A Distributed Cluster-Based Self-Organizing Approach to Resource Allocation in Femtocell Networks

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***Abstract*—Femtocell networks are an advantageous low-cost technology for providing indoor coverage and high-capacity solutions. Femtocell networks reuse the spectrum resources in co-channel environments due to its high geometric density. In this paper, a distributed algorithm is proposed, which uses a cluster-based self-organizing approach to managing the spectrum and power resources among femtocells. The aim of the proposed algorithm is to achieve an optimized throughput of the networks in a decentralized manner. The algorithm involves three phases: sensing phase, sniffer phase, and power control phase, and is performed in each femtocell. Simulation results indicate that the proposed algorithm improves the uplink throughput of the femtocell networks and effectively avoids interference with the conventional macro-cellular networks.**

Keywords-distributed resource allocation; self-organization; femtocell; co-channel deployment; interference mitigation.

I. INTRODUCTION

Femtocell networks are an advantageous solution to improving the Quality of Serves (QoS), user capacity, and indoor coverage with the increasing requirement for bandwidth by mobile data services in wireless networks. Despite the benefits they offer, femtocells are overlaid on the conventional cellular networks, and their topology creates new design challenges, such as interference management, resource allocations, and security [1]. For example, femtocells can cause interference in conventional macro-cellular networks if the resources are not properly managed. Moreover, mutual interference can occur between users in different femtocells [2]. In particular, uplink interference is a crucial problem in femtocell networks. One major issue is how to protect the conventional macrocell users when both conventional users and the femtocell users are using the same radio band. In this case, in order to save the signaling overhead, a distributed algorithm is desired to allocate the spectrum and power resource.

A number of uplink interference problems for co-channel operation in femtocell networks have been investigated. In [3], the authors used non-cooperative game analysis to solve the uplink power control problem in femtocell networks. The authors of [4] proposed adjustable transmit power strategies for femtocell users to mitigate uplink interference in open-loop and close-loop schemes. The authors of [5] proposed a distributed and self-organizing power control management method in femtocell networks that addressed a bursty interference control scheme for the uplink. Furthermore, the decentralized resource allocation methods for femtocell networks were studied. In [6], the authors proposed a graph-based distributed scheme to manage resources, which achieved a tradeoff between the system throughput and user fairness in femtocell networks. The authors of [7] used a game theory approach to allocate resources, in which they proposed a self-organization network (SON) method in a decentralized manner to manage the cooperative cross- and co-tier interference problem. The main objectives of these studies have been centralized resource allocation for optimizing global objectives or the use of an overall network self-organizing approach to optimize the system capacity. However, decentralized resource allocation for coordination between groups of femtocells has not been well addressed.

This paper proposes a distributed resource allocation algorithm, which uses a cluster-based self-organizing approach [8] for co-channel deployment to perform high spectrum resource reuse within each femtocell. The algorithm mitigates the uplink interference by using a number of nearby femtocells to organize an exchanged information group. It is referred to as a distributed cluster-based SON algorithm, and uses a dynamic spectrum access scheme to obtain spectrum opportunities in the licensed spectrum. Moreover, it exploits the cooperation between femtocells to mitigate the interference they produce to the conventional macrocell networks. The goal of the proposed algorithm is thus to maximize the system throughput of the femtocell networks, while protecting the macrocell users in the uplink. The proposed distributed cluster-based SON algorithm involves the following three phases: sensing phase, sniffer phase, and power control phase. First, the sensing phase determines the minimal interference of macro user equipments (MUE) in each physical resource block (PRB). Second, the sniffer phase requests exchanged information to avoid the co-tier interference. Finally, the power control phase protects the uplink communication of the MUEs. The proposed scheme uses an iterative technique to achieve convergence of the distributed algorithm.

The remainder of this paper is organized as follows:

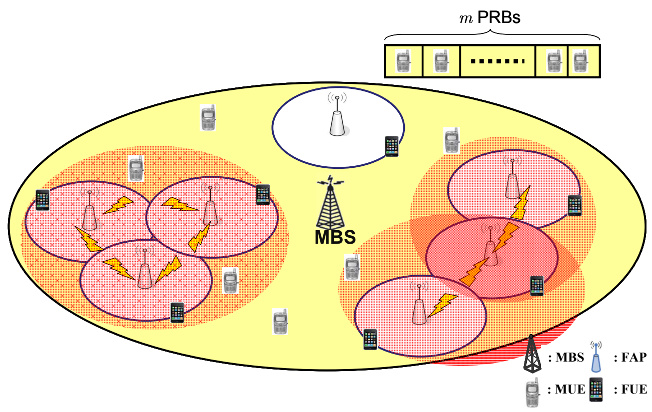

Figure 1. Coexistence of femtocell and macrocell systems.

Section II presents a brief discussion of a network model and problem formulation; Section III presents a distributed algorithm, which exploits a cluster-based self-organizing approach to allocate the resource; the simulation results of the proposed algorithm are presented and discussed in Section IV; and lastly, conclusions are offered in Section V.

II. SYSTEM MODEL

In this section, we describe the network architecture and problem formulation for femtocell networks. First, we consider a macro cellular network in which femtocells are overlaid on the conventional network. Next, we discuss a resource allocation problem in the uplink scenario, in which the resource management involves a joint spectrum and power allocation. Finally we formulate a global optimality objective function for the uplink resource allocation problem.

A. Network Architecture

We consider an orthogonal frequency-division multiple access (OFDMA) system, whose network topology is illustrated in Fig. 1 The uplink OFDMA system with a single macrocell base station (MBS), N_f femtocells, and N_m MUE is considered. In addition, the system has m PRBs, where each femtocell access point (FAP) has m_c available PRBs. In the current study, the PRBs represent frequency slots available at the same time. Furthermore, each PRB is used by an MUE (that is, we consider a full load situation). We assume that the deployment of MUEs and femtocells is uniformly distributed in the networks. Also, the femtocells operate in a closed subscriber group (CSG) model. Each FAP only serves a femtocell user equipment (FUE), in which the FUE exhibits low mobility and is located at the cell edge of the FAP with a radius of 30 m.

B. Channel Model

The path loss model as suggested by [9], is given as follows:

1) *MUE to MBS:*

$$PL_{\mathrm{dB}} = 15.3 + 37.6 \log_{10}(R), \tag{1}$$

2) *FUE to MBS:*

$$PL_{\mathrm{dB}} = 15.3 + 37.6 \log_{10}(R) + L_{\mathrm{ow}}, \tag{2}$$

3) *MUE to FAP:*

$$PL_{\mathrm{dB}} = \max\,(38.46 + 20 \log_{10}(R),\ 15.3 + 37.6 \log_{10}(R)) + 0.7\times d_{\mathrm{2D,indoor}} + 18.3^{n((n+2)/(n+1)\text{-}0.46)} + q\times L_{\mathrm{iw}} + L_{\mathrm{ow}}, \tag{3}$$

4) *FUE to FAP, same building:*

$$PL_{\mathrm{dB}} = 38.46 + 20 \log_{10}(R) + 0.7\times d_{\mathrm{2D,indoor}} + 18.3^{n((n+2)/(n+1)\text{-}0.46)} + q\times L_{\mathrm{iw}}, \tag{4}$$

where R is the separation distance in meters, L_{iw} and L_{ow} are the penetration losses due to the inner wall between apartments and the outer wall of the building, and q and n are the number of penetrated walls and floors. The term $0.7*d_{\mathrm{2D,indoor}}$ represents the penetration loss within the apartment.

C. Problem Formulation

The resource allocation problem in femtocell networks aims to maximize the uplink throughput of all FAPs and to protect the MUEs. The uplink capacity of FUEs in a femtocell may be calculated according to Shannon's formula as:

$$C_i = B\log_2\left(1 + \frac{p_i g_i^h \delta_i^h}{I_{femto-femto} + I_{macro-femto} + \sigma_n^2}\right), \tag{5}$$

where B denotes the bandwidth of PRB h. p_i is the uplink transmission power for FUE i on PRB h. g_i^h is the channel gain for FUE i on PRB h. δ_i^h is a binary indicator. If δ_i^h=1, user i is working on PRB h, otherwise δ_i^h = 0. σ_n^2 denotes the background noise power. $I_{macro\text{-}femto}$ represents the interference between MUE and FAP. $I_{femto\text{-}femto}$ represents the interference between FAP and nearby FUEs, as follows:

$$I_{macro-femto} = \sum_{j\in N_m} p_j g_j^h \delta_j^h\ , \tag{6}$$

$$I_{ftmto-femto} = \sum_{i\neq j} p_{i,j} g_{i,j}^h \delta_{i,j}^h\ , \tag{7}$$

where $p_{i,j}$ is the uplink transmit power of FUE i in FAP j. $g_{i,j}^h$ is the channel gain for FUE i in FAP j on PRB h. $\delta_{i,j}^h$ is a binary indicator. $\delta_{i,j}^h$=1 indicates that user i in FAP j is working on PRB h, otherwise, $\delta_{i,j}^h$ = 0.

The main problem is formulated as:

$$\max \sum_{i\in N_f} C_i\ , \tag{8}$$

subject to

$$\delta_{i,j}^h \in \{0,1\}, \forall i,j \in N_f, h \in m_c\ , \tag{9}$$

$$\sum_{i,j\in N_f} \delta_{i,j}^h = m\ , \tag{10}$$

$$p_i > p_{\max}\,,\ \text{if } \delta_{i,j}^h = 1,\ i,j \in N_f,\ h \in m_c\ , \tag{11}$$

$$p_{i,j} = 0,\ \text{if } \delta_{i,j}^h = 0,\ \forall i,j \in N_f,\ h \in m_c\ , \tag{12}$$

$$0 \le p_{i,0} g_{i,0} \le p_{\mathrm{budget}},\ \forall i,j \in N_f\ , \tag{13}$$

where $SINR_i$ denotes the signal-to-interference-plus-noise ratio (SINR) for FUE i. $SINR_{\min}$ denotes the minimal SINR of the code set. P_{budget} is the maximal allowed interference in the macrocell due to the femtocells. Constraints (9) and (10) indicate the conditions of the PRB allocation. Constraints (11), (12), and (13) indicate the conditions of transmit power for FUEs.

The objective function in (8) is an NP-hard mixed integer nonlinear programming problem [10]. Its solution can be obtained through a combined PRB allocation and power allocation. In [11], the dual decomposition method is adopted, which suggests decoupling (8) into the following two sub-problems: spectrum sharing problem and power allocation problem.

- Sub-problem 1: spectrum sharing

$$\max_{h} \sum_{i\in N_f} B\log_2\left(1+\frac{p_i g_i^h \delta_i^h}{I_{femto-femto}+I_{macro-femto}+\sigma_n^2}\right), \quad (14)$$

subject to

$$\delta_{i,j}^h \in \{0,1\}, \forall i,j \in N_f, h \in m_c, \quad (15)$$

$$\sum_{i,j\in N_f} \delta_{i,j}^h = m. \quad (16)$$

In spectrum sharing, given a feasible power level p_i for FAP_i, the objective function (14) is a monotonously increasing function. Hence, we can use an exhaustive search to find the optimal PRB allocation. The time complexity of this exhaustive search would be $O(N_f^m)$. From the result of the PRB allocation solution in sub-problem 1, we obtain the optimal power allocation in sub-problem 2.

- Sub-problem 2: power allocation

$$\max_{p_i} B\log_2\left(1+\frac{p_i g_i^{h^*} \delta_i^{h^*}}{I_{femto-femto}+I_{macro-femto}+\sigma_n^2}\right), \quad (17)$$

subject to

$$p_i \le p_{\max}, \text{ if } \delta_{i,j}^h = 1, \; i,j \in N_f, \; h \in m_c, \quad (18)$$

$$p_{i,j} = 0, \text{ if } \delta_{i,j}^h = 0, \; \forall i,j \in N_f, \; h \in m_c, \quad (19)$$

$$0 \le p_{i,0} g_{i,0} \le p_{\text{budget}}, \; \forall i,j \in N_f. \quad (20)$$

Applying the Lagrange multipliers method, we obtain the optimal transmission power p_i^* as

$$p_i^* = \max\left(0, \frac{1}{\lambda_1+\lambda_2 g_{i,0}} - \frac{I_{femto-femto}+I_{macro-femto}+\sigma_n^2}{g_i}\right), \quad (21)$$

where λ_1 and λ_2 are the Lagrange multipliers.

III. Distributed Cluster-Based Self-Organization Algorithm

The above optimal resource allocation strategy is a centralized approach, whose complexity is markedly high. In general, the complexity of the decentralized approach is lower than the centralized approach; therefore, the decentralized strategy would be a more suitable scheme in practice. We here develop a distributed algorithm to create cooperation between a femtocell and its neighboring femtocells, and use a cluster-based self-organization method to establish a distributed SON algorithm. The proposed algorithm is performed for each femtocell in parallel and iteratively, as illustrated in Fig. 2, and is further explained as follows:

A. *Sensing Phase*

In this phase, the channel state of PRBs is sensed, which is then used to search the available PRBs in each femtocell.

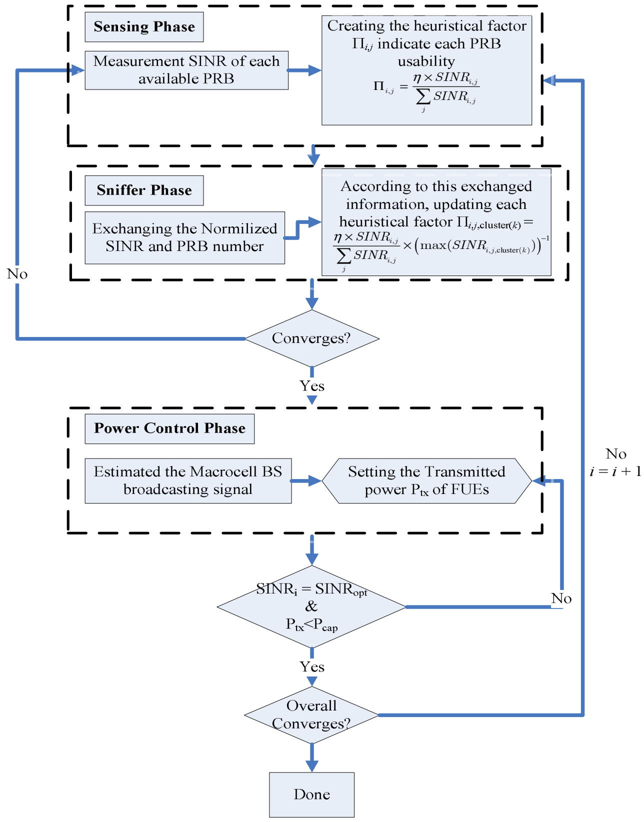

Figure 2. Flowchart of proposed algorithm for each femtocell.

According to the sensing phase, each femtocell may obtain a heuristic factor in each available PRB. The main objectives in this phase are as follows: (i) determining the available PRBs at which the interference to femtocells is minimal, and (ii) reducing the interference from MUEs to FAPs in the uplink.

The problem of resource allocation is dependent on the SINR in the distributed scheme in Section II-C; therefore, we create a heuristic factor at each available PRB in the femtocells. This heuristic factor indicates the usability of the PRB, and its formulation is as follows:

$$\Pi_{i,j}^h = \frac{\eta \times SINR_{i,j}^h}{\sum_{h\in m_c} SINR_{i,j}^h}, \quad (22)$$

where η is the weight factor. η=2 denotes that this PRB is used, otherwise η=0.5. $SINR_{i,j}^h$ denotes h-th PRB's SINR of FUE i in FAP j.

B. *Sniffer Phase*

The FAPs exchange information about their measured SINR and PRB. According to the exchanged information, each femtocell updates its heuristic factor in each available PRB. By doing so, the sniffer phase reduces the uplink interference to the neighboring femtocell.

In this phase, the heuristic factor is updated as follows:

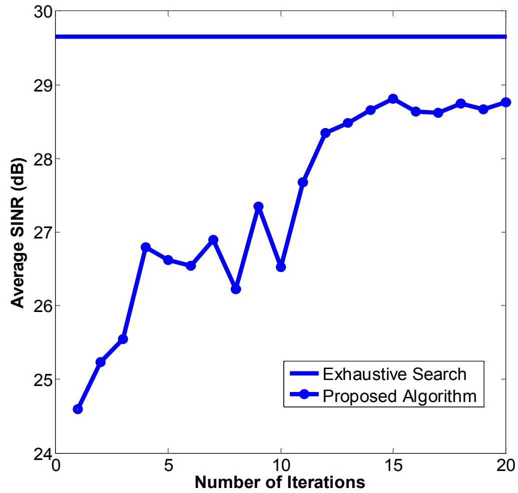

Figure 3. SINR vs. number of iterations for proposed algorithm.

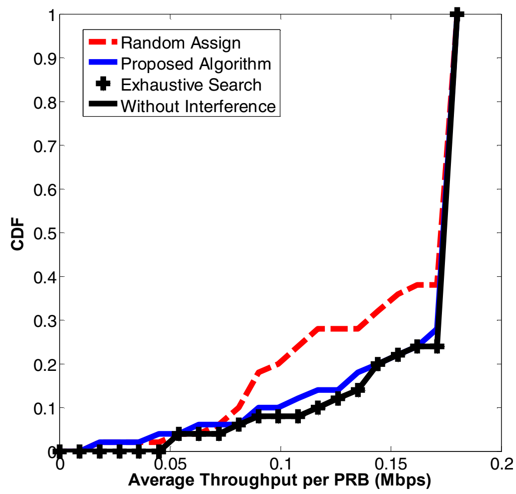

Figure 4. CDF of average throughput of femtocell user per PRB using different schemes in femtocell networks.

$$\Pi^{h}_{i,j,\text{cluster}(k)} = \frac{\eta \times SINR^{h}_{i,j}}{\sum\limits_{h \in m_c} SINR^{h}_{i,j}} \times \left(\max(SINR^{h}_{i,j,\text{cluster}(k)})\right)^{-1}, \qquad (23)$$

where cluster(k) denotes the k-th group self-organization indicator. The cluster-based self-organization involves an anchor femtocell and a few nearby femtocells. We first set the receiver sensitivity range of the anchor FAP, which is the maximum range of the broadcast signals that the anchor FAP sends to other FAPs [8]. Moreover, if the signal received from a neighboring femtocell is within the sensitivity range, that neighboring femtocells is considered to interfere with the anchor FAP, as illustrated in Fig. 1 in which the center FAP on the right hand side is the anchor. In other words, if the signal received from a neighboring femtocell is out of the sensitivity range, that neighboring femtocell is considered to have a small influence on the anchor FAP and could therefore be ignored. Compared to (22), the update equation (23) includes a weight,

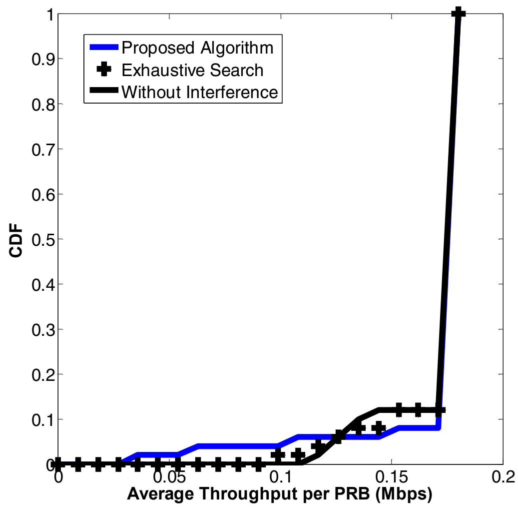

Figure 5. CDF of average throughput of macrocell user per PRB using different schemes in femtocell networks.

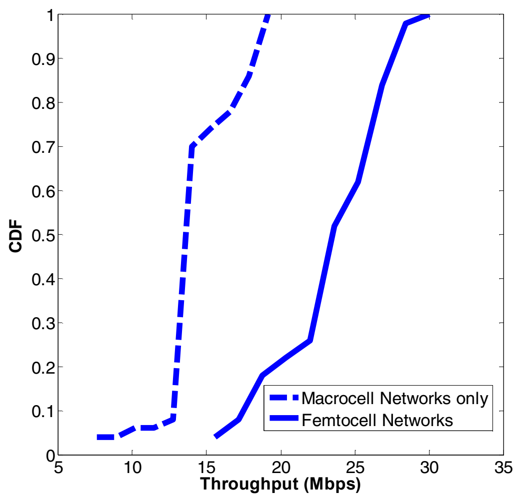

Figure 6. CDF of overall throughput of proposed algorithm in different networks.

which helps avoid using the same PRB in the FAPs of same group.

The goal of the sensing and sniffer phases is to solve the sub-problem of spectrum sharing, whose convergence is achieved by using an iterative technique. Upon the convergence of the sensing and sniffer phases, the power control phase is subsequently performed.

C. *Protection Rule and Power Control*

We obtain the information of femtocell to macro uplink interference before performing the power control phase. The uplink interference information may be estimated by the broadcast signal from MBS to FUEs. We set the protection rule, which ensures that the MUEs do not experience interference. The main objective of the protection rule is to limit the maximal transmission power of FUE. The protection rule is described as follows:

$$P_t = \min(p_r, p_{\text{budget}}, p_{\max}), \quad (24)$$

where P_t is the transmit power of FUEs. P_r is the required uplink transmitting power of FUEs, depending on the requirement of SINR. P_{budget} denotes the maximal allowed interference in a macrocell due to the femtocells. $P_{\max}$ denotes the maximal transmit power of the FUE device.

In uplink co-channel operations, the function of the protection rule is to limit the aggregate interference from all FUEs to MBS. According to the maximal transmit power of the protection rule, we set the transmit power of FUE by equation (24) in each FAP. In this phase, the main objective is to solve the sub-problem of power allocation to achieve the maximal SINR at the PRB.

Taking Fig. 2 and (22)-(23) into account, the overall complexity of the above proposed self-organization algorithm can be seen to be bounded by $O(N_f^2 \times m_c \times K)$, where K is the number of iterations.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Scenario size	Hexagonal 500×500 m²
Carrier frequency	2 GHz
Systrem bandwidth	10 MHz with 50 PRBs
FAP transmit power	20 dBm
FUE transmit power	20 dBm
MBS transmit power	43 dBm
MUE transmit power	26 dBm
Inner wall (Liw) / Outer wall (Low)	5 dB / 20 dB
No. of penetrated walls and floors	1 / 0
Penetration loss (d2D,indoor)	0
Average no. of femtocells	50
Average no. of MUEs	50
Termal noise PSD	-174 dBm/Hz
Noise figure	9 dB
Shadowing standard deviation	8 dB

IV. SIMULATION RESULTS

In this section, we evaluate the femtocell uplink throughput by using the proposed algorithm. The algorithm is preformed and iterated in each femtocell. The detailed simulation parameters and values are illustrated in Table I. The path loss is as illustrated in Section II-B. We evaluate the throughput as suggested in [12], and set the maximal SINR threshold to ensure a suitable transmit power of FUEs.

The results of SINR by iterating the proposed algorithm is illustrated in Fig. 3. They show that after a few iterations the proposed method can approach the SINR obtained with exhaustive search. The cumulative distribution functions (CDF) obtained by using various existing methods and the proposed algorithm are plotted in Fig. 4. The proposed algorithm sets a maximal SINR, which is determined by the modulation and coding scheme (MCS) [12]; therefore, the proposed algorithm can determine a more suitable transmit power to achieve the optimal throughput. As illustrated in Fig. 4, the result of the proposed algorithm is nearly consistent with that of the exhaustive search scheme and without interference. These confirm that the proposed algorithm can indeed achieve the optimal throughput.

Fig. 5 illustrates the throughput of conventional cellular users. The proposed algorithm obtains an approximate result of that without interference. These confirm that the proposed algorithm can avoid interfering with conventional cellular users. Finally, Fig. 6 illustrates the overall throughput of various networks. The proposed algorithm improves spectrum reuse effectively and maximizes the throughput of the overall system. In particular, the proposed algorithm improves the overall throughput by 8 ~ 10 Mbps.

V. CONCLUSIONS

We propose a decentralized uplink resource allocation algorithm, which exploits cluster-based self-organizing technology in macro/femtocell heterogeneous networks. This algorithm is used to allocate the spectrum and power resources and to maximize the throughput of the overall networks and protect conventional cellular users. Minimal exchanged information is required between the femtocell and neighboring femtocells to achieve an optimal resource allocation. The proposed algorithm is verified by simulations and the results are nearly consistent with those of the optimal centralized methods.

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