A Bankruptcy Game Approach for Resource Allocation in Cooperative Femtocell Networks

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***Abstract*—Femtocells have recently appeared as a viable solution to enable broadband connectivity in mobile cellular networks. Instead of redimensioning macrocells at the base station level, the modular installation of short-range access points can grant multiple benefits, provided that interference is efficiently managed. In the case where femtocells use different frequency bands than macrocells (i.e., split-spectrum approach), interference between femtocells is the major issue. In particular, congestion cases in which femtocell demands exceed the available bandwidth pose an important challenge. If, as expected, the femtocell service is going to be separately billed by legacy wire-line Internet Service Providers, strategic interference management and resource allocation mechanisms are needed to avoid performance degradation during congestion cases. In this paper, we model the resource allocation in cooperative femtocell networks as a bankruptcy game. We identify possible solutions from cooperative game theory, namely the Shapley value and the Nucleolus, and show through extensive simulations of realistic scenarios that they outperform two state-of-the-art schemes, namely Centralized-Dynamic Frequency Planning, C-DFP, and Frequency-ALOHA, F-ALOHA. In particular, the Nucleolus solution offers best performance overall in terms of throughput and fairness, at a lower time complexity.**

***Index Terms*—femtocell networks, resource allocation, nucleolus, Shapley value, bankruptcy game.**

I. Introduction

Femtocells have recently appeared as a viable solution to enable broadband connectivity in mobile access networks. Instead of redimensioning macrocells at the base station level, the modular installation of short-range and small mobile access points can grant multiple benefits. Strategically, femtocells are an attractive solution because they are easy to install, inexpensive, and with already present hardware components.

There are however technical challenges with femtocells deployment. The major issue remains, nevertheless, interference management. Interferences can occur with the macrocells as well as with neighboring femtocells, especially in suburban and urban environments. Under certain assumptions, cross-layer interference with the macrocell is manageable, while co-layer interference among femtocells requires collaboration among neighboring cells. In this context, we can often refer to as collaborative femtocell networks since coordination or cooperation mechanisms are needed between independent and opportunistic femtocells to manage reciprocal interferences and resource allocation. The independence of femtocells resides in the fact that the installation of a femtocell for residential or enterprise usages is expected to be subject to separate billing, while the opportunistic behaviour can be motivated by the attempt of each femtocell to satisfy its users, by acquiring the maximum number of resources. Therefore, inter-femto resource allocation needs to be managed via collaborative approaches that have as motivation the performance improvement for all the participating femtocells.

In this paper, we envision a strategic resource allocation among independent subscribers in collaborative femtocell networks. This is especially needed in urban environments, with a high density of femtocells, and where femtocells have different levels of interference and resource demands, and the overall demand exceeds the available bandwidth. The motivation behind our approach is that femtocell's interference level and demands volume, femtocell subscriber independence from other subscribers, as well as opportunistic behaviour of those femtocells, should be taken into account when allocating resources to users. We model such situations using cooperative game theory, which guarantees that interference management and resource allocation solutions are strategically and rationally justified. Results show that our approach grants important improvements in throughput and fairness.

The paper is organized as follows. Section II presents an overview of related works. In Section III, we analytically introduce the context of our work and formulate the problem as a bankruptcy game. Section IV describes the proposed approach, followed by a presentation of simulation results in Section V. Finally, Section VI concludes this paper.

II. Related Work

Resource allocation in OFDMA femtocell networks has been considered in recent research works. The general objective of these works is the computation of efficient allocation of time-frequency resource slots, while accounting for cross-layer interference (between macrocell and femtocell users) and co-layer interference (between femtocells' users) [1]. In the following, we discuss a selection of relevant approaches proposed to solve these types of interferences.

Authors in [1] present an overview of possible approaches to manage cross-layer and co-layer interferences. Two main directions are outlined: shared spectrum and split-spectrum schemes. In the first, co-channel assignment mitigates the capacity problems of both femtocells and macrocells thanks to the use of larger spectrum, but cross-layer interference needs to be managed. In the second scheme, an orthogonal channel assignment eliminates cross-layer interference by dividing the spectrum into two independent fragments, one used by the macrocells and the other by the femtocells. For both cases of shared spectrum and split-spectrum, the authors in [1] outline the requirements of centralized approaches, called C-DFP (Centralized−Dynamic Frequency Planning), in which a sub-channel broker receives demands and interference information from the femtocells and/or the macrocells, so as to compute the best resource allocation considering a tradeoff between optimality and computational complexity. In [2], the authors show that with a dynamic spectrum splitting among femtocell and macrocell, the area spectral efficiency can be optimized. In their framework, within the femtocell layer an adapted version of ALOHA (for the time-frequency domain, called Frequency ALOHA, F-ALOHA), is proposed to schedule the femtocell access to the co-tier shared spectrum in a distributed fashion. However, the pseudo-random characteristic of this method can generate irrational resource allocations, because not strategically computed. A hybrid centralized/distributed approach is proposed in [3], in which the authors exploit cooperation among neighboring femtocells and improve resource allocation and throughput satisfaction. First, femtocells are grouped in a distributed fashion into disjoint clusters with respect to interference maps. Then, within each cluster, resource allocation is centralized at a cluster-head that periodically optimizes the throughput satisfaction.

Recently, there has been significant interest in applying game theory to the analysis of collaborative communication networks, with the aim to identify rational strategic solutions for multiple decision-maker situations. Indeed, as opposed to mono-decision maker problems which can be solved with centralized approaches, game-theoretic approaches adopt a multi-agent perspective to account for different objective functions and/or counter objections to rationally non justified solutions [4]. Besides, game-theoretic approaches differ from distributed ones by setting a common rule for shared information between different agents. When the collaboration among network agents does not imply binding agreements and need just coordination, non-cooperative game theory can identify strategic solutions as a function of various types of game equilibria [5]. When binding agreements are required to motivate cooperation, cooperative game theory allows solutions with the desirable properties of efficiency and rationality [6].

In this paper, rather than partitioning the femtocell network topology in disjoint clusters as in [3], we allow femtocells negotiate resources in multiple femtocell groups, where groups are locally detected as function of interferer femtocell neighbors. We believe that, in dense urban environments, joint online scheduling among groups of femtocells as [7] may be counterproductive in terms of signaling overhead. Hence, we target a solution in which the resource allocation is periodically pre-computed based on changing femtocell resource demands and interference maps. In particular, we consider dense environment situations in which the overall demand is quite often higher than the available bandwidth on the shared media, which mathematically corresponds to a bankruptcy game situation [8]. We investigate two solution concepts: the well-known Shapley value [9] ; and the less-known Nucleolus [10], which shows additional interesting properties in bankruptcy situations.

III. Context and Problem Formulation

We consider a network composed of a macrocell with several femtocell access points (FAPs) that represent residential or enterprise networks. As in [1] and [2], we assume an orthogonal channel assignment that eliminates the cross-layer interference. The femtocells and the macrocell are assumed to operate using the OFDMA technology (e.g., WiMAX or LTE) whose frame structure can be viewed as time-frequency slots, also called tiles. A certain number of users is attached to each femtocell; user demands represent the required bandwidth, expressed in number of required tiles. As already mentioned, in urban dense environment, we expect that the sum of demands of the femtocells often exceeds the available resources. Therefore, our objective is to find, for such congestion situations, a strategic resource allocation that satisfies throughput expectations while controlling the interference between femto-femto users. In the following, we first present the corresponding optimization problem, then, we highlight possible alternative solutions and finally describe the properties of bankruptcy games along with possible solutions.

A. Notations

Let $\mathcal{F}$ be the set of femtocells in the network, d_i the demand of $F_i \in \mathcal{F}$, and x_i the number of allocated resources to the femtocell F_i. Also, let $\mathcal{I}_i$ be the interference set of F_i, which corresponds to the set of femtocells composed of F_i and the femtocells causing interference to F_i. It is worth noting that interference is not symmetric since it depends on user positions. For example, consider the situation depicted in Fig. 1, with six femtocells where arrow's direction indicates the femtocell whose users suffer from a neighboring femtocell interference. The corresponding interference relationships are reported in Table I.

B. Related centralized optimization problem

For the sake of comparison with common approaches for resource allocation between *non-independent femtocell* networks, let us show how the resource allocation problem could be formulated as a centralized mono decision-maker optimization problem, i.e., as the C-DFP approaches mentioned in Section II. If femtocells are not independent, a centralized node may solve the problem as:

$$\begin{aligned} \text{objective} \quad & f(d_i, x_i) \\ \text{subject to} \quad & 0 \leq x_i \leq d_i, \ \forall F_i \in \mathcal{F} \\ & \sum_{j | F_j \in \mathcal{I}_i} x_j \leq E, \ \forall \mathcal{I}_i \\ & x_i \in \mathcal{Z}^+, \ \forall F_i \in \mathcal{F} \end{aligned}$$

where E is the number of tiles in an OFDMA frame (also referred to in the following as 'estate'). The objective typically depends on the demand and the allocated resources; a common objective is the minimization of the maximum gap between the number of allocated and required tiles in each FAP (i.e., the worst case is optimized). Therefore $f(d_i, x_i) = \min \max_i (\frac{d_i - x_i}{d_i})$ as proposed in [3]. The constraints are integrity constraints, on the allocated tiles to individual femtocells and to femtocells belonging to same interference sets. Later, we compare game-theoretic approaches to this C-DFP solution highlighting the interest in strategic approaches and stressing the tradeoffs between them.

C. Possible distributed approaches

For each interference set, we have therefore a situation in which a group of femtocells can either: (i) randomly access

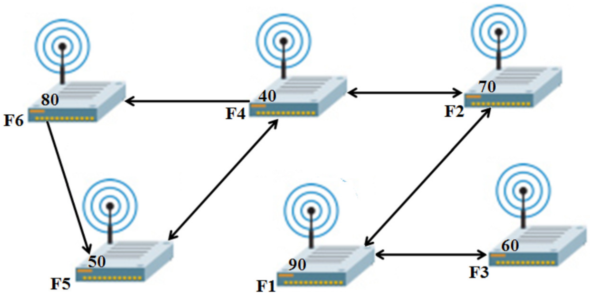


Fig. 1. Example 6-femtocell network

TABLE I
INTERFERENCE RELATIONSHIPS

Femtocell	Interferers
F_1	$\{F_2, F_3\}$
F_2	$\{F_1, F_4\}$
F_3	$\{F_1\}$
F_4	$\{F_2, F_5\}$
F_5	$\{F_4, F_6\}$
F_6	$\{F_4\}$

TABLE II
INTERFERENCE SETS

Steps	Femtocell sets
1	$\{F_1, F_2, F_3\}$
2	$\{F_1, F_2, F_4\}$
3	$\{F_4, F_5, F_6\}$
4	$\{F_2, F_4, F_5\}$
5	$\{F_1, F_3\}$
6	$\{F_4, F_6\}$

the spectrum hoping that collision will not occur (e.g., as in F-ALOHA [2]); or (ii) self-organize to define an online joint scheduling (as in [7]); or (iii) divide the available spectrum proportionally. Clearly, (i) excludes any form of coordination and would favor opportunistic wealth-aversive behaviors (e.g., setting a minimum waiting time upon collision in F-ALOHA) that other femtocells can not control. Approaches like (ii) risk to generate enormous signaling for large interference sets (likely in urban dense environments). Under (iii), inefficiency can arise whether many demands are less than the proportional share, and a weighted proportional share would favor cheating demands (higher claims than what is really needed). The path forward is therefore towards cooperative approaches that dissuade malicious behaviors in setting demands, under an adequate binding agreement fixing common rules on shared information and allocation scheme, i.e., our algorithm to compute the allocation, and possibly also the implementation of node blacklisting mechanisms. Before detailing the proposed algorithmic approach, let us introduce the bankruptcy game that can model interactions among femtocells.

D. Bankruptcy game modeling

In urban environments, a dense deployment of femtocells is expected, so that situations in which the overall resource tile claim (i.e., sum of the demands) surpasses the number of available tiles (E) in the shared spectrum are likely. Assuming that femtocells belonging to the same interference set, share information about respective demands, the interaction can be modeled as a cooperative game. The choice of the game characteristic function, representing the profit attributed to each coalition of players in a canonical coalitional game, is an important tiebreak. We stay under the assumption that a coalition S of femtocells, within the same given interference set $\mathcal{I}_i$, group apart so as to decide among them how to share the spectrum. In the most pragmatic case, they will be able to share what the other femtocells have left after getting what they claimed. That is, $E - \sum_{i \in \mathcal{N} \setminus S} d_i$, where $\mathcal{N} \equiv \mathcal{I}_i$. In order to avoid secessions, the utility or characteristic function of the game should be superadditive [4], that is, the best coalition should be the grand coalition grouping all femtocells in the same interference set. Such a characteristic function corresponds, in fact, to what is known as 'bankruptcy game' precisely defined hereafter.

Definition III.1. A bankruptcy game [8] is defined as $G(\mathcal{N}, v)$ where $\mathcal{N}$ represents the claimants of the bankruptcy situation and v is the characteristic function given in (1) that associates to each coalition its worth defined as the part of the estate not claimed by its complement. $E \geq 0$ is an estate that has to be divided among the members of $\mathcal{N}$ and $d \in R_+^{|\mathcal{N}|}$ is the claim vector such that: $E < \sum_{i \in N} d_i$. This function has been proven to be superadditive [4]. Moreover, it satisfies the supermodularity property [9] [11], stronger than the superadditivity, which means that the marginal utility of increasing a player's strategy rises with the increase in other player strategies.

$$v(S) = max(0, E - \sum_{i \in \mathcal{N} \setminus S} d_i) \,, \forall S \subseteq \mathcal{N} \setminus \{\emptyset\} \qquad (1)$$

E. Possible imputation schemes

Solutions to cooperative games are essentially qualified with respect to the satisfaction of rationality constraints, desirable properties and existence conditions.

As already mentioned, a commonly adopted solution for cooperative games in networking is the Shapley value, because it shows desirable properties in terms of null player, symmetry, individual fairness, and additivity [9]. It is computed by averaging the marginal contributions of each femtocell in the network in each strategic situation i.e., (players' permutation). Nevertheless, the Shapley value is not consistent [8], in the following sense.

Definition III.2. An allocation $x = (x_1, x_2, ..., x_N)$ is consistent if $\forall i \neq j$ the division of $x_i + x_j$, prescribed for claims d_i and d_j, is $(x_i; x_j)$.

This means that no player or group of players can gain more by unilaterally deviating from a consistent solution since it will always obtain the same profit. For cooperative femtocell networks, this discourages clustering-like solutions inside an interference set. Another appealing solution concept, the Nucleolus, the unique consistent solution in bankruptcy games. The Nucleolus is the imputation that minimizes the worst inequity. It is computed by minimizing the largest excess, expressed as: $e(x, S) = v(S) - \sum_{j \in S} x_j \,, \forall S \subset \mathcal{N}$. This excess measures the amount by which the coalition S falls short of its potential $v(S)$ in the allocation x; the Nucleolus corresponds to the lexicographic minimum imputation of all possible excess vectors.

IV. AN ALGORITHMIC GAME APPROACH

The game-theoretic approach we propose is composed of two main phases: an Interference Set Detection phase and a Bankruptcy Game Iteration phase. Formally, it represents a binding agreement between cooperating femtocell subscribers.

A. Interference Set Detection

Upon each significant change in demands or in network topology, each femtocell determines the set of interferer femtocells that cause interference to its users based on the minimum required Signal to Interference plus Noise Ratio (SINR)[1] Femtocells are able to share their interference set with other femtocells in the network[2]. Next, the list of interference sets are sorted, firstly with respect to their cardinality, and secondly with respect to the overall demands, both in a decreasing fashion; i.e., first the largest sets with highest overall demands.

B. Bankruptcy Game Iteration

In the second phase, resources are eventually allocated, proceeding with solving a bankruptcy game for each interference set, following the order in the sorted list from the first phase. The rational behind such an agreement is that we first solve the most critical bankruptcy situations. Strategically, in this way we do not penalize femtocells that interfere less compared to femtocells that interfere more, as well as femtocells that claim a little compared to femtocells that claim a lot. Since a femtocell can belong to many interference sets, if it has already participated to a game in a previous game iteration, it is excluded from the next game iteration in which it appears. This corresponds in iterating a game differing in that:

- $\mathcal{N}$ includes only the unallocated femtocells in the set;
- the estate E is decreased by the amount already allocated to the set's femtocells.

The definition of tiles assignment algorithm in OFDMA frame is out of the scope of this paper.

C. An illustrative example

We consider a femtocell network composed of six FAPs as shown in Fig. 1, where the interference relationships are represented by the arrows in the graph and reported in Table I. To each femtocell, we associate a value representing the demand of attached users (expressed in number of tiles). The OFDMA frame is composed of $E = 100$ tiles. The interference set list is presented in Table II; the first step includes the players of a bankruptcy game $G(\mathcal{N}, v)$ where $\mathcal{N} = \{F_1, F_2, F_3\}$, and the coalitional payoffs are given in Table III; $v(\mathcal{N}) = E = 100$ since no femtocell has participated to any previous game. Table IV reports the Shapley values (rounded) as well as the detail on each femtocell's marginal contributions (columns). For the Nucleolus, one starts at an arbitrary point such that $x_1 + x_2 + x_3 = 100$, e.g., $(50, 30, 20)$, as in the step-1 part of Table V. Then, one minimizes the largest excess, corresponding to coalition F_3 in our case; but, this coalition can claim that every other coalition is doing better than it is. So, one tries to improve this coalition by making x_3 larger or, equivalently, $x_1 + x_2$ smaller since $x_3 = 100 - x_1 - x_2$ (feasibility property); but, decreasing the excess of F_3, the excess of $F_1 \cup F_2$ increases at the same rate and these excesses then meet at -30, when $x_3 = 30$. Clearly, no allocation x can make the excess smaller than -30 since at least one of the coalitions F_3 or $F_1 \cup F_2$ can have at least an excess of -30. Hence, $x_3 = 30$ is the first component of the Nucleolus. Proceeding in the same manner, one finally obtains the Nucleolus allocation $(35, 35, 30)$ in which no femtocell interference with the others.

TABLE III
COALITIONAL PAYOFFS

Coalition	$v(S)$
$\emptyset$	0
F_1	0
F_2	0
F_3	0
$F_1 \cup F_2$	40
$F_1 \cup F_3$	30
$F_2 \cup F_3$	10
$F_1 \cup F_2 \cup F_3$	100

TABLE IV
SHAPLEY VALUE COMPUTATION

Permutation	F_1	F_2	F_3
F_1,F_2,F_3	0	40	60
F_1,F_3,F_2	0	70	30
F_2,F_1,F_3	40	0	60
F_2,F_3,F_1	90	0	10
F_3,F_1,F_2	30	70	0
F_3,F_2,F_1	90	10	0
Average	42	32	26

TABLE V
NUCLEOLUS COMPUTATION

Step 1:

Coalition	$e(x, S)$	$(50, 30, 20)$	$(38, 32, 30)$	$(35, 35, 30)$
F_1	$-x_1$	-50	-38	-35
F_2	$-x_2$	-30	-32	-35
F_3	$-x_3$	-20	-30	-30
$F_1 \cup F_2$	40-x_1-x_2	-40	-30	-30
$F_1 \cup F_3$	30-x_1-x_3	-40	-38	-35
$F_2 \cup F_3$	10-x_2-x_3	-40	-52	-55

Step 3:

Coalition	$e(x, S)$	$(40, 34)$	$(25, 49)$
F_5	-x_5	-40	-25
F_6	24-x_6	-10	-25

We move now to the second step. In this situation we have three femtocells, F_1, F_2 and F_4, and among them F_1 and F_2 have already taken their required resources; the remaining resources, not assigned to F_1 and F_2, are assigned to F_4.

Then, at the third step, the total estate to distribute among femtocells is not 100 tiles any longer since F_4 has already participated to a game and obtained its resources; thus the new game is formed of two players, F_5 and F_6, and the total payoff $v(\mathcal{N})$ is then equal to $E - x_4 = 100 - 26 = 74$ tiles (i.e. the tiles not assigned to F_4), as reported in Table VI. The Shapley value computation for this second game is illustrated in Table VII. Moreover, for the Nucleolus, we obtain the step-3 part of Table V. The algorithm stops at this point since all femtocells have received their resources. As it can be noticed, the Nucleolus smoothes the maximum and the minimum allocation, preventing from extremely low and extremely high allocations for femtocells that interfere a lot and interfere a little, respectively.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed game-theoretic approaches (i.e., Shapley value and Nucleolus). C-DFP and F-ALOHA schemes, presented in Section II, are used as benchmarks. We simulated realistic scenarios with a dense network size of 200 FAPs where, for each simulation, FAPs are randomly distributed in a 400m×400m area. We

[1] In LTE networks, user feedback reports can include interferer femtocell identifiers (Physical Cell Identity) [13].

[2] In LTE networks, this can be aggregated at, or relayed by, Home-enhanced Node B (i.e., femtocell) gateways (i.e., HeNB-GW) [14].

TABLE VI
COALITIONAL PAYOFFS

Coalition	Payoff
$\emptyset$	0
F_5	0
F_6	24
$F_5 \cup F_6$	74

TABLE VII
SHAPLEY VALUE COMPUTATION

Permutations	F_5	F_6
F_5, F_6	0	74
F_6, F_5	50	24
Average	25	49

TABLE VIII
MEAN FAIRNESS INDEXES

SINR	Nucleolus	Shapley Value	C-DFP	F-ALOHA
10 dB	0.92465	0.91511	0.88741	0.90291
25 dB	0.81668	0.78391	0.71604	0.72324

considered two interference level scenarios, a low-level one and a high-level one, based on two SINR thresholds, 10 and 25 dB, to show the impact of the interference degree on the performance metrics. Based on the SINR, the path loss model given in the A1 scenario for indoor small office and residential of WINNER for the frequency range 2−6 GHz [12] where the path loss depends upon the number of floors and traversed walls, and with static user positions; each femtocell determines the set of its interferer femtocells depending on the received signal strength. Users are uniformly distributed within the femtocells with a maximum number of four users per femtocell. Each user uniformly generates its traffic demand that can be directly translated to a certain number of tiles, with a maximum value of 25 tiles per user. As in [2], the analysis is achieved using a typical OFDMA frame (downlink LTE frame) consisting of $E = 100$ tiles. We note that the strategy adopted to serve the associated users to each femtocell is out of the scope of this paper, because it does not affect the outcome of the resource allocation (which is supposed to be run on a longer time-scale). We will focus on the comparison among the different strategies based on the offered throughput, the allocation fairness and the computation time.

A. Throughput analysis

Fig. 2 reports the mean normalized throughput (i.e., mean ratio of the number of allocated tiles to the total demand; in the following referred to as throughput) for the two considered datasets. The game-theoretic approaches outperform the other schemes, for both interference levels. We can here appreciate how much the strategic constraints contribute in avoiding low throughputs. In particular, we can assess that:

- At low throughputs, F-ALOHA and C-DFP offer very low performance, especially in high interference level; around 3% of the femtocells obtain null throughput, and about 30% obtain a throughput less than 30%, while these numbers are roughly halved with game-theoretic approaches.
- The median throughput is always higher for the Nucleolus; e.g., in the high interference case, 55% for the Nucleolus, 47% for the Shapley value, 45% for F-ALOHA and 41% for C-DFP, and the gap between the Nucleolus and the other methods decreases at lower interference level.
- At high throughputs, F-ALOHA shows a small benefit over the Nucleolus, but in all cases the median throughput of the Nucleolus is still the highest among all approaches.
- Among the game-theoretic approaches, the Nucleolus persistently outperforms the Shapley value, with relevant differences at medium-low throughputs.

All in all, the Nucleolus seems the most appropriate approach with respect to the offered throughput, especially in high femtocell density and high interference environments as, e.g., in urban environments with a dense deployment of femtocells. Moreover, the C-DFP approach appears as the most inadequate one, and the F-ALOHA offers low throughputs to a significant portion of femtocells.

B. Fairness analysis

We evaluate the fairness of the solutions using three aspects.

(i) with respect to the Jain's fairness index [15], defined as:

$$FI = \left(\sum_{i=1}^{N} (x_i/d_i) \right)^2 / \left(N \sum_{i=1}^{N} (x_i/d_i)^2 \right) \qquad (2)$$

reported in Table VIII. It is easy to notice that game-theoretic approaches give the highest fairness, thanks to the strategic constraints that avoid penalizing femtocells presenting low interference degree and those with lower demands.

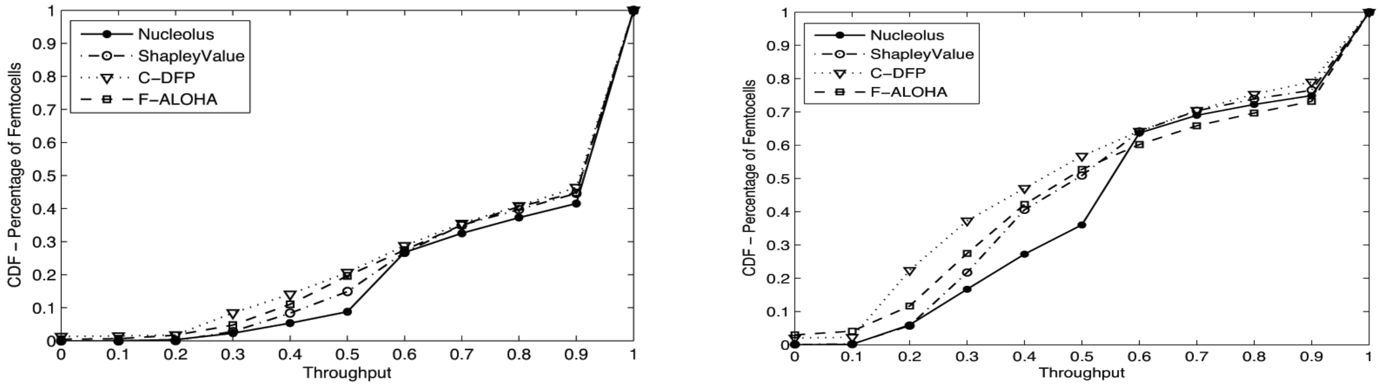
(ii) Fig. 3 further investigates how femtocell interference degree is taken into account, illustrating the mean normalized throughput as a function of the interference degree, for high interference. We can notice clearly that the Nucleolus always outperforms the other methods. It seems appropriate to conclude that the interference degree is taken into account in a significantly different way with the Nucleolus, showing an interesting fairness performance certainly, especially desirable for urban dense environments.

C. Computation time analysis

Last but not least, it is important to assess if the overall good performance of game-theoretic approaches come at the expense of a higher time complexity. Fig.4 reports boxplots (i.e., quartile boxes plus maximum, minimum and outliers) of the computation time for the C-DFP, Shapley value and Nucleolus for the high interference level. It is easy to notice that C-DFP has quite high computation times, on the order of dozens of seconds. A stronger dependence on the interference set size (higher for high interference levels) appears for the Shapley value, which is not surprising since the number of marginal contributions equals the factorial of the interference set size. In turn, the Nucleolus does not show any important dependence neither on the network size nor on the interference level, with a median computation time of roughly 2s for very dense high-interference environments.

VI. CONCLUSION

On the way toward fixed-mobile convergence, modern telecommunication networks are introducing novel technologies that better meet user requirements in terms of experienced quality. Femtocell offload is a promising direction to enable broadband access via legacy mobile handsets. Since femtocells are expected to be commercialized as an added-value service subject to separate billing, strategic self-organization among femtocells is needed to cooperatively manage interference



(a) SNIR=10 dB (b) SNIR=25 dB

Fig. 2. Throughput Cumulative Distribution Function (CDF) for the two datasets.

and resource allocation. In this paper, we have investigated novel approaches based on the theory of cooperative games motivated by the fact that such approaches allow accounting for strategic interactions among independent and opportunistic femtocells, and by the intuition that they shall offer better performance in urban dense environments.

In particular, we presented a game-theoretic approach for strategic resource allocation in cooperative femtocell OFDMA networks. Upon detection of interference maps, the proposed approach iterates bankruptcy games from the largest interference set with highest demand to the lower sets. We motivated the adoption of solutions from coalitional game theory, the Nucleolus and the Shapley value, highlighting how their properties can help meeting performance goals. Through extensive simulations using realistic datasets, we compared the game-theoretic approaches to state-of-the-art proposals. With respect to throughput, fairness and computation time the proposed approaches outperform the others. In particular, the Nucleolus solution is strictly superior to all the others. The Nucleolus approach represents therefore a promising approach for resource allocation in future femtocell network deployments. As further work, we plan to investigate how the cooperative interaction among independent femtocell can motivate the definition and the deployment of novel future services such as inter-femtocell roaming for urban environments, depending on femtocell user mobility habits and by taking into account cheating behaviors of femtocell users.

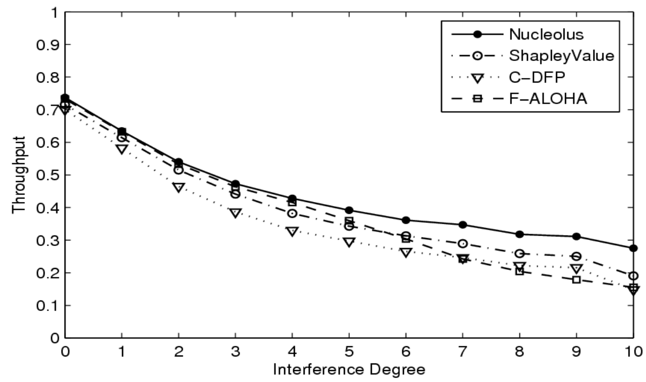
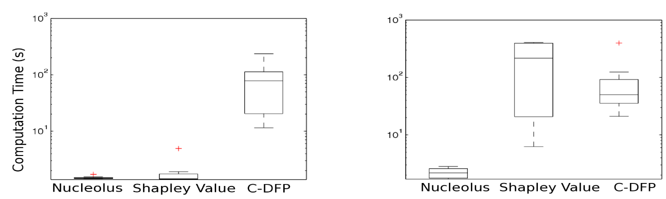


Fig. 3. Throughput distribution as a function of the interference degree - SNIR=25 dB.



(a) SINR=10 dB (b) SINR=25 dB

Fig. 4. Computation time comparison for the two datasets.

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