# Power Minimization Based Resource Allocation for Interference Mitigation in OFDMA Femtocell Networks

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***Abstract*—With the introduction of femtocells, cellular networks are moving from the conventional centralized network architecture to a distributed one, where each network cell should make its own radio resource allocation decisions, while providing inter-cell interference mitigation. However, realizing such distributed network architecture is not a trivial task. In this paper, we first introduce a simple self-organization rule, based on minimizing cell transmit power, following which a distributed cellular network is able to converge into an efficient resource reuse pattern. Based on such self-organization rule and taking realistic resource allocation constraints into account, we also propose two novel resource allocation algorithms, being autonomous and coordinated, respectively. Performance of the proposed self-organization rule and resource allocation algorithms are evaluated using system-level simulations, and show that power efficiency is not necessarily in conflict with capacity improvements at the network level. The proposed resource allocation algorithms provide significant performance improvements in terms of user outages and network capacity over cutting-edge resource allocation algorithms proposed in the literature.**

***Index Terms*—Femtocell, OFDMA, interference mitigation, inter-cell interference, self-organization, resource allocation, transmit power, subchannel.**

## I. Introduction

FEMTOCELLS are foreseen to play a key role in the deployment of next generation cellular networks, e.g., Wireless Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE). Femtocells were designed for improving indoor coverage and capacity, and they are served by low-cost low-power user-deployed Base Stations (BSs) that are connected to the network operator via a broadband connection. Due to the deployment of more network cells overlaying the existing macrocells, femtocells will improve spatial reuse and spectral efficiency, and off-load traffic from existing macrocells. Femtocells will also provide power and battery savings due to short range transmissions [1].

Since femtocells are experiencing the first signs of maturity with important operators already deploying them in households, the mobile industry is looking for new femtocell markets, e.g., use of femtocells in enterprises. However, installing femtocells in these challenging scenarios, where more than one femtocell may co-exists and many users may enter femtocells' coverage, leads to major interference challenges never addressed before in residential deployments. Moreover, since operators cannot manage femtocell interference using the classic centralized frequency planning/optimization, because they do not know the exact number and position of femtocells and may not own the femtocell backhaul, the development of distributed radio resource management techniques is necessary to handle femtocell interference.

In order to address the femtocell interference problem in Orthogonal Frequency Division Multiple Access (OFDMA)-based networks, several schemes have already been proposed in the literature. In [2] and [3], the authors propose the use of orthogonal and partially shared spectrum to avoid cross-tier interference. In [4], the authors also propose a dynamic fractional frequency reuse approach that assigns users with bad geometry in neighboring femtocells to orthogonal subbands. However, these kinds of schemes may result in low spectral efficiency, and thus co-channel femtocell deployments are preferred for making a better spectrum reuse. In [5] and [6], the authors analyze the use of sector antennas and multiple antenna elements at femtocells, respectively, to mitigate interference in co-channel femtocell deployments. However, these types of approaches need a more complex hardware, which increases the final femtocell complexity and price too. Therefore, Subchannel (SC) allocation and power control have been heralded as the most promising way of coping with interference in co-channel femtocell deployments. However, the assignment of SCs and transmit power is an intricate optimization problem, which becomes even more complex due to the existence of several Modulation and Coding Schemes (MCSs) in WiMAX and LTE standards. Moreover, multiple SCs assigned to one user must use the same MCS [7], although each user may observe different channel gains in each SC.

In the OFDMA literature, due to the existence of link adaption, in the DownLink (DL), dynamic SC assignments with equal transmit power per SC are usually preferred to complex joint dynamic SC and transmit power assignments due to mathematical tractability and easier implementation. Previous analyses [8] [9] also demonstrated that improvements in the overall system performance caused by the assignment of different transmit powers to different SCs is negligible in scenarios with a wide range of users demanding diverse Quality of Service (QoS). In this line, in LTE and WiMAX systems, power control is not adopted in the DL (only in the

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TABLE I
(MODULATION AND CODING SCHEMES)

| RAB | Modulation | Code Rate | SINR | Efficiency |
|---|---|---|---|---|
| MCS1 | QPSK | 1/2 | 2.88 dB | 1.00 b/s |
| MCS2 | QPSK | 3/4 | 5.74 dB | 1.50 b/s |
| MCS3 | 16QAM | 1/2 | 8.79 dB | 2.00 b/s |
| MCS4 | 16QAM | 3/4 | 12.22 dB | 3.00 b/s |
| MCS5 | 64QAM | 1/2 | 15.88 dB | 4.00 b/s |
| MCS6 | 64QAM | 3/4 | 17.50 dB | 4.50 b/s |

UpLink (UL)), and transmit power is uniformly distributed among SCs. The same philosophy applies to femtocells, where the cell transmit power may be tuned for adaptive coverage, but afterwards is usually uniformly distributed among SCs. For example, in [10], in order to allow for a better spatial reuse, the maximum DL transmit power of femtocells is tuned to guarantee a constant femtocell coverage radius according to the received signal strength from the closest macrocell. In [11], a network listening mode at femtocells is used to estimate interference, and SCs with the lowest interference are allocated to users. In [12], user measurements are used to estimate interference at user locations, and SCs with the lowest interference are allocated to users. None of these schemes uses a per SC power control, or takes the mentioned one-MCS-per-user constraint into account.

In this paper, we show that in distributed systems, where cells make decisions independently, allocating different transmit powers to different SCs according to user QoS requirements and channel conditions can lead to remarkable Self-Organazing Network (SON) behaviors. Indeed, minimizing transmit power, giving every user what it requires, could lead to new scheduling opportunities and enhanced network capacity due to better spatial reuse. In this line, we first introduce a simple self-organization rule, based on minimizing cell transmit power, following which a distributed cellular network is able to converge into an efficient resource reuse pattern. Thereafter, based on the proposed self-organization rule and considering realistic resource allocation constraints (e.g., the one MCS per user constraint), we propose two novel resource allocation algorithms, being autonomous and coordinated, respectively. We evaluate the performance of the proposed self-organization rule and resource allocation algorithms using system-level simulations, and show that power efficiency is not necessarily in conflict with capacity improvements at the network level. Finally, we show that the proposed algorithms provide significant performance improvements in terms of user outages, connected users and network capacity over cutting-edge resource allocation algorithms proposed in the literature.

## II. NETWORK MODELING AND NOTATION

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

- femtocells: $\mathcal{F} = \{F_1, ..., F_m, ..., F_n, ..., F_F\}$,
- users of femtocell $F_m$: $\mathcal{U}^m = \{U_1^m, ..., U_u^m, ..., U_{U_m}^m\}$,
- SCs: $\mathcal{K} = \{1, ..., k, ..., K\}$,
- MCSs: $\mathcal{R} = \{1, ..., r, ..., R\}$ (Table I).

### A. Network Assumptions

For analytical tractability, we make the following assumptions, which will not cause any loss of generality in system-level performance evaluations [13].

1) A full buffer traffic model is used for each user, i.e., there is always data available to be sent for a user [14].
2) A perfectly synchronized OFDMA network is assumed. Inter-cell interference occurs when users in neighboring cells are allocated to the same SC.
3) The coherence bandwidth of the channel is larger than the bandwidth of an SC, so that fading in all subcarriers of an SC is constant.
4) The coherence time of the channel is larger than the time duration of an SC, so that fading remains constant over all OFDM symbols within an SC.
5) The same transmit power is allocated to every subcarrier of an SC, i.e., the transmit power of an SC is given by the transmit power per subcarrier multiplied by the number of subcarriers per SC.

### B. Signal Quality Modeling

According to previously introduced assumptions, the Signal to Interference plus Noise Ratio (SINR) $\gamma_{m,u,k}$ of user $u$ in SC $k$ is modeled as follows:

$$\gamma_{m,u,k} = \frac{P_{u,k}^m \cdot \Gamma_{m,u,k}}{w_{u,k} + \sigma^2} = \frac{P_{u,k}^m \cdot \Gamma_{m,u,k}}{\sum_{m'=1,m'\neq m}^{M} P_{u',k}^{m'} \cdot \Gamma_{m',u,k} + \sigma^2} \quad (1)$$

where $P_{u,k}^m$ is the transmit power applied by femtocell $F_m$ to SC $k$, which has been allocated to user $u$, $\Gamma_{m,u,k}$ is the channel gain between femtocell $F_m$ and user $u$ in SC $k$, $w_{u,k}$ is the interference suffered by user $u$ in SC $k$, and $\sigma^2$ is the noise power.

### C. User Capacity Modeling

Both the bit rate $BR_r$ and the throughput $TP_{u,r,k}$ of user $u$ in SC $k$ when using MCS $r$ are modeled as follows:

$$BR_r = \Theta \cdot \text{eff}_r = \frac{\text{SR}_{\text{ofdm}} \cdot \text{SY}_{\text{ofdm}}}{T_{\text{subframe}}} \cdot \text{eff}_r \quad (2)$$

$$TP_{u,r,k} = BR_r \cdot (1 - BLER(r, \gamma_{m,u,k})) \quad (3)$$

where $\Theta$ is a fixed parameter that depends on network configuration, being $\text{SR}_{\text{ofdm}}$ and $\text{SY}_{\text{ofdm}}$ the number of data subcarriers (frequency) and symbols (time) per SC, respectively, and $T_{\text{subframe}}$ the frame duration in time units, $\text{eff}_r$ is the efficiency ($bits/symbol$) of the selected MCS $r$, which is illustrated in the right most column of Table I, and $BLER(r, \gamma_{m,u,k})$ is the BLock Error Rate (BLER) suffered by SC $k$ that is a function of both MCS $r$ and SINR $\gamma_{m,u,k}$.

### D. Channel Quality Indicator

User $u$ sends at regular time intervals ($T_{u,cqi}$) a Channel Quality Indicator (CQI) $\text{CQI}_\text{u}$ to its serving femtocell $F_m$ to assess user channel conditions. User CQIs indicate the received signal strength $w_{u,k}$ of the interference suffered by femtocell user $u$ in all SCs $\mathcal{K}$, or can be derived through it.

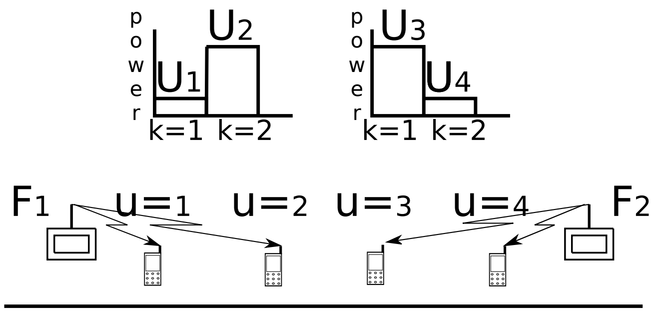


Fig. 1. Users co-existing in the same SC.

## III. Proposed Self-Organization

In order to achieve a self-organized radio resource reuse pattern across a network, through the distributed and dynamic optimization of radio resource allocations independently in each cell (with the least possible or no inter-cell communications), it is necessary that the optimization metric in each cell well represents a self-organizing behavior. In this paper, we use the minimization of cell DL transmit power [15] [16] as a simple self-organization rule for distributed radio resource allocation at each femtocell. More specifically, we propose that each femtocell distributedly and dynamically allocates MCS, SC and transmit power to its users in a way that its cell DL transmit power is minimized, while users' throughput demands and radio resource allocation constraints are satisfied. The reasons why minimizing cell DL transmit power well represents a self-organizing behavior are as follows:

1) A femtocell that aims at minimizing its DL transmit power reduces inter-cell interference and creates radio resource reuse opportunities for its neighboring cells, since it allocates lower transmit power to SCs assigned to users with good geometry or low throughput demands. This is obvious from the Shanon-Hartley theorem [17].

$$C = B \cdot log_2(1 + \frac{P^m_{u,k} \cdot \Gamma_{m,u,k}}{w_{u,k} + \sigma^2}) \rightarrow$$
$$P^m_{u,k} = (2^{\frac{C}{B}} - 1) \cdot \frac{w_{u,k} + \sigma^2}{\Gamma_{m,u,k}} \qquad (4)$$

where $C$ is the capacity in $bps$ and $B$ is the bandwidth in $Hz$.

2) A femtocell that aims at minimizing its DL transmit power tends to use SCs that are not used by its neighboring cells, because less transmit power is needed in a less interfered or faded SC to achieve a targeted SINR.

In order to illustrate the advantage of the proposed radio resource allocation over uniform power distribution approaches, let us introduce the example depicted in Fig. 1, where there are 2 SCs with $\mathcal{K} = \{1, 2\}$, 2 femtocells with $\mathcal{F} = \{F_1, F_2\}$, and 4 users with $\mathcal{U}^1 = \{U_1, U_2\}$ and $\mathcal{U}^2 = \{U_3, U_4\}$, i.e., $F_1$ serves users 1 and 2, while $F_2$ serves users 3 and 4. In this example, it is also assumed that users 1 and 4 are cell-center users, whereas users 2 and 3 are cell-edge users, and that the channel gains are symmetric, i.e., $\Gamma_{1,1,k} > \Gamma_{1,2,k} > \Gamma_{1,3,k} > \Gamma_{1,4,k}, \Gamma_{2,4,k} > \Gamma_{2,3,k} > \Gamma_{2,2,k} > \Gamma_{2,1,k}$, $\Gamma_{1,1,k} = \Gamma_{2,4,k}$, and $\Gamma_{1,2,k} = \Gamma_{2,3,k}$, $\forall\, k \in \mathcal{K}$.

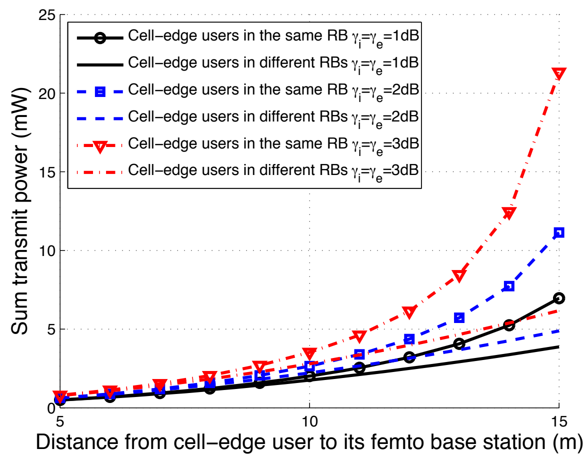


Fig. 2. Transmit power in the example of Fig. 1 when allocating cell-edge users in different or the same SC. In this case, the spectrum bandwidth is 2.5 MHz, the noise density is -174 dBm/Hz, the noise figure is 9 dB, the cell-edge SINR $\gamma_e$ and cell-centre SINR $\gamma_i$ targets are set to 1, 2 or 3 dB, the inter site distance is 40 m, the distance between the cell-centre users and their femtocell BSs is 2 m, the distance between the cell-edge users and their femtocell BSs range from 5 m to 15 m, and the path loss exponent is 2.

- *Case A) Cells minimizing its DL transmit power*: According to 1), users located closer to the cell center will be assigned less transmit power than those at the cell edge. Without loss of generality, we assume that cell $F_2$ allocates SC 1 to user 3 with a high power and SC 2 to user 4 with a low power. As a result, a user in cell $F_1$ will see stronger interference in SC 1 than in SC 2. Then, cell $F_1$ will have two options a) allocate SC 1 to user 1 and SC 2 to user 2; or b) allocate SC 2 to user 1 and SC 1 to user 2. It is easy to see that the former option (depicted in Fig. 1) will result in minimal cell-edge inter-cell interference, because cell-edge users will not be much interfered due to the low transmit power used by the neighboring cell in the corresponding SC. Moreover, Fig. 2, which illustrates the transmit power consumption of both options a) and b) and has been derived according to Appendix I, also demonstrates that allocating cell-edge users in different SCs results in a lower transmit power consumption than allocating them in the same SC. Hence, according to 2), transmit power minimization leads to inter-cell interference mitigation[1].

- *Case B) Power uniformly distributed among SCs*: Both cells assign the same transmit power to SCs 1 and 2, and allocate them to their users. Consequently, cell-edge users will suffer from a higher level of inter-cell interference than in *Case A)*.

## IV. Resource Allocation Problem (RAP)

This section defines our model for the MCS, SC and transmit power assignment in each femtocell, i.e., an optimization problem that will be referred to as Resource Allocation Problem (RAP), whose target is to minimize cell DL transmit power. RAP does not imply communication among femtocells,

[1]Simulation results in Section X also indicate that transmit power minimization leads to inter-cell interference mitigation for more complex setups with respect to cutting-edge radio resource allocation algorithms presented in the literature.

and thus each femtocell independently takes its own scheduling decisions.

First of all, let us indicate that the transmit power $P^m_{u,k,r}$ that femtocell $F_m$ has to allocate to SC $k$ in order to achieve the SINR threshold $\gamma_r$ of MCS $r$ is:

$$P^m_{u,k,r} = \gamma_r \cdot \frac{w_{u,k} + \sigma^2}{\Gamma_{m,u,k}} \tag{5}$$

where the derivation of $P^m_{u,k,r}$ is straightforward from (1) and femtocell $F_m$ knows both $w_{u,k}$ and $\Gamma_{m,u,k}$ due to its users' CQIs.

In order to avoid fast variations of $P^m_{u,k,r}$ caused by fast fading, user feedback is averaged over time. Channel quality in terms of instantaneous $w_{u,k}$ averaged over tens of CQIs is used in calculating $P^m_{u,k,r}$ [15].

Once $P^m_{u,k,r}$ has been introduced, RAP can be formulated as the following Integer Linear Programming (ILP) problem:

$$\min_{\chi_{u,k,r}} \sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{r=1}^{R} P^m_{u,k,r} \cdot \chi_{u,k,r} \tag{6a}$$

subject to:

$$\sum_{u=1}^{U}\sum_{r=1}^{R} \chi_{u,k,r} \leq 1 \qquad \forall k \tag{6b}$$

$$\sum_{r=1}^{R} \rho_{u,r} \leq 1 \qquad \forall u \tag{6c}$$

$$\chi_{u,k,r} \leq \rho_{u,r} \qquad \forall u,k,r \tag{6d}$$

$$\sum_{k=1}^{K}\sum_{r=1}^{R} \Theta \cdot \mathit{eff}_r \cdot \chi_{u,k,r} \geq TP^{req}_u \qquad \forall u \tag{6e}$$

$$\rho_{u,r} \in \{0,1\} \qquad \forall u,r \tag{6f}$$

$$\chi_{u,k,r} \in \{0,1\} \qquad \forall u,k,r \tag{6g}$$

where $\chi_{u,k,r}$ (6g) is a decision binary variable that is equal to 1 if user $u$ uses MCS $r$ in SC $k$, or 0 otherwise, $\rho_{u,r}$ (6f) is a decision binary variable that is equal to 1 if user $u$ uses MCS $r$, or 0 otherwise, constraint (6b) makes sure that SC $k$ is only assigned to at most one user $u$, constraints (6c) and (6d) together guarantee that each user is allocated to at most one MCS, and constraint (6e) makes sure that each user $u$ achieves its throughput demand $TP^{req}_u$, which may differ for each user.

In real-time services, $TP^{req}_u$ should be selected according to the throughput demand of the service (e.g, VoIP demands around 12.2 kbps), while in best-effort services, $TP^{req}_u$ should be selected according to a rate control scheme that may depend on, e.g., traffic load, number of best-effort users [18]. Moreover and independently of the service type, there may be more users connected to a cell than it can actually handle, or their throughput requirements may be so large that it cannot satisfy them all at once. In this case and according to traditional approaches, a time-domain scheduler that may sit on top of the proposed frequency-domain scheduler may schedule subsets of connected users and provide a certain degree of fairness among them. This time-domain scheduler can be based on existing methods, e.g., proportional fair, but is not covered in this paper due to limited space.

## V. COORDINATED RAP

On the one hand, cell-edge users are more prone to inter-cell interference than cell-center users. On the other hand, the high power assigned by cells to their cell-edge users may magnify inter-cell interference. Therefore, in order to further mitigate the inter-cell interference experienced by cell-edge users, we propose to upgrade the proposed method and that neighboring cells coordinate their resource allocations to cell-edge users through a message passing approach over the femtocell gateway. Assisted by this inter-cell coordination, the distributed minimization of cell DL transmit power may converge faster towards stable solutions. This inter-cell coordination can only be used when femtocells have sufficiently high bandwidth and low latency at the back-haul.

The proposed coordination is as follows:

In femtocell $F_m$, if cell-edge user $u$ is assigned with MCS $r$, SC $k$ and transmit power $P^m_{u,k,r}$, then femtocell $F_m$ computes the maximum interference power $w^{max}_{u,k}$ that user $u$ can suffer in SC $k$ to get the SINR threshold $\gamma_r$ required for MCS $r$ as follows:

$$w^{max}_{u,k} = \frac{P^m_{u,k,r} \cdot \Gamma_{m,u,k}}{\gamma_r} - \sigma^2 \tag{7}$$

The inter-cell interference seen by user $u$ is caused by the set of interfering cells of femtocell $F_m$, i.e., $\Psi_m (\subset \mathcal{M})$, which has a cardinality of $N^{intrf}_m$. Without loss of generality, we assume that the maximum interference power $w^{max}_{u,k}$ is equally shared by the $N^{intf}_m$ potential interfering cells of femtocell $F_m$, and thus the maximum interference power per interfering cell $w^{maxN}_{u,k}$ can be modelled as follows:

$$w^{maxN}_{u,k} = \frac{w^{max}_{u,k}}{N^{intf}_m} \tag{8}$$

In order to prevent the outage of its cell-edge user $u$, femtocell $F_m$ then computes the maximum transmit power $P^{m',max}_k$ that interfering cell $F'_m$ ($\forall F'_m \in \Psi_m$) can use in SC $k$ as follows:

$$P^{m',max}_k = \frac{w^{maxN}_{u,k}}{\Gamma_{m',u,k}} \tag{9}$$

where channel gain $\Gamma_{m',u,k}$ is assessed using the measurement reports fed back by users; and then it forwards $P^{m',max}_k$ and the SC index of SC $k$ to cell $F_{m'}$ through the femtocell gateway.

In LTE Release 8, a cell can use High Interference Indicator (HII) messages through LTE-X2 interface to inform neighboring cells that uplink transmissions of its cell-edge users will be scheduled in certain SCs, and thus the neighboring cells would not schedule their cell-edge users in the specified SCs [19]. In this paper, we follow a similar approach and let cell $F_m$ send a DL HII message carrying the transmit power constraint $P^{m',max}_k$ and the SC index $k$ to cell $F_{m'}$ ($\forall F_{m'} \in \Psi_m$), so that cell $F_{m'}$ would not allocate a transmit power $P^{m'}_{u',k,r'}$ greater than $P^{m',max}_k$ in SC $k$. When receiving more than one DL HII messages for the same SC $k$, cell $F_{m'}$ will follow the lowest transmit power constraint for SC $k$. At the same time, any cell cannot use a DL transmit power per SC higher than the maximum transmit power $P_k^{S,max}$ specified by the operator [20]. For a fair comparison with other resource allocation schemes, we set $P_k^{S,max}$ as the transmit power resulted from uniformly distributing the total DL transmit power among all SCs. All power constraints, $P_k^{m',max}$ $(\forall F_{m'} \in \Psi_m, \forall k \in \mathcal{K})$, are thus initialized to $P_k^{S,max}$. If there is no transmit power constraint set by neighboring cells, $P_k^{m',max} = P_k^{S,max}$. When a transmit power constraint $P_k^{m',max}$ expires, cell $F_m$ informs cell $F_{m'}$ through a DL HII with $P_k^{m',max} = P_k^{S,max}$.

In order to inject stability into the network and avoid the exchange of a large number of DL HII messages, a femtocell sends out a new DL HII message only if the updated $P_{u,k,r}^m$ has changed by at least 1 dB with respect to its current value.

This coordination can be realized in RAP (6), by adding the following constraint:

$$\chi_{u,k,r}^m \cdot P_{u,k,r}^m \leq P_k^{m,max} \qquad \forall u, k, r \tag{10}$$

which guarantees that power constraints imposed by neighboring cells through the DL HII messages presented in this section are fulfilled.

In order to distinguish the autonomous and coordinated version of the proposed RAP, without and with constraint (10), we call the former as autonomous RAP (auRAP) and the latter as coordinated RAP (coRAP).

## VI. Subchannel and Power Allocation Subproblem (SPAP)

This section discusses an important subproblem of RAP referred to as SC and Power Allocation subProblem (SPAP) that happens when the MCS to be used for each user is known a priori.

An efficient solution to this subproblem has two important applications:

- It can be used as a sub-routine in order to solve RAP, as it will be presented in Section VII.
- It can be used as a low latency SC and transmit power allocation scheme, as it will be discussed in Section IX.

Assuming that a MCS $r_u$ has been already given to user $u$, i.e., $\rho_{u,r} \forall u \forall r$ is known and fixed a priori as part of the input, the whole optimization problem transforms to an easier form.

Clearly, the used MCS $r_u$ determines the number $D_u$ of SCs needed for satisfying the throughput requirement $TP_u^{req}$ of user $u$. Namely,

$$D_u := \left\lceil \frac{TP_u^{req}}{\sum_{r=1}^{R} \Theta \cdot \mathit{eff}_r \cdot \rho_{u,r}} \right\rceil = \left\lceil \frac{TP_u^{req}}{\Theta \cdot \mathit{eff}_{r_u}} \right\rceil \tag{11}$$

In addition, let us introduce the binary decision variable $\phi_{u,k}$, which indicates whether user $u$ makes use of SC $k$, i.e.,

$$\phi_{u,k} := \sum_{r=1}^{R} \chi_{u,k,r} \tag{12}$$

Substituting them into (6a)-(6g), we obtain the following SC and transmit power allocation problem.

$$C_{\mathcal{S}} = \min_{\phi_{u,k}} \sum_{u=1}^{U} \sum_{k=1}^{K} P_{u,k,r_u}^m \cdot \phi_{u,k} \tag{6a*}$$

subject to:

$$\sum_{u=1}^{U} \phi_{u,k} \leq 1 \qquad \forall k \tag{6b*}$$

$$\sum_{k=1}^{K} \phi_{u,k} = D_u \qquad \forall u \tag{6e*}$$

$$\phi_{u,k}^m P_{u,k,r_u}^m \leq P_k^{m,max} \qquad \forall u, k, r \tag{10*}$$

$$\phi_{u,k} \in \{0, 1\} \qquad \forall u, k \tag{6g*}$$

where constraint (10) is not used if autonomous SPAP, a.k.a., auSPAP, is adopted, or is used if coordinated SPAP a.k.a., coSPAP, is considered.

### A. Solving SPAP Optimally

The next observation makes it possible to solve SPAP[2] optimally even more efficiently. Problem (6) can be formulated and efficiently solved as a minimum cost network flow (assignment problem), where users are assigned SCs so as to minimize cell DL transmit power. Formally,

*Claim 1:* Let us define the following *network flow* problem [21] with vertex set

$$V := \mathcal{U} \cup \mathcal{K} \cup \{s, t\}, \tag{13a}$$

being $s, t \in V$ the source and the sink of $V$, respectively.

edge set

$$\begin{aligned} E := &\{(su) : u \in \mathcal{U}^m\} \cup \{(uk) : u \in \mathcal{U}^m, k \in \mathcal{K}\} \cup \\ &\{(kt) : k \in \mathcal{K}\}, \end{aligned} \tag{13b}$$

capacity function

$$cap(ab) := \begin{cases} D_b, & \text{if } a = s, b \in \mathcal{U}^m \\ 1 & \text{otherwise,} \end{cases} \tag{13c}$$

and cost function

$$cost(uk) := \begin{cases} P_{u,k,r_u}^m, & \text{if } u \in \mathcal{U}^m, k \in \mathcal{K} \\ 0 & \text{otherwise.} \end{cases} \tag{13d}$$

Then, a minimal cost network flow of capacity $\sum_{u \in \mathcal{U}} D_u$ will provide an optimal solution to SPAP.

In order to solve this problem, the *network simplex* algorithm [22] implemented in the LEMON library [23] has been used for our simulations.

In a similar way, we can also efficiently solve coSPAP, if we replace edge set (13b) by $E := \{(su) : u \in \mathcal{U}^m\} \cup \{uk : u \in \mathcal{U}^m, k \in \mathcal{K} \,|\, P_{u,k,r_u}^m \leq P_k^{m,max}\} \cup \{kt : k \in \mathcal{K}\}$, in which the edge between user $u$ and SC $k$ is broken if $P_{u,k,r_h}^m > P_k^{m,max}$ and thus user $u$ cannot make use of SC $k$.

Note that if the cell DL transmit power demanded by all connected users is higher than the maximum allowed DL transmit power per BS, then not all users throughput requirements can be met. This issue may be handled using a time-domain scheduler as previously indicated. In this paper, users requesting the highest transmit power levels are removed from the current resource allocation, and may be served in subsequent subframes.

[2] In order to illustrate our solving approach we adopt first auSPAP in here.

## VII. Solving RAP

ILP solving techniques can be adopted to solved RAP [24], where these ILP solving techniques may solve RAP up to the optimality. However, the running times incurred by ILP solvers are unpredictable (exponential in the worst case), which renders them inappropriate for their use in femtocells.

In this section, we reduce the complexity of RAP (defined in Section IV) by means of a two-level decomposition approach, and propose a smart exhaustive search to solve it.

The key idea behind this technique is that a smart search can be performed over the MCS assignment solution space, where for each MCS solution, the optimal SC and transmit power allocation can be obtained by solving SPAP, presented in Section VI.

In order to provide a better description of this technique, we define $\mathcal{S}_m$ as the vector that indicates the MCSs assigned to all users $\mathcal{U}^m$ of femtocell $F_m$.

For an arbitrary $\mathcal{S}_m$, solving SPAP, the SC and transmit power assignment associated to MCS allocation $\mathcal{S}_m$ is derived. Then, the quality of this MCS allocation $\mathcal{S}_m$ is evaluated according to $C_{\mathcal{S}}$ (6a*), i.e., the cost of the SC and transmit power assignment found by SPAP. Using this cost function, a smart search is carried out to find the MCS assignment that yields the lowest transmit power. Some assignments can be safely excluded from this search:

- If an MCS $r_{max}$ can be found, which is suitable to satisfy the throughput demand $TP_u^{req}$ of user $u$ by using 1 SC, no higher-order MCSs are tester thereafter for user $u$. Allocating a higher-order MCS would unnecessarily increase the required transmit power.
- If an MCS allocation $\mathcal{S}_m$ is found, which requires more SCs than that are available to satisfy the throughput demand of users, no other MCS allocation $\mathcal{S}'$ that can be derived from $\mathcal{S}_m$ by lowering the selected MCS of a single user is then tried. The reason behind is that $\mathcal{S}'_m$ would also require more SCs than that are available.

This approach solves RAP optimally and sufficiently fast thanks to the limited number of connected users per femtocell and the speed of the network simplex scheme for solving SPAP.

## VIII. Convergence

In this section, we will demonstrate that RAP, based on distributed transmit power minimization at each cell, leads to a stable resource allocation equilibrium in a simple 1-dimensional symmetric system (as presented in Section III and Fig. 1). Convergence to stable solutions for more complex setups will be verified by simulation results to be presented in Section X-D.

Without loss of generality, we assume that all users share the same required throughput $TP^{req}$ with the corresponding MCS $r$ and its SINR threshold $\gamma_r$. The SC allocated to user $u$ is denoted as $k_u$, where $k_u \in \mathcal{K}$ and $u \in \{1,2,3,4\}$. Now, let us present 4 lemmas:

*Lemma 2:* Given the transmit powers $P^2_{3,k_3,r}$ and $P^2_{4,k_4,r}$ in cell $M_2$, if $P^2_{3,k_3,r} > P^2_{4,k_4,r}$ and $P^1_{2,k_4,r} = \frac{\gamma_r(P^2_{4,k_4,r}\Gamma_{2,2}+N_0)}{\Gamma_{1,2}} \leq P^{1,max}_{k_4}$, allocating cell-edge user 2 to SC $k_4$ is the optimum solution in cell $M_1$.

*Proof:* This is true because cell-edge users should be allocated to SCs with the least transmit power applied in neighboring cells to minimize interference. ■

Because the considered scenario in Fig. 1 is symmetric, Lemma 2 also applies to $M_2$ with respect to transmit powers $P^1_{1,k_1,r}$ and $P^1_{2,k_2,r}$.

*Lemma 3:* In the stable state, transmit powers $P^{*m}_{u,k_u,r}$ ($\forall u \in \{1,2,3,4\}$) are symmetric, i.e., $P^{*1}_{u,k_u,r} = P^{*2}_{5-u,k_{5-u},r}$ for $u = 1,2$.

*Proof:* This is true due to the symmetry. ■

*Lemma 4:* In the stable state, cell-edge users need more transmit power than cell-center users, i.e., $P^{*1}_{2,k_2,r} > P^{*1}_{1,k_1,r}$.

*Proof:* This can be derived by checking all possible SC assignments in the stable state. For simplifying the notation, let us assume in the sequel that $P_e = P^{*1}_{2,k_2,r}$ and $P_i = P^{*1}_{1,k_1,r}$:

If cell-edge users use the same SC in both cells. Since the system is in the stable state, we have

$$\frac{P_e\Gamma_{1,2}}{P_e\Gamma_{2,2}+\sigma^2} = \frac{P_i\Gamma_{1,1}}{P_i\Gamma_{2,1}+\sigma^2} = \gamma_r.$$

Thus since $\Gamma_{1,1} > \Gamma_{1,2}$ and $\Gamma_{2,2} > \Gamma_{2,1}$, we have $P_e > P_i$.

If cell-edge users use different SCs in both cells. Since the system is in the stable state, we have

$$\frac{P_e\Gamma_{1,2}}{P_i\Gamma_{2,2}+\sigma^2} = \frac{P_i\Gamma_{1,1}}{P_e\Gamma_{2,1}+\sigma^2} = \gamma_r.$$

Since $\Gamma_{1,1} > \Gamma_{1,2}$ and $\Gamma_{2,2} > \Gamma_{2,1}$, we also have $P_e > P_i$. ■

*Lemma 5:* Since $k_4$ and $k_3$ are allocated to a cell-center user and a cell-edge user, respectively, and because cell-center users do not impose transmit power constraints in neighboring cells, then $P^{*1,\max}_{k_3} \leq P^{*1,\max}_{k_4} = P^{S,max}_k$.

*Proof:* See Section V for the definitions of both concepts DL HII and $P^{S,max}_k$. ■

With the help of these lemmas, we define Theorem 6 to demonstrate the convergence of coRAP in the considered scenario.

*Theorem 6:* Given an initial SC allocation $k_u$ and transmit powers $P^m_{u,k_u,r}$ ($\forall u \in \{1,2,3,4\}$), in the stable state of coRAP, cell-edges users are allocated to different SCs, i.e., $k^*_2 \neq k^*_3$.

*Proof:* Without loss of generality, we focus on the output of coRAP for cell $M_1$ when it 'observes' from cell $M_2$ SC allocation $(k_3,k_4)$, transmit powers $(P^2_{3,k_3,r}, P^2_{4,k_4,r})$, and transmit power constraints $(P^{1,\max}_{k_3}, P^{1,\max}_{k_4})$.

We consider all cases:

**Case 1: $P^2_{3,k_3,r} \geq P^2_{4,k_4,r}$ and $P^1_{2,k_2,r} \leq P^{1,\max}_{k_4}$:** According to Lemma 2, the optimal allocation is $k_2 = k_4$, because cell-edge user 2 suffers from lower interference in SC $k_4$, allocated to cell-center user 4, than in SC $k_3$.

**Case 2: $P^2_{3,k_3,r} \geq P^2_{4,k_4,r}$ and $P^1_{2,k_2,r} > P^{1,\max}_{k_4}$:** Since $P^1_{2,k_2,r} > P^{1,\max}_{k_4}$ and $P^{1,\max}_{k_3} < P^{1,\max}_{k_4}$, following Lemma 5, cell-edge user 2 should not be allocated to any SC because it cannot reach its aimed SINR anyway.

**Case 3: $P^2_{3,k_3,r} < P^2_{4,k_4,r}$ and $P^1_{2,k_2,r} \leq P^{1,\max}_{k_3}$:** Since cell-edge user 2 can obtain its aimed SINR in $k_3$ due to the favorable transmit power constraint imposed by $M_2$, the optimal SC allocation is $k_2 = k_3$.

**Case 4: $P^2_{3,k_3,r} < P^2_{4,k_4,r}$ and $P^1_{2,k_2,r} > P^{1,\max}_{k_3}$:** Since cell-edge user 2 cannot obtain its aimed SINR in $k_3$ due to the adverse transmit power constraint imposed by $M_2$, the only viable allocation is $k_2 = k_4$.

We observe that Case 3 is the only one that makes $k_2 = k_3$, thus contradicting our theorem.

However, if the system remains in Case 3 until coRAP converges, then $P^{*2}_{3,k_3,r} < P^{*2}_{4,k_4,r}$, which contradicts Lemma 3. Thus, we can say that Case 3 cannot be the final stable state, thus being our theorem correct.

In the sequel, we will show that, in the process of coRAP, the system always leaves Case 3, and eventually converges. Without any loss of generality, if macrocell $M_1$ is in Case 3, it will eventually leave Case 3, and fall into Case 1, 2 or 4. Indeed, cell $M_1$ will leave Case 3 under the following cases:

- When cell $M_2$ changes the transmit power constraint in cell $M_1$, i.e., when $P^{1,\max}_{k_3}$ is reduced and $P^{1}_{2,k_2,r} > P^{1,\max}_{k_3}$, thereafter, the system will move from Case 3 to Case 4.
- Due to the large interference between cell-edge users allocated to the same SC, and in order to meet its cell-edge user's SINR requirement, if cell $M_1$ allocates its cell-edge user 2 to SC $k_3$, then cell $M_2$ will react using more transmit power in SC $k_3$ in the next coRAP round. Thus, updated $P^{2'}_{3,k_3,r} > P^{2}_{3,k_3,r}$ and $P^{1,\max'}_{k_3} < P^{1,\max}_{k_3}$. Eventually, coRAP will thus lead to $P^{2}_{3,k_3,r} > P^{2}_{4,k_4,r}$, and the system will move from Case 3 to Case 1 or 2.

If $k^*_2 = k^*_4$, then the SC allocation becomes stable, and the problem reduces to the standard distributed power control problem under given SINR requirements and maximum transmit power constraints [25]. It was shown in [25] that this standard power control problem has an unique fixed solution that minimizes cell DL transmit power and guarantees convergence. Therefore, the convergence of coRAP in the symmetric system in Section III can also be ensured. ∎

## IX. Resource Management Architecture

Because SPAP can be solved very fast, which will be shown in the following section, and thus can be run much more frequently than RAP (SPAP can be solved much faster than RAP), we propose the following Resource Allocation Architecture (RAA) to implement the proposed self-organization in femtocells.

- By solving RAP, the MCSs of users can be updated on a second by second basis in order to cope with per cell time fluctuations of traffic load as well as user mobility.
- By solving SPAP, the SC and transmit power allocation to users can be updated on a much faster basis than the assignment of MCSs in order to cope with the fast variations of the channel due to interference/fading.

Recall that the goal of RAA is to mitigate inter-cell interference through distributed minimization of cell DL transmit power, and thus each cell may tend to allocate more SCs with lower order MCS and less transmit power to users in order to meet their throughput demands. In this way, inter-cell interference towards other cells may be reduced and a better spatial reuse may be achieved. Due to the dynamics of the above proposed RAA, cells can quickly respond to incoming users, and effectively avoid overload issues. Since some part of bandwidth may be set aside to ensure that sessions are not

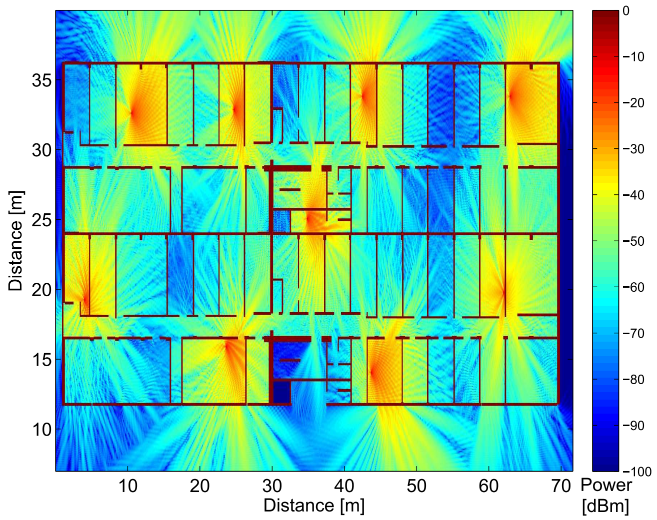


Fig. 3. Office scenario with 9 femtocells: Best server.

dropped during handovers, incoming users can also rely on this bandwidth until the proposed self-organization runs [26].

In order to distinguish the proposed coordinated and autonomous RAAs, without and with constraint (10), we refer to the former as coordinated RAA (coRAA) and to the latter as autonomous RAA (auRAA).

## X. Simulations and Results

The scenario used for system-level simulations is an enterprise of $69\,m \times 32\,m$ hosting 9 OFDMA femtocells. It is assumed that macrocells and femtocells are allocated to orthogonal spectrum resources or that there is no macrocell so that we can focus on the femtocell tier (no cross-tier interference).

Fig. 3 illustrates the femtocell locations within the scenario, while Table II provides details of simulation parameters. Path losses and shadowing were modeled according to the Finite-Difference Time-Domain (FDTD)-based model in [27], and BLER was modeled using Look Up Tables (LUTs) from [28]. 4, 6 or 8 static users attempted to connect to each femtocell (this is a 50%, 75% and 100% cell traffic load since the simulated network had 2,5 MHz bandwidth and 8 SCs). Users were uniformly distributed within femtocells coverage, held their connection for a given time dictated by an exponential distribution (mean $\mu_p$), and thereafter disconnected. When users disconnected, new ones appeared in new positions. A full buffer model was used to simulate the traffic of users, i.e., there was always data available to transmit for a user. In this case, all users had a throughput demand of $250\,kbps$. Users suffered from outage if they could not transmit at a throughput no less than their demands[3] for a time $T_{outage}$. When a user suffered from outage its resources were freed, but a new user was not created until its holding time expired. A user was considered as cell-edge user, and thus involved in the coordination procedure, if its wideband SINR (SINR measured over pilot signals across the entire bandwidth) was smaller than the cell-edge SINR threshold $\gamma^e$ = 3 dB. In order

[3]Applications based on real-time or streaming services are insensitive to bit rate slow downs if the expected QoS, i.e., transmission rate, is achieved.

TABLE II
SIMULATION PARAMETERS

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Femtocells | 9 | User Ant. Height | 1.5 m |
| Simulation time | 600 s | User Noise Figure | 9 dB |
| Scenario Size | 72 m × 39 m | User Body Loss | 0 dB |
| Carrier Frequency | 2.0 GHz | Path Loss Model | FDTD-based model |
| Channel Bandwidth | 2.5 MHz | Shadowing | Predicted by FDTD |
| Frame Duration | 5 ms | Users per cell | 4,6,8 |
| Data subcarriers | 192 | User distribution | Uniform |
| Subchannels | 8 | Min. dist. UE to FAP | 1 m |
| DL OFDM data symbols | 39 | Mean Holding Time | 45 s |
| FAP Tx Power ($P_m^{tot}$) | 20 dBm | Type of Service | Full buffer |
| FAP Ant. Base Gain | 0 dBi | Min Service TP | 250 kbps |
| FAP Ant. Pattern | Omni | $T_{outage}$ | 4 s |
| FAP Ant. Height | 1.5 m | user CQI freq. | 10 ms |
| FAP Ant. Tilt | - | NLM updating freq. | 100 ms |
| FAP Noise Figure | 5 dB | IM updating freq. | 100 ms |
| FAP Body Loss | 0 dB | Stolyar's updating freq. | 100 ms |
| Thermal Noise Density | -174.0 $dBm/Hz$ | $T_{rap}$ | 1 s |
| User Ant. Gain | 0 dBi | $T_{spap}$ | 100 ms |
| User Ant. Pattern | Omni | $\gamma^e$ | 3 dB |

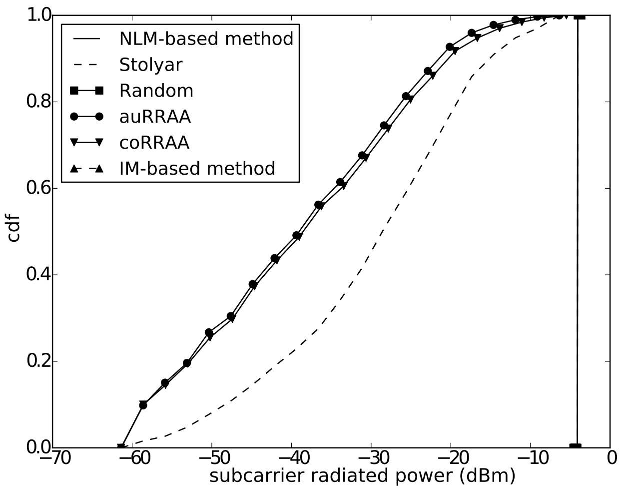


Fig. 4. CDF of the transmit power per subcarrier.

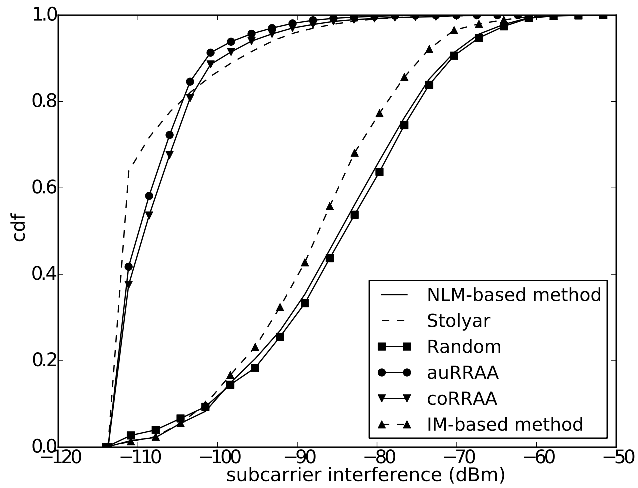


Fig. 5. CDF of the received interference per subcarrier.

to mitigate ping-pong effects, only those assignments that were at least 5 % better than the current ones in terms of cost function (6a*) were adopted.

### *A. Approaches Used for Comparison*

Four radio resource management schemes were used for performance comparison. Note that in the first three schemes transmit power is uniformly distributed among all SCs.

*a) Random assignment:* SCs are assigned randomly to users without taking into account any kind of information. Therefore, inter-cell interference coordination does not exist.

*b) Network listening mode (NLM):* Each femtocell periodically measures the received strength of the interference in each SC, and subsequently allocates the SCs suffering from the lowest interference to their users. Let us note that the information used for the scheduling is collected at the femtocell location, and not at user positions.

*c) Interference minimization (IM):* Each femtocell periodically performs an optimization process, whose objective is to allocate SCs to users while minimizing the sum interference suffered by the femtocell. This scheme is assisted by user CQIs, and thus the information used for the radio resource management is measured at user locations.

*d) Stolyar's Approach:* This scheme is based on a completely distributed architecture and a dynamic allocation of transmit power to users, in which users are allocated to sub-bands according to a cell DL transmit power minimization problem similar to SPAP [15]. In order to allow comparison, sub-bands in Stolyar's approach correspond to SCs in our implementation. Stolyar's approach also uses frequency hopping within sub-bands. In order to free the maximum number of subcarriers for hopping, the least number of subcarriers within a sub-band are allocated to users to meet their targeted throughput demands, thus leading to larger transmit powers and MCSs per subcarrier.

A more detailed description of these allocation approaches can be found in [29].

In the following, we will always refer to auRAA rather than coRAA, unless it is otherwise specified.

### B. Running Time and Solution Quality

One way of solving the joint MCS, SC and transmit power allocation problem is to solve formulation (6) directly by an ILP solver. In this way, the optimality of the solution can be guaranteed. To compare the performance of our two-level decomposition approach with that of an ILP[4], we extracted 100 instances from the simulations of the described scenario and run both solving techniques. The computer used for this simulation contained an AMD Opteron 275 dual-core processor running at 2,2GHz with 16 GB of RAM.

With regard to running times, the average running time of the ILP solver was $23.4\,s$, but this running time varied significantly between instances, being the maximum $91.4\,s$. On the contrary, the average running time of network simplex when solving auSPAP was around $0.20\,ms$, whereas that of the exhaustive search when solving auRAP was around $0.39\,s$. These results show that our two-level decomposition approach provides a large running time improvement over ILP solvers, and makes it possible to run auRAA much more frequently. Let us also note that our two-level decomposition approach was able to find the optimal solution in all problem instances.

According to obtained results, when running the proposed approach in our simulations, each femtocell will independently solve auSPAP after a time uniformly distributed in [2, 100] ms after its last auSPAP update and auRAP after a time uniformly distributed in [0.5, 1.0] s after its previous auRAP update. Note that we use the same parameters for coSPAP and coRAP.

### C. Transmit Powers and Interference

Fig. 4 shows the Cumulative Distribution Function (CDF) of the transmit power per subcarrier[5] during the simulation. When using the proposed self-organizing approach, the transmit power applied by each cell changes depending on traffic and channel conditions, and is lower than when using uniform distributions (the CDFs of random, NLM and IM are superposed). Stolyar's approach also uses more transmit power than the proposed approach, because its objective is to allocate as less subcarriers as possible within a SC in order to allow a better hopping, thus allocating larger MCSs and transmit power per subcarrier.

As a result of using lower transmit powers and therefore a greener approach, the proposed approach reduces interference towards neighboring femtocells. This is corroborated by Fig. 5, which illustrates the CDF of the interference suffered per subcarrier during the simulation. Additionally, Fig. 5 also illustrates that random, NLM and IM perform similarly in terms of inter-cell interference mitigation. This is because when cells are fully loaded and the transmit power is uniformly distributed, these schemes measure approximately the same interference in all SCs during their sensing phase. Hence, no scheduling opportunity exists, and the behaviors of these algorithms are similar to that of random assignments.

Since coRAA results in less user outages/larger traffic load due to coordination, inter-cell interference and transmit power is slightly larger in coRAA than in auRAA. Details on network performance in terms of user outages will be presented in Subsection X-E.

[4]In this case, the used ILP solver was: IBM ILOG CPLEX (version 9.130).
[5]Recall that the same transmit power is applied to all subcarriers of an SC.

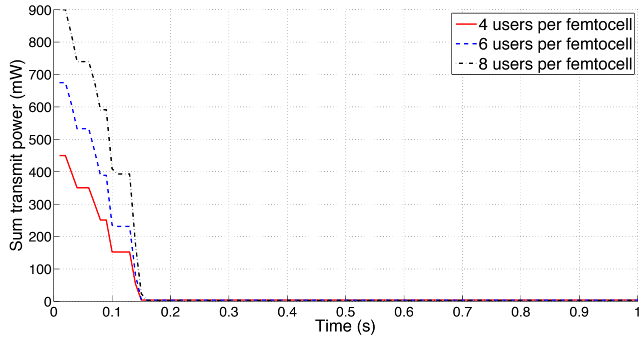


Fig. 6. Sum of transmit power.

### D. Convergence

In Section VIII, the convergence of RAP to stable solutions in the 1-dimensional scenario of Fig. 1 was demonstrated. In this subsection, the convergence of RAP to stable solutions in the more complex scenario of Fig. 3 is also investigated. In order to study convergence, 4, 6 or 8 users per femtocell were randomly deployed at the beginning of our simulations, and their locations were kept fixed throughout each simulation.

Fig. 6 illustrates the evolution over time of the sum cell DL transmit power of all femtocells when using the proposed distributed self-organization for the above mentioned three femtocell user loads[6]. We can see that all cases converge to stable solutions, independently of the number of users in each femtocell, i.e., femtocells' DL transmit power allocations are stable with no power changes after a time, meaning that femtocells self-organize themselves and the entire network solution converges. This is inline with the proof of convergence presented in Section VIII for the 1-dimensional scenario of Fig. 1. A larger number of users led to a larger transmit power use in the initial and the final stable state. As in game theory [30], [31], it took a number of iterations and thus time for the proposed distributed self-organization to converge. However, in all simulated cases, convergence was quickly achieved, i.e., in less than 0.2 s.

Fig. 7 illustrates the quantity of transmit power allocated by three neighboring femtocells in each of the 8 existing SCs. This figure depicts how interference mitigation is not only achieved due to transmit power reduction, but also because the network settles into an efficient SC reuse pattern when utilizing RAP. In this figure, it can be observed, as explained in Section III, how cells tend to allocate high transmit power in those SCs in which the neighboring cells assign low transmit power and vice versa. In other words, there is an implicit coordination between cells in the allocation of resources to their cell-edge and cell-centre users.

### E. Femtocells' Capacity

Table III illustrates the network performance in terms of outages, average number of network connected users, and average network throughput when running all presented schemes. Three different scenarios were simulated where in each one 4, 6 or 8 users attempted to connect to each femtocell. We can observe that these different scenarios follow exactly the same

[6]Note that the results of each curve were averaged over 100 simulations.

TABLE III
SYSTEM-LEVEL SIMULATION RESULTS.

| Cell load | Scheme | Random | MNL | IM | Stolyar | auRAA | coRAA |
|---|---|---|---|---|---|---|---|
| **4 users/cell 50 % load** | Outage | 70 (15.09 %) | 40 (8.62 %) | 12 (2.59 %) | 25 (5.39 %) | 4 (0.86 %) | 1 (0.22 %) |
| | Users | 31.13 | 33.11 | 35.20 | 34.44 | 35.75 | 35.87 |
| | $Mbps$ | 7.65 | 8.24 | 8.77 | 8.56 | 8.83 | 8.91 |
| **6 users/cell 75 % load** | Outage | 141 (20.06 %) | 114 (16.22 %) | 55 (7.82 %) | 47 (6.69 %) | 15 (1.99 %) | 14 (2.13 %) |
| | Users | 43.65 | 45.15 | 49.64 | 49.92 | 52.71 | 52.79 |
| | $Mbps$ | 10.73 | 11.18 | 12.35 | 12.33 | 12.87 | 13.02 |
| **8 users/cell 100 % load** | Outage | 187 (19.87 %) | 186 (19.77 %) | 146 (15.52 %) | 77 (8.18 %) | 30 (3.19 %) | 16 (1.70 %) |
| | Users | 58.36 | 58.59 | 60.47 | 65.93 | 69.63 | 71.00 |
| | $Mbps$ | 14.40 | 14.48 | 14.98 | 16.23 | 16.78 | 17.45 |

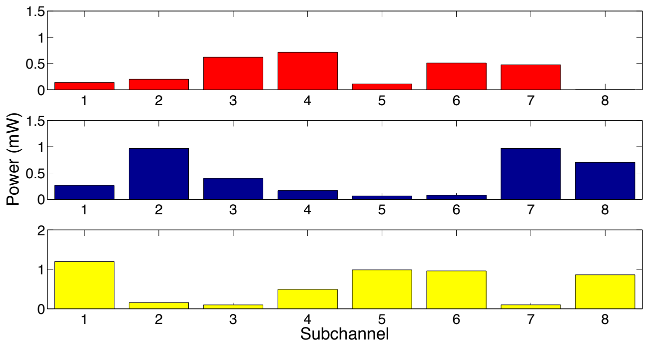


Fig. 7. Transmit power allocation of three neighboring enterprise femtocells.

trend. But, when the number of users increased, outages also increased because of larger inter-cell interference.

coRAA and auRAA provided a significant improvement in network performance over all methods used for comparison. This indicates that minimizing transmit power, giving every user what it requires, could lead to enhanced network capacity due to better spatial reuse, thus showing that power efficiency is not necessarily in conflict with capacity improvements at the network level. Specifically, coRAA resulted in an average performance improvement over the fourth best method, i.e., IM, of 130 user outages, 10.53 connected users and 2.47 Mbps (16.48 %). Furthermore, coRAA provided an average performance improvement over the third best method, i.e., Stolyar's, of 61 user outages, 5.07 connected users and 1.22 Mbps (7.51 %).

Within the proposed models, i.e., coRAA and auRAA, coRAA resulted in the best performance since it allows inter-cell communication and thus a better inter-cell interference coordination through DL HIIs. However, we can observe that for the most challenging case, i.e., the 8 users per cell case, the performance of auRAA is not far from that of coRAA. It incurred 15 outages more and was 1.37 and 3.99 % worse in terms of average connected users and network throughput, respectively. Hence, because auRAA does not require any signaling between femtocells, it may be more appealing for femtocell roll-outs where backhaul QoS may not be guaranteed.

coRAA, auRAA and Stolyar's approach outperform all other existing schemes because they allow all cells to allocate all available SCs to its users in an intelligent way: minimizing DL transmit power at every cell by applying low transmit power to SCs allocated to users with good geometry or low throughput demands. This allows for reduced inter-cell interference and creates scheduling opportunities in neighboring cells. This spatial reuse is not possible by using uniform power distributions when cells are highly loaded.

coRAA and auRAA provided a better performance than Stolyar's approach due to its better interference mitigation:

- The coordination provided by coRAA introduces stability in the network. When new users with bad geometry appear in the network, they are allocated to SCs that suffer from low interference due to inter-BS coordination, which aids the convergence to stable solutions. On the contrary, when using Stolyar's approach, since there is no explicit coordination among cells, ping-pong effects may occur, and it may take long time to reach a new stable solution over decentralized optimization.
- Frequency hopping may degrade performance when network load and user throughput demands are high. In order to allow for frequency hopping, Stolyar's approach assigns the least possible number of subcarriers within a sub-band with high order MCSs and transmit power, which may increase interference compared to solutions with all subcarriers of an SC modulated with the lowest possible oder MCS and transmit power. Users are also likely to suffer from service disruption when the least number of subcarriers per SC is used, if one of them fails to provide its contribution to obtain the user throughput requirement.

### *F. Signaling Overhead*

In this section, the signaling overhead incurred by coRAA due to DL HII is analyzed. Let us recall that every DL HII contains two items, transmit power constraint $P_k^{m,max}$ and SC index $k$. Assuming that 10 bits and 3 bits are used to encode $P_k^{m,max}$ (1024 levels) and $k$ (8 SCs), respectively, the number of bits needed per exchanged DL HII is $(10 + 3)\cdot D_u$ bits, where $D_u$ is the number of SCs allocated to cell-edge user $u$. Let us note that according to our simulations, an average of 9.32, 14.07 and 18.91 DL HIIs per second were sent per femtocell for the 4, 6 and 8 users per cell cases, respectively. Therefore, the back-haul bit rate required for these three different scenarios was in average of 0.28, 0.42 and 0.57 kbps, respectively, which is well below of current back-haul capabilities. Nonetheless, since femtocell-to-femtocell interfaces may be handled via user-provided back-hauls, points of failure and delay issues may arise during DL HII exchange that could compromise coRAA performance.

## XI. Conclusion

In this paper, we have shown that minimizing DL transmit power independently at every cell has remarkable SON features, which are particularly useful in femtocell networks due to their distributed nature. Applying low DL transmit power to SCs allocated to users with good geometry or low throughput demands in a femtocell, allows for reduced inter-cell interference and creates scheduling opportunities in neighboring ones, thus showing that power efficiency is not necessarily in conflict with capacity improvements at the network level. This spatial reuse is not possible by using uniform power distributions. Based on this self-organizing rule and taking realistic resource allocation constraints into account, we have proposed two novel resource allocation algorithms, autonomous and coordinated, respectively, whose performance have been evaluated using system-level simulations. The proposed resource allocation algorithms provide significant performance improvements in terms of user outages and network capacity over cutting-edge resource allocation algorithms proposed in the literature. The coordinated algorithm resulted in a slightly better performance than the autonomous one, at the expense of inter-cell communication. However, because the latter does not require any signaling between femtocells, it may be more appealing for femtocell roll-outs.

## Appendix A

Assuming that in the example of Fig. 1, $P_e$ is the transmit power allocated to cell-edge users, $P_e = P^{*1}_{2,k_2,r}$, $P_i$ is the transmit power allocated to cell-centre users, $P_i = P^{*1}_{1,k_1,r}$, $\gamma_e$ and $\gamma_i$ are the SINR targets of cell-edge and cell-centre users, respectively, $D$ is the inter-site distance, $d_1$ is the distance between the cell-centre users and their BSs, $d_2$ is the distance between the cell-edge users and their BSs, and $\Gamma_{m,u,k} = \frac{\xi}{d^n}$, where $\xi = (\frac{\lambda}{4\pi})^2$, $\lambda$ is the wave length and $n$ is the path loss exponent, the total DL transmit power usage per cell when allocating cell-edge users in different or the same SC be expressed as $P^{\text{diff}}_{\text{tot}}$ and $P^{\text{sam}}_{\text{tot}}$, respectively, where

$$\begin{aligned} P^{\text{diff}}_{\text{tot}} &= (P^{\text{diff}}_e + P^{\text{diff}}_i) \\ &= \frac{\sigma^2}{\xi}\left(\frac{\frac{d_1^n \gamma_i d_2^n \gamma_e}{(D-d_1)^n} + \frac{d_1^n \gamma_i d_2^n \gamma_e}{(D-d_2)^n} + d_1^n \gamma_i + d_2^n \gamma_e}{1 - \frac{d_1^n \gamma_i d_2^n \gamma_e}{(D-d_1)^n (D-d_2)^n}}\right) \end{aligned} \tag{14}$$

$$\begin{aligned} P^{\text{sam}}_{\text{tot}} &= (P^{\text{sam}}_e + P^{\text{sam}}_i) \\ &= \left(\frac{\frac{\sigma^2}{\xi} d_2^n \gamma_e}{1 - \frac{d_2^n \gamma_e}{(D-d_2)^n}} + \frac{\frac{\sigma^2}{\xi} d_1^n \gamma_i}{1 - \frac{d_1^n \gamma_i}{(D-d_1)^n}}\right) \end{aligned} \tag{15}$$

## References


[1] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell Networks: A Survey," *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sept. 2008.

[2] V. Chandrasekhar and J. G. Andrews, "Spectrum Allocation in Tiered Cellular Networks," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 3059–3068, Oct. 2009. [Online]. Available: http://arxiv.org/abs/0805.1226

[3] J. D. Hobby and H. Claussen, "Deployment Options for Femtocells and their Impact on Existing Macrocellular Networks," *Bell Labs Technical Journal*, vol. 13, pp. 145–160, 2009.

[4] M. Y. Arslan, J. Yoon, K. Sundaresan, S. V. Krishnamurthy, and S. Banerjee, "Fermi: A femtocell resource management system for interference mitigation in ofdma networks," in *MobiCom11*, Las Vegas USA, Sept. 2011.

[5] V. Chandrasekhar and J. G. Andrews, "Uplink Capacity and Interference Avoidance for Two-Tier Femtocell Networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3498–3509, July 2009.

[6] H. Claussen and F. Pivit, "Femtocell Coverage Optimization using Switched Multi-element Antennas," in *IEEE International Conference on Communications (ICC)*, Dresden, Germany, June 2009.

[7] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G Evolution: HSPA and LTE for Mobile Broadband*, 2nd ed. Elsevier, Oct. 2008.

[8] G. Song and Y. Li, "Cross-layer optimization for OFDM wireless networks-part I: theoretical framework," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 614–624, 2005.

[9] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 2, pp. 171–178, Feb. 2003.

[10] H. Claussen, "Co-Channel Operation of Macro- and Femtocells in a Hierarchical Cell Structure," *International Journal of Wireless Information Networks*, vol. 15, no. 3, pp. 137–147, Dec. 2008.

[11] J. Ling, D. Chizhik, and R. Valenzuela, "On Resource Allocation in Dense Femto-deployments," in *IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS 2009)*, Tel Aviv Israel, Nov. 2009.

[12] D. López-Pérez, Á. Ladányi, A. Jüttner, and J. Zhang, "OFDMA femtocells: A self-organizing approach for frequency assignment," in *IEEE Personal, Indoor and Mobile Radio Communications Symposium (PIMRC)*, Tokyo, Japan, Sept. 2009.

[13] S. Hussain and V. C. M. Leung, "Dynamic Frequency Allocation in Freactional Frequency Reuse OFDMA Networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 4286–4295, Oct. 2009.

[14] M. Necker, "Interference Coordination in Cellular OFDMA Networks," *IEEE Network*, vol. 22, no. 6, pp. 12–19, Nov./Dec. 2008.

[15] A. Stolyar and H. Viswanathan, " Self-organizing Dynamic Fractional Frequency Reuse in OFDMA Systems," in *IEEE Conference on Computer Communications (INFOCOM 2008)*, April 2008, pp. 691–699.

[16] D. López-Pérez, X. Chu, A. V. Vasilakos, and H. Claussen, "Minimising cell transmit power: towards self-organized resource allocation in ofdma femtocells," in *Proc. ACM SIGCOMM 2011 conference on SIGCOMM*, ser. SIGCOMM '11. New York, NY, USA: ACM, 2011, pp. 410–411. [Online]. Available: http://doi.acm.org/10.1145/2018436.2018494

[17] C. E. Shannon, "A mathematical theory of communication," *Bell System Technical J.*, vol. 27, pp. 379–423, July 1948.

[18] E. Altman, "Capacity of multi-service cellular networks with transmission-rate control: a queueing analysis," in *Proc. 8th annual international conference on Mobile computing and networking*, ser. MobiCom '02. New York, NY, USA: ACM, 2002, pp. 205–214. [Online]. Available: http://doi.acm.org/10.1145/570645.570671

[19] S. Sesia, I. Toufik, and M. Baker, *LTE: The UMTS Long Term Evolution, From Theory to Practice*. John Wiley & Sons Ltd, Feb. 2009.

[20] X. Chu, Y. Wu, D. López-Pérez, and X. Tao, "On Providing Donwlink Services in Collocated Spectrum-Sharing Macro and Femto Network," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 4306 – 4315, Dec. 2011.

[21] R. K. Ahuja and T. L. M. J. B. Orlin, *Network Flows: Theory, Algorithms, and Applications*. Prentice Hall, 1993.

[22] G. B. Dantzig, *Linear Programming and Extensions*. Princeton University Press, 1963.

[23] "Library for Efficient Modeling and Optimization in Networks (LEMON)," http://lemon.cs.elte.hu.

[24] *Optimization in Operations Research*. upper Saddle River, NJ, USA: Prentice Hall, 1998.

[25] R. Yates, "A framework for uplink power control in cellular radio systems," *IEEE J. Sel. Areas Commun.*, vol. 13, no. 7, pp. 1341–1348, Sept. 1995.

[26] C. Oliveira, J. B. Kim, and T. Suda, "An adaptive bandwidth reservation scheme for high-speed multimedia wireless networks," *IEEE Jour. Select. Areas in Comm.*, vol. 16, no. 6, pp. 858–874, Oct. 1998.

[27] A. Valcarce, G. de La Roche, A. Jüttner, D. López-Pérez, and J. Zhang, "Applying FDTD to the coverage prediction of WiMAX femtocells," *EURASIP J. Wireless Communications and Networking. Special issue on Advances in Propagation Modelling for Wireless Systems*, Feb. 2009.

[28] Forsk Atoll-Global RF Planning Solution, http://www.forsk.com.

[29] D. López-Pérez, "Practical models and optimization methods for inter-cell interference coordination in self-organizing cellular networks," Ph.D. dissertation, University of Bedforshire, Luton UK, April 2011.

[30] L. Chen and J. Leneutre, "A game theoretic framework of distributed power and rate control in ieee 802.11 wlans," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 7, pp. 1128 –1137, Sept. 2008.

[31] T. Alpcan, T. Basar, and S. Dey, "A power control game based on outage probabilities for multicell wireless data networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 4, pp. 890 – 899, April 2006.

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