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Game theoretical framework for clustering and resource allocation in macro-femtocell networks

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

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

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ABSTRACT

We address the femtocell clustering together with the resource allocation in macro-femtocell networks. The clustering schemes allow the implementation of distributed approaches that can run locally within each cluster. Nevertheless, several limitations should be addressed for dense femtocell deployment, such as: lack of clustering schemes that encourage femtocells to grant service to public users and to become cluster members while guaranteeing their subscriber satisfaction, inefficient bandwidth usage due to the lack of bandwidth adaptation per tier when the cluster configuration changes, and lack of power control mechanisms to reduce interference. In this paper, we propose a distributed clustering model based on a cooperative game, where femtocells are encouraged to cooperate by forming clusters and rewarded with resources from macrocell. Our solution consists of: a cluster formation based on a coalitional game among femtocells and the macrocell to determine the subcarrier distribution per tier, a base station selection for public users and a resource allocation algorithm using Particle Swarm Optimization. We compare our solution with a centralized clustering approach and our cooperative clustering model using the well-known Weighted Water Filling resource allocation algorithm. Simulation results show that our proposal obtains throughput values similar to the centralized approach, satisfies the service requirements for both types of users and reduces the interference in comparison with the benchmark models.

1. Introduction

Femtocell (FC) technology has been used to solve the main limitations of the traditional cellular networks, such as: poor indoor coverage, degraded signal at cell-edge, offloading traffic and the inefficient use of spectrum. However, there are still several challenges such as base station (BS) selection, resource allocation, power control and interference mitigation due to the dense deployment of femtocells.

Femtocells are connected to the mobile core network by means of an Internet backhaul (e.g. DSL connection) [1]. A femtocell supports all cellular standard protocols such as CDMA, GSM, WCDMA, LTE, WiMAX, and also all the protocols standardized by 3GPP, 3GPP2 and IEEE/WiMAX [2].

In a macro-femtocell network, mobile users are classified as public users (PUs) or subscribers (SUs). The public users are the traditional users of the wireless network while the FC subscribers are the authorized users that can connect to their own femtocells. Three access control modes are defined for the public users access to FCs. These are the closed, open and hybrid access modes [1]. In closed access mode, only FC subscribers can connect to their femtocells and these users get full benefit of their own FCs. However, the network capacity is limited and the interference caused by FCs to nearby macro users is increased. Open access mode allows any mobile user to use FCs, which requires a tight coordination between the macrocell (MC) and FCs. Hybrid access mode allows public users to access FCs but FCs reserve some resources for their own subscribers. Valcarce et al. [3,4] demonstrated that the hybrid access mode outperforms the closed and the open access modes due to its ability to reduce the interference while guaranteeing the performance of their own subscribers.

The resource allocation problem for macro-femtocell networks was proved to be NP-hard due to the non-convexity of the signal-to-interference-plus-noise ratio (SINR) [5]. In the literature, some

* Corresponding author at: Escuela Superior Politécnica del Litoral (ESPOL), ReDIT & FIEC, Guayaquil, Ecuador.

E-mail addresses: karohoden@utpl.edu.ec (K. Rohoden), restrada@espol.edu.ec, aj49050@ens.etsmtl.ca (R. Estrada), Hadi.Otrok@kustar.ac.ae (H. Otrok), Zbigniew.Dzion@etsmtl.ca (Z. Dziong).

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centralized approaches have addressed different challenges such as interference mitigation [6] and resource allocation [7] for non-dense FC deployment. Nevertheless, these solutions require global knowledge in real-time and long running times which make these approaches unfeasible for dense deployment.

The complexity of the resource allocation problem is still a very challenging issue for dense femtocell deployment. Recently, FC clustering schemes have attracted the attention of researchers in order to reduce this complexity. The main goal is to form FC groups that allow the implementation of distributed resource allocation approaches within each FC group. The majority of these approaches focuses on FCs deployed in the closed access mode (e.g. [8]), despite the benefits of the hybrid access mode.

To the best of our knowledge, there are no related works that dynamically change the bandwidth allocated per tier taking into account the offloading traffic from macrocell and the cooperative femtocell networks. The main issues that need to be addressed when combining clustering and resource allocation for the hybrid access FCs are: (1) the bandwidth starvation in macrocell or cluster, (2) guarantees for the FC subscriber transmissions; and (3) inter-cluster interference mitigation.

The limitations of the previous works can be summarized as follows:

- Lack of appropriate clustering schemes that encourage FCs to grant service to the public users while guaranteeing the quality of service of FC subscriber transmissions without depriving the macro user transmissions.
- Lack of dynamic bandwidth allocation per tier when the public user distribution changes with the cluster configuration.
- Lack of appropriate FC power control mechanisms to reduce not only co-tier interference but also inter-cluster interference.

To overcome these limitations, we propose a distributed clustering model using a game theoretical framework for cooperation between macrocell and femtocells that is able to determine the amount of MC resources (i.e. subcarriers) that can be allocated to the femto-tier without depriving macro user transmission of resources. Our cooperative game determines first the top-coalition C^* formed by a set of femtocells and the macrocell such that FCs maximize their subscribers satisfaction and the network operator maximizes the satisfaction of the public users. Then, other coalitions are formed using a fair portion of the allocated bandwidth to femto-tier. Finally, a distributed resource allocation algorithm is run locally within each cluster. The objective of this algorithm is to maximize the cluster throughput. We use Particle Swarm Optimization (PSO) technique for the resource allocation algorithm due to its ability to obtain a satisfying near-optimal solution while speeding up the optimization process.

1.1. Motivating example

In this section, we use a motivating example to demonstrate that all entities of the macro-femtocell network (i.e. network, macrocell, femto-tier, clusters and femtocells) can effectively enhance their throughput by means of the clustering.

Fig. 1 shows a macrocell with eleven deployed femtocells ($FC_1, FC_2, \ldots, FC_{11}$) represented by houses. Each FC is serving one subscriber (i.e. a total of 11 subscribers) and 17 public users are located within the FCs' vicinity. We assume equal demand for subscribers and the public users (e.g. 1 Mbps). The macrocell has 22 available channels for both tiers and each channel reaches a maximum data rate of 1 Mbps if it is not reused. Spectrum partitioning approach [9] is assumed among tiers. This means that a dedicated number of subcarriers is allocated for each tier. The number of subcarriers allocated to the femto-tier should satisfy at least the

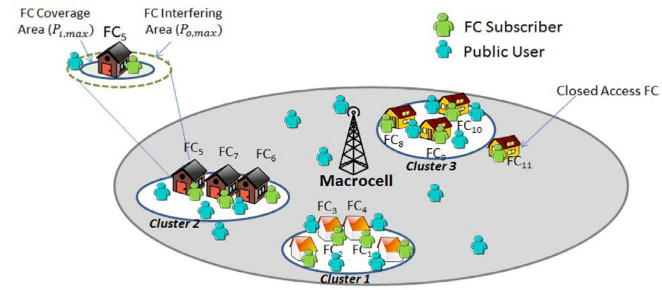


Fig. 1. Network model: $FC_1, FC_2, \ldots, FC_{10}$ work in the hybrid access mode and become cluster members, FC_{11} works in closed access mode.

average demand requested by FCs, $\overline{D^f_{SUE}}$, that is defined as the sum of FC's data rate demands divided by the FC number.

The network utility can be defined as the sum of all user data rates:

$$U^N = \sum_{i \in MS} \alpha_i^m R_i^m + U^{FT} \tag{1}$$

where the first term corresponds to the throughput delivered by macrocell m and the binary variable α_i^m indicates if user i is served by macrocell m. U^{FT} is the femto-tier utility, which is the sum of the data rates of the users served by FCs and is given by

$$U^{FT} = \sum_{c \in C} \sum_{f \in F^c} U^c + \sum_{f \in F^{sa}} R^f_{SU} \tag{2}$$

where F^c, F^{sa}, C are the sets of femtocells in coalition or cluster c, stand-alone femtocells, and clusters, respectively. The first term in (2) represents the sum of clusters' utilities, U^c, and the second term is sum of the stand-alone FCs' utilities. The cluster utility is estimated as the sum of data rate of both type of users being served by cluster members (i.e. $\sum_{f \in F^c} (R^f_{PU} + R^f_{SU})$).

R^f_{PU} represents the sum of the data rate of public users being served by the femtocell f, i.e. $\sum_i^{PU} \alpha_i^f R_i^f$. R^f_{SU} corresponds to the sum of the data rate of the subscribers of femtocell f, i.e. $\sum_i^{SU} \alpha_i^f R_i^f$. R_i^f is the achievable data rate offered by femtocell f to user i and α_i^f is the binary variable indicating the allocation of user i to the femtocell f. Finally, FC's utility is given by

$$U^f = \begin{cases} \sum_{j \in PU} \alpha_j^f R_j^f + \sum_{i \in SU} \alpha_i^f R_i^f & f \text{ in a cluster} \\ \sum_{i \in SU} \alpha_i^f R_i^f & \text{otherwise} \end{cases} \tag{3}$$

Let us consider three scenarios: (i) FCs work in closed access mode, (ii) FCs work in hybrid access and they are cooperative forming clusters of equal size, and (iii) FCs work in hybrid access but they form clusters of different size.

In the first scenario, each FC serves only its own subscriber because of its closed access mode. To reach the maximum data rate provided by a channel (i.e. 1 Mbps), dedicated channels are allocated to the users such that the cross-tier and co-tier interferences are avoided. Thus, the femto-tier needs 11 channels to satisfy the total demand required by subscribers while the macro-tier needs 17 Mbps (1 Mbps per PUs) to fulfill the PUs demand. However, the available channels are not enough to satisfy the total users' demand. To maximize the femto-tier throughput, the macrocell should allocated 11 channels to the femto-tier, grant access to 11 PUs and block 6 PUs. Table 1 summarizes the channel distribution per BSs and their respective utilities. Table 2 shows the throughput values for the scenarios with coalition. In the second scenario, 9 FCs ($FC_2, \ldots, FC_{10}$) choose to form three clusters of equal size

Table 1
Scenario with no coalition.

BS	Utility (U^m, U^f)	BS	Utility U^f	BS	Utility U^f
m	11	FC_4	1	FC_8	1
FC_1	1	FC_5	1	FC_9	1
FC_2	1	FC_6	1	FC_{10}	1
FC_3	1	FC_7	1	FC_{11}	1
Femto-tier utility, U^{FT}: 11					
Total network utility U^N: 22					
Available channels: 0					

while FC_1 and FC_{11} work in the closed access mode. The macrocell rewards with one additional channel to each FC belonging to clusters. These two channels can reach the maximum data rate owing to the fact that the clusters are far from each other and the inter-cluster interference can be considered negligible. Each cluster reaches an utility of 6 Mbps and the femto-tier utility is 20 Mbps using only 6 channels. The femto tier serves 9 public users and 11 subscribers while the macrocell serves 8 public users. The macrocell and network utilities are equal to 8 Mbps and 28 Mbps respectively while keeping 8 available channels for new arriving users. Fig. 1depicts the third scenario where only femtocell FC_{11} is working alone and the remaining FCs form three clusters of different size. Table 2(b) summarizes the utility of the network entities. The femto-tier utility is increased to 21 Mbps in comparison with the second scenario, the overall utility is the same while the number of available channels is lower than the scenario with cluster of equal size.

In summary, the coalitions allow the network to increase the throughput by means of rewarding FC with extra resources to grant service to PU and reduce the power consumption due to the proximity of the serving BSs. There is no gain for subscribers when their FCs become cluster members through the additional allocated channel but the co-tier interference reduction. This motivates our work to investigate how to reward cooperative femtocells with additional resources from the unused channels in the network to improve the subscribers satisfaction. For example, three additional channels could be easily allocated to FC clusters in the second scenario and the FCs can increase the subscriber throughput to 2 Mbps and still keep some available channels for new arriving users.

1.2. Contributions

We propose a new framework that consists of three components: a distributed clustering model, a BS selection algorithm for public users, and a distributed resource allocation. In particular, our contribution is a model that provides:

- Bandwidth adaptation per tier based on the bandwidth allocated to a top coalition that maximizes the throughput of public users of the network.
- Enhanced subscriber satisfaction and reduction of the inter-cluster interference owing to the fact that FCs can choose to join or leave their current coalition depending on their SU satisfaction and the inter-cluser interference.
- Improved public user satisfaction by means of a BS selection algorithm, where each PU prefers to be connected to a FC, which is member of a cluster and provides higher data rate than the MC.
- Enhanced throughput per cluster by means of a cluster based resource allocation algorithm that maximizes its throughput using PSO technique.

Moreover, extensive simulations are carried out to perform a comparison between the proposed solution and two benchmark models: (1) its modified version using the same proposed distributed clustering scheme with a resource allocation algorithm based on the Weighted Water Filling (WWF) applied within each cluster, and (2) a centralized clustering model proposed in [10].

1.3. Organization

The rest of the paper is organized as follows: Section 2 presents an overview of related works. Section 3 describes the system model and problem formulation. Section 4 presents the components of the game theoretical framework for clustering and resource allocation as well as the benchmark models. Section 5 presents and analysis the numerical results obtained for the proposed and benchmark models. Finally, Section 6 concludes the paper.

2. Related work

To overcome the limitations of the traditional cellular networks, two technologies have been investigated: the integration of WiFi and cellular networks (i.e. heterogeneous wireless networks) and the deployment of femtocell networks (i.e. two tier cellular networks). Several approaches have focused on the design of integrated WiFi and cellular network such as mobility management and admission control [11], QoS support for mobile users [12], efficient data offloading from the cellular to WiFi [13], and energy-efficient network management [14] to benefit from the heterogeneous wireless network.

Regarding the two-tier networks, several resource allocation approaches have been proposed in the literature. Some approaches perform bandwidth optimization [15], or power optimization [16]. Other approaches attempt to jointly optimize bandwidth and power for the femtocell network by means of maximizing of femtocells network throughput [17]. For non-dense deployment, a dedicated number of subchannels can be assigned to each tier [18,19] while for dense deployment, the spectrum should be shared among macrocell and femtocells and interference management schemes need to be implemented to enhance network throughput, such as: power control [20], fractional spectrum reuse [21], soft

Table 2
Scenarios with coalition.

(a) Equal size clusters				(b) Different size clusters			
Cluster	Utility (U^m, U^c)	F^{sa}	Utility U^f	Cluster	Utility (U^m, U^c)	F^{sa}	Utility U^f
m	8			m	7		
$\{FC_2, FC_3, FC_4\}$	6	FC_1	1	$\{FC_1, FC_2, FC_3, FC_4\}$	8	FC_{11}	1
$\{FC_5, FC_6, FC_7\}$	6	FC_{11}	1	$\{FC_5, FC_6, FC_7\}$	6		
$\{FC_8, FC_9, FC_{10}\}$	6			$\{FC_8, FC_9, FC_{10}\}$	6		
Femto-tier utility, U^{FT}: 20				Femto-tier utility, U^{FT}: 21			
Total network utility U^N :28				Total network utility U^N: 28			
Available channels : 8				multicolumn4lAvailable channels : 7			

spectrum reuse [22] and dynamic or opportunistic spectrum reuse by means of the use of cognitive radios [23].

We addressed the resource allocation problem for non-dense FC deployment using linear programming(LP) by means of a linear approximation of the signal-to-noise ratio [24] or signal-to-interference-plus-noise ratio [7]. Due to the complexity of the LP solutions, we investigated alternative meta-heuristic models to find a satisfying near-to-optimal solution in less time such as genetic algorithm [25] or Particle Swarm Optimization (PSO) [26]. Moreover, we proposed a centralized meta-heuristic model to address the problem of joint clustering and resource allocation using PSO and demonstrated that the obtained results were close to our optimal solution for non-dense scenarios [10]. The disadvantage of our prior solutions is that they employed centralized approaches either to solve the resource allocation or the clustering and therefore they are not suitable for dense deployment.

Recently, game theory has been proposed as a mechanism to implement distributed cluster based resource allocation algorithm such as in [27,28], [29]. Abdelnasser et al. [30] propose a semi-distributed interference management scheme to group femtocells into clusters aiming at the minimization of the co-tier interference. In [27], a resource allocation algorithm based on clustering and quality of service (QoS) for hybrid access mode is proposed. Their algorithm maximizes the number of satisfied FC subscribers while serving public users as best-effort service users. These approaches aim at the maximization of the femtocell network throughput. On the contrary, other approaches consider that femto users are the secondary users and they are served as best-effort service users in the network [31].

In [32], an incentive mechanism to motivates FC owners to share their FC resources with public users is proposed. This mechanism is formulated using game theory where the network operator seeks to maximize its revenue by determining the revenue distribution among the FC owners, while the FC owners decide the amount of FC resources to share with public users. This approach assumed that femtocells have enough allocated resources to share with public users, which leads to an inefficient bandwidth usage if the public user density close to femtocell decreases.

3. System model

We consider a network structure where femtocells are deployed within the macrocell coverage as shown in Fig. 1. SC denote the set of available subcarriers in the network. To avoid the cross-tier interference, the set of subcarriers is split among the two tiers assuming the spectrum partitioning approach presented in [18,19]. The physical bandwidth of subcarrier s is denoted by B_s.

For OFDMA downlink (DL) transmissions [33], the Shannon's link capacity or spectral efficiency is given by

$$\gamma_k^s = log_2(1 + SINR_i^{s,k}) \tag{4}$$

where $SINR_i^{s,k}$ denotes signal-to-interference-plus-noise ratio perceived by the mobile user i being served by femtocell k or a macrocell m. Since the spectrum partitioning approach among the tiers is assumed, the spectral efficiency γ_m^s for macro-users DL transmissions is only affected by the signal to noise ratio, which is given by:

$$SNR_i^{s,m} = \frac{P_i^{s,m}}{PL_i^{s,m} \times N_0}; i \in MS, s \in SC \tag{5}$$

For DL transmission in femto-tier, as the allocated subcarriers can be reused among the cluster, the inter-cluster interference is considered for the estimation of the SINR as follows:

$$SINR_i^{s,k} = \frac{\alpha_i^k P_i^{s,k}}{PL_i^{s,k} \times (N_0 + \sum_{h \in \{C \setminus c\}} \sum_{f \in \{F^h\}} I_i^{s,f})}; c \in C, k \in F^c, i \in MS \tag{6}$$

where $P_i^{s,k}$ is the transmitted power from serving BS k to user i in subcarrier s, $PL_i^{s,k}$ is the path loss due to the channel propagation models for outdoor and indoor environment, and $I_i^{s,k}$ represents the interference. The interference source is the inter-cluster interference and it is represented by the second term of the denominator in Eq. (6).

The propagation models used to estimate the path loss are similar to the ones presented in our previous work [7] and are given as follows:

$$PL_i^{s,k}(dB) = \begin{cases} 10log_{10}(d_{ik}^{\omega_m}) + 30\ log_{10}(f_c) + 49, & k = m \\ 10\ log_{10}(d_{ik}^{\omega_f}) + 37, & k \in FC \end{cases} \tag{7}$$

where d_{ik} is the distance from BS k to user i that should be given in meters for FCs and kilometers for MC, fc is the carrier frequency adopted by the macrocell (in MHz), ω_k is the outdoor/indoor attenuation factor is assumed to be equal to 3.7 or 3 for outdoor and indoor environments, respectively, in accordance with the carrier frequency [34].

3.1. Problem formulation

The proposed model aims at 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. Then, the objective function is formulated as

$$\max_{\boldsymbol{\epsilon},\boldsymbol{\alpha},\boldsymbol{\beta},\mathbf{P}} \sum_{i \in \{MS\}} \sum_{s \in \{SC\}} \alpha_i^m \beta_i^{s,m} \gamma_m^s + \sum_{c \in \{C\}} \sum_{i \in \{MS\}} \sum_{f \in \{FC\}} \sum_{s \in \{SC\}} \epsilon_f^c \alpha_i^f \beta_i^{s,f} \gamma_f^s, \tag{8}$$

where ϵ is the vector of binary variables and ϵ_f^c defines the FC membership. α and β are the vectors that represent user base station association and bandwidth allocation per user, respectively. In other words, α is the vector composed of the binary variables, α_i^f, α_i^m described in Section 1.1 and β comprises binary variables $\beta_i^{s,f}$, that indicate if subcarrier s is allocated to user i in femtocell f.

This objective function is subject to the upper bound for transmitted power per BS:

$$\sum_{i \in MS} \sum_{s \in SC} \alpha_i^k P_i^{s,k} \le P_k^{Total} \tag{9}$$

where vector $\mathbf{P}$ consists of power allocations per user $P_i^{s,k}$, $k \in \{m, FC\}$. **MS** and **SC** are the sets of mobile stations and subcarriers, respectively, C is the set of disjoint FC clusters, and γ_k^s is the spectral efficiency given in (4).

Exhaustive search could be applied to find the optimal cluster configuration, which means performing the joint BS selection and resource allocation over all possible cluster configurations. However, an exhaustive search would require long running times since the number of possible cluster configuration increases exponentially with the number of femtocells [35].

In [36], we presented a centralized cluster formation that aims at balancing the traffic load of public users. The model attempts to find the best cluster configuration by means of the evaluation of the throughput after running the resource allocation algorithm. If the network throughput is enhanced and the interference level is reduced, then, the cluster configuration is kept as the new best cluster configuration.

3.2. Optimization of the cluster based resource allocation problem

Once the cluster are established, the goal of the resource allocation problem within each cluster is to maximize its throughput.

Thus, the objective function for the cluster based resource allocation problem is given by

$$\max_{\boldsymbol{\epsilon},\boldsymbol{\alpha},\boldsymbol{\beta},\mathbf{P}} \sum_{f\in\{F^c\}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \epsilon_f^c \alpha_i^f \beta_i^{s,f} \gamma_f^s \tag{10}$$

subject to:

$$\sum_{k\in\{m,F^c\}} \sum_{s\in\{SC\}} \beta_i^{s,k} \le 1 \quad ; i \in MS \tag{11}$$

$$\sum_{f\in\{F^c\}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \epsilon_f^c \alpha_i^f \beta_i^{s,f} \le N_s - \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \alpha_i^m \beta_i^{s,m} \tag{12}$$

$$log_2\left(1 + SINR_i^{s,f}\right) \ge \alpha_i^f \beta_i^{s,f} \gamma_f \quad ; i \in MS,\ f \in \{F^c\},\ s \in \{SC\}, \tag{13}$$

$$\sum_{k\in\{F^c\}} \alpha_i^k \le 1 \quad ; i \in MS \tag{14}$$

$$B_s \times \sum_{s\in\{SC\}} \beta_i^{s,k} \gamma_k^s \ge \alpha_i^k \times D_i \quad ; i \in MS \tag{15}$$

Constraint (11) is used to avoid the cross-tier interference, which means that a subcarrier being used in the macro-tier cannot be used in a cluster. We also assume orthogonal transmission among the users in a cluster to avoid the intra-cluster interference. Constraint (12) indicates that the number of subcarriers allocated to cluster c (i.e. femto-tier) should be less or equal to the unused subcarriers in the macro-tier. Constraint (13) guarantees that the spectral efficiency achieved by user i within a cluster is higher or equal than a target spectral efficiency. Finally, constraint (14) indicates that one user can be assigned to only one BS and constraint (15) establishes the lower bound for minimum data rate for public users, which is equal to the data rate that macrocell can offer to the user at any given instant. This optimization problem is solved using Particle Swarm Optimization (PSO) technique as described in Section 4.1.7.

3.3. Model parameters

For sake of clarity, Table 3 summarizes the notation used in our model.

Table 3
Model parameters.

Name	Description
C	Set of clusters
SC	Set of available subcarriers
MS	Set of mobile users
FC	Set of deployed femtocells
PU	Set of public users
SU	Set of subscribers
S	Coalition o Cluster
F^c, F^h	Set of FCs per cluster c or h
B_s	Bandwidth per subcarrier
N_s^{FT}	Number of subcarriers allocated to femto tier
N_s	Number of subcarriers
$\overline{N_s^f}$	Average number of subcarriers required by FCs
$N_{used,S}^{PU}$	Number of subcarriers used for PU in the coalition S
$N_{used,S}^{SU}$	Number of subcarriers used for SU in the coalition S
N_s^{FT}	Number of subcarriers allocated to femto tier
P_k^{Total}	Total transmitted power in BS k
$P_k^{max,s}$	Maximum transmitted power per subcarrier in BS k
r_k	Coverage radius of the BS $k \in \{m, FC\}$
θ_f, θ_m	Attenuation factor of indoor and outdoor environments
γ_k^s	Spectral efficiency for subcarrier s in BS $k \in \{m, FC\}$
ω_k	Outdoor/indoor attenuation factor $k \in m \cup FC$
f_c	Carrier frequency adopted by the MC (in MHz)
N_0	Average thermal noise power
U^c, U^{FT}, U^N	Utility of cluster c, femto-tier, and macro-femtocell network
D_i	Data rate demand of mobile user i
R_{SU}^f	sum of data rate of subscribers served by FC f
R_{PU}^k	sum of data rate of public users served by BS $k \in \{m, FC\}$
d_{ik}	Distance from BS k to the user i
α_i^k	User i is assigned to BS k
ϵ_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

4. Game theoretical framework for resource allocation in macro-femtocell networks

The proposed framework consists of: (i) BS selection for public users, (ii) clustering and (iii) resource allocation within each cluster. Fig. 2 presents a flowchart of the proposed framework. Initially, each FC is consider a cluster or singleton coalition (i.e. $|C| = |FC|$) working in the closed access mode. This means that each FC serves only its own subscribers.

4.1. Clustering

Here, we present our clustering approach based on the coalitional game theory. The classical coalitional games in characteristic form are based on the assumption that the value of a coalition can be computed independently of other coalitions. In our model, the situation is different because the utility of a coalition depends on the inter-cluster interference caused by other clusters due to the resource sharing. Note that we use the terms cluster and coalition interchangeably.

Our coalitional game is based on formation of a top-coalition [37]. The top-coalition is the FC group that maximizes the sum of the data rate of public users in the two-tier network. This coalition allows our model to determine the bandwidth that should be used for both tiers. Then, other coalitions can be formed using a fair amount of bandwidth allocated for femto-tier, which depends on the PUs demand satisfied by each coalition.

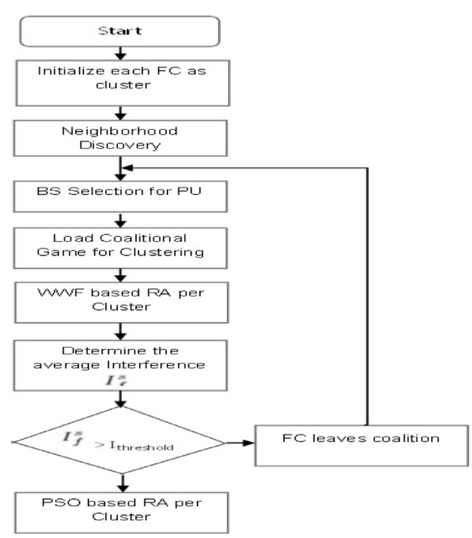


Fig. 2. Game theoretical framework.

4.1.1. Coalition formation game fundamentals

Since coalitional game modelling is a natural way of doing clustering in a multi-agent environment and this paper addresses the FC clustering in a macro-femtocell network, we introduce the notions from coalitional game theory in this section.

Definition 1 (Game)**.** A coalitional game is defined as the pair $(\mathcal{N}, v)$ where $\mathcal{N}$ is the set of players, and function v is defined for each coalition $C \subseteq \mathcal{N}$, $v(S)$ as a real number representing the utility that coalition S receives. This utility can be distributed in any arbitrary way among the players in the coalition.

Definition 2 (Preference relation)**.** A preference relation, denoted by $\succeq_i$, is a reflexive, complete and transitive binary relation on $\mathcal{S}_i = \{\mathcal{S} \in 2^{|\mathcal{N}|} : i \in \mathcal{S}\}$, where $\mathcal{S}, \mathcal{T} \in V$. The strict preference and the indifference relation are denoted by $\succ_i$ and $\sim_i$ respectively ($\mathcal{S} \succ_i \mathcal{T} \iff [\mathcal{S} \succeq_i \mathcal{T}$ and
and $\mathcal{S} \sim_i \mathcal{T} \iff [\mathcal{S} \succeq_i \mathcal{T}$ and $\mathcal{T} \succeq_i \mathcal{S}]$).

Definition 3 (Partition)**.** Partition $\pi := \mathcal{S}_\infty, ..., \mathcal{S}_\| \in \pi(N)$ is a way of allocating the society of n players into disjoint non-empty coalitions S_1, ..., S_k that defines a coalition structure (CS). Coalition structure $\pi = \{\mathcal{S}_1, \mathcal{S}_2, \ldots, \mathcal{S}_K\}$ is a partition of $\mathcal{N}$, where $K \leq |\mathcal{N}|$ is a positive integer and $C_k \neq \emptyset$ for any $k \in 1, 2, \ldots, \mathcal{K}$. $\bigcup_{k=1}^{K} S_k = \mathcal{N}$, and $S_l \bigcap S_k = \emptyset$ for any $k, l \in 1, 2, \ldots, K$ and $k \neq l$. The collection of all coalition structures in $\mathcal{N}$ is denoted by $\Pi(\mathcal{N})$.

Definition 4 (Top coalition)**.** Given a non-empty set of players $V \subseteq \mathcal{N}$, a non-empty subset $\mathcal{S} \subseteq V$ is a top-coalition of V if and only if $\mathcal{S} \succeq_i \mathcal{T}$ for any $i \in \mathcal{S}$ and any $\mathcal{T} \subseteq V$ with $i \in \mathcal{T}$. A coalition formation game satisfies the top-coalition property if and only if for any non-empty set of players $V \subseteq \mathcal{N}$, there exists a top-coalition of V [37].

4.1.2. Coalitional game for FC clustering

In our coalitional game, the set of players includes the subset of available FCs and MC (i.e. $\mathcal{N} = \{FC\} \cup m$) and the function v is defined for each coalition S or FC cluster FC^c is given by

$$v(S) = \begin{cases} \dfrac{\sum_{k \in S} \frac{R_{PU}^f}{\gamma_f}}{\frac{R_{PU}^m}{\gamma_m} + \sum_{k \in S} \frac{R_{PU}^f}{\gamma_f}} \times (N_s - \overline{N_s^f}) & |S| \geq 1 \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

where $\overline{N_s^f}$ is the initial number of subcarriers allocated for FC subscribers transmission as the average number of subcarriers required per femtocells, which is given by:

$$\overline{N_s^f} = \frac{\sum_{f \in \{FC\}} R_{SU}^f / \gamma_f}{|FC| \times B_s} \tag{17}$$

where B_s is the bandwidth per subcarrier. Femtocells in stand alone mode are allowed to reuse this set of subcarriers. Note that a coalition S is equivalent to the definition of cluster F^c given in Section 1.1. From now on, we will use S instead of the set F^c.

The utility in (16) represents the resources gained by the coalition and should be divided between the coalition members (i.e. FCs and MC). The top coalition is the one that maximizes v(S) for the macrocell and the set of FCs in the coalition S. The information available at each decision point of the game is the set of candidate FCs and their demand. We assume that each femtocell is able to collect the needed information about the corresponding data rate demand of nearby PU and neighboring FCs by means of the cognitive pilot channel mechanism [38].

We use the same idea as the dynamic coalition formation proposed in [39], where the payoff of each player in a characteristic form is not defined. The characteristic function provides a worth for the coalition, and each player claims a share of this worth. If the claims can be met, each player gets it, otherwise, each player gets the worth it would get if it were to form a single coalition. We assume fair subcarrier allocation between the coalition members. Therefore, the payoff of any player (MC and FCs) $k \in S$ is

$$\phi_k(S) = \begin{cases} \dfrac{b \times v(S)}{(|S| - 1)} & k \in S \backslash m \\ (1 - b) v(S) & k = m \end{cases} \tag{18}$$

where b is a value between [0,1] that represents the portion of the available subcarriers used by the femto-tier. The number of available subcarriers for public users can be determined as:

$$N_s^{PU} = (N_s - \overline{N_s^f}) \tag{19}$$

The first step of the coalition formation process is to determine the top-coalition that maximizes the sum of the PU data rates, guaranteeing their subscribers satisfaction and avoiding the starvation of resource in the macrocell. It is assumed that the macrocell is the major player and takes precedence over the other players (femtocells) because the wireless resources belong to the mobile operator. Therefore, public users served by FCs in coalitions can use the unused subcarriers in the macrocell, which is given as $\frac{b \times N_s^{PU}}{|FC|}$.

At each step (i.e. each time new public users arrive), the available actions for the femtocells in stand alone mode are to stay as singleton coalition or to join any established coalition that maximizes its payoff without depriving the utilities of the coalition and the coalition members. The available actions for the femtocells in a coalition are either to stay or leave the current coalition. If the average perceived interference per subcarrier is higher than the interference threshold, then, the femtocell decides to leave the coalition and acts in the stand-alone mode.

Within a coalition, the femtocell payoff corresponds to the extra resources for their own subscribers based on the offloaded traffic from the macrocell. Thus, the payoff received by FCs depends on the sum of public user data rates (i.e. $\sum_i^{PU} \alpha_i^f R_i^f$). FC subscribers can access the initial number of allocated subcarriers per femtocell $\overline{N_s^f}$ plus the remaining resources that public users did not use in the coalition S, $\lambda_f \times (b \times N_s^{PU} - N_{used,c}^{PU})$. The parameter λ_f considers the data rate granted to the public user by femtocell f in the coalition S and is given by:

$$\lambda_f = \frac{\sum_{i \in PU} \alpha_i^f R_i^f}{\sum_{f \in S} \sum_{i \in PU} \alpha_i^f R_i^f} \tag{20}$$

It is important to notice that FCs choosing to stay in the closed access mode can increase their throughput if their neighboring FCs become members of a cluster due to the inter-cluster interference reduction. This is owing to the fact that number of FCs sharing the initial number of subcarriers allocated to the femto tier is reduced. To mitigate the inter-cluster interference, we propose to perform power control using two different maximum transmitted power thresholds per FC in order to reach the target spectral efficiency for the users. One threshold for users inside the FC coverage area, $P_{i,max}^f$, and another threshold for users in the interfering area of the femtocell, $P_{o,max}^f$, as shown in Fig. 1.

4.1.3. Coalition formation algorithm

The proposed strategy aims to find the best partition of players, containing a top-coalition S^* of femtocells and the macrocell and several coalitions of femtocells (S_j). Note that the top-coalition is the one that maximizes the sum of achievable data rate of public users in the network. This allow the model to determine the bandwidth allocated to macro-tier and the femto-tier cluster. Top-coalition S^* may change over time when new public users arrive or depart. The coalition formation is described in Algorithm 1. The complexity of Algorithm 1 is evaluated by simulations in Section 5.4 in terms of the running time required by the clustering scheme.

4.1.4. Cluster head selection

The cluster head is responsible for the clustering formation. This means that the cluster head is responsible for searching femtocells working in stand-alone mode and invite them to join the cluster such that the inter-cluster interference can be reduced. If the invitations are accepted, more resources from the macrocell

Algorithm 1: Coalition formation algorithm.

```
begin
    Initial State of Femtocell:
    Each FC is a cluster, i.e. |FC| = |C|.
    Each FC computes its payoff φ_i(C, π_N).
    Neighbor Discovery:
    for f ∈ C do
        f collects RSSI of the neighboring FCs using measurement
        reports from its active users.
        Each FC f keeps a list of neighboring FCs, Neighbor^f.
    Coalition Formation
    Step 1 - Base Station Selection
    Run Algorithm 2
    Step 2 - Coalition Formation
    for each f ∈ F^sa do
        for each j ∈ Neighbor^f that are CH do
            Coalition S_j computes the its throughput gain with the
            using Algorithm 3
            If φ_i^*(S_j ∪ f) ≥ φ_i^*(S_j)S_j sends the estimated throughput for
            f being
            a member of the coalition
        S_f^* ← max_j R_f^{SU,S_j}
        S_f^* ← S_f^* ∪ f
        F^sa ← F^sa \ f
    Step 3 - Top Coalition Selection
    for each S_j ∈ π_N do
        Run Algorithm 3 (WWF based resource allocation algorithm)
    TC ← max_{j∈N}(R_{S_j}^{PU} + R_m^{PU})
    N_s^{FT} = N_{used,S_j}^{PU} + N_{used,S_j}^{SU} + \overline{N_s^f}
    Step 4 - Cluster Head Selection
    for each S_j ∈ π_N do
        CH ← max_{f∈S_j} |Neighbor^f ∩ F^sa|.
    Step 5: Cluster based Resource Allocation
    for each S_j ∈ π_N do
        Run Algorithm 4 (PSO based resource allocation algorithm)
    Step 6 - Interference Control per FC
    for each S_j ∈ π_N do
        for each f ∈ S_j do
            f computes I_f^s using (29)
            If I_f^s > I_threshold (30)
            f leaves the coalition S_j (S_j ← S_j \ f
            F^sa ← F^sa ∪ f
```

can be granted to the cluster. Therefore, our model selects the femtocell with the highest number of neighbors outside of its coalition as a cluster head, which is responsible of sending the invitations to the nearby stand alone FCs. Moreover, the cluster head is also responsible of the resource allocation.

The required information exchange among the cluster head and other femtocells can be done via the wired backhaul link. For convenience, we assume that the wired backhaul communication meets the tight demands for reliable and low latency communication to avoid a negative impact on the proposed framework. However, this issue can be investigated as a future work and is out of the scope of this paper.

4.1.5. BS selection for public users

Public users can be close to several FCs that belong to different clusters and our objective is to select the BS that can allocate the highest data rate. Thus, the required information for this selection is the data rate demands of public users and the link rate conditions between the surrounding FCs and the MC. First, each public user sends its data rate demand to each nearby FC that in turn sends this information to its cluster head. Second, the cluster head processes the WWF based resource allocation algorithm and returns to FCs the estimated subcarriers allocation for the users and then each FC returns the achievable data rate to the public user. Finally, each public user sorts the possible data rates in descending order and sends a request to the femtocell with the highest data rate. If the BS with the highest data rate has no available capacity (in terms of number of connected users), the public user sends the request to the next BS in its list. This procedure for BS selection for public users is described formally in Algorithm 2.

Algorithm 2: BS selection for public users.

```
Data: PU Set of public 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 PU in decreasing order by their weighted demand (D_i);
    for each i ∈ MS do
        Determine the set of neighboring FC_user with higher link rate
        than the macrocell.
        if FC_user != 0 then
            Sort FC_user 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 femtocell f in the ordered list.
            α_i^f ← 1;
            Increase the number of public users on FCs.
            N_PU^f ← N_PU^f + 1;
            Reduce the available capacity of femtocell f.
        else
            Assign user to the macrocell.
            α_i^m ← 1;
```

4.1.6. WWF based resource allocation per cluster

WWF is an algorithm that fairly allocates bandwidth based on users' data rate demands [15]. In this case the users are sorted in ascending order according to their data rate demands. The weights used in the proposed WWF based algorithm are given by

$$w_i = \frac{D_i}{\sum_{f\in\{S\}} \sum_{i\in\{MS\}} \alpha_i^f D_i} \tag{21}$$

Then, pieces of bandwidth are allocated sequentially to the users in several rounds until the available bandwidth is exhausted or the last user data rate demand is satisfied. The WWF based resource allocation is presented in Algorithm 3. Since the PSO approach takes longer computation time than the WWF approach, we propose to apply the pre-processing of the offered data rate for public users within a cluster using WWF algorithm. Then, once the BS selection for the public users is finally made, the final resource

Algorithm 3: WWF algorithm per cluster.

```
Data: Bandwidth assigned to femto-tier (B_f^m),
        Set of users assigned to femtocell in cluster f ∈ S (MS^S)
Result: Data Rate and resources allocated per user ((T_i^c), (B_MS^f, P_MS^f).
begin
    Sort MS^c according to the bandwidth required divided by the total
    required bandwidth;
    while i ∈ MS^S do
        b_i^wwf ← min( (b_i^required − b_i^{k−1}) / w_i^f , (B_f^m − Σ_{k=1}^{i−1} Σ_{j=k}^{MS^f} b_j) / (Σ_{j=i}^{MS^f} w_j^f) );
        for j = i → |MS^S| do
            while b_i is not satisfied and B_f and P^f are not exhausted do
                b_j^k ← b_j^{k−1} + w_j^f b_i^wwf;
        p_i^f ← min( SNR_th^f N_0 PL_i^f , min(P_f^max, P_f^res) );
    Calculate the data rate using Shannon Law's Capaciy, T_i^S
```

allocation is carried out using the PSO based resource allocation, which is described in Section 4.1.7. For the comparison purposes, we also run simulations using this algorithm as the final resource allocation within each cluster.

4.1.7. PSO based resource allocation per cluster

We propose the Particle Swarm Optimization technique for solving the optimization problem, defined by Eqs. (10)–(15) presented in Section 3.2, since this technique has been proven to obtain a satisfying near-optimal solution while speeding up the optimization process.

PSO is a population-based search approach that requires information sharing among the population members to enhance the search process by using a combination of deterministic and probabilistic rules. 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:

$$x_n^{k+1} = x_n^k + \delta_t v_n^k, \tag{22}$$

$$v_n^{k+1} = \omega v_n^k + c_1 r_1 (p_k^{local} - x_n^k) + c_2 r_2 (p_k^{global} - x_n^k), \tag{23}$$

where δ_t is the time step value typically considered as unity [40], 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 ω, c_1 and c_2 are the configuration parameters that determine the PSO convergence behavior. The first term of Eq. (23) 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. (23) are associated with cognitive knowledge that each particle has experienced and the social interactions among particles respectively [41]. The convergence of PSO is guaranteed if the following two stability conditions are met:

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

In order to apply the PSO technique to our optimization problem, we define vectors **b** and **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 cluster, i.e. $|MS^S|$. We use two different velocity vectors (v_b, v_p) to update the particle location in each iteration and they are updated using Eq. (23).

PSO algorithm is formulated as an unconstrained optimizer. One way to accommodate constraints is to augment the objective function with 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 [40]. Therefore, penalty coefficients are determined as

$$cp_l = |\overline{f(x)}| \frac{\overline{g_l(x)}}{\sum_{j=1}^{CP} [\overline{g(x)}]^2}, \tag{24}$$

where $\overline{f(x)}$ is the average objective function, $\overline{g(x)}$ is the average level of l_{th} constraint violation over the current population and CP is the number of constraints [40]. Then, the fitness function is defined by

$$f^*(x) = \begin{cases} f(x_n^k), & \text{if } x_n^k \text{ is feasible} \\ f(x_n^k) + \sum_{l=1}^{CP} cp_l \widehat{g}(x_n^k), & \text{otherwise} \end{cases} \tag{25}$$

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

$$\widehat{g}(x_n^k) = \max\left(0, [g_j(x_n^k)]\right). \tag{26}$$

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

The 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. There are several techniques for such conversion [42]. We use a simple one, in which the original objective function defined by Eq. (10) is subtracted from a large number Q so the objective function for our PSO based resource allocation (RA) model is determined as follows:

$$f_{RA}(\mathbf{b},\mathbf{P}) = Q - \sum_{i\in\{MS\}} \sum_{\in\{m,FC\}} \alpha_i^k b_i log_2(1 + SINR_i^{s,f}) \tag{27}$$

where Q is a large number (at least twice of the maximum throughput that can be achieved in a cluster). The binary parameter α_i^k is the user-base station association and is equal to 1 if $bs_n(i)$ is equal to k and 0 otherwise as already described in Section 4.1.5. Following the PSO parameter-less scheme, the fitness function of our PSO based resource allocation model is defined by

$$f_{RA}^*(x) = \begin{cases} f_{RA}(\mathbf{b},\mathbf{P}), & \text{for feasible solutions} \\ f_{RA}(\mathbf{b},\mathbf{P}) + \sum_{l=1}^{CP} k_l \widehat{g}(\mathbf{b},\mathbf{P}), & \text{otherwise} \end{cases} \tag{28}$$

where constraints (11)–(15) are included in $\sum_{l=1}^{CP} k_l \widehat{g}(\mathbf{b},\mathbf{P})$ to penalize unfeasible solutions. Algorithm 4 presents the PSO based resource allocation executed at the cluster head that knows the allocated bandwidth per cluster and pre-fixed BS selection per user. Our PSO based resource allocation algorithm executed by each cluster head is presented in Algorithm 4.

Algorithm 4: PSO based resource allocation algorithm.

Data: *MS* User Locations (x_i, y_i),
Set of FC member of the cluster (x_f, y_f),
Users Demands (D_i),
BS selection per user (bs_i),
bandwidth per cluster (B_c).
Result: Bandwidth and power allocation per user (b_i, P_i).
begin
  for *each* $i \in MS$ **do**
    $b_i^{max} \leftarrow \frac{D_i}{\gamma_f}$;
    $P_i^{max} \leftarrow \min(P_f^{max}, SINR_k^{max} \times (N_o + I_{th}) \times PL_i^f)$;
  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;

4.1.8. Interference control mechanism

Since the proposed solution is distributed, the interference received by femtocells in a cluster cannot be estimated before the resource allocation. Therefore, we propose an interference mitigation mechanism that allows FCs to leave its current coalition when the interference levels given by

$$I_i^{s,k} = \sum_{f\in\{F^c\backslash k\}} \sum_{j\in\{MS\backslash i\}} \sum_{s\in\{SC\}} \frac{\beta_j^{s,f} P_j^{s,f}}{PL_i^f}, \quad k \in S \tag{29}$$

are higher than the interference threshold denoted as $I_{threshold}$. This interference threshold is estimated as the average interference level received by the subscribers being served by femtocells when all the femtocells work in the closed access mode:

$$I_{threshold} = \frac{1}{|FC|} \sum_{f\in\{FC\}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} \alpha_i^f I_i^{s,f} \tag{30}$$

4.2. Benchmark models

In order to assess performance of our proposal, we use two benchmark models. The first benchmark model (BC-WWF) is a centralized clustering approach using a WWF resource allocation algorithm within each cluster. BC-WWF model corresponds to our previous work, presented in [36]. This approach attempts to balance the traffic load of the public users among the clusters without causing the bandwidth starvation at the macro-tier. The model consists of three components: (1) a centralized BS selection procedure that ensures that the traffic load of public users is fairly balanced among the FC clusters, (2) a WWF based resource allocation within each cluster that maximizes the cluster throughput and avoids co-tier interference, (3) a cluster formation algorithm to mitigate the co-tier interference and to balance the number of FC per cluster. This model tries to merge stand-alone FCs with the cluster that has the highest available capacity in terms of available subcarriers guaranteeing QoS subscriber transmission without exceeding the maximum number of FCs per cluster allowed in a given period of time. The second benchmark model (WWF-Dist) is a modified version of the solution proposed in this paper and it consists of our distributed clustering model combined with the WWF resource allocation algorithm, instead of the PSO based resource allocation model, within each cluster.

5. Simulation results

We consider a single hexagonal macrocell with 10 femtocells and high density public users located near the femtocells. The hybrid access policy is adopted for FC if it is in a coalition; otherwise it works in the closed access mode. For each FC, we set two values of maximum transmit power, $P^f_{o,max}$ and $P^f_{i,max}$, that are used for users in the surrounding of the FC house or inside the FC house, respectively. Transmissions are affected by the distance dependent path loss according to the 3GPP specifications [43] and the external FC house wall loss attenuation of 3 dB. The number of available subcarriers is 256 and each one has a bandwidth of 15 KHz. We consider the spectrum partitioning approach, in which different sets of subcarriers are allocated to the macro-tier and the femto-tier to avoid the cross-tier interference. All relevant network and environment parameters are described in Table 4.

The simulations are executed for different number of public users (increasing from 10 to 60 with 5 user increment) and with 10 FCs deployed within an area of 240 × 80 m as illustrated in Fig. 1. The public users are randomly located within FCs' vicinity.

The proposed approach motivates FCs to cooperate and become member of a cluster by means of the allocation of extra subcarriers. To show well this feature, we consider only one subscriber

Table 4
Parameter settings.

Name	Description	Value
Network configuration		
N_s	Number of subcarriers	256
P_m^{Total}	Transmitted power per MC	60 dBm
P_f^{Total}	Transmitted power per FC	10 dBm
r_m, r_f	Macrocells and femtocell radius	500 m, 20 m
θ_f, θ_m	Attenuation factor of indoor and outdoor	3, 3.7
γ_m, γ_f	Spectral efficiency for MC or FC	(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	1
$\|PU\|$	Number of public users	5–60
FC	Number of deployed femtocells	10
PSO parameters		
Name	Description	Value
c_1	Cognitive knowledge parameter	2.0
c_2	Social interactions parameter	1.5
ω	Inertia	0.85

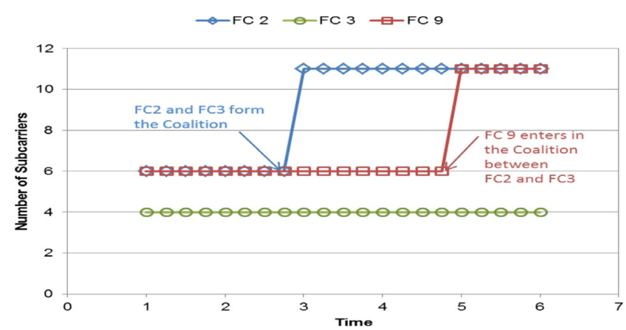


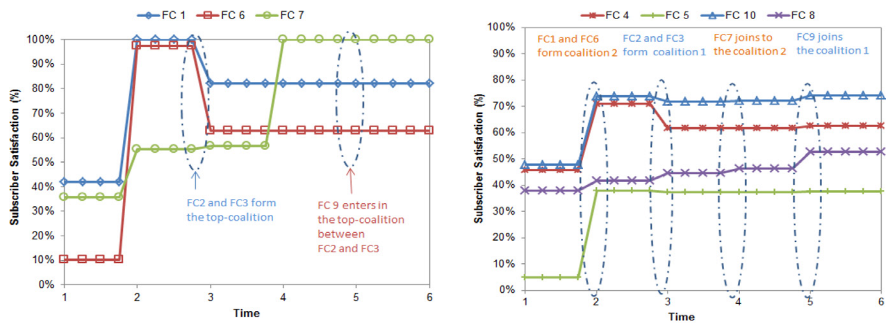
Fig. 3. Subcarriers allocated for subscriber transmissions in FCs forming the top-coalition.

per FC with random data rate demand (128 kbps to 1 Mbps) in the following analysis. With more subscribers per FC, more resources would be required to satisfy the subscriber data rate demands and less public users can be connected to FCs, as it was shown in our prior work [10].

5.1. Analysis of the proposed coalition formation

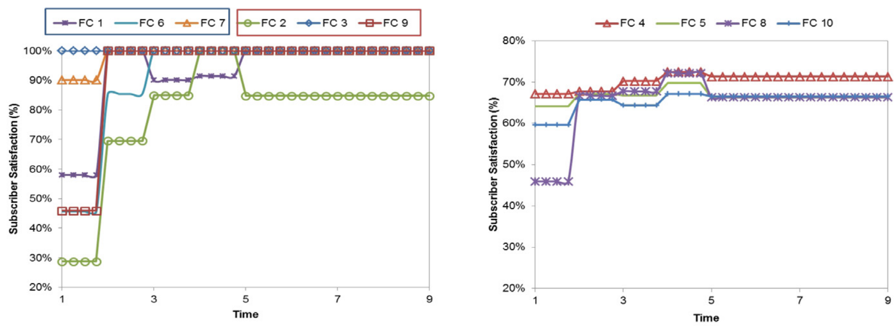
In this section, we illustrate how the number of FC subcarriers is increased when FCs cooperate and form a top-coalition and several other coalitions. First we focus on the top-coalition and its dynamic adaptation caused by new PUs arrivals. This dynamic adaptation is illustrated in Fig. 3 where the number of subcarriers allocated to femtocells forming the top-coalition is shown. Initially, the considered three femtocells, FC_3, FC_2 and FC_9, work in the stand-alone mode and share the same subcarriers allocated to the femto-tier, $\overline{N_s^f}$. Note that the number of subcarriers allocated for FC_3 in the stand-alone mode is lower than the number of subcarriers allocated to FC_2 and FC_9 because the data rate demanded by FC_3's subscriber is lower than the average data rate demand $\overline{D^f_{SUE}}$.

Fig. 3 shows the resulting top-coalition is formed by FC_2, FC_3 and FC_9 at time 5. Note that the top-coalition may change with the arrivals of new PUs. In this particular scenario, a top coalition was formed before at time 2 by FC_1 and FC_6 which can be observed in Fig. 4(a) when the subscribers' satisfaction increases to 100%. However, at time 3, FC_2 and FC_3 form the top-coalition that maximizes the public users achievable data rate. In this case, FC_2 receives extra-subcarriers for its subscriber transmission and FC_3 keeps the same number of subcarriers because its subscriber sat-



(a) FC in coalition 2 (b) Stand-alone FCs

Fig. 4. Subscribers satisfaction in FCs belonging to coalition no. 2 and in stand-alone FCs.



(a) FC in coalitions (b) Stand-alone FCs

Fig. 5. Subcarriers satisfaction in FC belonging to the coalitions and stand-alone FC.

isfaction was already 100% as shown in Fig. 5(a). FC_3's subscriber data rate is enhanced by the reduction of the co-tier interference caused previously by FC_2. At time 5, FC_9 joins the top-coalition and is awarded with additional subcarriers for its subscriber transmission. Moreover, the subscriber satisfactions for femtocells FC_2 and FC_9 are improved because of the extra-subcarriers obtained from the macrocell and the reduction of the co-tier interference caused previously by FC_3. The total number of subcarriers allocated to the final top-coalition for subscribers transmissions is 26.

Since our model is distributed, we analyze the subscriber satisfactions when the coalitions add new femtocells. Fig. 4(a) and (b) depicts the subscriber satisfactions for coalition 2 with femtocells FC_1, FC_6, and FC_7 and for stand-alone FCs, respectively. We denote the points where the top-coalition changes in both figures. Fig. 4(b) shows that stand-alone femtocells are affected when the changes occur in the coalitions. It can be observed that most of the changes in coalitions can effectively enhance the subscribers satisfaction when compared to their initial subscriber satisfactions, even for the stand-alone FCs.

It can be noticed that the subscriber satisfactions are also affected by the formation of other coalitions in the network. For example, Fig. 4(a) shows that subscribers transmission in FC_6 is severely affected when FC_2 and FC_3 form the top-coalition. To avoid this problem, we propose to implement a splitting mechanism for FCs that have joined any coalition. The idea is that each member of a coalition evaluates its interference level. If the interference value is higher than the average value per FC in the coalition, then, the FC chooses to stay in the stand-alone mode and considers joining other coalitions.

Fig. 5(a) presents the subscribers satisfactions for the FCs in coalition, where the mentioned above preference for leaving a coalition is applied if a FC senses high interference levels in a given period of time. In this figure, the legends are separated to indicate femtocells in the same coalition. After period 5, we can see that subscriber satisfaction is 100% for almost all FC except for FC_2. After period 5, the satisfaction of FC_2 decreases to 85%. This is owing to the fact that other coalitions cause interference to the top-coalition due to the resources sharing. However, this satisfaction value is still higher than the ones obtained by the subscribers in stand-alone mode FCs that are depicted in Fig. 5(b) or its initial subscriber satisfaction (i.e. 30%).

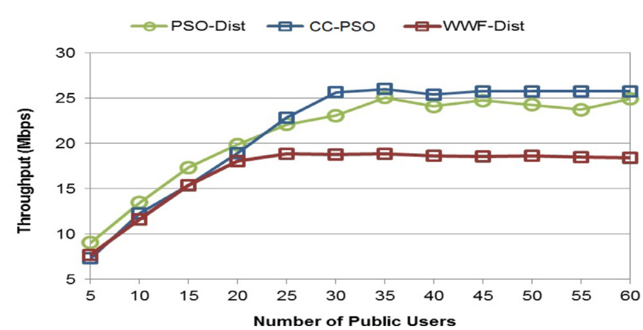
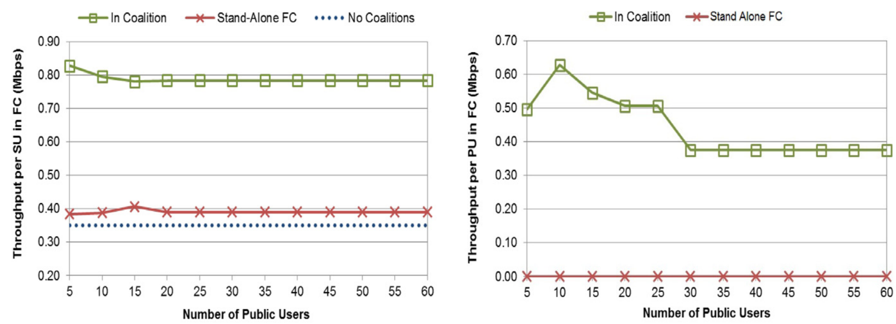


Fig. 6. Network throughput.

In summary, the top-coalition C^* is determined as the subset of femtocells, S, and the macrocell that achieve the maximum sum of data rate for public users without starving the MC resources. Then, other FCs form coalitions using a portion of the allocated bandwidth to the top-coalition while the FC subscriber satisfaction is guaranteed and inter-cluster interference is minimized.

5.2. Network throughput

Here, we present a comparison between the proposed distributed clustering model, that uses the PSO based distributed resource allocation model, (PSO-Dist) and the WWF based resource allocation algorithms (WWF-Dist) within each cluster. We also include the simulation results of our centralized clustering approach (CC-PSO) [10]. Fig. 6 presents the overall network throughput using the three models. It can be observed that the centralized clustering approach and PSO-Dist model give similar throughput val-



(a) Average Throughput per FC subscriber. (b) Average Throughput per public user in femto-tier.

Fig. 7. Impact of FC coalition over average throughput per user.

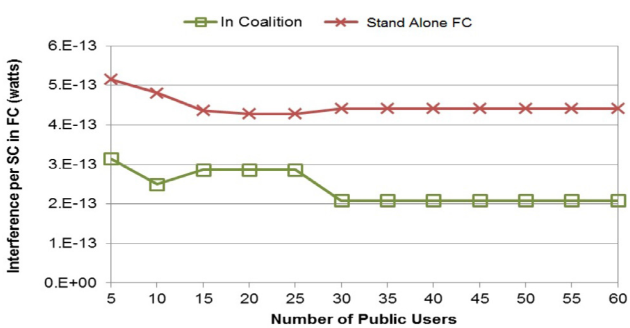


Fig. 8. Average interference per subcarrier.

ues for more than 30 users in the network. For less than 30 users, the WWF-Dist and CC-PSO models present similar throughput values while PSO-Dist enhances the network throughput. As stated in Section 4.1.3, a FC that perceives an interference higher than the interference threshold can decide to leave its current coalition and go back to work in the closed access mode. This can be seen in Fig. 6, where some throughput fluctuations exist for the PSO-Dist model. These fluctuations reflect the fact that a femtocell belongs to a coalition temporarily but leaves it taking into account the received interference level.

5.3. FC performance metrics analysis

Some femtocell performance metrics are analyzed in this section. In particular the average throughput per type of user (i.e. public user or subscriber) and the average interference per subcarrier are presented for both types of femtocells: the ones that form coalitions and the stand-alone femtocells. Fig. 7(a) and (b) shows the average throughput of FC subscribers and the public users being served by femtocells in coalition and in the stand-alone mode (i.e. the closed access mode).

These results show that the FC subscribers in a coalition can reach higher throughput than the subscribers served by stand-alone FCs. This is due to two main features: (1) stand-alone FCs work in the closed access mode and they do not get extra resources from macrocell since they do not grant access to public users and (2) the interference in stand-alone FCs is higher than in FCs that form coalitions. The second feature is illustrated in Fig. 8. In summary, the simulation results show that the proposed approach finds the top-coalition while guaranteeing the minimum level of FC subscriber satisfaction, which is determined by the subscriber satisfaction in a femtocell working in the closed access mode.

Table 5
Running time for different FC number and high density of PU.

FC number	PU number	Clustering time (s)
10	30	1.81
20	60	6.48
30	90	18.48
40	120	39.78
50	150	89.78

Table 6
Running time.

PU number	Time (s)	
	Clustering	Cluster based RAM
10	1.81	1.75
20	2.22	2.65
30	1.62	2.87
40	0	0

5.4. Complexity

Table 5 presents the running times for different number of femtocells and nearby PUs. First and second column represent the number of femtocells and number of public users close to their vicinity. The third column corresponds to the time spent on the clustering formation. We assume that one subscriber is located inside each FC and three public users are located in the FC vicinity, which gives high density of the nearby PUs. We can see that the running time increases as the number of FC increases.

Nevertheless, we propose a distributed clustering scheme, which means that the model can select disjoint set of FCs in different areas and solve the problem for the top coalition in each area. Then, the model selects the one that maximizes the public users data rate in each respective sector among all the top coalitions. If we consider that each sector has 10 FC and that the clustering problem per sector can be solved in parallel, then, the running time with high PU density is 1.81 s.

For the case of one sector with 10 FCs, Table 6 presents the running times for different public users density. First column represents the number of public users, the second column corresponds to the time spent on the clustering formation and the third column indicates the average running time of the model for resource allocation within a cluster.

In the initial step, the clustering running time is measured for the initial coalition formation when 10 public users arrive to the FC vicinity, then, at the next step (i.e. 10 new PUs arrive), the running time corresponds to the process of joining the stand alone femtocells to the already established clusters from the previous step, and so on. We can see that after 30 users the running time of the clustering scheme and resource allocation algorithm becomes 0. This means that for more than 30 public users close to FC vicinity, neither the clusters can increase their utility by admitting new femtocells nor the FCs can get extra resources to increase their subscriber satisfactions and the users can keep the allocated resources from previous step. Finally, it can be observed that the running time for the resource allocation algorithm is increased when more users are assigned to each coalition.

6. Conclusions

We propose a game theoretical framework for clustering and resource allocation in macro-femtocell networks. The proposed solution consists of the FC coalition formation model aiming at maximization of the sum of public user data rate and the Particle Swarm Optimization based resource allocation algorithm that is executed locally by the cluster head within each cluster. For simplicity, we select the cluster head as the femtocell with the highest number of neighbors outside of its coalition. The proposed model is able to determine the best serving BS and the bandwidth and power allocation for each user taking into account its data rate demand, location and FC proximity. Our solution was compared with the centralized clustering model. The comparison showed that the proposed approach presents similar values of network throughput without reducing the subscribers satisfaction by means of rewarding FCs with extra resources for their subscriber transmission. In the tested scenarios, the subscriber satisfaction is at least 85% for the femtocells belonging to a coalition while for the stand-alone FCs it is 60%. Moreover, the proposed solution reduces the inter-cluster interference and allows efficient bandwidth usage. As future work, we propose to investigate other evolutionary computational techniques for the resource allocation within a cluster to reduce further the computational time, the evaluation of other cluster head selection techniques, and the incorporation of inter-cluster interference models.

References

[1] J. Zhang, Femtocells: Technologies and Deployment, Wiley, Chichester, West Susssex, UK, Hoboken, NJ, 2010.
[2] V. Chandrasekhar, J.G. Andrews, A. Gatherer, Femtocell networks: a survey, IEEE Commun. Mag. 46 (9) (2008) 59–67.
[3] A. Valcarce, D. Lpez-Prez, G.D.L. Roche, J. Zhang, Limited access to ofdma femtocells, in: IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2009, pp. 1–5.
[4] Y.-Y. Li, L. Yen, E. Sousa, Hybrid user access control in HSDPA femtocells, in: Proceedings of the IEEE GLOBECOM, 2010, pp. 679–683.
[5] H. Ju, B. Liang, J. Li, Y. Long, X. Yang, Adaptive cross-network cross-layer design in heterogeneous wireless networks, IEEE Trans. Wireless Commun. 14 (2) (2015) 655–669.
[6] P. Xue, P. Gong, J.H. Park, D. Park, D.K. Kim, Radio resource management with proportional rate constraint in the heterogeneous networks, IEEE Trans. Wireless Commun. 11 (3) (2012) 1066–1075.
[7] R. Estrada, A. Jarray, H. Otrok, Z. Dziong, H. Barada, Energy-efficient resource-allocation model for OFDMA macrocell/femtocell networks, IEEE TVT 62 (7) (2013) 3429–3437. ISSN=0018-9545.
[8] S. Mishra, C.S.R. Murthy, An efficient location aware distributed physical resource block assignment for dense closed access femtocell networks, Comput. Netw. 94 (2016) 164–175.
[9] S. Ryoo, C. Joo, S. Bahk, A decentralized spectrum allocation and partitioning scheme for a two-tier macro-femtocell network with downlink beamforming, EURASIP J. Wireless Commun. Netw. 2012 (1) (2012) 160.
[10] R. Estrada, H. Otrok, Z. Dziong, A novel cluster based resource sharing model for femtocell networks, Comput. Commun. 94 (2016) 85–102.
[11] E. Stevens-Navarro, A.H. Mohsenian-Rad, V.W.S. Wong, Connection admission control for multiservice integrated cellular/wlan system, IEEE TVT 57 (6) (2008) 3789–3800.
[12] R. Mahindra, H. Viswanathan, K. Sundaresan, M.Y. Arslan, S. Rangarajan, A practical traffic management system for integrated lte-wifi networks, in: Proceedings of the 20th Annual International Conference on Mobile Computing and Networking (MobiCom'14), ACM, 2014, pp. 189–200.
[13] J. Lee, Y. Yi, S. Chong, Y. Jin, Economics of wifi offloading: trading delay for cellular capacity, in: Proceedings of the IEEE INFOCOM, 2013, pp. 3309–3314.
[14] P. Luong, T.M. Nguyen, L.B. Le, N.D.O.E. Hossain, Energy-efficient wifi offloading and network management in heterogeneous wireless networks, IEEE Access 4 (2016) 10210–10227.
[15] C.H. Ko, H.Y. Wei, On-demand resource-sharing mechanism design in two-tier OFDMA femtocell networks, IEEE TVT 60 (3) (2011) 1059–1071.
[16] V. Chandrasekhar, J. Andrews, Uplink capacity and interference avoidance for two-tier femtocell networks, IEEE Trans. Wireless Commun. 8 (7) (2009) 3498–3509.
[17] J. Zhang, Z. Zhang, K. Wu, A. Huang, Optimal distributed subchannel, rate and power allocation algorithm in OFDM-based two-tier femtocell networks, in: Vehicular Technology Conference, 2010, pp. 1–5.
[18] D. Lopez-Perez, A. Valcarce, G. de la Roche, J. Zhang, OFDMA femtocells: a roadmap on interference avoidance, IEEE Commun. Mag. 47 (9) (2009) 41–48.
[19] K. Sundaresan, S. Rangarajan, Efficient resource management in OFDMA femto cells, in: Proceedings of the MobiHoc, 2009, pp. 33–42.
[20] V. Chandrasekhar, J. Andrews, T. Muharemovict, Z. Shen, A. Gatherer, Power control in two-tier femtocell networks, IEEE Trans. Wireless Commun. 8 (8) (2009) 4316–4328.
[21] A. Dalal, H. Li, D. Agrawal, Fractional frequency reuse to mitigate interference in self-configuring LTE-femtocells network, in: Mobile Adhoc and Sensor Systems International Conference, 2011, pp. 49–54.
[22] Y. Jeong, J.Y. Lee, M.Y. Chung, T.-J. Lee, H. Choo, Femtocell frequency planning scheme in cellular networks based on soft frequency reuse, in: Cyber-Enabled Distributed Computing and Knowledge Discovery Conference, 2010, pp. 176–180.
[23] T.M. Nguyen, L.B. Le, Opportunistic spectrum sharing in poisson femtocell networks, in: IEEE Wireless Communications and Networking Conference, 2014, pp. 1467–1472.
[24] R. Estrada, A. Jarray, H. Otrok, Z. Dziong, Base station selection and resource allocation in macro-femtocell networks under noisy scenario, Wireless Netw. 20 (1) (2014) 115–131.
[25] H. Marshoud, H. Otrok, H. Barada, R. Estrada, A. Jarray, Z. Dziong, Resource allocation in macrocell-femtocell network using genetic algorithm, in: International Conference on Wireless and Mobile Computing, Networking and Communications, 2012, pp. 474–479.
[26] R. Estrada, H. Otrok, Z. Dziong, Resource allocation model based on particle swarm optimization for OFDMA macro-femtocell networks, in: IEEE ANTS Conference, 2013, pp. 1–6.
[27] A. Hatoum, R. Langar, N. Aitsaadi, R. Boutaba, G. Pujolle, Cluster-based resource management in OFDMA femtocell networks with QoS guarantees, IEEE TVT 63 (5) (2014) 2378–2391.
[28] H. Zhang, D. Jiang, F. Li, K. Liu, H. Song, H. Dai, Cluster-based resource allocation for spectrum-sharing femtocell networks, IEEE Access 4 (2016) 8643–8656.
[29] K. Rohoden, R. Estrada, H. Otrok, Z. Dziong, A coalitional game for femtocell clustering in OFDMA macro-femtocell networks, in: NETWORKS Conference, 2016, pp. 221–226.
[30] A. Abdelnasser, E. Hossain, D.I. Kim, Clustering and resource allocation for dense femtocells in a two-tier cellular OFDMA network, IEEE Trans. Wireless Commun. 13 (3) (2014) 1628–1641.
[31] R. Ramamonjison, V.K. Bhargava, Energy efficiency maximization framework in cognitive downlink two-tier networks, IEEE Trans. Wireless Commun. 14 (3) (2015) 1468–1479.
[32] Y.Y. Shih, A.C. Pang, M.H. Tsai, C.H. Chai, A rewarding framework for network resource sharing in co-channel hybrid access femtocell networks, IEEE Trans. Comput. 64 (11) (2015) 3079–3090.
[33] S. Yang, OFDMA System Analysis and Design, Artech House, Boston, 2010.
[34] ITU, Guidelines for Evaluation of Ratio Transmission Technologies for IMT-2000, ITU, 1997. Recommendations, RM.1225
[35] K. Bogart, Discrete Mathematics for Computer Science, Key College Pub, Emeryville, CA, 2006.
[36] R. Estrada, H. Otrok, Z. Dziong, Clustering and dynamic resource allocation for macro-femtocell networks, in: NETWORKS Conference, 2014, pp. 1–6.
[37] S. Banerjee, H. Konishi, T. Sönmez, Core in a simple coalition formation game, Soc. Choice Welfare 18 (1) (2001) 135–153.
[38] E. W. P. 5, A White Paper by the FP7 Project End-to-End Efficiency (E3) Support for Heterogeneous Standards Using CPC, White Paper XP055143298, E3 Work Package 5.
[39] Dynamic coalition formation and the core, J. Econ. Behav. Org. 49 (3) (2002) 363–380.
[40] R. Perez, K. Behdinan, Particle swarm optimization in structural design, in: Swarm Intelligence: Focus on Ant and Particle Swarm Optimization, 2007, pp. 532–555.
[41] D. Bratton, J. Kennedy, Defining a standard for particle swarm optimization, in: Proceedings of the IEEE SIS, 2007, pp. 120–127.
[42] V. Chvatal, Linear Programming, Series of Books in the Mathematical Sciences, W. H. Freeman, 1983.
[43] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); TDD Home eNode B (HeNB) Radio Frequency (RF) Requirements Analysis, 3GPP, 2011. Draft Version 10.0.0

Katty Rohoden graduated as Electronic and Telecommunications Engineer from Universidad Tecnica Particular de Loja (UTPL) in 2006. She obtained her master degree in Telecommunication Networks for Developing Countries at Universidad Rey Juan Carlos (URJC) in Madrid, Spain, in 2012. Since March 2014 she is a Ph.D. candidate at the Ecole de Technologie Superieure (ETS) of the University of Quebec. Since December 2006, she has been working in the Department of Computer Science and Electronic at UTPL. Her main research interests are in communication systems, information theory, and cellular networks. Currently, she is working on resource allocation for cellular heterogeneous networks.

Rebeca Estrada holds a computer science engineering degree from ESPOL (Ecuador) and a telecommunication master degree from ITESM (Mexico). She completed her doctoral and postdoctoral studies at the Ecole de Technologie Superieure and the CIISE Department of Concordia University, respectively. She worked as leader of telecommunication research group of program VLIR-ESPOL between 2006 and 2010, and as professor in the Electrical and Computer Science Engineering Department of ESPOL from 1998 to 2010. Currently, she is a research group director at ESPOL, and her current research work is oriented to task allocation in mobile crowd-sensing systems, cloud service providers federation formation and resource management in wireless network.

Dr. Hadi Otrok holds an associate professor position in the Department of ECE at Khalifa University, an affiliate associate professor in the Concordia Institute for Information Systems Engineering at Concordia University, Montreal, Canada, and an affiliate associate professor in the electrical department at Ecole de Technologie Superieure (ETS), Montreal, Canada. He received his Ph.D. in ECE from Concordia University. He is a senior member at IEEE, and associate editor at ad hoc networks (Elsevier), IEEE communications letters, wireless communications and mobile computing (Wiley). He co-chaired several committees at various IEEE conferences. Dr. Otrok is an expert in the domain of computer and network security, web services, ad hoc networks, application of game theory, and cloud security.

Zbigniew Dziong is an expert in the domain of performance, control, protocol, architecture and resource management for data, wireless, optical, and cloud networks. He participated in research projects realized for many leading companies including Bell Labs, Nortel, Ericsson, and France Telecom. He received his Ph.D. degree from the Warsaw University of Technology, Poland, where he also worked as an assistant professor. From 1987 to 1997 he was a professor at INRS-Telecommunications, Montreal, Canada. From 1997 to 2003 he worked for Performance Analysis Department at Bell Labs, Lucent Technologies, Holmdel, New Jersey, USA. Since 2003 he is with Ecole de Technologie Superieure (University of Quebec), Montreal, Canada, as a full professor.