Decentralized Interference Management in Femtocells: A Game-Theoretic Approach

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Abstract—**Femtocells are receiving considerable interest in mobile communications as a strategy to overcome the indoor coverage problems as well as to improve the efficiency of current macrocell systems. One of the most critical issues in femtocells is the potential interference between nearby femtocells and from femtocells to macrocells or to mobile handsets. In this work, we illustrate some decentralized strategies for an OFDMA femtocell system, based on game theory, where non-cooperative femtocells self-organize in order to find out the most appropriate access strategy, considering the decision phase and radio access jointly. The strategies illustrated in this work fall within the context of the FREEDOM European Project.**

I. Introduction

Two of the major limitations of current cellular systems are indoor coverage and base station deployment. A recent survey shows that 50 percent of phone calls and 70 percent of data communications are expected to take place indoors [1]. Current macrocells provide indoor coverage, of course, but with very high performance variability and in a rather inefficient way. The typical means to contrast the wall penetration propagation losses consist in either increasing the transmit power or decreasing the information rate by adopting heavier channel coding. Both approaches go against the ever increasing need for higher data rate services in indoor links and the demand for lower radiating power. Within this context, the use of home base stations or femto access points (FAP) provides a more efficient way to handle indoor coverage [2] and to improve the spatial reuse of radio resources. FAP's are low-power, relatively inexpensive, small base stations, typically installed at home or in companies, fully compliant with radio cellular standards, like GSM, UMTS, WiMAX, or LTE. FAP's handle short range wireless communications with mobile handsets, within distances in the order of some tens of meters, in a way totally transparent to the mobile user. One important aspect of FAP's is that they can exploit the broadband wired backhaul link, such as the optical fiber or digital subscriber line (DSL), typically available at home, to communicate with other FAP's and to send data to the macrocell base stations (MBS). As suggested in the European Project FREEDOM [3], the existence of a wired backhaul link creates the possibility of some sort of coordination among FAP's, depending on the link quality. Three operating situations can be foreseen: a) the backhaul is unavailable or of very poor quality - in such a case, the FAP's operate as competitors over common radio resources; b) the backhaul link is available, but with limited performance - in such a case, the FAP's may coordinate among each other by exchanging low data rate control signals; c) the backhaul link is a high performance link - in this case, the FAP's are able, at least in principle, to exchange information data and transmit in a cooperative way [3].

One of the most critical aspects of femtocells is interference management, since FAP's, even if designed for short range wireless communications, can still interfere with nearby FAP's or mobile handsets. One possibility to eliminate femto-macro interference requires allocating femto-channels on channels orthogonal to the macro-channels. However, this choice might be highly inefficient, especially because the presence and activation or deactivation of FAP's is something that cannot be planned a priori. An alternative approach consists in allowing macro and femto communications to take place over common channels. This strategy is less rigid, but it requires some form of interference management to handle co-channel interference. In view of a potential massive deployment of femtocells, a centralized control does not look viable. Hence, it is of interest to look for decentralized optimization strategies allowing the FAP's to sense the channel and self-organize, consequently, in terms of topology and resource allocation.

Given this framework, in this paper, we illustrate an approach based on game theory (GT) to design decentralized mechanisms useful to optimize the resource allocation of each individual FAP dynamically, given the strategy of the others. GT has been recently proposed for cognitive radios (CR), as a powerful and systematic tool to devise and analyze distributed resource allocation strategies, with no cooperation or minimal coordination among the radio nodes [4]. The femtocell scenario is indeed intrinsically different from the CR scenario, because in femtocells, as opposed to CR, FAP's and MBS's belong to the same operator. Furthermore, the FAP's are connected to the core network in order to receive the data streams intended for their mobile receivers. Hence, the MBS can also send some control bits to the FAP's to letting them know which channels are currently occupying. However, especially in view of a potential massive deployment of FAP's, we may have near FAP's associated to different operators or FAP's transmitting near mobile users belonging to different operators. Hence, a distributed optimization of

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resource allocation based on game theory is still useful, yet considering that all information that each FAP can get from its MBS should be properly taken into account. We concentrate on the worst case scenario, where there are near FAP's belonging to different operators or mobile users passing nearby FAP's associated to different operators. In such a situation, the FAP's compete with each other over the radio resources. The problem is then how to handle the interference generated by each FAP towards other FAP's as well as to macrocells users.

Within the GT-based works, considerable attention has been devoted to analyze the so called Nash Equilibrium (NE), intended to be the situation where each player (FAP, for example), given the strategy of the other players, is not willing to deviate from his current strategy as this would cause a performance loss (see e.g. [5] and the references therein). However, a NE may be far from the Pareto boundary, representing globally optimal solutions. This happens, for example, in the simple case of flat fading channels, where there exist several Nash equilibrium points [6], some of them totally inefficient. For this reason, different mechanisms have been studied to move the NE towards the Pareto optimal boundary. Some possibilities are, for example, through bargaining [6] or pricing [7]. In this paper, we will show a simple example of pricing leading to maximum sum-rate, in the two-user flat fading case.

II. Optimal radio access from individual femtocell

The radio access from FAP's requires prior sensing of the channels already occupied by nearby FAP's or by macro base stations or mobile users. Performing channel sensing on each FAP is then mandatory to assess the channel status. Individual channel sensing may be critical because, if the FAP is in a shadow, it might take for unoccupied channels which are actually busy. A possible approach to improve the robustness of channel sensing against shadowing is to perform *cooperative* sensing, as suggested in [8] for example, where nearby FAP's exchange information in order to reduce the effects of observation noise and shadowing. In general, for any given estimate of the spectrum occupancy, the FAP has to decide which channels are really occupied by an interferer. Clearly, the choice of the detection thresholds is critical in this application as it has a direct impact on the probability of missing transmission opportunities, in case of false alarms, or of generating undue interference toward primary users, in case of miss detection. Several previous works have considered the tradeoff between sensing capabilities and throughput of secondary users, primarily in the context of cognitive radios, where the users sense the channels, learn and adapt their behavior consequently. The optimal power allocation maximizing the aggregate throughput in multi-carrier systems, under constraints on the transmit power and on the interference towards primary receiver, was proposed for example in [9]. In [10], it was proposed a decision-theoretic approach integrating the design of spectrum access protocols at the MAC layer with spectrum sensing at the physical layer and traffic statistics determined by the application layer of the primary network. In [11], it was proposed a method for optimizing the detection thresholds, in a multichannel transmission scheme, in order to maximize the so called *aggregated opportunistic throughput*, under a constraint on the maximum interference power generated towards the primary users, for a given set of rates over the available subchannels. In [12], we proposed a method to jointly optimize detection thresholds and power allocation, in a single secondary scenario. The method is recalled here below and cast in a femtocell framework, where we focus on the access strategy from a single FAP considering the macrocell users as interference.

Assuming that the wideband channel is composed by N nonoverlapping subbands, let us denote by p_k the power transmitted over the k-th subchannel, by $H(k)$ the channel transfer function over the k-th subband, and by $\sigma_k^2 = \sigma_n^2(k)+\sigma_I^2(k)$ the total disturbance, i.e. noise plus interference present over the k-th subcarrier. For each subband, the detection problem can be cast as a binary hypothesis test, with $\mathcal{H}_{1,k}$ and $\mathcal{H}_{0,k}$, denoting, respectively, the presence and absence of the macrocell users. The probability of correctly deciding to transmit over the k-th carrier is $p(\mathcal{H}_{0,k}|\mathcal{H}_{0,k}) = 1-p_{fa}(\gamma_k)$, where $p_{fa}(\gamma_k)$ is the false alarm probability, over channel k, resulting from the use of the detection threshold γ_k. In particular, we apply, over each subband, the energy detector with fixed samples size (see [12] for further details on the detection strategy).

Hence, we may introduce the average aggregated opportunistic throughput, defined as

$$\begin{aligned} R(\boldsymbol{p}; p_{fa}(\gamma_1), \ldots, p_{fa}(\gamma_N)) = \\ = \sum_{k=1}^{N} (1 - p_{fa}(\gamma_k)) \log_2 \left(1 + \frac{p_k |H(k)|^2}{\sigma_k^2}\right) \end{aligned} \quad (1)$$

where $\boldsymbol{p} = [p_1, \ldots, p_N]$ is the power vector. Our objective is to maximize this throughput, under the constraint of inducing negligible interference to macrocell users. An interference over, let us say, the k-th subchannel is generated only when the FAP erroneously misses the presence of a macrocell user over that channel. Hence, denoting by $P_d(p_{fa}, k)$ the detection probability over the k-th channel (depending on the detection threshold or, indirectly, on the false alarm rate), the average interference generated by the FAP is $\sum_{k=1}^{N} p(\mathcal{H}_{0,k}|\mathcal{H}_{1,k}) p_k = \sum_{k=1}^{N} (1-P_d(p_{fa}, k)) p_k$. If we denote by P_{max} the maximum tolerable interference power that can be induced to macrocell users, and incorporate the usual transmit power constraint, we may formulate a joint optimization problem over both the vector power allocation and detection thresholds (equivalently, false alarm rate), as follows:

$$(\boldsymbol{p}^*, p_{fa}^*) = \underset{\boldsymbol{p}, p_{fa}}{\operatorname{argmax}} \left\{ \sum_{k=1}^{N} (1 - p_{fa}) \log_2 (1 + p_k a_k) \right\} \quad (2)$$

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subject to:

$$\sum_{k=1}^{N}(1-P_d(p_{fa},k))p_k \leq P_{max}$$
$$\sum_{k=1}^{N} p_k \leq P_t, \quad \mathbf{p} \geq \mathbf{0}, \quad 0 \leq p_{fa} \leq 1 \tag{3}$$

where $a_k = \frac{|H(k)|^2}{\sigma_k^2}$ and P_t is the transmit power budget of the FAP. The value P_{max} depends on the distance between the FAP and the macrocell base stations and it is typically much lower than P_t. Unfortunately, problem (3) is not convex because the feasible set (the interference constraint) is not jointly convex in $(\boldsymbol{p}, p_{fa})$. Nevertheless, in [12] it has been shown that the problem can be reformulated, by expressing the optimal transmit powers as a function of p_{fa} and then optimizing the throughput over the single unknown p_{fa}. The solution is a multivel water-filling, with levels depending on the channels *and* on the false alarm rate as well. As a numerical example, Fig. 1 shows $R(\boldsymbol{p}^*(p_{fa}), p_{fa})$ vs. p_{fa}, for different values of P_{max}, i.e. considering different femto-macro distances d_{fm}, since the maximum tolerable interference P_{max} is directly proportional to d_{fm}^2. The curves reported in Fig. 1 show that, for every d_{fm}, there exists an optimal value p_{fa}^* that maximizes the aggregate rate. The value p_{fa}^* increases as the interference constraint gets stronger, i.e. as the femto-macro distance and, consequently, P_{max} decrease. In particular, the interference constraint is inactive when the femto-macro distance is higher than a given threshold, i.e. $d_{fm} \geq d_{th}$ (in Fig. 1 it is $d_{th} = 20$) ; in such a case, the optimal solution to (3) reduces to the classical waterfilling and $p_{fa}^* = 0$.

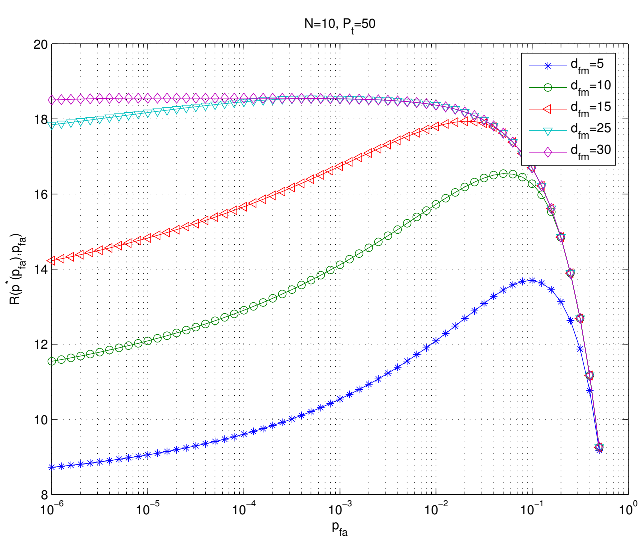

Fig. 1. Optimal sum rate versus the false alarm probability.

III. Multiuser throughput maximization: A game theoretic approach

Let us start considering the simple two-user case, with flat-fading channels. In spite of its simplicity, this is indeed a critical situation for game theory, as multiple NE's coexist, with totally different efficiencies [6]. This happens because, if a user starts using the whole band, the other user will react using the whole bandwidth as well, so that they will interfere over the entire bandwidth. The performance would improve if the first user would choose a fraction of the bandwidth. But then the question is: What is the optimal fraction for each user? Let us denote by α the percentage taken by user 1. In such a case the other user would take the remaining $(1-\alpha)$ fraction, so that the users' rate will be respectively:

$$R_1 = \alpha \cdot \log_2\left(1 + \frac{P_1}{\alpha \cdot \sigma_n^2}\right) \tag{4}$$

$$R_2 = (1-\alpha) \cdot \log_2\left(1 + \frac{P_2}{(1-\alpha) \cdot \sigma_n^2}\right), \tag{5}$$

where P_i is the i-th user received power while σ_n^2 denotes the noise variance. For large $\frac{P_i}{\sigma_n^2}$ ratios, the rates can be approximated as follows:

$$R_1 \approx \alpha \cdot \log_2\left(\frac{P_1}{\alpha \cdot \sigma_n^2}\right) \tag{6}$$

$$R_2 \approx (1-\alpha) \cdot \log_2\left(\frac{P_2}{(1-\alpha) \cdot \sigma_n^2}\right). \tag{7}$$

Under this approximation, it is easy to show that the percentage α that maximizes the sum rate can be obtained equating the derivative of $R_1 + R_2$ to zero and the optimal result is

$$\alpha^* = \frac{P_1}{P_1 + P_2}. \tag{8}$$

This means that a simple way for the two users to optimize the sum-rate consists in exchanging a simple information about each received power. More generally, the desired behavior of preventing each user from occupying the whole bandwidth can be achieved, in a decentralized manner, by adding a pricing term, on each user's utility function, increasing with the used bandwidth: The larger is the band occupied, the higher is the penalty. Considering, for the moment, the information rate, the optimization problem for each user, in the general case of frequency selective channels, would be:

$$\max_{\boldsymbol{p}_q} \sum_{k=1}^{N} \log_2\left(1 + \frac{p_q(k)|H_{qq}(k)|^2}{\sigma_n^2 + \sum_{r \neq q} p_r(k)|H_{rq}(k)|^2}\right) - \nu_q \|\mathbf{p}_q\|_{l_1}$$
$$\text{subject to} \quad \sum_{k=1}^{N} p_q(k) \leq P_t, \quad \mathbf{p}_q \geq \mathbf{0}, \quad \nu_q > 0, \tag{9}$$

where ν_q is the penalty coefficient, $p_q(k)$ is the power allocated by the q-th user over the k-th subchannel, while $H_{rq}(k)$ denotes the user channel transfer function between source r and destination q over the k-th subband. The optimal ν_q may be searched as the value that maximizes the sum-rate. This

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last quantity can be evaluated, at each terminal, by using a consensus algorithm [13] among all the players (FAP's). This requires that there is a link, possibly composed of multiple hops, between each pair of FAP's. The problem has still its difficulties because the sum-rate is neither convex nor concave, with respect to the whole set of transmit powers. Nevertheless, in the simple flat-fading case, it can be shown, analytically, that the optimal penalty coefficients are

$$\nu_q^* = \frac{|H_{qq}|^2}{\sigma_n^2} - \mu_q, \tag{10}$$

where $|H_{qq}|^2$ is the (flat-fading) channel of user q and μ_q is the inverse of the water-level of user q. This is the choice that will make every user to adopt the portion of the bandwidth that will maximize the sum-rate. As an example let us consider again the two-user case. If we denote with Q and $N-Q$ the number of subcarriers used, respectively, by the first and second user, we can approximate $Q \approx \lfloor \alpha^* N \rfloor$. Then, the inverse water levels μ_1 and μ_2 for the first and second user are given by

$$\mu_1 = \frac{1}{P_t/(\alpha^* N) + 1/\lambda_1} \tag{11a}$$

$$\mu_2 = \frac{1}{P_t/[(1-\alpha^*)N] + 1/\lambda_2} \tag{11b}$$

with $\lambda_i = |H_{ii}|^2/\sigma_n^2$ for $i = 1, 2$. The more general case of frequency selective channels may be cast as a game, where every player aims at maximizing its own rate, under a constraint on the maximum interference towards macrocell users, besides the usual transmit power constraint. This problem has been analyzed both theoretically and analytically in [5] and the solution is the so called iterative water-filling algorithm, with constraints imposed by the interference limit.

In practice, the maximization of each user rate requires the knowledge of the channel at both transmit and receive sides. This can be obtained through a feedback link between receiver and transmitter. Indeed, the channel will be known only within a certain estimation error. It is then of interest to quantify the effect of the estimation error. In such a case, the rate can be quantified using a lower bound on the mutual information derived in [14], in the case in which the estimation errors on the channel coefficients are equal to each other and uncorrelated. In such a case, if the transmitter knows the estimated channel and the estimation variance, it can allocate the power across the subchannels taking into account the estimation variance. A numerical example is shown in Fig. 2, reporting the sum-rate of a set of four FAP's, as a function of the channel estimation error variance. This curve allows us to quantify what is the maximum estimation variance compatible with the achievement of the desired sum-rate.

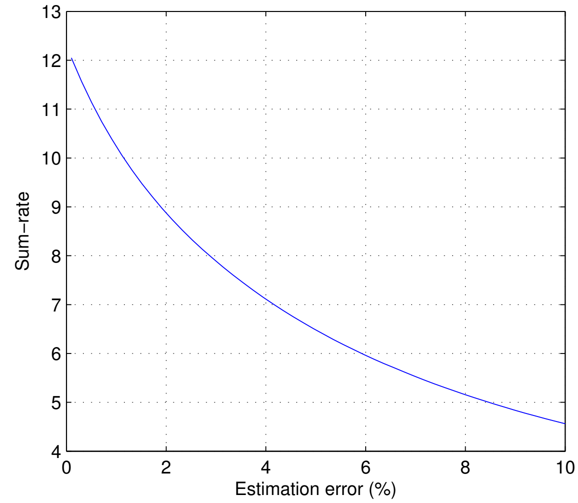

Fig. 2. Sum-rate vs. channel estimation error variance.

The previous curve does not take into account the decision process. If we take into account the joint optimization of decision thresholds and power allocation, for each user, the competition among FAP's can then be cast as a non-cooperative strategic game, where each player aims to maximize its opportunistic throughput that, for the q-th player, can be written as

$$R_q(\boldsymbol{p}; p_{fa}(\gamma_1^q), \ldots, p_{fa}(\gamma_N^q)) = \\ = \sum_{k=1}^{N} (1 - p_{fa}(\gamma_k^q)) \log_2 \left(1 + \frac{p_q(k)|H_{qq}(k)|^2}{\sigma_k^2 + \sum_{r \neq q} |H_{rq}(k)|^2 p_r(k)} \right) \tag{12}$$

so that the game can be formulated as

$$\begin{aligned} &\max_{\boldsymbol{p}_q, p_{fa}^q} \quad R_q(\boldsymbol{p}_q, \boldsymbol{p}_{-q}, p_{fa}^q) \\ &\text{subject to} \quad \sum_{k=1}^{N} (1 - P_d(p^q{}_{fa}, k)) p_q(k) \le P_{max}^q \\ &\qquad\qquad\quad \sum_{k=1}^{N} p_q(k) \le P_t{}^q \\ &\qquad\qquad\quad \mathbf{p}_q \ge \mathbf{0}, \quad 0 \le p_{fa}^q \le 1/2 \end{aligned} \tag{13}$$

for each $q \in \{1, \ldots, M\}$, where M is the number of the players (FAP's) and $\boldsymbol{p}_{-q} \triangleq \{\boldsymbol{p}_j\}_{j=1, j\neq q}^{M}$. Unfortunately, the existence of a Nash equilibrium for the game (13) appears quite difficult to prove because the admissible strategies space is nonconvex. Nevertheless, in [15], we proposed two alternative strategies, one aiming at optimizing the power allocation and p_{fa}, for every user, through a totally decentralized approach, the other forcing the same p_{fa} for all users and maximizing the sum throughput through a local exchange of information between nearby nodes. More specifically, the two proposed algorithms use an iterative water-filling, where each user adopts a *multi-level* water-filling, where the level depends not only by the transmit power, but also on the decision threshold.

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In this work, we have generalized the approach of [15] to the case where the channel is not known exactly, but only within a certain estimation error. In such a case, the aggregated throughput of the multiuser game, where every user maximizes his/her own throughput, is shown in Fig. 3, as a function of the macro-femto distance, for different values of the error variance.

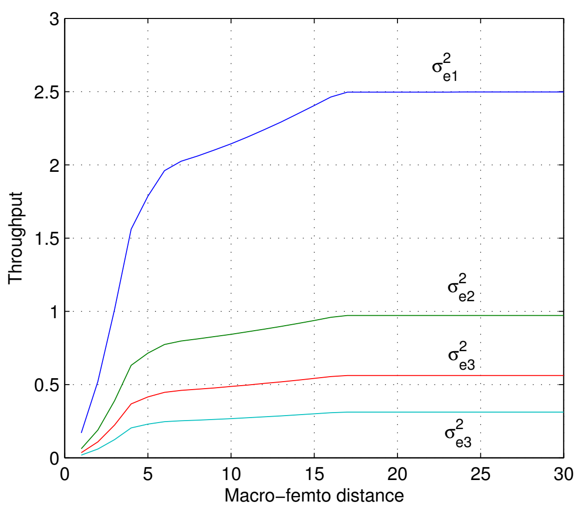

Fig. 3. Aggregated throughput vs. macro-femto distance, for different channel estimation error variances.

IV. Conclusions

In this work, we have proposed a game-theoretical approach to design decentralized strategies for an OFDM femtocell system where different FAP's compete against each other to find out the optimal spectrum allocation under the constraint of inducing a limited interference to macrocell users. In particular, taking into account the impact of the detection phase on the overall network efficiency, we have proposed decentralized strategies where each player (FAP) optimizes his own opportunistic throughput by choosing detection thresholds and vector power allocation jointly, under a constraint on the interference to macrocell users. We have generalized the approach to the case where the channel is not known exactly, taking into account the impact of the channel estimation errors on the FAP's spectrum power allocation. Finally, in the two-user case, with flat-fading channels, it has been shown that adding a proper pricing term on each user's utility function, we can induce each user to occupy the most appropriate fraction of the available bandwidth.

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