}^{\mathcal{N}}$ is a core allocation of the cooperative game $(\mathcal{N}, v)$ if for every coalition:

$$\sum_{i \in c} x_i \geq v(c) \tag{11}$$

If the core for a set of payoff vectors exists, it means that no subset of players $c'$ could increase their payoff by deviating from their current coalition. However, as the number of players increases the computation of the core becomes intractable since its computation turns into a combinatorial problem [26]. Furthermore, considering that there is a possibility of not finding a distribution of payoffs that assures the stability of coalitions, we use the $\varepsilon$-core concept [26]. This concept relaxes the notion of the core by requiring that no member of a coalition would benefit significantly, or within a constant amount, $\varepsilon$, by deviating from its current coalition. Consequently, a coalition is stable if the following is true

$$\sum_{i \in c} x_i \geq v(c) - \varepsilon \tag{12}$$

In addition, the minimum value of $\varepsilon$ guarantees that the $\varepsilon$-core is not empty. We use the least-core of a game to find the minimum amount of $\varepsilon$ since the least-core minimizes the incentive of a femtocell to drop out of its current coalition.

#### 4.2.2. Coalition formation algorithm

In order to motivate cooperation among femtocells, we propose to reward cooperative FCs with extra-resources (i.e. extra-subcarriers). A cooperative femtocell is defined as the femtocell that joins into coalitions and grants service to nearby PUs. We assume that femtocells are aware of their surrounding PUs and their demanded data rates. Note that in the proposed coalition game $(\mathcal{N}, v)$, the coalition $c_i$ is $\varepsilon$-core stable and the value of an empty coalition is 0, $v(\emptyset) = 0$. Our distributed coalition formation algorithm is presented in Algorithm 2.

***Value function and payoff***. The value function, $v(c)$, of a coalition is determined by the sum of data rates demanded by PUs within a coalition, which constitutes the coalition demand, $D_c$. Since the coalitional game has a transferable utility, $v(c)$ is a real number and it can be transferable among the members of the coalition and is defined as:

$$v(c) = \begin{cases} \dfrac{|F^c| \times BW_c}{c_{max} \times B_s}, & D_c > \dfrac{\gamma_f \times |F^c| \times BW_c}{c_{max}} \\ \dfrac{D_c}{\gamma_f \times B_s}, & otherwise \end{cases} \tag{13}$$

where $|F^c|$, $c_{max}$, $BW_c$, and $D_c$ represent the size of a coalition, the maximum size achieved by a coalition, the reserved bandwidth for the formation of coalitions, and the demand of the coalition, respectively. $\gamma_f$ is the spectral efficiency for FCs and $B_s$ is the bandwidth per subcarrier.

We define the individual payoff of an FC $f$ in coalition $c$ as:

$$x_{f,c} = \frac{Ra^{f,c}_{SU} - R^f_{SU}}{\gamma_f \times B_s} \tag{14}$$

where $Ra^{f,c}_{SU}$ and $R^f_{SU}$ are the allocated and requested data rate of subscriber served by FC $f$, respectively.

***Femtocell rewarding method***. As already mentioned, to encourage femtocells to join any cluster, we propose a rewarding method based on the allocation of extra-subcarriers for their own subscribers.

In particular, the subcarriers allocated for PUs and SUs served by femtocells within a cluster are provided by offloading traffic from the macrocell. Data offloading is a solution that reduces network congestion by moving mobile data traffic from a congested Radio Access Network (RAN) to a RAN with available capacity [27]. The data rate allocated to femtocell $f$ within coalition $c$ to serve PUs is based on PU data rate demands in FC $f$, $R^f_{PU}$, and is defined as:

$$Ra^{f,c}_{PU} = \frac{R^f_{PU}}{D^{f,c}} \times (N^{f,c}_{s-extra} \times \gamma_f \times B_s) \tag{15}$$

while the allocated data rate to a femtocell $f$ in coalition $c$ to serve their subscribers is given by:

$$Ra^{f,c}_{SU} = \frac{R^f_{SU}}{D^{f,c}} \times ((N^{f,c}_{s-extra} + \overline{N^f_s}) \times \gamma_f \times B_s) \tag{16}$$

where $\overline{N^f_s}$ represents the average number of subcarriers required per femtocells, $D^{f,c}$ is the requested data rate demand of femtocell $f$ in coalition $c$, and $N^{f,c}_{s-extra}$ is the number of extra-subcarriers received by femtocell $f$ in coalition $c$ and is determined by the following equation:

$$N^{f,c}_{s-extra} = \frac{\phi_f \times v(c)}{\sum_{i \in c} \phi_i} \tag{17}$$

where $\phi_f$ represents the Shapley value of femtocell $f$, that is determined from Eq. (10).

***Stability analysis***. In our proposal, femtocells cooperate in the formation of coalitions as long as their subscribers achieve the highest available satisfaction. Consequently, we should guarantee that the subscriber's satisfaction will be kept during all the clustering process. It can be stated that by guaranteeing the highest achievable subscriber's satisfaction, any deviation from the current coalition would be harmful to the femtocell. Also, it is assumed that the mobile users have low mobility so they would not frequently switch from the femto-tier to the macro-tier and vice versa. This assumption makes possible to have stable clusters. Moreover, a stability condition is used to maintain a stable coalition formation.

The stability condition is based on the $\varepsilon$-core concept of game theory, which is defined by Eq. (12). The use of the $\varepsilon$-core concept states that femtocells get a minimal amount of $\varepsilon$ by deviating from the coalition while keeping the $\varepsilon$-core of the game non-empty. The minimum value of $\varepsilon$ for which the $\varepsilon$-core is not empty is defined by the least-core of the game. To find the least-core value, $\varepsilon$, the relative $\varepsilon$-core is applied since it states that no coalition would benefit more than $\varepsilon \times v(c)$ by deviating [28]. In order to get the least core value for the considered scenario, we run the clustering stage varying $\varepsilon$ from 0 to 1 and showed the results in Fig. 2. For $\varepsilon$ values of 0.1 or less, there are seven femtocells in stable coalitions thus 70% of the femtocells in coalition have a non-empty core. While for $\varepsilon$ values equal or higher than 0.2 ten deployed femtocells are within stable coalitions. Consequently, we conclude that a gain of 20% of $v(c)$ is enough to join all femtocells in stable coalitions while guaranteeing the non-emptiness of the $\varepsilon$-core.

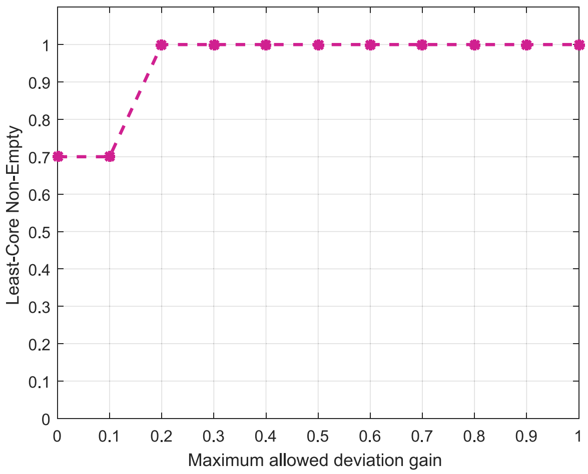



**Fig. 2.** Analysis of $\varepsilon$-core set to find the least-core value.

Thus, based on the $\varepsilon$-core analysis a coalition formed by cooperative femtocells is said to be stable if $\mathbb{S} = 1$, otherwise it is not stable:

$$\mathbb{S} = \begin{cases} 1, & \min x_{f,c} > 0 \\ & \min N^{f,c}_{s-extra} \neq 0 \\ & \sum_{f \in F^c} N^{f,c}_{s-extra} \geq v(c) - \varepsilon \\ 0, & otherwise \end{cases} \tag{18}$$

**Algorithm 2:** Coalition formation algorithm

**begin**
  **Initial State of Femtocell:** Initially, each FC is a cluster, so there are totally $|FC|$ clusters and all femtocells are in the stand-alone (SA) mode.
  **Proposed Coalition Formation**
  Step 1 - Neighbor Discovery
  **for** $f \in F^{sa}$ **do**
    Collects RSSI of the neighboring FCs from each of its own active mobile users.
    Based on the collected RSSIs, each FC $f$ discovers the neighbor FC j and keeps a list of neighboring FCs, $Neighbor^f$.
    Form initial clusters by joining each FC $f$ with its neighboring femtocells, $C_{ini}$
  **end**
  Step 2 - Cluster Head Selection
  **for** *each coalition* $C_{ini}$ **do**
    $CH = max_{f \in F^c} |Neighbor^f - Neighbor^f \cap F^c|$.
  **end**
  Step 3 - Coalition Formation
  **for** *each coalition* $C_{ini}$ **do**
    Compute the value of the coalition, $v(C_{ini})$, based on the demanded data rate of PUs served by FCs within the coalition $C_{ini}$.
    **for** *each* $f \in C_{ini}$ **do**
      Calculate the extra-subcarriers per femtocell $f$.
      Calculate the payoff per femtocell $f$, $\phi_f$, based on the received extra-subcarriers, use Eq. (10).
    **end**
    Evaluate the stability by applying the Eq. (11).
    Determine the set of stable coalitions, $C_s$, by verifying the conditions in (18).
  **end**
  Step 4: Resource Allocation per Cluster
  **for** *each coalition* $C_s \in \pi_N$ **do**
    Determine the set of users for the current coalition $C_s$.
    Run the PSO based resource allocation algorithm for the mobile users in the coalition
  **end**
**end**

#### 4.2.3. Cluster head selection

The cluster head is responsible for managing the clustering of femtocells and the resource allocation per cluster. For convenience, the proposed cluster head selection is similar to [5,29], where the selected cluster head is the femtocell with the highest number of neighboring femtocells. By doing so, the cluster head is able to communicate with stand-alone femtocells and to invite them to join the coalition. Moreover, a cluster head should be aware of the amount of resources needed for the new members of the coalition, considering that these resources are taken from the macrocell.

### 4.3. PSO based resource allocation per cluster

PSO is a technique that has been studied for the resource allocation in OFDMA macrocell systems [30] and in LTE systems [31]. In [32], it was demonstrated that the resource allocation based on PSO requires between 100 to 1000 iterations to converge to a solution. In fact, PSO has been demonstrated to speed up the optimization process and find a satisfying near-optimal solution [33]. The implementation of PSO requires relatively small number of code lines since it is based on simple operations. In particular, it takes only one operation to update the velocity and position to coordinate and control the particles movements. Since no overlapping and mutation calculations are involved, PSO demands less time to find solutions when compared to genetic algorithms [34].

PSO is considered as a meta-heuristic global optimization method where the set of candidate solutions to the optimization problem is defined as a swarm of particles. These particles move through the search space defining trajectories that are driven by the best solution that they individually have found and the best solution that any particle in their neighborhood has found [33,35].

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 a particle $n$ at each iteration $k$ are updated as follows:

$$x_n^{k+1} = x_n^k + \delta_t v_n^k, \tag{19}$$

$$v_n^{k+1} = \omega v_n^k + c_1 r_1 (p_k^{local} - x_n^k) + c_2 r_2 (p_k^{global} - x_n^k), \tag{20}$$

where $\delta_t$ is the time step value typically considered as unity [36], $p_k^{local}$ and $p_k^{global}$ are the best ever position of particle $n$ and the best global position of the entire swarm so far, and $r_1$ and $r_2$ represent random numbers from interval [0,1]. Moreover, parameters $\omega$, $c_1$ and $c_2$ are the configuration parameters that determine the PSO convergence behavior. The first term of Eq. (20) corresponds to the inertia of particle $i$ which is used to control the exploration abilities of the swarm. Large inertia values produce higher velocity updates allowing the algorithm to explore the search space globally. Conversely, small inertia values force the velocity to concentrate in a local region of the search space. The second and third terms of Eq. (20) are associated with cognitive knowledge that each particle has experienced and the social interactions among particles respectively [33]. The convergence of PSO is guaranteed if the following two stability conditions are met:

$$0 \leq (c_1 + c_2) \leq 4 \quad \text{and} \quad \frac{c_1 + c_2}{2} - 1 \leq \omega \leq 1$$

In order to apply the PSO technique to our optimization problem, we define vectors $\mathbf{b}$ and $\mathbf{P}$ to represent the location of each particle $n$ in our search space. These vectors represent the allocated bandwidth and transmitted power per user, respectively. The dimension of each vector is equal to the cardinality of the set mobile users in the vicinity of the cluster, i.e. $|MS^c|$. We use two different velocity vectors $(v_b, v_p)$ to update the particle location in each iteration and they are updated using Eq. (20).

PSO parameter-less scheme is used to solve minimization problems and our objective is to maximize the cluster throughput. Therefore, we need to convert our maximization problem into a minimization problem. We use a simple technique, in which the original objective function defined by Eq. (4) is subtracted from a large number $Q$ so the objective function for our PSO based resource allocation (RA) model is determined as follows:

$$f_{RA}(\mathbf{b},\mathbf{P}) = Q - \sum_{i\in\{MS\}}\sum_{f\in\{F\}} \alpha_i^f b_i log_2(1 + SINR_i^{s,f}) \quad (21)$$

where $Q$ is a large number (at least twice of the maximum throughput that can be achieved in a cluster) in order to guarantee the maximization of the cluster throughput. Following the PSO parameter-less scheme, the fitness function of our PSO based resource allocation model is defined by

$$f_{RA}^*(x) = \begin{cases} f_{RA}(\mathbf{b},\mathbf{P}), & \text{for feasible solutions} \\ f_{RA}(\mathbf{b},\mathbf{P}) + \sum_{l=1}^{CP} k_l \hat{g}(\mathbf{b},\mathbf{P}), & \text{otherwise} \end{cases} \quad (22)$$

where constraints (5)–(9) are included in $\sum_{l=1}^{CP} k_l \hat{g}(\mathbf{b},\mathbf{P})$ to penalize unfeasible solutions. Algorithm 3 presents the PSO algorithm executed at the cluster head that knows the allocated bandwidth per cluster and BS selection per user.

**Algorithm 3:** PSO based resource allocation algorithm

**Data:** $MS$ Locations $(x_i, y_i)$, Set of FC member of the cluster $(F^c)$, Users Demands $(D_i)$, BS selection per user $(\alpha_i^f)$, Bandwidth per cluster $(BW_c)$.
**Result:** Bandwidth and power allocation per user $(b_i, P_i)$.
**begin**
  **for** *each* $i \in MS$ **do**
    $b_i^{max} = \frac{D_i}{\gamma_f}$;
    $P_i^{max} = \min(P_f^{max}, SINR_k^{max} \times (N_o + I_{th}) \times PL_i^f)$;
  **end**
  Generate initial swarm with the particle positions and velocities as follows:
  $\mathbf{b} = \mathbf{r_1}.\mathbf{b^{max}}$;
  $\mathbf{P} = \mathbf{P^{min}} + \mathbf{r_2}.(\mathbf{P^{max}} - \mathbf{P^{min}})$;
  $\mathbf{v_b} = \mathbf{r_3}.\mathbf{b^{max}}$;
  $\mathbf{v_P} = \mathbf{P^{min}} + \mathbf{r_4}.(\mathbf{P^{max}} - \mathbf{P^{min}})$;
  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;
  **end**
**end**

### 4.4. Benchmark models

We compare our model with two benchmark models, namely a centralized clustering model and a distributed clustering model. The centralized model, named as load balanced clustering (LBC) model, uses the WWF algorithm for the resource allocation. Furthermore, the LBC model proposes a femtocell power control to mitigate interference and to achieve a target SINR [16]. The distributed model (ED-WWF) works with the WWF algorithm which is performed locally within each cluster. Besides, this model allocates resources in an equal distribution manner [10]. These models apply the same BS selection for public users as well as our proposed model. The main difference of the proposed model is the fair resource allocation per cluster and the analysis of stability executed during the clustering process.

## 5. Performance metrics

The following metrics were used to evaluate the performance of our model:

1. Throughput: It is defined as the sum of the achievable data rates of the users served by the femtocells and the macrocell. The throughput achieved by the network is based on Shannon's Law Capacity:

$$T = \sum_{i\in\{MS\}}\sum_{j\in\{MC,F\}} \alpha_i^j \beta_i^j log_2(1 + SINR_i^j) \quad (23)$$

**Table 3**
Parameter settings.

| Name | Description | Value |
|---|---|---|
| *Network configuration* | | |
| $N_s$ | Number of subcarriers | 256 |
| $P_{MC}^{Total}$ | Transmitted power per MC | 60 dBm |
| $P_f^{Total}$ | Transmitted power per FC $f$ | 10 dBm |
| $r_{MC}, r_f$ | Macrocells and femtocell radius | 500 m, 20 m |
| $\theta_f, \theta_{MC}$ | Attenuation factor of indoor and outdoor | 3, 3.7 |
| $\gamma_{MC}, \gamma_f$ | Spectral efficiency for MC or FC $f$ | (2, 4), 6 |
| $W_l$ | Wall loss penetration | −3 dB |
| $f_c$ | Carrier frequency | 2300 MHz |
| $N_0$ | Noise | −174 dBm/Hz |
| $\|SU\|$ | Number of subscribers per FC $f$ | 1 |
| $\|PU\|$ | Number of public users | 5-60 |
| $N_f$ | Number of deployed femtocells | 10 |
| *PSO parameters* | | |
| Name | Description | Value |
| $c_1$ | Cognitive knowledge parameter | 2.0 |
| $c_2$ | Social interactions parameter | 1.5 |
| $\omega$ | Inertia | 0.85 |

2. Subscriber satisfaction: It is given by the ratio between the sum of achieved subscribers' data rates and the demanded subscribers' data rates:

$$S_{SU} = \frac{\sum_{i\in\{SU\}}\sum_{j\in\{F\}} \alpha_i^j \beta_i^j \gamma_f}{\sum_{i\in\{SU\}} D_i} \quad (24)$$

3. Jain's fairness index: It is used to measure how fairly the resources are distributed among the mobile users [37]. It is expressed as:

$$J_{index} = \frac{(\sum_{i\in\{MS\}} Th_i)^2}{(|MS| \times \sum_{i\in\{MS\}} Th_i^2)} \quad (25)$$

where $|MS|$ is the total number of mobile users, and $Th$ is the throughput of user $i$.

## 6. Simulation results

In this section, we show the performance of the proposed model in terms of subscribers' satisfaction, public users' throughput, network throughput, Jain's fairness index, and running times for the clustering process. In addition, we compare these results with the two benchmark models described in Section 4.4.

Table 3 presents the system parameters for the network configuration and the PSO parameters. We perform our simulations using MATLAB R2018a running on a Lenovo computer with an Intel(R) Core(TM) i7-7500 processor and RAM of 8.00 GB. In the simulated scenario the number of PUs varies from 10 to 60 with increments of five users. 10 femtocells are deployed in an area of 500 × 500 m. One subscriber is assigned to each FC with variable demand from 128 Kbps to 1 Mbps. The available spectrum is split between the macro-tier and femto-tier to avoid the cross-tier interference. Additionally, a dedicated number of macrocell subcarriers is used for the PUs served by femtocells in coalitions and for giving extra-subcarriers to femtocells subscribers, $BW_c = b \times Bs \times Ns$, where $b$ is a value between $[0, 1]$ that represents the portion of available subcarriers used by the femto-tier. From the analysis of Section 4.2.2, we set the epsilon value to 0.2 in order to evaluate the stability of the coalitional game.

The simulation results are obtained by running the experiments several times and then averaging them for use in the following analysis. First, we analyze the network performance by comparing the network throughput of the three models. Then, we analyze the subscribers' satisfaction resulting from the proposed model and compare it with the benchmark models. We also present a subscriber satisfaction analysis per coalition for 20 PUs and 40 PUs for the proposed model and the LBC

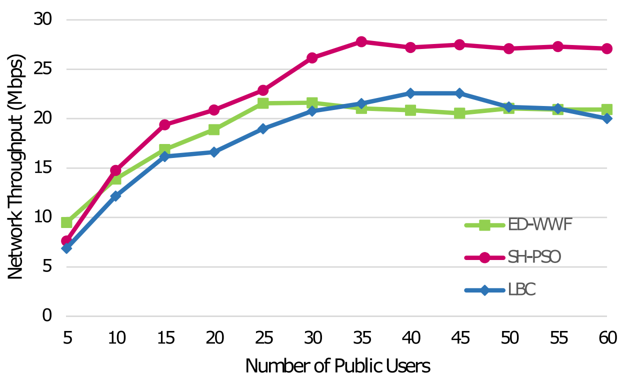



**Fig. 3.** Network throughput for SH-PSO, LBC, and ED-WWF models.

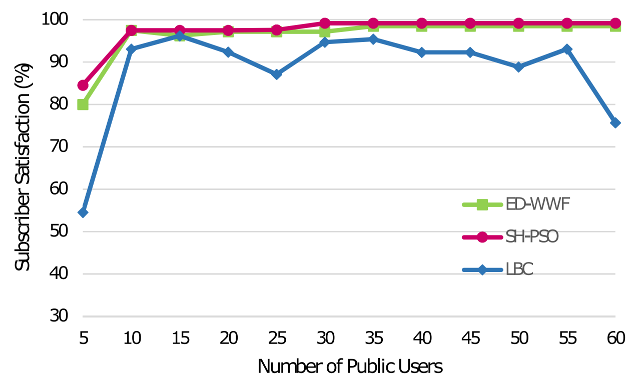



**Fig. 4.** Subscribers' satisfaction for SH-PSO, LBC, and ED-WWF models.

model. A fairness performance comparison is done for the SH-PSO and LBC models. Finally, we analyze the models' complexity by computing the running times of the clustering phase of the distributed models.

### 6.1. Network performance analysis

In this subsection, we compare the network performances of the SH-PSO, LBC, and ED-WWF models. Fig. 3 shows the network throughput as a function of the number of PUs varying from 10 to 60. As can be seen, the highest throughput is achieved by the proposed model.

In this particular scenario, starting from 30 PUs the SH-PSO model throughput gain is in the range from 25% to 35% compared to LBC model and from 21% to 34% compared to ED-WWF model. Note that starting from 30 PUs the network throughput for the SH-PSO model rises considerably in comparison with the two benchmark models. This increase in the network throughput is due to the fact that in this range of PU numbers all femtocells are within coalitions. Consequently, the users served by femtocells suffer less interference resulting in higher data rates. This also implies that all the subscribers within coalitions increase their throughput since they receive extra-resources and more public users are being served by femtocells in a coalition.

It is important to underline that in the centralized LBC model the traffic load is balanced among the clusters in order to have the same cluster sizes. In our model, the clusters have different sizes depending on the achievable stability. This allows increasing the network throughput since more nearby public users can improve their performance by being served by femtocells in a coalition.

### 6.2. Subscribers performance analysis

Here, we analyze the satisfaction of subscribers served by femtocells forming coalitions. We define the subscriber satisfaction as the relation between the assigned data rates and the demanded data rates, see Eq. (24). As can be seen from Fig. 4, the distributed models SH-PSO and ED-WWF give higher satisfaction for subscribers within coalitions in comparison with the centralized model.

In particular, our proposal allows having 100% subscribers' satisfaction starting from 30 PUs due to the fair resource allocation method based on the Shapley value. At the beginning of the clustering phase, with 5 PUs, only 5 femtocells cooperate in the formation of coalitions and the other 5 FCs prefer to work in stand-alone mode causing interference to the femtocells in a coalition resulting in satisfaction below 100%. Nevertheless, starting from 30 PUs more femtocells are joining coalitions, which allows to increase the subscriber satisfaction to 100%.

In Fig. 5, we show the performance of the coalitions in terms of SU satisfaction. The SUs satisfaction is shown specifically for two cases, namely 20 PUs and 40 PUs. For the case of 20 PUs, we can observe that in the proposed model two coalitions are formed, $c_1 = \{f_1, f_3\}$ and $c_2 = \{f_2, f_6, f_7, f_8, f_9\}$. Then, for the case of 40 PUs, femtocells $f_4$, $f_5$ and $f_{10}$ form a third coalition, $c_3$. All the SUs served by the FCs within these three coalitions have 100% SU satisfaction, as can be seen in Figs. 5(a) and 5(b). This is owing to the fact that the cooperative femtocells are rewarded with extra-subcarriers.

Figs. 5(c) and 5(d) present the subscriber satisfaction for 20 PUs and 40 PUs, respectively, for the LBC model. It can be observed that with our proposal more femtocells are in coalition, for both 20 PUs and 40 PUs. In addition, with 20 PUs, the LBC model allows only the subscribers served by $f_1$ to obtain 100% satisfaction, unlike the case of 40 PUs, where all FCs in coalition except $Fc_6$ obtain a 100% of satisfaction. This is owing to the fact that the proposed model uses a fair resource allocation based on Shapley value for the cooperative femtocells.

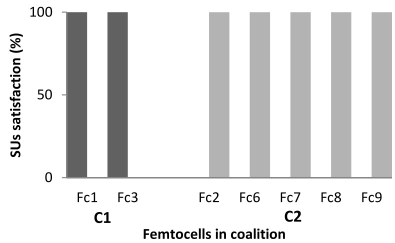
### 6.3. Public users performance analysis

In this subsection, we compare the total PUs throughput, estimated as the sum of the public users data rates, for the SH-PSO and ED-WWF models and the particular case with no coalitions. Fig. 6 shows that for the SH-PSO and ED-WWF models the PUs throughput is higher in comparison with the no-coalition model. Namely, starting from 30 PUs the SH-PSO model throughput gain is in the range from 38% to 83% and the ED-WWF model throughput gain is in the range from 16% to 44% when compared to the no coalition model. This is because the PUs that cannot be served by the macrocell are being served by nearby femtocells.

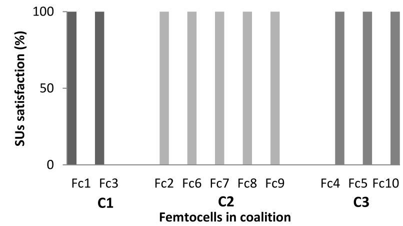
Note that the SH-PSO model outperforms the no coalition model for more than 15 PUs. This implies that in the no coalition model the first 15 PUs are better served by the macrocell. It can be noticed that in the no coalition model the PUs throughput does not increase when the number of public users increases. This is due to the low link rate conditions among the PUs and the macrocell. In scenarios with coalitions of femtocells, the link rate conditions are improved due to the proximity between FCs and PUs and therefore PUs improve their throughput.

### 6.4. Mobile users performance analysis

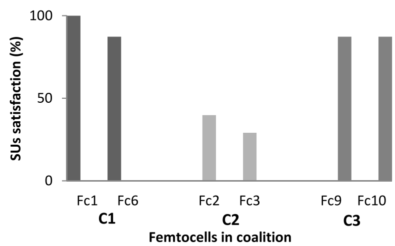
Here, we analyze the performance of mobile users within a cluster. For this purpose, we show the satisfaction of subscribers and public users that are within the cluster 2, $c_2 = \{f_2, f_6, f_7, f_8, f_9\}$. In this cluster there are 4 subscribers and 9 public users giving a total of 13 mobile users. From Fig. 7, it can be observed that all mobile users achieve similar satisfaction demonstrating that our solution performs a fair allocation of resources. In particular, the subscribers achieve the highest satisfaction of 100% demonstrating the fair allocation of extra-resources. Moreover, the public users served by femtocells in coalition have a good performance in terms of the achieved satisfaction.



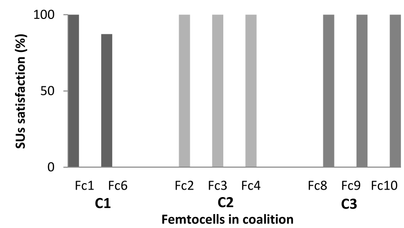

(a) SUs satisfaction using SH-PSO model for 20 PUs.




(b) SUs satisfaction using SH-PSO model for 40 PUs.




(c) SUs satisfaction using LBC model for 20 PUs.




(d) SUs satisfaction using LBC model for 40 PUs.

**Fig. 5.** Subscriber satisfaction per coalition for the proposed model and the LBC model.

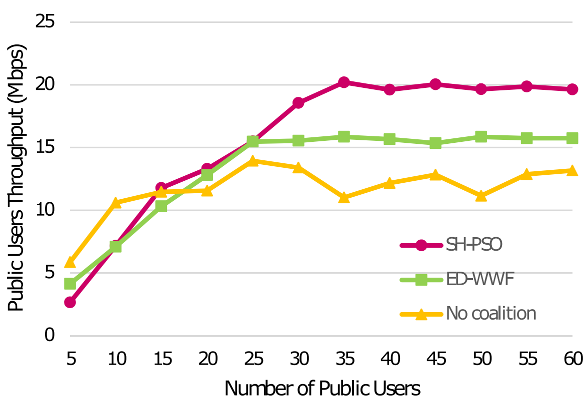



**Fig. 6.** Public users' throughput for SH-PSO, ED-WWF, and no-coalition models.

### 6.5. Jain's fairness index

We used the Jain's fairness index [37] to measure the fairness in the resulting distribution of resources among the users in the femto-tier. From Fig. 8 we can see that the resource allocation using the Shapley value yields better fairness than the centralized resource allocation. This comes from a fair resource allocation applied per coalition in the Shapley value case. Note that the minimum index for the LBC model is 61% while for the SH-PSO model is 70%.

### 6.6. Complexity

Table 4 reports the computation time associated with the clustering process of the proposed model and the ED-WWF model for different public users density. The first column represents the number of PUs, the second column corresponds to the clustering time using the SH-PSO model, and the third column shows the clustering time of the ED-WWF model. Note that the running times are significant only for the cases with 10 and 30 PUs. This follows from the fact that only in these cases

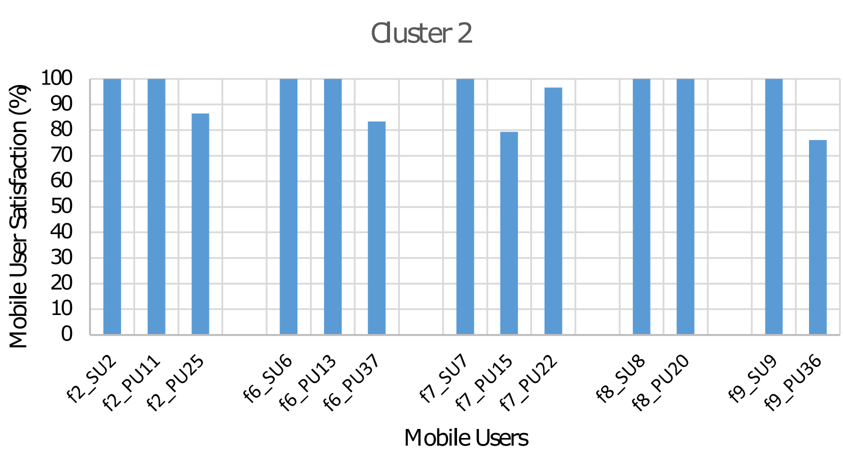



**Fig. 7.** Mobile users' satisfaction for SH-PSO model.

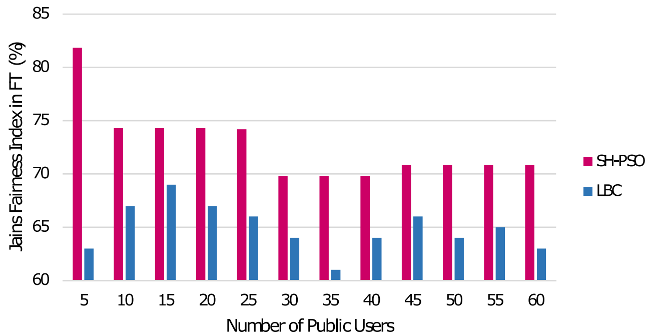



**Fig. 8.** Jain's fairness index for users in the femto-tier.

**Table 4**
Running times for the clustering component.

| Number of PUs | Clustering time (s) | |
|---|---|---|
| | SH-PSO | ED-WWF |
| 10 | 0.241 | 1.015 |
| 20 | 0 | 0 |
| 30 | 0.075 | 0.953 |
| 40 | 0 | 0 |
| 50 | 0 | 0 |

there is formation of new coalition. In the remaining cases no coalition can increase their utility by admitting stand-alone femtocells and no femtocell can obtain extra-resources to improve the satisfaction of its subscribers so the running time is negligible.

## 7. Conclusions

In this work, a coalitional game to form stable coalitions of femtocells that enhances femto-tier throughput and subscribers' satisfaction is proposed. Femtocells are motivated to join a coalition by the payoff that they receive in terms of extra-subcarriers allocated to their own subscribers. This work also defines stability criteria for hybrid access femtocells and demonstrates that the formed coalitions lie in the $\epsilon$-core of the proposed game. Moreover, resources are fairly allocated among cooperative femtocells using the Shapley value. Simulations results demonstrate that the proposed model improves the network throughput compared to the benchmark models, and the gain is up to 26% in the considered scenarios. Further, the simulation results show that the subscriber satisfaction increases by rewarding cooperative femtocells. Moreover, with our proposal, the public users' throughput gain is in the range from 60% to 90% compared to the no coalition model. Fairness in the distribution of resources among the femto-tier users is also evaluated with the Jain's Fairness index. The results obtained with the SH-PSO model present a better fairness than the centralized resource allocation model.

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