Throughput-Based Incentives for Residential Femtocells

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***Abstract*—In this paper, we investigate a simple throughput based incentive mechanism that could convince home users to install residential femtocells, avoid most of the curse of free riders (i.e., selfish users who gets improved service just because others are investing in femto technology) and, at the end, be beneficial to both the users and the operator. We show that it is cost-effective for a network operator to allocate a pool K of its licensed channels to a certain number of femto cells, even under our incentive mechanism. We first study a static scenario with fixed numbers of macro and femto users. We identify the range of values of an incentive parameter that can be supported to reward femto users without harming macro users and we quantify the throughput gains for both macro and femto users in different situations. Then, we consider a dynamic scenario, where the numbers of users and the number of active femtocells change continuously, and we propose a simple and very accurate method for computing K with a minimal amount of information to be collected at the macro base station. Our numerical results show that by using our proposed approach both macro and femto users are better off than in a pure macrocellular scenario.**

***Index Terms*—Femtocells, Macrocell networks, Quality of Service, Throughput-incentive mechanism**

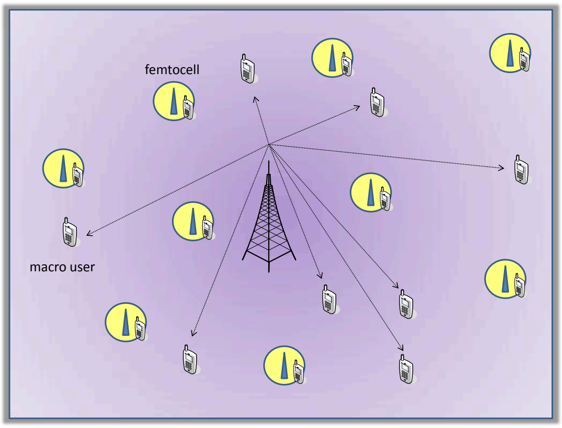

Fig. 1. System model

I. Introduction

The disruptive concept of femtocell [1], which allows the operation of low-power base stations (BS) inside a macrocell coverage area using the same licensed band has raised many technical challenges (see [2] and references therein). Femtocells enable the cellular operator to offload traffic, increase capacity and provide better coverage in areas where access would otherwise be limited or unavailable, such as in buildings. Femtocells improve service and coverage without the major costs involved in deploying fixed infrastructure (antennas, base stations, etc.), while also decreasing backhaul costs since traffic is routed on existing broadband access network (e.g., DSL). Today a commonly accepted assumption is that home users are ready to bear the costs and the inconveniences (e.g., space occupancy, load on their access links) of a femto BS installation at their homes. Based on this, many works proved that both service providers and home users benefit with the deployment of femto BSs within the service area of a macro BS. The reason is that typically in a wireless network the bottleneck is the limited number of channels available for transmission. By encouraging the end users to install femto BS at home, the same channel can be re-used multiple times in the same macro-cell and this helps increasing the capacity.

Here, however, we do not rely on the same assumption. On the contrary, we investigate what is, or could be, the reason for a user to install a femto BS at home. Currently, a user receives services from her cellular operator irrespective of her location as long as she is in the coverage area. Then why would she invest in another device such as a femto BS if the advantages are not clearly stated and guaranteed by service level agreement? It seems that a vague statement claiming that a home user would "benefit" from a femto BS might not be enough to convince users. We investigate a simple throughput-based incentive mechanism that could attract users, avoid most of the curse of free riders (i.e., selfish users who gets improved service just because others are investing in femto technology) and, at the end, be beneficial to both the users and the operator. The incentive mechanism we propose is to offer users who have installed a femto BS at home a rate, *when they are at home*, which is at least α times ($\alpha > 1$) higher than the average rate received by a user associated with the macro BS.

The goal of this work is twofold. On the one hand we show that it is cost-effective for a network operator to allocate a pool of its licensed channels to a certain number of femto cells, even under our incentive mechanism. On the other hand we investigate and quantify the throughput gains for both femto and macro users under different values of the incentive parameter α. The rationale is that by giving incentives to users who install femto BS, we are going to offer *a)* much better services to those users when they are at home, i.e., when they are served by their own femto BS, and *b)* better services (than that they would receive in a system without femtocells)[1] to all users when they are not at home and/or they have not installed their own femto BS, i.e., when they are served by the macro BS.

We consider an OFDMA based cellular system using M sub-channels (in the following we use the term channel and sub-channels interchangeably) comprising one macro-cell and Y residential femtocells. We assume that *a)* $X \leq Y$ femtocells are active at a given time (each serving no more than one user) and *b)* if a user is at home it automatically associates with its femto BS (if any). The M channels are split between the macro BS and the X active femto BSs so that K channels are reserved for the pool of femtocells and $M - K$ for the macrocell only. Each active femto BS autonomously selects a (not necessarily contiguous) subset b of channels out of K for its transmissions. As detailed later, we assume that the pool K and the parameter b are periodically computed by the operator (and communicated to the femto BSs) such that the intra-femtocell interference is bounded and reasonable in almost all configurations and the incentive constraint is met.

The contributions of this paper are as follows. We first study a static scenario with fixed numbers of macro and femto users. We identify the range of values of the incentive parameter α that can be supported to reward femto users without harming macro users and we quantify the gains in terms of throughput for both macro and femto users in different situations. Then, we consider a dynamic scenario, where the numbers of users and active femtocells change continuously, and we propose a simple and very accurate method for computing K. In principle, the operator should collect a large amount of information to compute/update K. Our proposed method not only allows the operator to calculate K with a minimal amount of information to be collected, but also gives him the possibility to decide the interval at which it is worth to update and communicate the value of K to the femto BSs.

A. Related Works

Previous works have investigated the costs of homogeneous and heterogeneous networks. [3] shows that femtocell solutions are more cost efficient only when new macro base station sites need to be deployed. [4] [5] show that the cost for building and operating a cellular network is mainly driven by the characteristics of the base stations to be deployed. [6] shows that in urban areas a combination of publicly accessible base stations and microcells can reduce significantly the network costs. In these works the network operators bear all the cost for installation and maintenance of both macro and femto BSs. Our work, although related with some aspects above, tackles different issues. We work under the assumption that a home user has to decide whether to install a femto base station at home for his own usage, i.e., in closed access, and to bear the cost. Moreover, since we claim that home users need to be persuaded to afford costs and inconveniences for installing a femto BS, we propose a throughput-based incentive and show that this scheme can be beneficial to both the operator and the femto owners if α is chosen well.

[1]In that sense, free riders are benefiting lot less than those investing in femtocells.

II. Static Scenario

A. Model and Formulation

We consider an OFDMA based cellular system using M orthogonal subchannels comprising one macro-cell and X active residential femtocells. The macro BS serves N_{MC} users, while each femtocell serves one single user in closed access. The M channels are split between the macrocell and the pool of femtocells: $M - K$ channels are dedicated to the macrocell, while K channels are left for the exclusive use of the pool of femtocells.

We select K so that each femtocell can select, via scanning and with high probability, b (non necessarily contiguous) "good" channels out of the K, i.e., that offer a high Signal to Noise and Interference Ratio (SINR) to its user. We first discuss the relationship between K and b and then present how b should be computed. We introduce the notion of a *frequency reuse factor* u ($u > 1$) selected by the operator to ensure that indeed a femtocell can select b good channels, i.e., to take into account that a channel that is used by a given femtocell can be reused by another physically distant femtocell in the macrocell while keeping the interference manageable. We define the reuse factor u so that if a channel is reserved for exclusive use of the femtocells, it cannot be used at the same time by more than $\frac{1}{u}^{th}$ of all the femtocells while keeping the inter-femtocell interference at a reasonable level. Typically, we expect $u > 10$ and to be fine tuned via measurement campaigns. Consequently the relationship between K and b is determined by u, and the total number K of channels allocated for exclusive femtocell use can be computed as follows:

$$K = \min(u, X)b, \quad 1 \leq u \leq X. \tag{1}$$

When the number of active femtocell is low (i.e., $X \leq u$) the operator allocates Xb channels to the pool of femtocells so that each active femtocell can select a disjoint subset of frequencies for its interference-free transmissions; otherwise it allocates ub channels. We stress the similarity between the channel selection processes in our scenario and in WiFi systems [7] where a certain number of non overlapping channels have been allocated to the use of WiFi networks and a wireless access point selects via scanning the one with the best signal quality. Similarly here each femto BS autonomously selects b subchannels, out of the K reserved for the femtocell transmissions, under the assumption that by choosing u appropriately the inter-femtocell interference will remain manageable. In a dynamic system, the values of b and K will be recomputed regularly to take into account the changes in the system state and they sent to the femto BSs (see next section).

We explain next how to compute b. We work under the following assumptions:

a) the macro BS knows the SNR (Signal to Noise Ratio) γ_i^0 for each user i associated with it,

b) the rate function for the macro BS is the continuous rate function $\log_2(1 + \frac{SINR}{2})$,

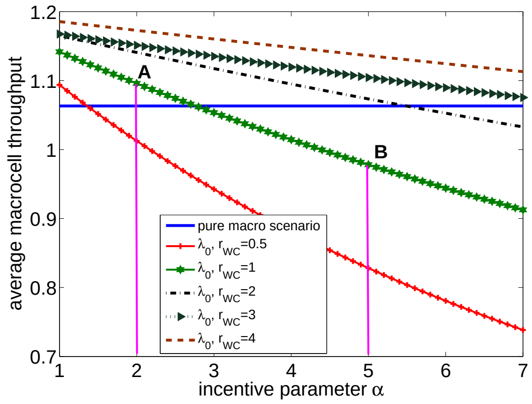

Fig. 2. Average throughput for macrocell users, $X = 100$.

c) the macrocell BS uses proportional fair scheduling (PFS) [8], a scheme which allocates the same fraction (here, $\frac{M-K}{N_{MC}}$) of bandwidth to each user regardless of the SNR seen by the user.

d) the femtocell BSs are configured with a set of modulation/coding schemes so that the base one (i.e., the one delivering the lowest rate) has a per channel rate of r_{WC}.

e) we focus on the downlink.

f) we relax the integer condition on K.

Hence if a femtocell uses b channels, its user would get a throughput λ_{FC} such that

$$\lambda_{FC} \geq r_{WC} b, \tag{2}$$

and a macro-cell user i will receive a throughput $\lambda_0(i)$ such that:

$$\lambda_0(i) = \frac{M-K}{N_{MC}} \log_2(1 + \frac{\gamma_i^0}{2}). \tag{3}$$

We compute K (and therefore b) so that a femtocell user sees, even in the worse case (i.e., when $\lambda_{FC} = r_{WC} b$), a rate bigger than α times the average rate of the macrocell users λ_0, i.e.,

$$\lambda_{FC} \geq r_{WC} b = \alpha \frac{M-K}{N_{MC}} \frac{\sum_{i=1}^{N_{MC}} \log_2(1 + \frac{\gamma_i^0}{2})}{N_{MC}}. \tag{4}$$

By substituting $b = \frac{K}{\min(u,X)}$, we can find the value of K^* which satisfies the condition in (4) and then

$$\lambda_{FC} \geq \alpha \frac{M-K}{N_{MC}} \frac{\sum_{i=1}^{N_{MC}} \log_2(1 + \frac{\gamma_i^0}{2})}{N_{MC}}. \tag{5}$$

B. Simulation Results

We assume a simple path loss model (parameters summarized in Table I), such that the Signal-to-Noise Ratio for a user i at a distance d_i of the macro BS is obtained as follows:

$$SNR(d_i) = \frac{P_{macro} G_i \left(\frac{d_i}{d_0}\right)^{-\eta}}{N_0} \tag{6}$$

where G_i denotes the channel gain on the link between the macro BS and i, N_0 is the average thermal noise power in the operating frequency band, d_0 is the reference distance, η is the path loss exponent and P_{macro} is the transmit power of the macro BS and is selected so that the SNR at the edge is 2dB. The macro BS is located at the center of a square whose side has length 1000 m. Macro and femto users are uniformly randomly distributed in the macro service area (Figure 1).

TABLE I
PHYSICAL LAYER PARAMETERS

M	300	$N = N_{MC} + X$	1000
u	$\min(X, 11)$	Cell Length	$1000\ m$
P_{macro}	$-66\ dBm$	N_0	$-116\ dBm$
d_0	100	η	3.7
G_i	$-16\ dB$	$SNR\ edge$	$2\ dB$

Figure 2 shows, for a specific deployment of macro and femto users, the average throughput of macro users λ_0 for different values of r_{WC}, versus the incentive parameter α ($X = 100$, other parameters in Table I). The minimum guaranteed average throughput of femto users, $\lambda_{WC} = \alpha\lambda_0$ is not shown in the figure. It grows almost linearly as a function of α. The average throughput λ_B for users in the reference system consisting of a pure macrocellular scenario (with no femtocells) is the horizontal line, independent of α. As expected, by deploying femto BSs within the macrocell area both femto and macro users are advantaged (i.e., $\lambda_{FC} > \lambda_0 > \lambda_B$), as long as α is not too high. In fact when α increases, λ_0 decreases and λ_{WC} increases: This happens because to offer better service to femto users, the resources left to macro users are reduced. In this sense, there is a value α_c such that, for any $\alpha > \alpha_c$, $\lambda_{FC} > \lambda_B > \lambda_0$, i.e., macrocell users do worse with our scheme than in the reference system. In a pure macro scenario, each user is allocated a fraction $\frac{M}{N}$ of the bandwidth, regardless of α. In our scenario, the $N_{MC} = N - X$ macro users are allocated a bandwidth $M - K$. Since K increases with α it follows that macro users are penalized more and more when α increases. For example consider $r_{WC} = 1$ and $\alpha = 2$ in Figure 2. Then λ_0 takes the value corresponding to point **A** shown in the figure and the following condition holds: $\lambda_{FC}(\alpha = 2) = 2\lambda_0(\alpha = 2) > \lambda_0(\alpha = 2) > \lambda_B$. In other words, with $\alpha = 2$ both macro and femto users are better off than in the pure macrocell scenario (point **A** is above the horizontal line). The situation is different with $\alpha = 5$. In this case, $\lambda_{FC}(\alpha = 5) = 5\lambda_0(\alpha = 5) > \lambda_B > \lambda_0(\alpha = 5)$ (point **B** is below the horizontal line). We also stress the influence of the parameter r_{WC} which affects both λ_{FC} and λ_0: When r_{WC} decreases, λ_{FC}, which is directly proportional to r_{WC} as in (2), takes lower values. To guarantee the condition $\lambda_{WC} \geq \lambda_0$ (notice that λ_0 is independent of r_{WC}) a larger K has to be reserved for femtocells' exclusive use which harms the macro users throughput for smaller values of α.

Let α_c be the value of α for which the two curves λ_B and $\lambda_0(\alpha)$ intersect. Figure 3 shows the crossing point α_c for different values of X and r_{WC} for 1000 realizations, where a realization corresponds to a specific deployment of the N_{MC} macrocell users and the X femto BSs in the square. As it can be seen α_c is not too sensitive to the deployment but more to the values of X and r_{WC}.

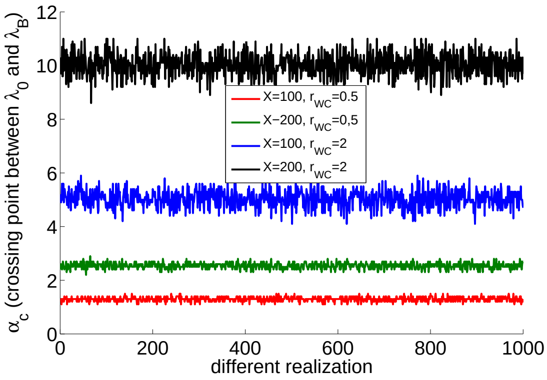

Fig. 3. Crossing point between λ_0 and λ_B for different realizations.

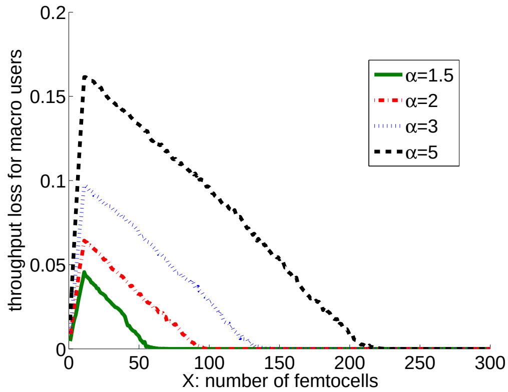

Fig. 5. Throughput loss for macrocell users as a function of X

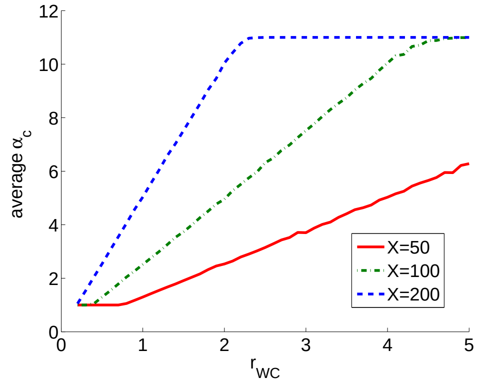

Fig. 4. Mean value of α_c as a function of r_{WC}

Figure 4 shows the average value of α_c as a function of r_{WC} for different values of X. It shows that, as expected, a system with femtocells and our incentive scheme will do better than the reference system even for large α if X is large especially when r_{WC} is not too small. For example, if $r_{WC} = 2$, it is possible to choose a value of $\alpha = 2$ without harming the macro users, regardless of $X \geq 50$ and if $r_{WC} = 1$, it is possible to choose a value of $\alpha = 1.5$ without harming the macro users, regardless of $X \geq 50$

Figure 5 shows the relative throughput loss for macro users for different values of α versus the number of femtocells X when $r_{WC} = 1$. It is defined as the average over many different realizations of $\max(\frac{\lambda_B - \lambda_0(\alpha)}{\lambda_B}, 0)$, i.e. it is a measure of how much average throughput macrocell users could lose *if at all* for a given value of X with respect to the reference system if the incentive parameter α is too high. As it can be seen, with the higher values of α, macro users are harmed more and even for larger values of X since the macrocell is allocated less resources. The deployment of femtocells is beneficial for the macrocell users, among the other reasons, because it allows the macro station to offload part of its traffic. Figure 5 suggests that $\alpha = 1.5$ could be an appropriate choice for a network operator. With this value of α, femto users are offered a much better service (i.e., a throughput 50% higher than the average throughput seen by macrocell users) and at the same time the macro users only see a slight decrease in their throughput (as compared to the reference system) only for very small values of X. It is interesting to notice that the peak of the loss is for $X = 11 = u$, for any α. This happens because as long as $X < 11$ there is no frequency reuse and hence no gains can be obtained with femtocells.

III. Dynamic Scenario

In this section, we consider a *dynamic* scenario where the number of users served respectively by the macro BS (N_{MC}) and by their femto BSs (X) change with time. Specifically we assume that $X(t) \leq Y$ femtocells are active at time t and that the number of users associated with the macrocell at t is $N_{MC}(t)$. Let the number of active users at time t be $N(t) = N_{MC}(t) + X(t)$. At regular intervals t_n, the operator will collect data on the state of the system and compute updated values of K and b. Let K_n be the value of K computed at the beginning of interval t_n (note that when K_n is computed, b_n is given by 1). If K_n differs a lot from K_{n-1}, then the operator needs to send the new value to the active femtocells. Calculating and communicating the value of K_n very frequently to each active femto BS implies a lot of information to be exchanged; on the other hand, if t_n is very large, the value of K_n might be very suboptimal. Let X_n (resp. N_n and N_n^M) be the number of active femtocells (resp. the total number of users in the system, and the number of users associated with the macrocell) at the beginning of the interval t_n.

We propose (and validate) a method for computing K_n that is simple and does not require the operator to collect much information. We can compute K_n from (4), by substituting $b_n = \frac{K_n}{\min(u,X)}$, i.e.,

$$K_n = \frac{\alpha M B_n}{B_n \alpha + \frac{r_{WC}(N_n - X_n)}{\min(u, X_n)}} \qquad (7)$$

where $B_n = \frac{\sum_{i=1}^{N_n^M} \log_2(1+\frac{\gamma_i^0}{2})}{N_n^M}$. In our scenario the macro BS acts as central authority (it allocates resources for users in a centralized fashion) therefore it knows N_n and X_n (and N_n^M) and, assuming that it has an accurate estimate of B_n, it can calculate the value of K_n in (7). We conjecture that under the assumption that the number of users associated with the

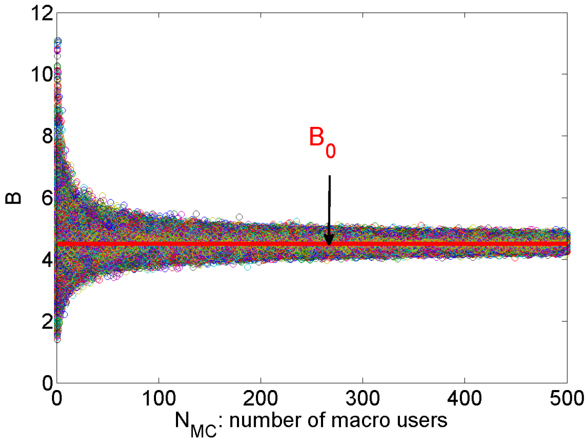

Fig. 6. B as a function of N_{MC}.

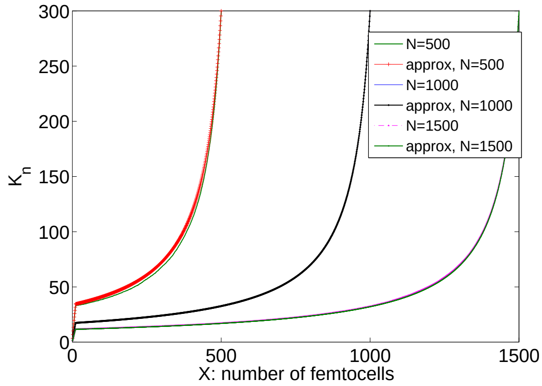

Fig. 7. Approximation of K_n with our proposed method.

macrocell is relatively large, B_n is quasi constant (i.e., does not depend much on the particular distribution of the users) and can be estimated by using measurements or by modeling a certain propagation scenario. We have verified numerically that if $N_{MC} > 50$, B_n is quasi constant, i.e., $B_n = B_0$ (see Figure 6 which shows $B = \frac{\sum_{i=1}^{N_{MC}} \log_2(1+\frac{\gamma_i^0}{2})}{N_{MC}}$ for 1000 realizations for different values of N_{MC}). In the following, we assume that, the operator has measured, or computed and validated B_0 and hence as long as $X > 50$, the following formula for K_n is used:

$$K_n = \frac{\alpha M B_0}{B_0\alpha + \frac{r_{WC}(N_n - X_n)}{min(u, X_n)}} \quad (8)$$

This equation is a simple yet effective and very powerful method to compute K_n. Figure 7 shows that the approximation in (8) is very accurate.

To validate our incentive scheme under a dynamic scenario, we consider the case where the total number of users $N = 1000$ remains constant but the number of active femtocells X_n at the beginning of the interval t_n is determined via the probability p that a femtocell is active at the beginning of the interval. Note that for a given p, the average number of active femtocells is pY. Figure 8 shows the average throughput for femto and macro users as a function of p. We set $\alpha = 1.5$ and

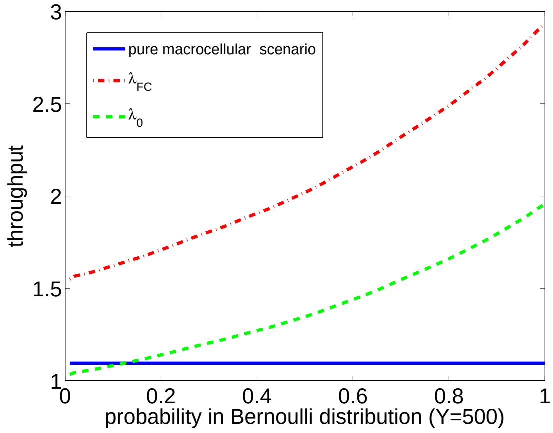

Fig. 8. Dynamic scenario: throughput as a function of p.

$Y = 500$, i.e., 500 femtocells are deployed within the macro service area ($p = 1$ corresponds to the case where all femto BSs are active, while for $p = 0$ all the femto BSs are switched off). The horizontal line represents the average throughput for users in the pure macrocellular scenario (i.e., the reference system) which is independent of p. As expected λ_{FC} is higher than λ_0 and λ_B for any value of p. It is interesting that if $p \leq 0.1$ (i.e., on average there are very few active femtocells) $\lambda_0 \leq \lambda_B$, i.e., macro users are slightly harmed and this is confirmed in Figure 8. On the contrary for any value of $p \geq 0.1$ both macro and femto users are better off than in the pure macro scenario and when the average number of active femto cells is greater than 150, the gains are substantial even for macrocell users.

IV. Conclusions and Future Work

In this paper, we have proposed a simple throughput based incentive mechanism to convince home users to install residential femto base stations. On the one hand, we have shown that, even under this mechanism, it is cost effective for a network operator to allocate a pool of its licensed frequencies for exclusive femtocell use. On the other hand we have quantified the gains in terms of throughput for both macro and femto users. Based on our findings, we think that it is reasonable to offer at least 50% more throughput to users when they are at home and have a femto BS. We have also proposed a very accurate and simple method to calculate the amount of bandwidth to reserve for exclusive femto use. This method needs very little information information to be collected. We have obtained similar results and conclusions (not shown in this paper due to the lack of space) for the case where the macro users are scheduled according to a max-min policy.

Our study opens a large number of items which deserve future investigations. For example, in this work it is assumed that each femtocell serve a single user in closed access. An interesting direction is to generalize this study to consider the cases where residential femtocells serve more users and/or work in open access.

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