Decentralized Spectrum and Power assignment in OFDMA Femtocells: Exploiting Different Levels of Coordination

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***Abstract*—This paper focuses on the task of spectrum assignment and the transmission power in the context of downlink OFDMA femtocell deployments. Concretely, the paper studies the impact of different levels of coordination between femtocells in a decentralized framework to perform spectrum and transmission power assignment. Two cooperative schemes are proposed, named non-communicative and communicative respectively. In the first case, each femtocell decide the spectrum and power assignment based on users' reported measurements, which are employed to sense intercell interference, including that from other femtocells or from macrocells in two-layer deployments. In the second case, femtocells are allowed to explicitly communicate other nearby femtocells the radio resource usage. Performance results have been obtained for a realistic indoor femtocell deployment with and without macrocell interference. The paper shows that both schemes based on self-organization can lead to sensible performance improvements over non-cooperative (selfish) schemes in terms of spectral efficiency and power consumption reductions. Finally, the dynamic response of the framework to changes in the network deployment has been analyzed.**

Keywords- femtocell; self-organization; OFDMA; coordination; performance tradeoff

I. Introduction

Self-organization is taking an important role in femtocell (FC) deployments [1][2]. Femtocells are small range and low cost user-deployed base stations introduced at a considerable amount of random locations such as users' homes and with end connectivity through a DSL (Digital Subscriber Line) backhaul. Differently from Wi-Fi access points, they are deployed in a network operator's frequency licensed band, allowing the extension of indoor coverage and thus increasing network capacity. However, FC deployments introduce several technical challenges that have to be overcome [3]. For instance, the assignment of frequency resources to FCs to mitigate intercell interference cannot be performed as in typical *macrocell* (MC) scenarios. In that case, the spectrum assignment task is carried out off-line during the network deployment phase, once the exact MCs' transmitter positions are known, usually requiring a lot of human supervision. On the other hand, the high number of FC transmitters and especially the random and distributed nature of the FC deployment would make unpractical the success of such manual configuration of the spectrum in use. Hence, it becomes necessary to include appropriate capabilities in each FC so that FCs can automatically reconfigure the spectrum assignment and minimize the human interaction. This is one of the main reasons to use self-organization to manage FC deployments.

Self-organization is the ability of a system composed of several entities to adopt a particular structure and perform certain functions to fulfill a global purpose without any external supervisor or central dedicated control entity [4]. In the field of mobile cellular networks, several tasks have been identified to adjust network parameters including *self-configuration* in pre-operational state, *self-optimization* in operational state, and *self-healing* in case of failure of a network element [5], bringing operational and capital expenditures reductions. Therefore, activities in several projects and standardization bodies are steered to study the automation of network procedures [6], [7].

The main characteristics of a self-organized system are its distributed nature and the localized interactivity between system elements. That is, each entity performs its operation based only on the information retrieved from other entities in its vicinity. Hence, self-organization clearly takes a relevant role in the context of FCs networks. For instance, [8] proposes a self-optimization scheme for frequency planning in the context of OFDMA (Orthogonal Frequency Division Multiple Access) FCs. It has been agreed that OFDMA radio access interfaces offer appealing properties such as robustness against multipath fading and high spectral flexibility. Then, as shown in [8], OFDMA FCs facilitate the development of such dynamic self-organization mechanisms, and proof of that is that they are being included in the latest specifications for LTE (Long-Term Evolution) system [9]. On the other hand, [10] presents a self-optimization scheme for the coverage (transmission power) in CDMA (Code Division Multiple Access) FCs in the presence of MC interference. However, it is expected that in OFDMA FCs, high transmission power reductions can be obtained. That is, the high spectral flexibility of OFDMA can allow finding spectrum assignments that enable a FC to operate in an 'interference free' state. Then, transmission power could be reduced from maximum power to a lower level for acceptable communications taking only into account thermal noise. Hence, energy saving is attained, being in line with recent trends within *green communications* [11] that pursue an efficient resource (energy) usage to reduce $CO2$ emissions.

More recently, other approaches to simultaneously optimize the spectrum assignment and transmission power in OFDMA FCs have been proposed [1][12]. However, the impact of the different coordination methods between FCs in the decentralized resource assignment problem has not been addressed.

This paper proposes a decentralized framework to jointly self-optimize the spectrum assignment and the transmission power for the downlink of an OFDMA FC deployment within the coverage area of an OFDMA MC deployment, and analyzes the performance of several coordination levels between FCs. Concretely, two cooperative schemes where each FC takes into account the spectrum and power usage in nearby FCs are compared. The two strategies are named *communicative* and *non-communicative schemes* depending on whether an explicit exchange of information between FCs is allowed. We have tested the framework over a realistic indoor FC scenario with and without MC interference. Numerical results show that, compared with reference schemes, the self-optimization framework can improve overall spectral efficiency (in bits/s/Hz) while quality-of-service (QoS) of ongoing users' sessions is preserved. Moreover, the self-optimization of the transmission power allows to save energy and to reduce intercell interference. Also, an analysis of the dynamic response of the framework reveals that the communicative scheme can react better to changes in the FCs deployment than the non-communicative scheme. On the other hand, the communicative scheme requires from signaling between FCs to exchange the resource utilization messages.

In the following, Section II introduces the deployment scenarios in OFDMA FCs and the different levels of coordination. Next, Section III presents the self-organized framework whereas Section IV describes the self-optimization algorithms for spectrum assignment and transmission power. Then, the simulation model is presented in Section V, and obtained results are discussed in Section VI. Finally, Section VII states conclusions of this work.

II. OFDMA Femtocell Deployments

In the following, the spectrum allocation and the different levels of coordination in OFDMA FCs are presented.

A. Spectrum Allocation

In general, OFDMA FCs will co-exist with large coverage operator-deployed OFDMA MCs, leading to a *two-layer deployment* (i.e., one layer for MCs and another for FCs). Since an OFDMA radio interface divides the available spectrum in several frequency subchannels, two or more cells using the same subchannel can interfere each other. This is particularly crucial in an OFDMA radio interface, because intercell interference dramatically reduces the data rate that users in a given cell can obtain. Therefore, intercell interference in the MC layer is mitigated through the use of Frequency Reuse Factors [13], where the available spectrum is distributed among MCs following a fixed regular pattern. Furthermore, interference between FCs in the FC layer cannot be in general neglected due to FCs' proximity, (e.g., in dense scenarios like buildings with at least one FC per home/office), and then appropriate interference avoidance methods are needed.

Nevertheless, one of the main challenges in the two-layer scenario is the management of the potential *cross-layer* intercell interference, due to the uncontrolled appearance of FCs from the network operator point of view. As depicted in Fig. 1, one of the simplest mechanisms to avoid the cross-layer interference is to employ an *orthogonal* spectrum deployment, where the macro- and femto- cell layers use different spectrum bands and spectrum management is independently performed for each layer. However, this deployment can reduce overall system capacity. On the contrary, *co-channel* spectrum assignment shares the available spectrum band between the MC and the FC layers, increasing the available capacity for each one but at the cost of complex management of the intercell interference. For instance, it has been determined that the MC coverage can decay dramatically around FCs due to the excessive interference leaked by FCs [14][15]. Moreover, it has been showed that [16] important capacity gains can be obtained in the MC layer by deriving indoor users to FC layer, where this gain depends on the MC transmit power configuration affecting the interference produced to the FC layer.

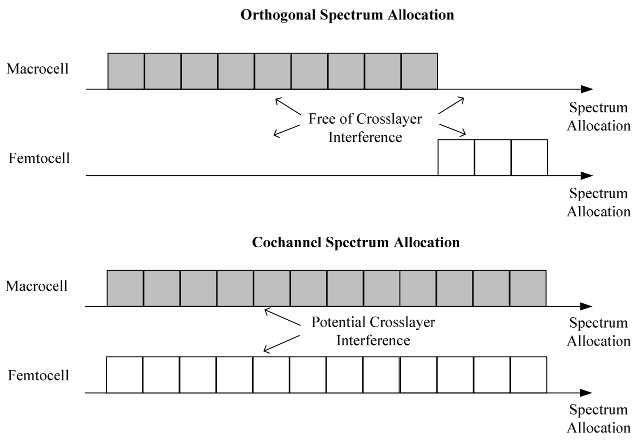

Figure 1. Possible spectrum allocations in OFDMA two-layer deployments

B. Levels of Coordination

For FC deployments, an operator-controlled spectrum assignment as in the MC case is unfeasible whereas decentralized approaches provide the necessary independency so that FCs can autonomously react to network changes. Nevertheless, some kind of coordination between FCs is needed to converge to appropriate solutions.

Different levels of coordination are possible depending on the information that a given FC handles to make its decision. This is sketched in Fig. 2 where three distinct coordination levels have been distinguished. First, resource assignment strategies can be classified between *non-cooperative* and *cooperative*. Non-cooperative strategies only take into account, for each FC, information from the own FC, without considering the actions taken by other cells in the surroundings. Then, they fall in a sort of selfish strategies and usually are used as reference approaches from comparison purposes. For instance, random schemes such as those used in [17][18] equally divide the available spectrum band into V portions,

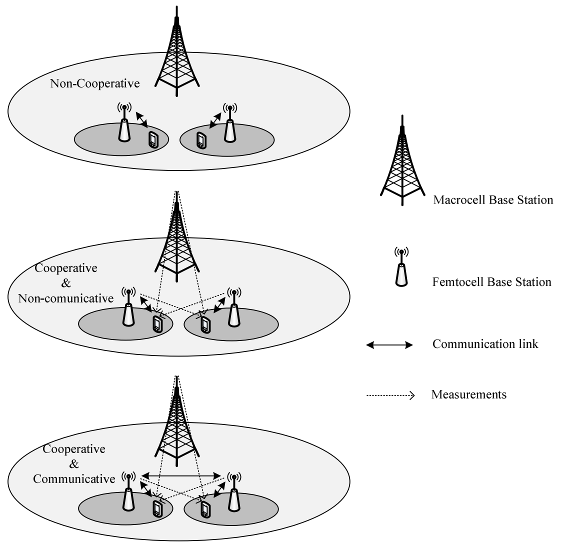

Figure 2. Levels of coordination between FCs.

and each FC randomly selects one of them. The greater V, the lower the probability that two adjacent FCs use the same portion, but also the lower the available capacity in each FC.

On the other hand, cooperative schemes do take into account information about resource assignment in other nearby cells in order to plan the spectrum assignment accordingly. Two subtypes can be distinguished named as *non-communicative* and *communicative*. The non-communicative scheme bases on the feedback of the users to analyze the spectrum and power usage in nearby cells including both other FCs and MCs. Hence it relies on users' *measurements reports* that are periodically sent to the FCs base station in uplink. On the other hand, the communicative scheme additionally allows that FCs can exchange explicit information regarding their spectrum and power usage. This can be done through the wireless interface or though the DSL backhaul. The main benefit of the communicative scheme is that a given FC manages the exact resource assignment decision taken by other cells in the surroundings, so that its decision could be more accurate and not only relies on users' measurements. In fact, we will see in the results section the impact of the measurements report period on the communicative and non-communicative strategies, showing that it could degrade the performance of the non-communicative schemes. However, communicative schemes suppose an additional signaling overhead for the wireless or DSL interface.

III. System Model and Functional Architecture

Fig. 3 depicts the system model and functional architecture for each OFDMA FC. Fig. 3(a) shows an *autonomous* FC surrounded by other cells (in general macro- and/or femto- cells). Each FC performs autonomous spectrum assignment and transmission power decisions with the objective of improving FC's spectral efficiency while guaranteeing FC users' QoS and optimizing power consumption.

An OFDMA radio interface is considered in downlink for users' data transmission, where a system bandwidth, W, is divided into N subchannels $\{1,\ldots,n,\ldots,N\}$. Hence the bandwidth of each subchannel is $B = W/N$ Hz. Moreover, time is divided into frames. The minimum radio resource block assignable to users is one subchannel per frame. On the other hand, there is an uplink control channel where users send instantaneous (frame-by-frame) measurements report messages. As it is explained in the following, these reports provide to the FC the means to approximate, *channel status* in the short-term to perform the link adaptation for each established downlink communication link, and *cell status* in the medium-term to perform reliable spectrum and power assignment.

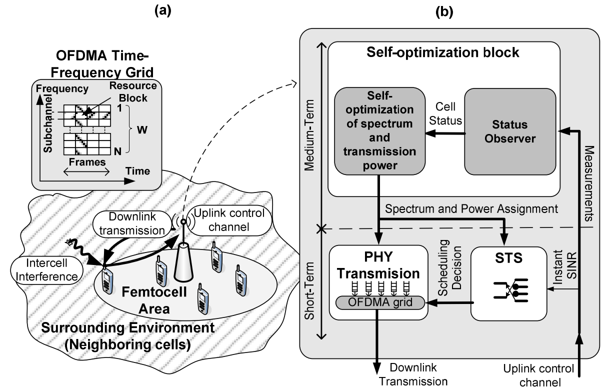

Figure 3. (a) Proposed system model and (b) functional architecture for a single FC with self-organization capabilities.

The functional architecture is depicted in Fig. 3(b). It is a hierarchical architecture where the operation of the FC is divided into two timescales.

A. Short-term

In the short-term, the FC schedules users' transmissions into the OFDMA time-frequency grid following standard scheduling strategies, which are implemented in the Short-Term Scheduler (STS) functional block. Moreover, STS also performs link adaptation. That is, users' transmission bitrate is variable by means of Adaptive Modulation and Coding (AMC), where an appropriate modulation and coding scheme is associated to each instantaneous quality measurement of the channel (i.e., Signal to Interference plus Noise Ratio: SINR) [19]. The detailed SINR thresholds for each modulation and coding rate considered are given in Table I.

B. Medium-term

In the medium-term (seconds or tens of seconds), the FC changes (if needed) the usage of spectrum and transmission power. To this end, the *Self-optimization* functional block is introduced as depicted in Fig. 3(b).

The core of the self-optimization block is the *self-optimization algorithms* (explained in next section) that determine which subchannels the FC should use and the transmission power per subchannel. The FC executes these algorithms following a *self-optimization period* of L frames, so that each FC is periodically reacting to changes in its environment, that is, changes in the perceived interference affecting the performance of the FC.

TABLE I. ADAPTIVE MODULATION AND CODING TABLE

Modulation [bits/s/Hz]	Coding Rate	Achievable spectral efficiency [bits/s/Hz]	SINR threshold [dB]
-	-	0	< 0.9
2 (QPSK)	1/3	0.66	≥ 0.9
2 (QPSK)	1/2	1	≥ 2.1
2 (QPSK)	2/3	1.33	≥ 3.8
4 (16QAM)	1/2	2	≥ 7.7
4 (16QAM)	2/3	2.66	≥ 9.8
4 (16QAM)	5/6	3.33	≥ 12.6
6 (64QAM)	2/3	4	≥ 15.0
6 (64QAM)	5/6	5	≥ 18.2

The *Status Observer* module is in charge of building the *cell status* given as an input to the self-optimization algorithms. The cell status consists of (*i*) the average intercell interference plus thermal noise per subchannel $\overline{I}_n$, (*ii*) the average pathloss in downlink in the FC $\overline{PL_{DL}}$, and (*iii*) the average spectral efficiency $\overline{\eta}$ in bits/s/Hz. The average intercell interference per subchannel and downlink pathloss in the FC can be obtained from the measurement reports given by users. It is worth mentioning that these measurements are usual in mobile cellular systems to perform typical radio resource management procedures like, e.g., handovers [20]. Then users are periodically reporting these measurements averaged during a *measurements period* of l frames. In order to have the most up-to-date information, only the metrics obtained during last period prior the execution of the self-optimization algorithms are passed to them. Moreover, the average spectral efficiency can be estimated by the FC by averaging the quotient between the short-term FC throughput and the assigned bandwidth to the FCs during the last measurements period. Note that $\overline{I}_n$ can include both the MC and the other FC interference. Then, the proposed scheme will be able to adapt in a general co-channel MC and FC deployment.

Finally, notice that if two adjacent FCs execute simultaneously the self-optimization algorithms, then the stability of the framework would be compromised, since both FCs would try to change the spectrum and power assignment at the same time without knowing the final solution of the other FC respectively. Then, in order to minimize the probability that two FCs execute the self-optimization algorithms simultaneously, each FC randomly selects, from the next L frames after switch-on, the initial frame where the self-optimization period starts. Then, since large values of L are expected, then the probability that two adjacent FCs choose the same initial frame can be very low. Moreover, as it will be seen in the results section, it is desirable that $l \ll L$ so that the measurements taken during the last measurement period before the execution of the self-optimization algorithms reflect the latest stable up-to-date information. In other words, a short measurements period reduces the probability that neighboring FCs of a given FC change the spectrum and power assignment during the last measurement period, thus compromising the accuracy of the measurements.

IV. SELF-OPTIMIZATION ALGORITHMS

In the following, two strategies (non-communicative and communicative) to optimize the spectrum assignment and transmission power of a FC are presented.

A. Cooperative and non-communicative strategy

In the non-communicative strategy, only measurements reported by users to de FC base station are considered.

1) Spectrum assignment

Regarding the spectrum assignment, the strategy divides the decision into two stages. In the first one the algorithm decides the number of subchannels, C, that the FC needs in order to fulfill in average with users' throughput expectations. Assume that there are U users in the FC and that the u-th user is satisfied if the assigned throughput is above QoS target $th_{\text{target},u}$. Then, the number of subchannels is computed as:

$$C = \max\left\{ \min\left\{ \left\lceil \Delta \frac{\sum_{u=1}^{U} th_{\text{target},u}}{B\overline{\eta}} \right\rceil, N \right\}, 1 \right\}, \quad (1)$$

where B is the subchannel bandwidth in Hz, and $\overline{\eta}$ is the average spectral efficiency (provided by Status Observer).

Basically, the expression in (1) computes C by dividing the total requested throughput in the FC between the estimated cell capacity for that FC. In addition, $\Delta > 1$ is a margin factor to allow the estimation of the number of subchannels to be conservative. That is, some extra subchannels could be needed to cope with instantaneous fluctuations of the wireless channel, affecting the spectral efficiency per subchannel, which could be punctually lower than $\overline{\eta}$. Finally, notice that C is bounded to a minimum of one subchannel and, to a maximum of N system available subchannels.

In the second stage, the spectrum assignment algorithm sorts the N available system subchannels in increasing order depending on the average intercell interference during the last period ($\overline{I}_n$). Then, the C first sorted subchannels are selected. Hence, the spectrum assignment algorithm in each FC tends to use the best subchannels according to the intercell interference perceived by its users. Finally, it is assumed that, after switch-on, a FC initially selects a random spectrum assignment.

2) Power assignment

Once the spectrum assignment is decided, the transmission power for each assigned subchannel, P_n, is adjusted as:

$$P_n(dBm) = \max\left\{ \min\left\{ \overline{I}_n + \overline{PL_{DL}} + \delta, P_{\max} \right\}, P_{\min} \right\}. \quad (2)$$

Based on the definitions given in the section before, the term $\overline{I}_n + \overline{PL_{DL}}$ stands for the transmission power needed in average to have an average SINR of 0 dB. Hence, the power adjustment in (2) tends to set the transmission power so that an average SINR of δ dB is attained in the FC. Notice that P_n is maintained between the range [$P_{\min}$, $P_{\max}$]. $P_{\min}$ is a minimum power necessary to avoid excessive power reduction in the absence of intercell interference (a possible situation in an OFDMA interface depending on the subchannel assignment in the femtocell and other adjacent femtocells). On the other hand, $P_{\max}$ is the maximum power per subchannel in dBm due to maximum FC power limitation. Finally, it is considered that after switch-on a FC starts with $P_{\max}$ in all assigned subchannels.

B. *Cooperative and communicative scheme*

The communicative scheme takes into account explicit information exchanged between FCs. In this case, we assume that after the execution period of L frames each FC k informs the other FCs in the set of neighboring FCs, Ψ_k , about the set of subchannels, Φ_k , that the FC is planning to use. Each FC can build the set of neighboring FCs, Ψ_k , using the measurement information reported by its users. Also, in case that a MC layer is present (i.e., co-channel spectrum allocation), the FC will add to Ψ_k the strongest MC (attending to received channel power from MCs), *m*, and will compute Φ_m from measurements of the MC activity. Notice that, in this paper, direct communication of the FCs with the MC is not allowed. However, this communication could be exploited if, for instance, the operator broadcasts some information about the MC deployment to FCs through the DSL backhaul.

1) *Spectrum assignment*

As in the non-communicative strategy, the spectrum assignment algorithm is divided into two stages. In the first stage the number of subchannels needed C is computed following (1), which considered the requested throughput by users in the FC and the estimated capacity.

In the second stage, the spectrum assignment algorithm exploits the information collected from nearby FCs:

- First selects the subchannels that are not used by any FC in the set of neighboring FCs (i.e., all subchannels n that fulfill that $n \notin \Phi_j \quad \forall j \in \Psi_k$).
- If the number of selected subchannels is still lower than C , then the FC selects from the remaining subchannels not selected in the previous step those with the lowest intercell interference $\overline{I}_n$.

Basically, the communicative algorithm pursues the same objective as the non-communicative one, since it tries, for a given FC, to minimize the interference received from other FCs (and strongest MC). What makes the difference is that the communicative algorithm uses the exact assignment in the set of neighboring FCs and this is key advantage regarding the adaptability of the algorithm as it will be seen in the results section.

2) *Power assignment*

As for the power assignment, it would be also possible for the FCs to exchange the transmission power per chunk and then it would be feasible to estimate the expected intercell interference received by users. However, this requires that users also report the estimated pathloss for all the cells in the set of neighboring FCs, thus increasing the signaling overhead. Then, we have opted for using the same procedure as for the non-communicative scheme where the intercell interference $\overline{I}_n$ per subchannel computed by Status Observer from measurements reports is used.

V. SIMULATION MODEL

We consider a downlink OFDMA-based scenario with a total of $N = 12$ subchannels of 375 kHz available in the system. The scenario is composed of 7 MCs and 12 FCs inside a building as depicted in Fig 4. MC radius is 500 m and the building is situated at approximately 200 m of the central MC. Each one of the offices has 20x20 m2, and the FC is located at the office's center. For indoor coverage, the COST 231 Multi-Wall Model (MWM) is used [21]. Height of the building's walls is 4 m. Inner walls are considered as 'narrow' walls (i.e., with small penetration losses), whereas external walls are considered as 'thick' walls. Penetration losses for doors and windows are also considered. Propagation model parameters and other default simulation values are presented in Table II.

On the other hand, indoor users in FCs are static and always have data ready to be sent (i.e., full-buffer traffic model), so that each user tries to obtain as much capacity as possible. However, a user is satisfied when a given throughput threshold $th_{\text{target},u}$ is reached. Finally, the well-known proportional fair scheduling [22] strategy is considered for resource assignment to users in the short-term according to functional architecture presented in Section III.

We will consider an orthogonal and co-channel spectrum allocation for the FC deployment. For the orthogonal spectrum allocation simply the MC layer is not considered, so that the N subchannels do not have MC interference. On the other hand, the co-channel allocation considers a MC deployment with a FRF3 spectrum assignment, i.e., the central MC uses one third of the spectrum and the rest of the MCs alternate one of the other 2 subbands.

Besides, we consider two distributions of the users in the FC scenario, named in the following as *homogeneous* and *heterogeneous* distributions. In the homogeneous distribution, 4 users are deployed in each office (i.e., FC) whereas in the heterogeneous distribution, half of the offices has 8 users and the rest 4 users.

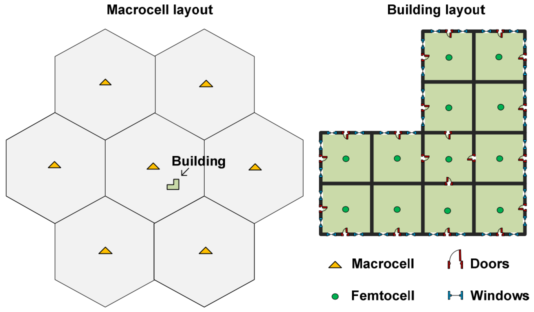

Figure 4. Scenario layout and building detail

TABLE II. SIMULATION PARAMETERS

Frame time T_f	2 ms
Subchannel bandwidth B	375 kHz
Carrier Frequency	2 GHz
Number of subchannels N	12 subchannels
UE thermal noise	-174 dBm/Hz
UE noise factor	9 dB
STS strategy	Proportional Fair
PF Averaging window	50 frames [22]
MC Radius	500 m
MC Antenna height	20 m
Power per subchannel (macro)	32.2 dBm
Minimum distance to FC	1 m
Antenna Patterns	Omnidirectional
Pmax	-0.7 dBm
Pmin	-7 dBm
Av. SINR target δ	16 dB
Margin factor Δ	1.3
Trigger period L	5000 frames
Measurements period l	500 frames
Path Loss model	Cost 231 multi-wall model
Penetration losses [external wall, inner wall, door, window]	[15,10,3,1] dB
Shadowing standard deviation	8 dB
Small Scale Fading Model	ITU Ped. A

VI. RESULTS

A. Tunig of the self-optimization algorithms

In this section we first assess the behavior of both the communicative and non-communicative schemes with regard to the value of the margin factor (Δ) and average target SINR (δ).

Fig. 5 and Fig. 6 show the evolution of the dissatisfaction probability (i.e., a QoS metric as the probability that the user's throughput is below the satisfaction throughput target), spectral efficiency, and transmission power consumption per subchannel for different values of Δ and δ respectively. These results are presented for the orthogonal and co-channel spectrum allocation and for 1024 and 2048 kbits/s (kbps) of requested throughput per user, with a homogeneous distribution

It can be seen in Figures that a better performance (i.e., lower dissatisfaction probability and transmission power and higher spectral efficiency) is achieved for an orthogonal spectrum allocation than for a co-channel allocation. This is because of the higher intercell interference that this latter allocation produces due to the presence of MCs.

More into details, it can be seen that increasing the margin factor Δ has a positive effect on dissatisfaction probability since this augments the number of estimated needed subchannels (see (1)). Hence more capacity is set per FC. However, this also increases the intercell interference between FCs (and also the MC) and thus the spectral efficiency is reduced. Also, the transmission power per subchannel is increased. Hence, there is a tradeoff on the selection of the margin factor. For instance a value around between 1.2 and 1.6 would be adequate for avoiding too high dissatisfaction probability and too low spectral efficiency. On the other hand, increasing the value of the target SINR δ in the power assignment algorithm (see (2)) has a logical positive impact on the dissatisfaction probability and spectral efficiency, since the power assignment tends to augment the average SINR in the FC. However, a too high target SINR does not translates into an improvement on dissatisfaction probability and spectral efficiency, and alternatively only produces an unnecessary increment of the transmitted power (and FC consumption). Thus, again, there is a tradeoff where in this case a value between 15 and 20 dB for the target SINR is adequate.

Nevertheless, the optimal values for Δ and δ can change depending on the scenario (e.g., the traffic load, the FCs deployment, etc.) and thus a static selection of these values can be inaccurate in some cases. Then self-tuning mechanisms for these parameters appear as a potential improvement that should be studied in future work.

B. Performance comparison

In the following, we compare the performance of the cooperative (communicative and non-communicative) schemes for spectrum and power assignment in FCs with a non-cooperative scheme. As stated previously in Section II.B, a random spectrum assignment with constant power is usually taken as a reference for a non-cooperative scheme in literature [17][18]. In this scheme, the spectrum is divided into V =3 equal portions and each FC randomly selects one of them to operate after switch-on.

Results are presented in terms of spectral efficiency, dissatisfaction probability, and transmission power consumption per subchannel. We have considered three different thresholds for the satisfaction throughput as 512, 1024, 2048 kbits/s, so that the behavior of the non-cooperative and cooperative strategies with different QoS requirements are assessed.

Fig. 7 and Fig. 8 show the performance comparison for the orthogonal and co-channel spectrum allocation respectively. Both Figures show the same qualitative performance, but, Fig. 8 attains lower spectral efficiency, slightly higher the dissatisfaction probability, and higher power consumption because of the presence of the MC layer, which increases the intercell interference. Fig. 7(a-c) and Fig. 8(a-c) show the performance comparison for the homogeneous distribution of the users in the building. Comparing the non-cooperative and the cooperative strategies, the cooperative schemes (communicative and non-communicative) demonstrates the best trade-off between QoS fulfillment and spectral efficiency. For instance, for 512 kbits/s satisfaction throughput, they obtain the best spectral efficiency with a reduced dissatisfaction probability. On the other hand, for 2048 kbits/s satisfaction throughput, each FC demands a higher number of subchannels to cope with the traffic demand, what translates into a higher intercell interference and hence into a reduction of the spectral efficiency. However, compared with the non-cooperative strategy, the cooperative schemes considerably reduce the dissatisfaction probability.

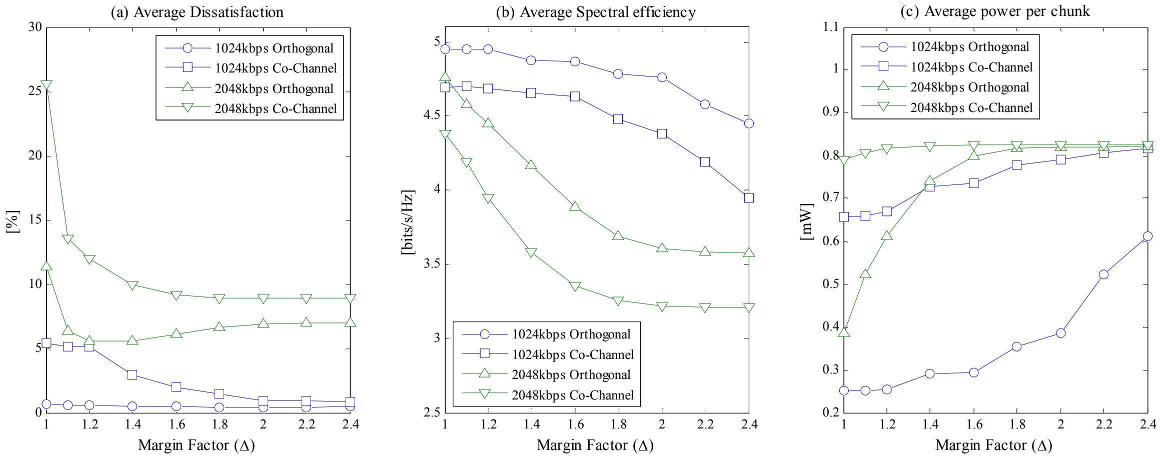

Figure 5. Impact of margin factor parameter on self-optimization algorithms performance

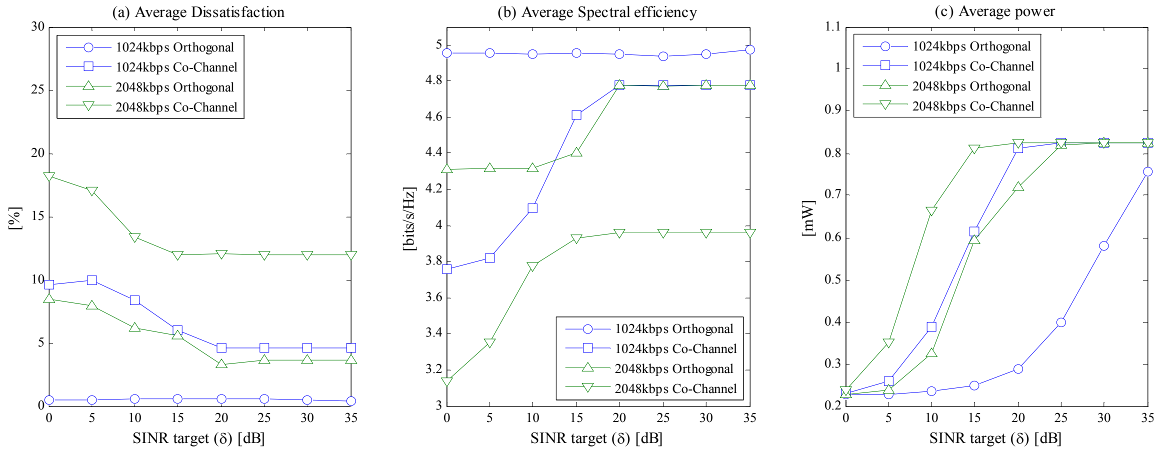

Figure 6. Impact of target SINR on self-optimization algorithms performance

Moreover, regarding the power consumption, the cooperative schemes can achieve important energy savings, especially in the orthogonal spectrum allocation and for low throughputs. In this case, due to low intercell interference, FCs can operate near the minimum power per subchannel with compromising neither the spectral efficiency nor the dissatisfaction probability. Notice that in the presence of MC interference (co-channel spectrum allocation) the FCs react by increasing the power per subchannel.

It is worth to remark the close performance that both the communicative and non-communicative schemes demonstrate, although a slightly better performance is attained by the communicative scheme. This reveals that both schemes are adequate for spectrum and power optimization in FCs attending to performance. However, results in next subsection reveal that other aspects should be taken into account such as the tradeoff between signaling overhead and dynamic response.

Moreover, it is important to highlight the effect of a heterogeneous spatial distribution of the traffic load as shown in Fig. 7(d-e) and Fig. 8(d-e). There, the benefits of the cooperative schemes are appreciable even with lower satisfaction throughputs than those achieved in the homogeneous case. Notice that, in general, a heterogeneous distribution of the load will be common in real scenarios. Thus, this calls for using adaptive approaches such as the proposed cooperative schemes.

Finally, as an example of the SINR improvements that self-organization could bring to FC deployments, Fig. 9 shows the SINR distribution in the proximities of the building for both the orthogonal and co-channel spectrum allocation. The spectrum and power assignments for the non-cooperative and the non-communicative schemes in the homogeneous distribution with 512 kbits/s are considered (analogous results have been found for the other tests and the communicative strategy). Points outside the building are taken as if they were connected to the central MC when applicable (co-channel). It can be seen that, the cooperative scheme considerably ameliorates overall FC's SINR with respect to the non-cooperative scheme. Concretely, in co-channel spectrum allocation the cooperative scheme does not create interference in the MC layer (brown color) whereas the non-cooperative scheme reduces in several dBs the SINR in the building's surroundings. It has been determined that in the former, FC layer self-organizes so that each FC uses different subchannels to those used by the central MC. However, it is appreciable a considerable reduction of the SINR in the FCs compared with the orthogonal spectrum allocation.

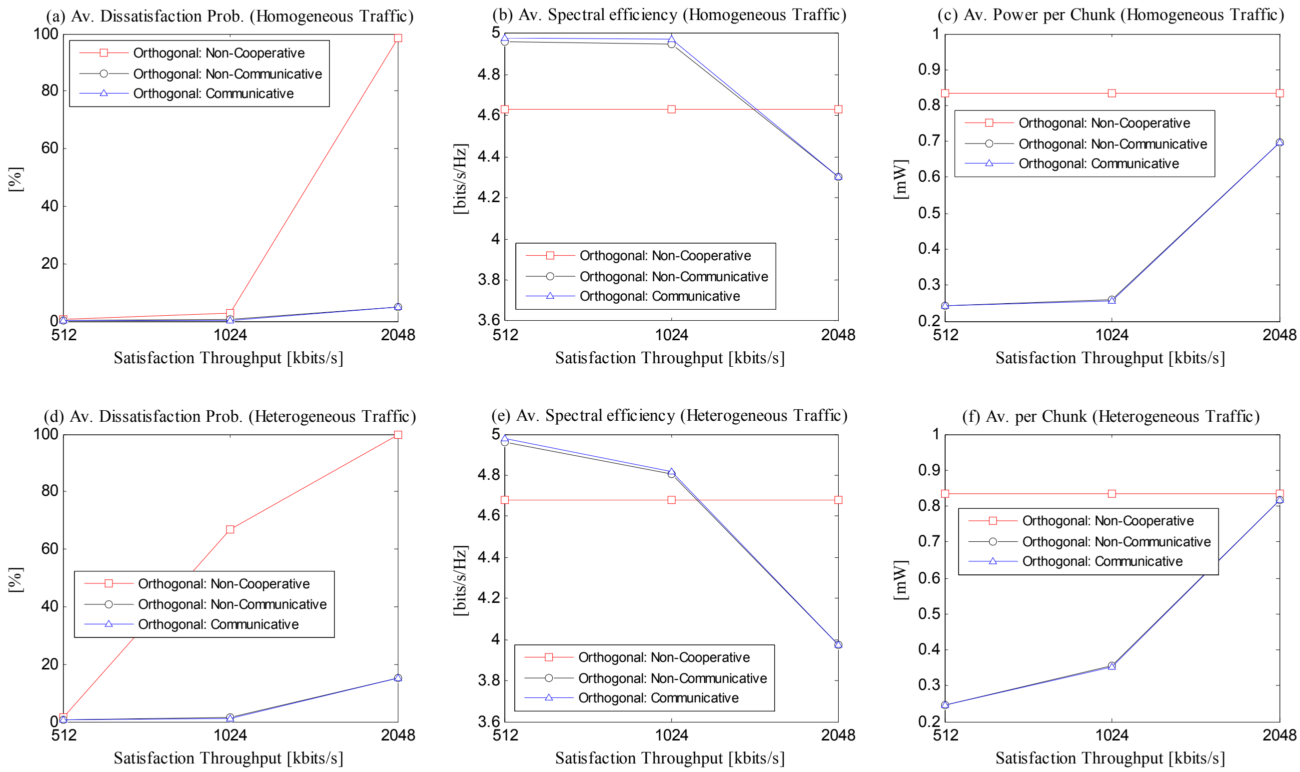

Figure 7. Performance comparision between random and self-organized schemes with orthogonal spectrum deployment.

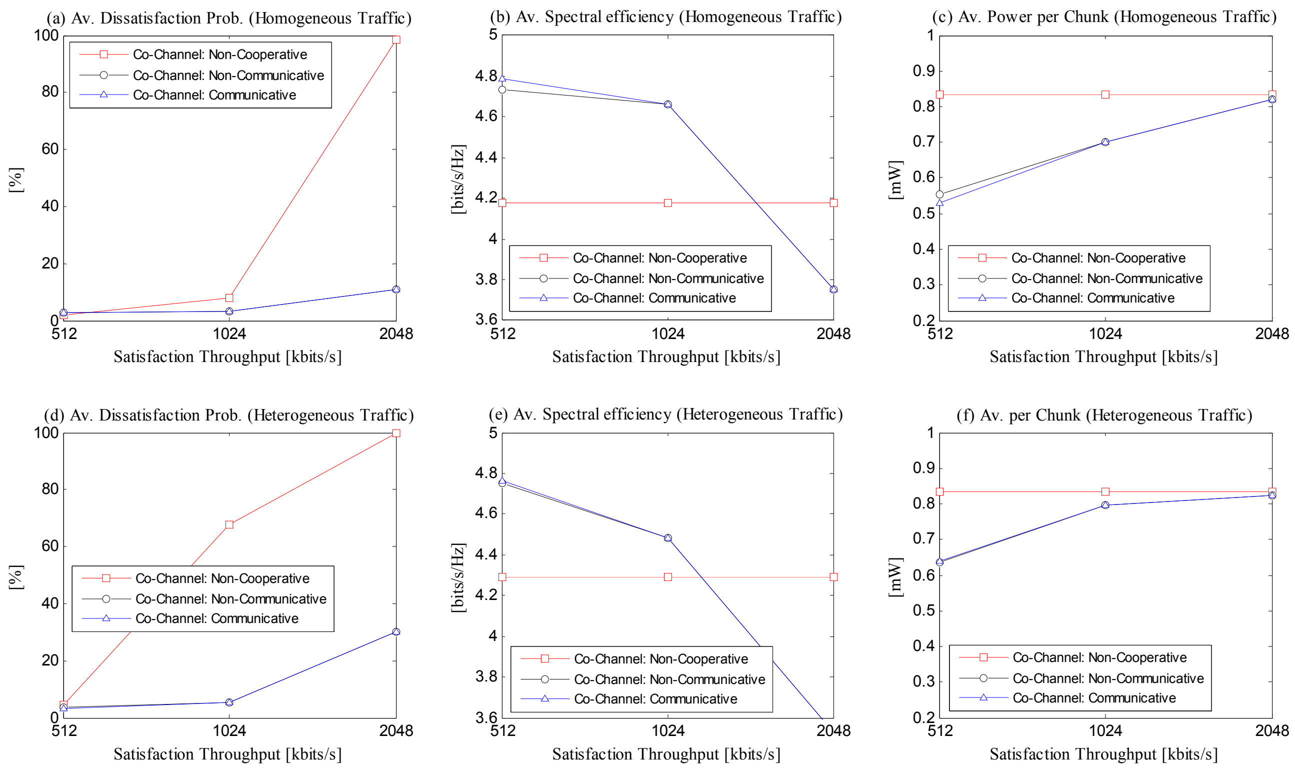

Figure 8. Performance comparision between random and self-organized schemes with orthogonal spectrum deployment.

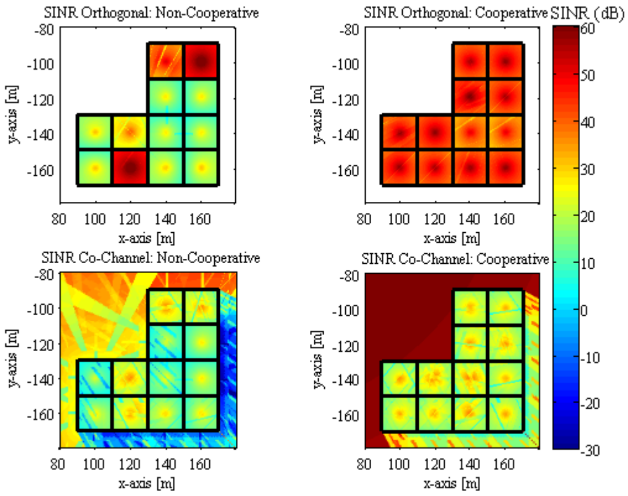

Figure 9. SINR comparision in the surroundings of the building.

It has been checked that, for each FC, this is mainly because of the interference produced by the other MCs, rather than by other FCs. Hence, in general, the interference from MCs distinct of the MC where FCs are deployed cannot be neglected.

C. Dynamic response

This section studies the dynamic response of the proposed framework, that is, the ability of the different FCs executing the self-optimization algorithms to adapt to changes in the network deployment. In the following, results are given for the orthogonal spectrum allocation with homogeneous traffic and a throughput target per user of 512 kbits/s.

Fig. 10 shows the adaptability (in terms of the time evolution of (a) dissatisfaction probability, (b) spectral efficiency and (c) transmission power per subchannel) of the non-cooperative, non-communicative and communicative schemes for the FC deployment. The figure shows a case where the central MC is activated at time instant 50 (time is normalized to the self-optimization period). Thus, at this moment, FCs in the building perceive an abrupt increment of the intercell interference in the subchannels used by the MC. Three different ratios of the measurements report period (l) to the self-optimization period (L) are evaluated. A high value (e.g., l/L =1) supposes that it is very probable that neighboring FCs of a given FC also change the spectrum and power assignment during the last measurement period. Hence, some averaged measurements during the last measurements period can be inaccurate.

It can be seen in all subplots of Fig. 10 that the response of the non-cooperative scheme does not depend on l/L , since the spectrum assignment is randomly selected without taking into account measurements. On the other hand, the non-communicative and communicative strategies show very different behaviors. For l/L =1, both algorithms demonstrate a very fast response to the increment on intercell interference. However, the non-communicative scheme reveals a poor performance since the measurements information that is taken is not up-to-date (i.e., neighbors of a FC were changing their resource assignment during the last measurements period). On the other hand, the communicative scheme achieves a good performance, since the spectrum assignment in a FC is based on the latest spectrum assignment sent by other FCs. Nevertheless, for l/L =0.1, both schemes show a very similar and good performance, although the response of the FC deployment to the activation of the central MC is slower. In this case, since $l \ll L$, it is less probable for a given FC that another neighbor FC changes the spectrum assignment during the last measurement period, thus supposing an improvement in performance of the non-communicative scheme.

Fig. 11 and Fig. 12 illustrate how the FCs in the building self-organize the spectrum and the power assignment after the activation of the central MC for l/L =1 and l/L =0.1 respectively. Figures show evolution of the average spectral efficiency for seven time instants around the activation of the central MC (time instant 50). Notice that, after MC activation, the spectral efficiency dramatically decays for all FC, but at time instant 70 (20 executions later), the spectral efficiency has increased for the communicative scheme. This is also the case for the non-communicative scheme in Fig. 12, although in Fig 11. the inaccuracy of the measurements avoids proper self-organization of the FC deployment.

Finally, it is important to remark that the success of the communicative scheme has an associated cost in terms of signaling overhead. Qualitatively, in order to communicate with adjacent FCs, each FC under the communicative scheme, has to transmit $\phi_k \cdot (Nb_s + b_{id}) \cdot (1/LT_f)$ bits/s. Here, ϕ_k is the number of neighboring FCs, b_s , is the number of bits needed to encode spectrum usage per subchannel, b_{id} is the number of bits devoted to code FC's identification, and T_f is the frame time and thus $(1/LT_f)$ is the update frequency that depends on the self-optimization period. On the other hand, the signaling needed for measurements in a given FC is $U \cdot (lNb_{\text{sinr}} + b_{In} + b_{PL}) \cdot (1/lT_f)$ bits/s, where U is the number of users in the FC, b_{sinr} are the bits needed to report instantaneous SINR per subchannel for frame-by-frame short-term scheduling, b_{In} and b_{PL} the bits needed to report intercell interference and pathloss respectively, and l the measurements period in frames.

Since the signaling for measurements is present in both the non-communicative and communicative schemes, and the signaling for communication of the FCs is exclusive of the communicative scheme, quotient between the signaling and for communication and the signaling needed for measurements can be used as a metric to analyze the signaling overhead of the communicative scheme. Fig. 13 shows this quotient for different values of ϕ_k , N and U , and with respect to the value of L . All magnitudes are encoded with 8 bits and $l = 500$ frames and T_f =2 ms. Certainly, the signaling overhead demonstrates an inverse relation with the self-optimization period L . Then low values of L can yield to a

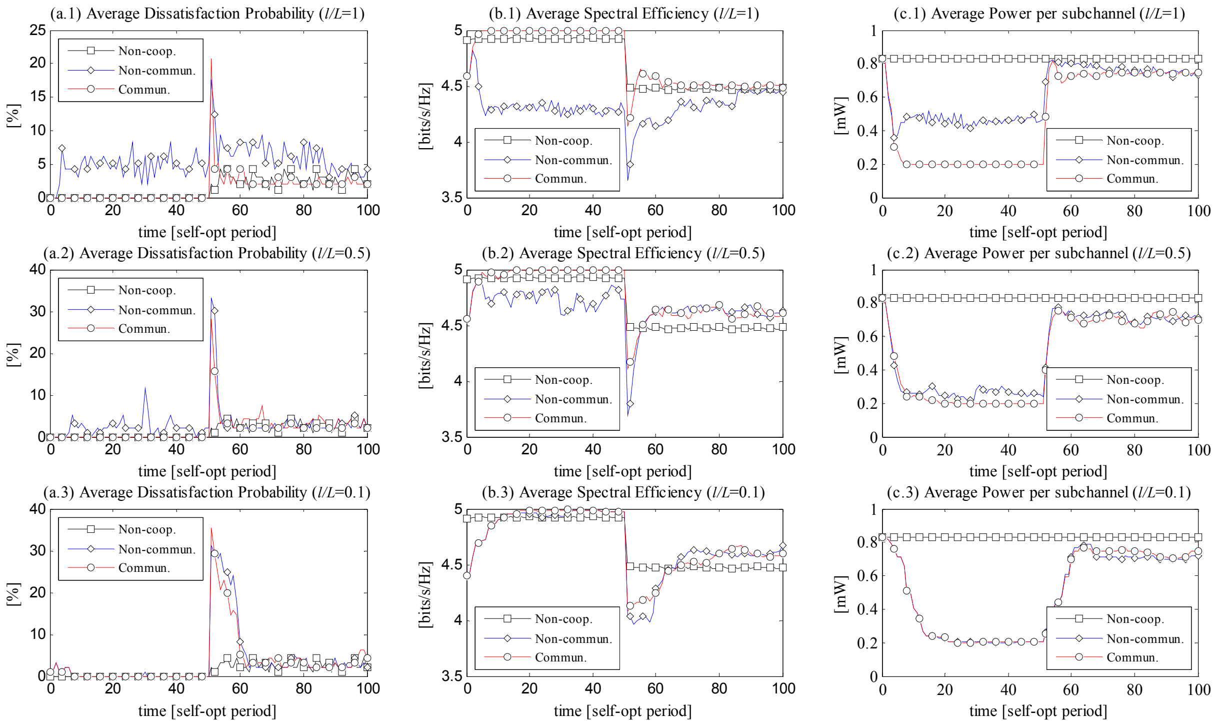

Figure 10. Dynamic response of the compared strategies under different ratios of the measurements and self-optimization periods

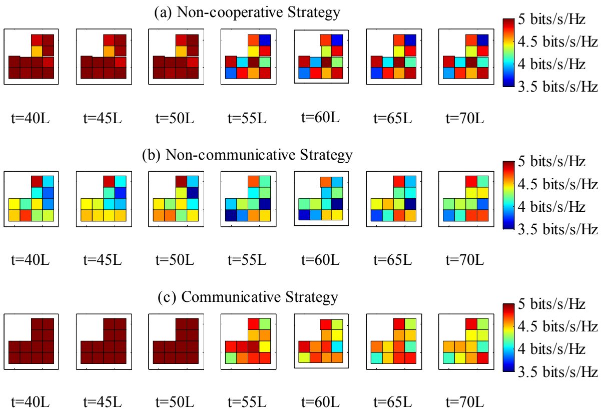

Figure 11. Average spectral efficiency per FC for compared schemes (l/L=1).

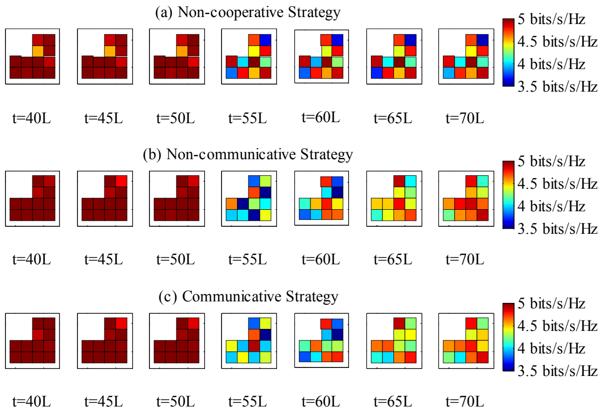

Figure 12. Average spectral efficiency per FC for compared schemes (l/L=0.1).

high signaling overhead of around 20%, especially for a low number of users and a high number of neighboring FCs as shown in Fig. 13. However, notice that for a high number of users in the FC, the signaling overhead tends to be negligible, since in this case the signaling for measurements is dominant.

VII. CONCLUSIONS

This paper has shown that self-organization is a suitable approach when facing resource management in OFDMA FC networks. Concretely, self-optimization algorithms for both spectrum and transmission power per OFDMA subchannel assignment have been proposed, showing that the inclusion of these algorithms can bring notable performance improvements, especially in two-layer deployments with MCs and heterogeneous spatial distribution of the traffic load.

Moreover, it has been determined that the effect of MCs distinct of the MC where FCs are deployed cannot be neglected. That is, those MCs could negatively interfere FCs producing a performance reduction. Hence, multicell MC deployments should be used in two-layer MC and FC per-

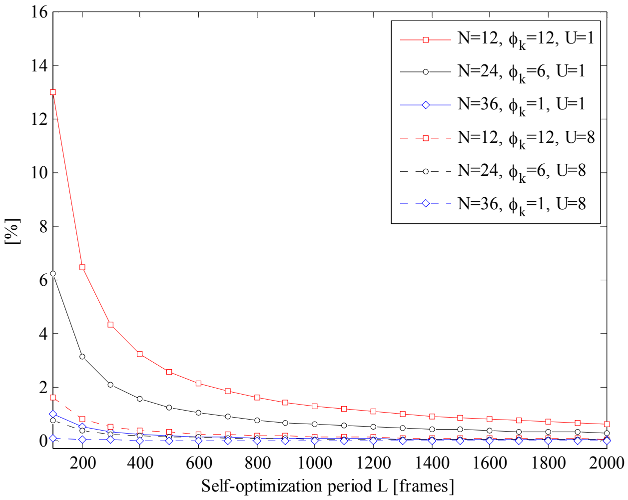

Figure 13. Signaling overhead of the communicative scheme over the non-communicative scheme

formance evaluations, rather than single-cell MC plus FCs, as usual in certain studies.

The paper has also studied the effectiveness of different levels of coordination between FCs. Communicative and non-communicative approaches have been compared, revealing that the performance of both schemes can be very close. However, when analyzing the dynamic response of the FC deployment under one scheme or the other, it has been observed that the relation between the measurements period and the self-optimization period can considerably degrade the performance of the non-communicative scheme. On the other hand, the communicative scheme demonstrates a robust behavior in this respect. The main drawback of the communicative scheme is the need of designing signaling interfaces between FCs, and the additional signaling that communication between FCs adds to the system. Finally, it is worth remarking the low complexity of the proposed self-optimization algorithms, showing that the simple inclusion of autonomous and adaptive mechanism could bring enormous performance benefits.

ACKNOWLEDGMENT

This work has been performed in the framework of the Spanish Research Council under COGNOS grant TEC2007-60985. Also, the European Regional Development Funds (FEDER) have supported this work.

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