OFDMA femtocells: A self-organizing approach for frequency assignment

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***Abstract*—This work presents 2 novel approaches for the self-organization of Orthogonal Frequency Division Multiple Access (OFDMA) femtocells, in which the femtocell is able to dynamically sense the air interface and tune its sub-channel allocation in order to reduce inter-cell interference and enhance system capacity. In the *sensing* phase, these techniques make use of either messages broadcast by the femtocells or measurements reported by the users, while in the *tuning* phase, they provide a good solution for the frequency assignment problem.**

Results shows that it is recommend to use information collected at the user position (measurement reports), when devising self-organization algorithms for tuning the parameters of femtocells.

I. INTRODUCTION

Recently, a new type of indoor Base Station (BS), called *femtocell*, has gained the attention of the industry and research. A femtocell is a low-cost, low-power BS deployed by the end-users, initially designed to extend indoor coverage [1]. Femtocells are connected to the network of the operator over a backhaul connection such as Digital Subscriber Line (DSL) or optical fiber. Meanwhile, femtocells also provide coverage to the end-customers using a cellular network standard, e.g. Universal Mobile Telecommunication System (UMTS), Wireless Interoperability for Microwave Access (WiMAX), Long Term Evolution (LTE).

It is expected that femtocells will benefit both end-users and network operators [2]:

- Users may enjoy better signal qualities due to the reduced distance between the transmitter and the receiver, the result of this being more reliable communications and higher throughputs, as well as power and battery savings.
- From the operators point of view, femtocells will extend indoor coverage and enhance system capacity. Femtocells will also help to manage the exponential growth of the traffic, thanks to the handover of the indoor traffic to the backhaul. Moreover, they will also reduce the system cost, since they are paid and maintained by the owners.

However, these benefits are not easy to accomplish, and there are some challenges that the operators must face before successfully deploying a femtocell network. For example, the management of the electromagnetic interference between the macrocell and femtocell tier, as well as between femtocells will play a very important role. This interference could counteract the above mentioned benefits and degrade the overall performance of the network [3].

Interference avoidance has never been a trivial task neither in macrocell deployments nor in femtocell networks. Furthermore, due to the individualistic nature of the femtocells and the uncertainty on the number and location of these devices, operators must use new approaches rather than the classic network planning and optimization [4] (BS location, frequency planing, etc.) to avoid interference.

In order to successfully react to the changes of the traffic and channel, and minimize interference in femtocell deployments, the use of sophisticated *self-organization* techniques is needed. Self-organization will allow femtocells to integrate themselves into the network of the operator, learn about their environment (neighboring cells, interference) and tune their parameters (power, frequency) accordingly [5].

In the existing literature, different self-organization strategies for femtocells have been introduced.

In [6] Claussen introduces a power control method for pilot and data channels in UMTS networks that ensures a constant coverage femtocell radius. Each femtocell sets its power to a value that on average is equal to the power received from the closest macrocell at a target femtocell radius.

In [7] Claussen presents a method for coverage adaptation for UMTS networks that uses information on mobility events of passing and indoor users. Each femtocell sets is power to a value that on average minimizes the total number of attempts of passing users to connect to such femtocell.

In [8] Chandrasekhar analyzes interference avoidance when using a time-hopped Code Division Multiple Access (CDMA) physical layer and also sectorial antennas.

These approaches are mostly based on Wide-band Code Division Multiple Access (WCDMA) networks, and they do not intend to mitigate interference through sub-channel allocation, which is a very important feature of OFDMA systems.

In order to avoid persistent collision within neighboring OFDMA femtocells, in [9] Chandrasekhar proposes that each femtocell accesses a random subset of sub-channels within the available femtocell spectrum. However, in this work, the authors will show that using self-organization leads to better system performance than using random assignments.

This work presents 2 novel approaches for the self-organization of OFDMA femtocells. In the *sensing* phase, these techniques make use either of messages exchanged by the femtocells or measurement reports coming from the users, while in the *tuning* phase, they provide a good solution for the sub-channel assignment problem. This way, the overall system interference is minimized and the network performance is maximized.

II. PRELIMINARIES

A. OFDMA/Time Division Duplex (TDD)

OFDMA/TDD is a multi-carrier technology where:

- the radio spectrum is formed by R orthogonal sub-carriers, which in turn are combined into K groups, called *sub-channels* or *resource blocks*.
- the time domain is segmented into consecutive frames of a given duration T_f, which in turn are divided into T_s time slots, known as Orthogonal Frequency Division Multiplexing (OFDM) symbols.

B. Network definition

Let us define an OFDMA femtocell tier as a set of:

- N femtocells $\{F_0, \cdots, F_i, \cdots, F_j, \cdots, F_{N-1}\}$ and M customers $\{UE_0, \cdots, UE_x, \cdots, UE_y, \cdots, UE_{M-1}\}$,
- K sub-channels $\{0, \cdots, k, \cdots, K-1\}$ and T_s OFDM symbols $\{0, \cdots, t, \cdots, T_s - 1\}$ ($T_s = T_s^{DL} + T_s^{UL}$),
- where H Radio Access Bearers (RABs) $\{RAB_0, \cdots, RAB_h, \cdots, RAB_{H-1}\}$ are available for transmission (Table I).

TABLE I

RAB (MODULATION AND CODING SCHEMES)

RAB	**Modulation**	**Code Rate**	**SINR[a] threshold**	**Efficiency**
RAB1	QPSK	1/2	2.88 dB	1.00 b/s
RAB2	QPSK	3/4	5.74 dB	1.50 b/s
RAB3	16QAM	1/2	8.79 dB	2.00 b/s
RAB4	16QAM	3/4	12.22 dB	3.00 b/s
RAB5	64QAM	1/2	15.88 dB	4.00 b/s
RAB6	64QAM	3/4	17.50 dB	4.50 b/s

[a] Signal to Interference plus Noise Ratio (SINR)

C. Network assumptions

For the sake of simplicity, assumptions have been made, which do not involve any loss of generality when assessing the performance of the system:

1) A user UE_x is allocated to only one sub-channel k, containing T_s^{DL} or T_s^{UL} OFDM symbols, in each frame.
2) A given sub-channel, e.g. $k = 0$, is always built from the same sub-carriers across the network, independently of the permutation scheme employed by the system [10].
3) A perfectly synchronized OFDMA network is assumed. This way, inter-cell interference will occur only when more users are allocated to the same sub-channel at the same time slot in different cells.
4) The coherence bandwidth of the channel is larger than the bandwidth of the sub-channel. In this case, the fading of all sub-carriers within the sub-channel remains equal.
5) The coherence time of the channel is larger than the duration of the OFDMA/TDD frame. In this case, the fading of all OFDM symbols within the frame is equal.

III. MESSAGE BROADCAST BASED APPROACH

This section introduces the first proposed approach in this paper for the distributed assignment of sub-channels in OFDMA femtocell networks. This method is based on *broadcast messages*.

The idea is that each femtocell estimates the probability of usage of each sub-channel and distributes this information to its neighboring femtocells, sending a local broadcast message.

Besides these sub-channel usage probabilities, the broadcast message also contains information about the power applied to each sub-channel, and the power of the pilot signal.

Based on the information obtained from its neighbors over the broadcast messages, a femtocell prioritizes the usage of its sub-channels, i.e. according to the following quality indicator:

$$badness_j(k) = \sum_{i \in \mathcal{N}_j} p_i^{interf}(k) \cdot p_i^{usage}(k), \qquad (1)$$

where:

- $\mathcal{N}_j$ is the set of the neighbors of femtocell F_j.
- $p_i^{usage}(k) \in [0, 1]$ denotes the probability of usage of sub-channel k in femtocell F_i, which was reported by the last broadcast.
- $p_i^{interf}(k) \in [0, 1]$ indicates the intensity (near/far neighboring femtocell) of the possible interference coming from F_i towards F_j.

Using the pilot signal power indicated in the broadcast message, and measuring the pilot signal strength of the sender, the receiving femtocell can estimate the path loss to the sender. Furthermore, using this path loss and the indicated power applied in each sub-channel, the receiver can estimate the received signal strength from the sender in each sub-channel. This is used for the calculation of $p_i^{interf}(k)$.

The femtocell uses the $badness$ value to update the sub-channel assignment of its users. This update procedure is performed periodically, and the time between consecutive updates is randomly chosen from the interval of $[1, 2T_{bm}^{up}]$ time units. This is done in order to avoid that several femtocells change their sub-channel allocation at the same time (coordination).

Between updates, the femtocell collects the messages broadcast by its neighbors. These are processed at the next update, in which the femtocell first recomputes the $badness$ of each sub-channel based on existing messages. Afterwards, the femtocell rearranges its sub-channel allocation so that the users get assigned to the sub-channels having the lowest $badness$ values. Finally, it estimates its own sub-channel usage probabilities using the new assignment and broadcasts them to its neighbors.

Note that the messages can be sent over the air interface, but also over the backhaul. However, this way, the overhead on the Internet Protocol (IP) backhaul would increase significantly.

$p_i^{usage}(k)$ and $p_i^{interf}(k)$ are computed using the models presented in the following sections.

A. Usage probability ($p_i^{usage}(k)$) calculation

Femtocell F_i estimates the probability of usage $p_i^{usage}(k)$ of each one of its sub-channels k according to the following probabilistic model before broadcasting a message. In this model, used sub-channels have a larger $p_i^{usage}(k)$ value than idle ones. The model also considers what sub-channels are more likely to be used or freed if a user connects or disconnects.

The probability of usage of the first used sub-channel that will be freed if a user disconnects (sub-channel 4 in Figure 1)

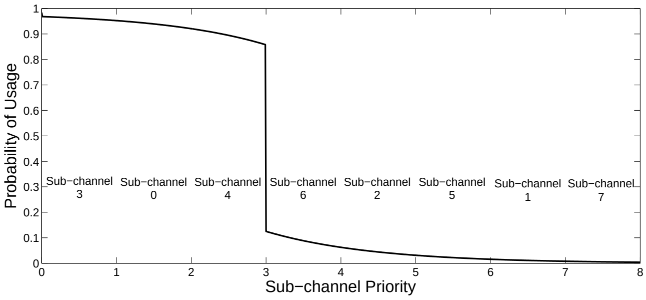

Fig. 1. Probability of sub-channel usage. In this case, there are 8 sub-channels, and 3 of them are being used by the femtocell (sub-channels 3, 0 and 4) and the rest is idle. If a new user connects, it will be assigned to sub-channel 6, while if a user disconnects, sub-channel 4 will be freed.

is equal to one minus the probability of one user leaving the femtocell ($1 - P_{\triangle}(-1)$). Likewise, the probability of usage of the first idle sub-channel that will be used (sub-channel 6 in Figure 1) is equal to the probability of one user connecting to the femtocell ($P_{\triangle}(1)$). The time interval considered is the period of uncertainty, i.e. the average time between updates of the sub-channel allocation (T_{bm}^{up}).

In the following, the mathematical formulation of this probabilistic model is introduced:

First of all, let us define $g(k)$ as the sequence number of sub-channel k according to the ordering by increasing $badness$:

$$\begin{array}{rcl} g : \{0, \cdots, K-1\} & \mapsto & \{0, \cdots, K-1\} \\ g(k) = g(d) & \Rightarrow & k = d \\ g(k) < g(d) & \Rightarrow & badness_i(k) \leq badness_i(d) \\ \forall k, d & \in & \{0, \cdots, K-1\} \end{array} \tag{2}$$

where k and d are sub-channels, and $g(k)$ and $g(d)$ are their sequence numbers.

The probability of exactly s users appearing in a femtocell tier in a time period of length T is modeled in this article by a Poisson process:

$$P(s, \lambda T) = P_s = \frac{(\lambda T)^s \cdot e^{-\lambda T}}{s!} \tag{3}$$

where λ denotes the intensity of such process.

Moreover, if exactly s users appear in a tier with N femtocells, the probability of that excatly a users get on a specific femtocell can be described as follows:

$$P_g^a = \left(\frac{1}{N}\right)^a \cdot \left(\frac{N-1}{N}\right)^{s-a} \cdot \binom{s}{a} \tag{4}$$

where the first term indicates the probability of that the first a users appear at a specific femtocell. The second term shows the probability of that the rest of the $s - a$ users appear at other femtocells. The last term shows in how many different ways the a users can arrive among all the s users.

Then, combining equations (3) and (4), the probability that exactly a users connect to a specific femtocell in a tier with N femtocells in a time interval of length T is calculated as:

$$P_{arrival}(a) = \sum_{i=0}^{\infty} P(a+i, \lambda T) \cdot P_{a+i}^a \tag{5}$$

Furthermore, assuming that the users' holding time is exponentially distributed, the probability of exactly one user leaving a femtocell in a time period of length T is:

$$P_{leave1} = 1 - e^{-\mu T} \tag{6}$$

where μ denotes the users' mean holding time.

Therefore, the probability of exactly l users leaving a specific femtocell, which has exactly Z connected users, in a time period of length T can be described as follows:

$$P_{leave}(l) = (P_{leave1})^l \cdot (1 - P_{leave1})^{Z-l} \cdot \binom{Z}{l} \tag{7}$$

where the first term indicates the probability of that the first l users leave a specific femtocell. The second term shows the probability of that the rest of the $Z - l$ users stay in that femtocell. The last term shows in how many different ways the l users can arrive among all the Z users.

Using equations (5) and (7), the probability $P_{\triangle}$ of having an increment of ΔZ users on a specific femtocell in a tier with N femtocells in a period of time T is given by:

$$P_{\triangle}(\Delta Z) = \sum_{(a,l) \in \theta} P_{arrival}(a) \cdot P_{leave}(l) \tag{8}$$

where $\theta = \{(a, l) \mid a - l = \Delta Z, 0 \leq a \leq K - Z, 0 \leq l \leq Z\}$ Here, we are taking into account that, for example, the probability of having an increment of 1 user is equal to the probability of 1 user arriving and no users leaving, plus the probability of 2 users arriving and 1 user leaving, and so forth.

Finally, femtocell F_i estimates the probability of usage $p_i^{usage}(d)$ of each one of its sub-channels d as follows:

$$p_i^{usage}(d) = \begin{cases} 1 - P_{\triangle}(\Delta Z = d - Z), & \text{if } d \leq Z \\ P_{\triangle}(\Delta Z = d - Z + 1), & \text{if } d > Z \end{cases} \tag{9}$$

B. Interference intensity ($p_i^{interf}(k)$) calculation

Given a worst case scenario where a femtocell A, whose cell radius is r_{femto} meters, provides coverage to a user B located in its cell edge, and considering the following:

- the maximum interference I_{max} that user B can tolerate in order to transmit leads to the minimum RAB defined in the system. The SINR threshold of such RAB is $SINR_{min}$.
- the maximum interference I_{min} that a user B can suffer in order to achieve maximum capacity leads to the maximum RAB. The SINR threshold of such RAB is $SINR_{max}$.
- the received signal strength $C_{A,B}$ suffered by user B from femtocell A can be estimated by using the interference model presented in Section V-E.

Note that I_{min} and I_{max} can be calculated as follows:

$$I_{min} = \frac{C_{A,B}}{SINR_{max}} - \sigma^2, \; I_{max} = \frac{C_{A,B}}{SINR_{min}} - \sigma^2 \tag{10}$$

where σ stands for the background noise density.

Then, by using $C_{i,j}(k)$ (signal strength of the sub-channel) and the linear penalty function defined by equation (11), the intensity of the possible interference (near/far) can be derived ($C_{i,j}(k)$, I_{max} and I_{min} must be in mW).

$$p_i^{interf}(k) = \begin{cases} 1, & \text{if } C_{i,j}(k) > I_{max} \\ \frac{C_{i,j}(k) - I_{min}}{I_{max} - I_{min}}, & \text{if } I_{min} < C_{i,j}(k) < I_{max} \\ 0, & \text{if } C_{i,j}(k) < I_{min} \end{cases} \tag{11}$$

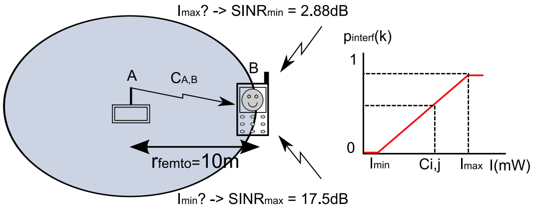

Fig. 2. Intensity of the possible interference. This model takes into account the path loss between femtocell and user, as well as the SINR thresholds of the RABs defined in the system.

IV. MEASUREMENT REPORTS BASED APPROACH

This section introduces the second proposed approach in this paper for the distributed assignment of sub-channels in OFDMA femtocell networks. This method is based on *measurement reports*.

In this approach, a user UE_x sends a Measurement Report (MR) MR_x to its serving femtocell F_i every T_{mr}^{send} time units. MR_x indicates the received signal strength suffered by user UE_x in each sub-channel k.

Then, femtocell F_i updates its sub-channel allocation according to the received MRs. This update event happens after a random time interval between 1 and $2T_{mr}^{up}$ time units after the last update event. In this way, several femtocells avoid changing their sub-channel allocation at the same time, enhancing the coordination.

When an update event occurs in F_i, it gathers the information of all received MRs and builds an interference matrix W_i. The dimensions of this matrix W_i are $Z_i \times K$, where Z_i refers to the number of connected users to femtocell F_i.

Once that the interference matrix W_i is built, F_i computes is new sub-channel allocation using the following optimization procedure, whose target is to minimize the sum of the overall interference suffered by the users of the femtocell.

$$min \sum_{z=0}^{Z_i-1} \sum_{k=0}^{K-1} w_{z,k} \cdot \gamma_{z,k} \tag{12a}$$

subject to:

$$\sum_{m=0}^{M_i-1} \gamma_{z,k} \leq 1 \qquad \forall k \tag{12b}$$

$$\sum_{k=0}^{K-1} \gamma_{z,k} = 1 \qquad \forall z \tag{12c}$$

$$\gamma_{z,k} \in \{0,1\} \qquad \forall z,k \tag{12d}$$

where $\gamma_{z,k}$ is a binary variable (12d) that is equal to 1 if user z is using sub-channel k, and 0 otherwise. Moreover, and taking assumption 1 of Section II-C into account, assumption (12b) ensures that a sub-channel is assigned to at most one user, while assumption (12c) ensures that all connected users have only one sub-channel.

This optimization problem can be solved efficiently using backtracking, since the solution space is small (4users/femto).

V. SYSTEM MODEL

In order to evaluate the performance of the two self-organization techniques presented in this paper, an event driven dynamic system-level simulation has been employed.

In this dynamic system-level simulation, the life of the network through the time is modeled as a series of events. An event happens when a user connects or disconnects, when the resource allocation of a femtocell changes, etc.

A. Traffic modeling

The arrival of the users follows a homogeneous Poisson process with an intensity of λ_{arr}. The holding time of the users is exponentially distributed with a mean of t_H.

B. Neighborhood definition

Femtocell F_i is considered neighbor of femtocell F_j if they are in the range of each other (there is 'visibility'), i.e. the received signal strength $C_{i,j}$ coming from femtocell F_i is larger than the sensitivity θ_j of the antenna of femtocell F_j:

$$\theta_j < C_{i,j} = P_{i,k} \cdot G_i \cdot L_i \cdot PL_{i,j} \cdot G_j \cdot L_j \tag{13}$$

where k is the sub-channel; i is the index of the transmitting femtocell, F_i; j is the index of the receiving femtocell, F_j; $P_{i,k}$ is the power applied by F_i in a sub-carrier of sub-channel k; $PL_{i,j}$ represents the path loss attenuation and shadow fading between F_i and F_j; G stands for the antenna gains and L for the equipment losses.

C. Radio Resource Management

When a new user UE_x appears, it is randomly placed within the coverage (r_{femto} radius) of a random selected femtocell. Note that the maximum number of users per femtocell is four. Afterwards, the femtocell assigns a sub-channel to the user. This sub-channel is selected according to the resource allocation strategy:

- When using *broadcast messages*, the user will be allocated to the sub-channel with the lowest badness among the unused ones.
- When using *measurement reports*, the user connecting to the femtocell will be assigned to a random free sub-channel, and reassigned at the next update procedure according to the optimization strategy previously defined.

For comparison, 3 other methods have been implemented:

1) A worst case assignment where the femtocell always assigns the first free sub-channel starting from $k = 0$.
2) A random assignment where the femtocell randomly selects an idle sub-channel from those that are available.
3) A self-organization approach based on the implementation of a network listening mode in the femtocell itself. In this case, the femtocell is able to switch on its network listening mode on regular basis and estimate the received

signal strength of each sub-channel. Then, the femtocell reassigns its connected users to the sub-channels having the smallest received signal strength. The delay between reassignments is randomly chosen from the interval of $[1, 2T_{nl}^{up}]$ time units.

D. Power Resource Management

Since the focus of this work is the analysis of self-organization sub-channel allocation techniques, a simple but realistic power allocation strategy has been considered.

The power P_i of femtocell F_i is equally distributed among all its existing sub-carriers (pilot + data), in the following way:

- If sub-channel k is busy, a power $P_i/(R_{pilot} + R_{data})$ is applied to each one of its data sub-carriers.
- If sub-channel k is idle, no power is applied.

E. Interference model

Interference happens when the signals of several users overlap in the frequency (sub-channel) and time (symbol) domain. Here, intra-cell interference has been neglected due to the orthogonality features of the OFDM sub-carriers [11].

The carrier $C_{x,k}^{DL}$ and interference $I_{x,k}^{DL}$ signal strength suffered by UE_x in sub-channel k can be derived from the following model:

$$C_{x,k}^{DL} = P_{i,k} \cdot G_i \cdot L_i \cdot PL_{i,x} \cdot G_x \cdot L_x \quad (14)$$

$$I_{x,k}^{DL} = \sum_{j=0, j\neq i}^{N-1} (P_{j,k} \cdot G_j \cdot L_j \cdot PL_{j,x} \cdot G_x \cdot L_x) \cdot \phi_{j,k} \quad (15)$$

where, $\phi_{j,k}$ is a binary variable that is equal to 1 if cell F_j is using sub-channel k, or 0 otherwise. The rest of the notation have been presented in Section V-B.

By using this interference model, and taking assumptions 1, 2, 3 and 4 of Section II-C into account, the SINR of a user UE_x can be calculated as the SINR of one of its sub-carriers, using $SINR_{x,k}^{DL} = \frac{C_{x,k}^{DL}}{I_{x,k}^{DL} + \sigma^2}$, where σ is the noise density.

F. Throughput calculation

The bit rate $BR_{x,k}$ of a user UE_x can be calculated as indicated by equation (16), taking assumptions 1 and 4 of Section II-C into account.

$$BR_{x,k} = \frac{RAB_{eff}^{x,k}}{T_{frame}} \cdot \frac{R_{data}}{K} \cdot T_{DL} \quad (16)$$

where $RAB_{eff}^{x,k}$ denotes the efficiency ($bit/symbol$) of the sub-carriers within sub-channel k. This value can be assessed by using the derived SINR of UE_x and Table I. Moreover, R_{data}/K represents the number of data sub-carriers per sub-channel. The rest of the notation have been presented above.

Once the bit rate $BR_{x,k}$ of the user UE_x is known, its throughpmt $TP_{x,k}$ can be derived as follows:

$$TP_{x,k} = BR_{x,k} \cdot (1 - BLER_{x,k}(SINR, RAB)) \quad (17)$$

where $BLER_{x,k}(SINR, RAB)$ represents the Block Error Rate (BLER) suffered by the user UE_x, which is a function of its SINR and RAB. This BLER has been extracted from Link-Level Simulations (LLSs) [12].

VI. EXPERIMENTAL EVALUATION

This section presents a performance comparison between the 2 proposed self-organization techniques and other sub-channel allocation strategies (worst case, random, network listening). This performance evaluation has been carried out using the system-level simulator presented above.

A. Scenario

The scenario used in this experimental evaluation consists of an ideal free space area of $300 \times 300\ m$, with a wide deployment of 121 femtocells (no macrocells are considered). The path loss is modeled assuming free space propagation, while an additional walls loss L_w is inserted every r_{femto} meters. The scenario and parameters of this simulation are illustrated in Figure 3 and Table II, respectively.

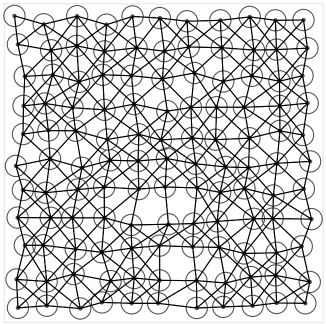

Fig. 3. The scenario. Each femtocell is represented by a point and a circle; neighbors are connected by lines.

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Scenario size	$300 \times 300m$	F_i TX Power	$10\,dBm$
Femtocells	121	F_i Ant. Gain	$0\,dBi$
Carrier	$2.3\,GHz$	F_i Ant. Pattern	Omni
Bandwidth	$5\,MHz$	F_i Ant. Sensi. (θ)	$-108\,dBm$
Duplexing	TDD 1:1	F_i Noise Figure	$4\,dB$
DLsymbols (T_s^{DL})	19	UE_x Ant. Pattern	Omni
ULsymbols (T_s^{UL})	18	UE_x Noise Figure	$7\,dB$
Preamble symbols	2	UE_x Body Loss	$0\,dB$
Overhead symbols	11	λ_{arr} $(1/h)$	2500
T_f	$5\,ms$	t_H	$600\,s$
Sub-carriers (R)	512	T_{nl}^{up}	$10\,s$
R_{pilot}	48	T_{bm}^{up}	$2\,s$
R_{data}	384	T_{mr}^{send}	$10\,s$
Sub-channels (K)	8	T_{mr}^{up}	$10\,s$
Simulation time	$4\,hour$	Path loss model	free-space
F_i radius (r_{femto})	$10\,m$	L_w	$5\,dB$
Noise density (σ)	$-174\,\frac{dBm}{Hz}$		

B. Overhead analysis

In case of using the broadcast messages based method, the required uplink (UL) bandwidth for the broadcast messages overhead is $(K \cdot d_u + K \cdot d_i + d_c) \cdot n \cdot f_{mb}$, whereas the required downlink (DL) bandwidth is $(K \cdot d_u + K \cdot d_i + d_c) \cdot f_{mb}$. This case, n denotes the number of neighbors of a given femtocell, d_u, d_i and d_c indicate the number of bits required to encode the sub-channel usage probability, the power applied to a sub-channel and the power of the carrier signal, respectively. Finally, f_{mb} is the updating frequency.

In case of using the measurement reports based method, the required UL bandwidth for the measurement reports overhead is $K \cdot d_r \cdot u \cdot f_{mr}$, whereas the required DL bandwidth is 0. This case, u denotes the number of connected users to the femtocell, d_r indicates the number of bits required to encode the received signal strength measured in a given sub-channel. Finally, f_{mr} is the reporting frequency.

Note that the UL bandwidth requirement of the broadcast messages based method is proportional to the number of neighboring femtocells, while the measurement reports requires a bandwidth proportional to the number of connected users, which is 4 at maximum. Moreover, the measurement reports based method does not require bandwidth for transmitting signaling in the DL, while the message broadcast one does.

Taking into account that in $1\,s$, 200 frames of $5\,ms$ with 18 UL (19 DL) data OFDM symbols can be transmitted, and assuming that there are $K = 8$ available sub-channels, 48 subcarriers per sub-channel and that the average RAB efficiency is $2\,bits/symbol$, the total UL (DL) bandwidth is by around $2.76\,Mbps$ ($2.92\,Mbps$).

Assuming a configuration, where the updating and reporting frequency is $1s^{-1}$, there are 8 sub-channels, 8 neighboring femtocells, 4 connected UEs and that every transmitted value is encoded using 8 bits, the UL (DL) bandwidth overhead requirement of the broadcast messages based method is $1.088\,kbps$ ($0.136\,kbps$), while for the measurement reports is $0.256\,kbps$ ($0.00\,kbps$).

Therefore, it can be concluded that only a small fraction of the whole available bandwidth is needed for system overhead. Note that contrarily to the femtocell case, in macrocell scenarios, the processing of the measurement reports constitutes a significant overhead, since hundreds of users can be simultaneously connected to the BS. Moreover, the channel conditions of macrocell users change faster due to their higher mobility and the large number of obstacles existing in the environment. Then, measurement reports must be sent more often in order to cope with these fluctuations, but this increases the overhead.

C. Throughput analysis

Table III shows the throughput averaged over all users and all measurement time points. It can be seen that the message broadcast and the measurement report based methods provide around 26% and 34% increase over the random assignment, respectively, indicating that is worth using optimization.

TABLE III
AVERAGE THROUGHPUT

Method name	**Average throughput** (kbps)	**Average throughput** (%[a])
measurement reports	641.34	134.36%
broadcast messages	600.11	125.72%
network listening	585.9	122.74%
random assignment	477.33	100%
worst assignment	284.97	59.7%

[a] compared to the random assignment

The fact that the method using measurement reports outperforms the method using message broadcasting suggests that using information collected at the user locations is important in this interference avoidance problem. Note that the information collected at the femtocell position does not accurately estimate the interference at the user position. For example, two users of the same femtocell have different signal qualities if one is close to the femtocell and the other close to an open window.

Furthermore, the broadcast messages method achieves better throughput than network listening. The reason behind this is that the network listening mode only relies on received signal strength measurements, while the broadcast messages method also takes into account future sub-channel allocations (probability of sub-channels usage) of neighboring femtocells. This indicates that taking the traffic of the network into account is also important for the avoidance of interference.

VII. CONCLUSION

In this paper two approaches were presented for the self-organization of OFDMA femtocells. In the first one the femtocells exchange messages in order to coordinate their sub-channel assignment, while in the second one they rely on the measurement reports sent by their users. Dynamic system-level simulations confirm that these approaches may improve user throughput by around 26% and 34% respectively compared to the random assignment. The obtained results also show that an efficient resource assignment algorithm must consider the circumstances at the user environment in order to efficiently mitigate interference, as well as the behavior of the traffic.

VIII. ACKNOWLEDGEMENT

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