Network Capacity Enhancement of OFDMA System Using Self-organized Femtocell Off-load

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Abstract

As plug-and-play devices, femtocells are expected to be self-managed, empowered by self-organization functionalities. This paper presents a Self-organizing networks (SON) process for off-loading macrocell traffic towards Open Subscriber Group (OSG) femtocells. The off-loading process comprises two SON functionalities: the first configures the femtocell transmitted pilot power, which depends on the received macrocell pilot power and the density of femtocells. The femtocell pilot powers are chosen using a look-up table generated through an off-line queuing theory based analysis. To mitigate interference from femtocells with different transmission powers, a self-optimizing Inter-Cell Interference Coordination (ICIC) functionality is activated. The performance gain of the self-organizing mechanisms is evaluated using a large scale network simulator. It is shown that in dense femtocell deployment, the SON off-loading can bring about considerable capacity gain. [1]

I. Introduction

Today, the indoor mobile traffic represents more than 50 percent of the total traffic, and femtocells could play an important role in enhancing the network capacity. Femtocells will be managed by the customer and hence should be fully plug-and-play devices. Classical operation tasks, from device configuration to optimization and troubleshooting, should be performed in a fully autonomic or self-organized manner. In this context, SON is considered as a key lever to reduce cost of operation (OPEX), to simplify the management and to enhance the performance of the femtocell technology.

In LTE [1], three modes of access are introduced for femtocells: closed access, open access, and hybrid access. In closed access mode, only users belonging to the Closed Subscriber Group (CSG) can connect to the femto station. In the case of open access mode, cellular users from the macrocells can connect to the femto station. In the hybrid case, part of the femtocell resources are operated in open access, while the rest follow a CSG approach. In both hybrid and open access modes, the amount of traffic that can be off-loaded by a femtocell depends on the coverage area of the femtocell, namely on its transmitted pilot power.

In this study, we focus on the downlink transmission of an OFDMA system where resources are used under full reuse by macro and femto stations. However, inside a cell, the resources are fairly divided among the users by a scheduler. The introduction of femtocells can be seen as a densification which, inspite of the additional interference, increases the network performance.

Different works have investigated the problem of improving the network spectral efficiency through the adaptation of inter-cell interference mitigation methods ([2], [3]). Authors in [4] compare the throughput optimal solutions of indoor users and outdoor users using a physical layer capacity model, i.e., assuming that the network is static in flow-level. They point out that it is better for home users to be attached to a femto-cell on closed access while outdoor users benefit more from open access one.

Nevertheless, to the best of our knowledge, the effect of femtocell offload in a *dynamic* network (in flow-level) has not been studied in literature. After the pioneering work [5] on network capacity considering network's flow-level dynamics, many studies focused on this approach. Extended studies on introducing convenient performance indicators for different network set-ups, e.g. different assumptions on scheduling, mobility, and QoS, are done by Karray in [6], [7].

The objective of the current work is to propose an efficient off-load mechanism, utilizing the *open/hybrid-access* femtocells, aiming at improving the *network capacity*. A queuing theory analysis, based on network dynamics, shows

[1]This work has been partially carried out in the framework of the CELTIC project HOMESNET (CP6-009)

that most of the macrocell load is generated by cell edge traffic [5]. Therefore, the gain of femtocell deployment is expected to depend on the location and density of femtocells.

In this work, setting femtocell *pilot* power is seen as a self-configuration mechanism which updates the cell coverage in order to improve the network capacity. On the other hand, the importance of the ICIC functionality is critical in a dense femtocell deployment. The ICIC is designed as a self-optimization over the femtocell transmission power. Note that these two algorithms update distinct power elements, namely pilot and data powers.

The contributions of this paper are (Fig. 1):

- Introduction of closed-form expressions of network Key Performance Indicators (KPIs) obtained based on a M/G/1/PS (Processor Sharing) queue model in a network consisting of both macro and femto cells.
- A self-configuration algorithm to set the femtocell pilot powers.
- Adaptation of an ICIC algorithm ([8], [9]) to the femtocell context, to set femtocell transmission power.

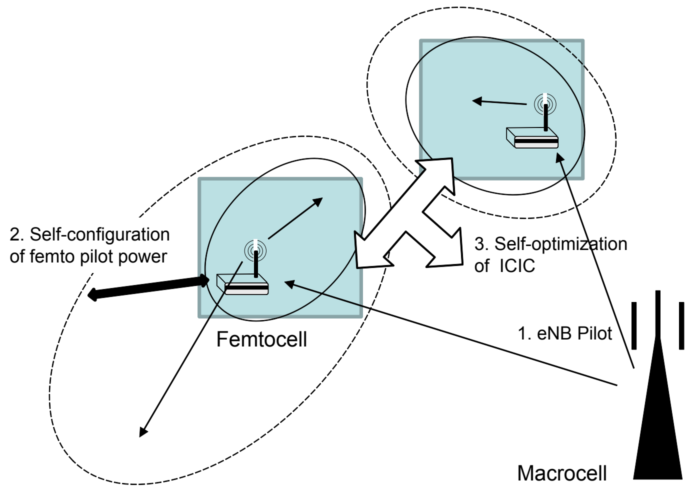

Fig. 1. Network model

II. System Model

We consider a network consisting of self-organized macrocells and femtocells. The downlink of OFDMA system is assumed. This study is done on the portion of the spectrum which is common among all stations.

We model the propagation-loss as the product of three factors called distance-loss, shadowing and fading. We assume that the fading on each sub-carrier is *flat*. In addition, the fading processes for different users or stations are assumed independent.

Time is divided into *time-slots* of length smaller than the coherence time of the channel (e.g. $1ms$ in LTE), so that, for a given sub-carrier, the fading remains constant during each time-slot and the fading process in different time slots may be assumed *ergodic*. Furthermore, we assume that a time-slot equals a *codeword duration*. In other words, *block-fading* channel is considered.

We consider a few time scales, each of which is associated to either the evolution of a stochastic process or an algorithm interval. We order our time scales from the fastest one to the slowest one, as being related to the following elements: (i) Block-fading process: smallest time unit is a time-slot which equals the duration of one codeword, (ii) ICIC algorithm's intervals, i.e., *transmission power* allocation, in the range of several tens of time slots along which the fading process is ergodic, (iii) Stochastic process of user's location, i.e., due to traffic arrival, departure, and mobility, (iv) Self-configured offload algorithm's intervals, i.e., *pilot power* allocation and cell coverage update.

We use the following notations: N_s denotes the number of stations (macro or femto). In this work, we may use the same notation for indicating a *station* and its corresponding *cell*. Each station is mapped to an index in the set $\mathcal{N}_S = \{1, ..., N_s\}$. $\mathbb{A} \in \mathbb{R}^2$ is the network area which is bounded and $r \in \mathbb{A}$ denotes a location on this area. $h_{s,r}$ denotes the path loss and shadowing between station s and location $r \in \mathbb{A}$. We assume that each station has N_{PRB} Physical Resource Blocks (PRBs) of size W_{PRB} available to transmit data. We write $P_s^{(p)}$ the transmitted power on PRB p, $P_s^{(0)}$ - the power of the pilot signal transmitted by station s and $\mathbf{P} = (P_s^{(p)})_{1 \leq s \leq N_s, 0 \leq p \leq N_{PRB}}$ is the matrix of transmission powers.

Let $\mathbb{A}_s \subset \mathbb{A}$ denote the area covered by station s, we assume that mobiles attach themselves to the station with the strongest pilot signal, namely: $\mathbb{A}_s(\mathbf{P}) = \{r \in \mathbb{A} | s = \arg\max_s (h_{s,r} P_s^{(0)})\}$. The mean Signal to Interference plus Noise Ratio (SINR) on PRB p of a user at $r \in \mathbb{A}_s(\mathbf{P})$ is defined by:

$$S_r^{(p)}(\mathbf{P}) = \frac{h_{s,r} P_s^{(p)}}{W_{PRB} N_0 + \sum_{s' \neq s} h_{s',r} P_{s'}^{(p)}} \tag{1}$$

with N_0 the thermal noise spectral power density. Note that, the *mean SINR* is by definition the SINR averaged over the fading process of the channel corresponding to station s, i.e., considering that the mean of the fading process is equal to one. As in [10], we assumed that the number of interfering stations is sufficiently large to ignore the fading of the interfering signals. In reality, (1) is a lower bound of the mean SINR (proof in [6]).

On each PRB, the fading of the channel corresponding to station s can be described by a multiplicative random variable. Let $p_\xi(x)$ denote the marginal probability density function (p.d.f) of the fading process on each PRB, and $\phi(\text{SINR}) \leq \log_2(1+\text{SINR})$ the spectral efficiency of the coding scheme used as a function of the SINR. Assuming ergodicity of the fading process, the ergodic rate of a user at $r \in \mathbb{A}_s$, $R(r, \mathbf{P})$, can then be calculated by:

$$\Psi(S_r^{(p)}) = W_{PRB} \int_0^{+\infty} \phi(S_r^{(p)}\ x) p_\xi(x) dx$$

$$R(r, \mathbf{P}) = \sum_{p=1}^{N_{PRB}} \Psi(S_r^{(p)}(\mathbf{P})) \tag{2}$$

Note that the *rate* (2) is calculated conditioned that the user is alone in the cell, i.e., no scheduling. In the following, the term *throughput* indicates user's rate which is averaged over the ergodic fading process of his channel.

III. Self-configured Off-load

In this section we assume Round Robin (RR) scheduling which allows us to use a Markovian analysis to adjust the femtocells size and find optimal offloading solutions. Assume that users arrive according to a spatial Poisson process with density $\lambda_r = \lambda$, $r \in \mathbb{A}$, and want to download a file of size σ with $\mathbb{E}[\sigma] < +\infty$. Based on M/G/1/PS queue ([5]), we can calculate the load of station s, $\overline{\rho}_s(\mathbf{P})$, and the corresponding KPIs:

$$\overline{\rho}_s(\mathbf{P}) = \int_{\mathbb{A}_s(\mathbf{P})} \frac{\lambda \mathbb{E}[\sigma] dr}{R(r)} \tag{3}$$

$$C_s(\mathbf{P}) = \left(\int_{\mathbb{A}_s(\mathbf{P})} \frac{1}{R(r, \mathbf{P})} dr \right)^{-1} \tag{4}$$

$$B_s(\mathbf{P}) = \frac{\overline{\rho}_s^{N_{max}}}{1 + \overline{\rho}_s + \cdots + \overline{\rho}_s^{N_{max}}} \tag{5}$$

$$\mu(r, \mathbf{P}) = R(r, \mathbf{P})(1 - \overline{\rho}_s(\mathbf{P})) \tag{6}$$

C_s is the cell capacity of s i.e., the maximum traffic density, $\lambda \mathbb{E}[\sigma]$ (bits/sec/surface), that can be served by s with stability being guaranteed. B_s indicates the blocking rate for station s where N_{max} is the maximum number of active users in a station. Finally, $\mu(r, \mathbf{P})$ is the flow throughput at location r. Furthermore we can calculate the following global KPIs:

$$C(\mathbf{P}) = \min_s C_s(\mathbf{P}) \tag{7}$$

$$B(\mathbf{P}) = \sum_{s=1}^{N_s} \left(\frac{\int_{\mathbb{A}_s(\mathbf{P})} dr}{\int_{\mathbb{A}} dr} \right) B_s(\mathbf{P}) \tag{8}$$

$$\mu(\mathbf{P}) = \frac{1}{\int_{\mathbb{A}} dr} \sum_{s=1}^{N_s} \left(\int_{\mathbb{A}_s(\mathbf{P})} \mu_s(r, \mathbf{P}) dr \right) \tag{9}$$

with C - the network capacity, B - the network blocking rate, and μ - the mean user throughput. C is the maximum traffic density (bits/s per surface unit) that keeps *all* stations stable. Hence it is the minimum of all stations' capacities. B is the probability that a user arriving in the network will be blocked by admission control. The probability that a user arrives in station s is equal to $\frac{\int_{\mathbb{A}_s(\mathbf{P})} dr}{\int_{\mathbb{A}} dr}$ since the traffic is uniform, and a user arriving in station s will be blocked with probability $B_s(\mathbf{P})$, which gives formula (8). Formula (9) is obtained in a similar way, by noticing that the location of a user arriving in station s is uniformly distributed in $\mathbb{A}_s$.

Note that, we can numerically obtain the value of the network KPIs,(7) , (8) and (9), as a function of the power allocation $\mathbf{P}$. This approach provides us with *charts* (set of curves) from which we can decide our desired operating point of the system, i.e. the power allocation $\mathbf{P}$ which provides us with our required performance. In other words, we can introduce a self-configured mechanism to choose the power allocation $\mathbf{P}$ corresponding to a certain network performance. An example of such mechanism is proposed in Section V.

IV. Self-optimized Interference Coordination

As the network becomes denser due to newly deployed femtocells, it is natural to use an ICIC mechanism to further increase the network capacity. We now describe such a mechanism, which was introduced in [8]. We assume that the stations pilot powers $(P_s^{(0)})_{1\le s\le N_s}$ are fixed, and that station can change dynamically the power they transmit on data channels. Every $1s$, each station observes its active users, calculates the derivative of a well-chosen utility function with respect to it's transmit powers and its neighbor's and forwards the result to its neighbors using the X2 interface (real or logical interface), which can be either air interface or wired. We group the PRBs into bands, and denote by $P_s^{(b)}$ the power transmitted by station s on a PRB of band b, and by N_b - the number of bands. We denote by $P_{s,max}$ and $P_{s,min}$ the maximal and minimal total transmit power for station s, and by $P_{s,PRB}$ the maximal transmit power on a PRB for s, and we define $\mathcal{H}_s = \{0 \le P_s^{(b)} \le P_{s,PRB}\ ,\ P_{s,min} \le \frac{N_{PRB}}{N_b}\sum_{b=1}^{N_b} P_s^{(b)} \le P_{s,max}\}$ the set of admissible power allocations for station s, and $\mathcal{H} = \mathcal{H}_1 \times \cdots \times \mathcal{H}_{N_s}$. The power update equation is:

$$P_s^{(b)} \leftarrow \left[P_s^{(b)} + \epsilon \frac{\partial U}{\partial P_s^{(b)}}(\mathbf{P})\right]_{\mathcal{H}_s}^{+} \tag{10}$$

with $\epsilon > 0$ a constant step size and $[.]_{\mathcal{H}}^{+}$ - the projection on $\mathcal{H}$. The projection is well-defined since $\mathcal{H}_s$ is convex. The utility derivative is calculated by:

$$\frac{\partial U}{\partial P_s^{(b)}}(\mathbf{P}) = \frac{\partial U_s}{\partial P_s^{(b)}}(\mathbf{P}) + \sum_{s'\in\mathcal{N}_n(s)} \frac{\partial U_{s'}}{\partial P_s^{(b)}}(\mathbf{P}) \tag{11}$$

with $\mathcal{N}_n(s)$ the set of neighboring stations of s. We use the results from [8], which incorporate closed-form formulas of the impact of Proportional Fair (PF) scheduling. The mean user throughput is given by:

$$T_i(\mathbf{P}) = \sum_{b=1}^{N_b} \sum_{k=0}^{N_u(s)-1} \binom{N_u(s)-1}{k} \frac{(-1)^k}{k+1} \Psi\left(\frac{S_{r(i)}^{(b)}(\mathbf{P})}{k+1}\right) \tag{12}$$

with $r(i)$ the location of user i, T_i - the mean throughput of user i allocated by the PF scheduler and $N_u(s)$ - the number of users served by s at the considered update instant. The utility gradient is then given by:

$$\frac{\partial U_s}{\partial P_s^{(b)}}(\mathbf{P}) = \sum_{i=1}^{N_u(s)} \frac{\sum_{b=1}^{N_b} \sum_{k=0}^{N_u(s)-1} \binom{N_u(s)-1}{k} \frac{(-1)^k S_{r(i)}^{(b)}(\mathbf{P})}{(k+1)^2 P_{r(i)}^{(b)}} \Psi'\left(\frac{S_{r(i)}^{(b)}(\mathbf{P})}{k+1}\right)}{(T_i(\mathbf{P})+d)^{\alpha}} \tag{13}$$

and:

$$\frac{\partial U_s}{\partial P_{s'}^{(b)}}(\mathbf{P}) = \sum_{i=1}^{N_u(s)} \frac{\sum_{b=1}^{N_b} \sum_{k=0}^{N_u(s)-1} \binom{N_u(s)-1}{k} \frac{(-1)^{k+1} h_{s',i} (S_{r(i)}^{(b)}(\mathbf{P}))^2}{(k+1)^2 h_{s,i} P_s^{(b)}} \Psi'\left(\frac{S_{r(i)}^{(b)}(\mathbf{P})}{k+1}\right)}{(T_i(\mathbf{P})+d)^{\alpha}} \tag{14}$$

with $d > 0$ a small constant to avoid singularity at 0, and $\alpha \ge 0$. α is a parameter of the algorithm, and it has been shown in [9] that $\alpha = 2$ gives the best performance.

V. Numerical Results

The simulation settings are listed in Table I. The parameters agrees with the 3GPP standard. Especially note that the maximum allowed transmission powers of macro and femto stations are defined as $46dBm$ and $20dBm$, respectively.

The dynamic algorithms are evaluated using a semi-dynamic LTE network simulator [11]. The simulator performs correlated Monte-Carlo snapshots with a time resolution relevant to the time scale of each algorithm.

Network settings	
Total simulated area	$4km \times 4km$
Apartment area	$10m \times 10m$
Inter-macrocell distance	1.5 km
macroCell layout	7 Macrocell's $\times$ 3 sectors
Number of femtocells per macrocell	4 or 20
File size	$10Mbits$
Service Type	FTP
Maximum macro station transmit power	$46dBm$
Bandwidth	
Number of sub-bands	10
Number of PRBs per sub-bands	5
Macro/Femto cell bandwidth	$10MHz$
Propagation model	
PL from femto to indoor/outdoor UE	$127 + 30\log_{10}(d)$ dB
PL from macro to indoor UE	$128 + 37.6\log_{10}(d) + 10$ dB
PL from macro to outdoor UE	$128 + 37.6\log_{10}(d)$ dB
Thermal noise	$-174dBm/Hz$
Shadowing standard deviation	$6dB$
ICIC algorithm parameters	
Scheduler Type	PF
α	2
Time resolution for ICIC	$1s$
Simulation time	$4000s$
User speed	$5km/h$

TABLE I
SIMULATION PARAMETERS

In the first set of simulations we represent the numerical results related to the self-configured static offload. Therefore, we calculate the network capacity and blocking rate versus femto's pilot power. To ease understanding the amplitude of the pilot power compared to the maximum permitted transmission power (20dBm in 3GPP), we scale the pilot resources (and hence the power) to the entire bandwidth.

We start with a scenario of 80 open access femtos uniformly distributed on the total simulation area, i.e. 4 femtocells per macrocell. We consider the distribution of the strongest received macrocell pilot power at each femtocell, and we divide femtocell into two groups taking the median of this distribution as a threshold.

We impose that for all the femtocells in a group, pilot is transmitted at the same power. We denote the femto station's total power in the regions *int* and *ext* by P_{int} and P_{ext}, respectively.

Figures 2 and 3 represent the network capacity and blocking rate, respectively. For each curve, for a fixed P_{int}, we evaluate the performance metrics when P_{ext} increases. Apart from $0mW$, the rest of the values are given in dBm. We observe that when P_{ext} increases, both KPIs start improving at $P_{ext} = 10dBm$. In order to evaluate the performance gain obtained from femtocell offloading, we take $P_{int} = 0mW,\ P_{ext} = 0mW$ as our reference point. This is the situation where all outdoor and indoor mobiles are served by macro stations. The optimal network performance is obtained for $P_{ext} = 20dBm$ and $P_{int} = 4dBm$. At $P_{ext} = 20dBm$ a gain of 5% in network capacity and 38% in blocking rate is achieved. One can see that the off-loading gain is limited by the maximum femto transmit power.

We now consider a denser scenario with a total 400 open access femtocells, i.e. with 20 femtocells per macrocell. The results for the network capacity and blocking rate are represented in Figures 4 and 5 respectively. One can see that performance gains are achieved with lower femtocell transmit power, compared to the sparse femto deployment case, making this scenario more interesting for a network operator. For example, using the same reference point as in the first scenario, a capacity gain of 40% is achieved for $P_{ext} = 20dBm$. We may conclude that, the optimal

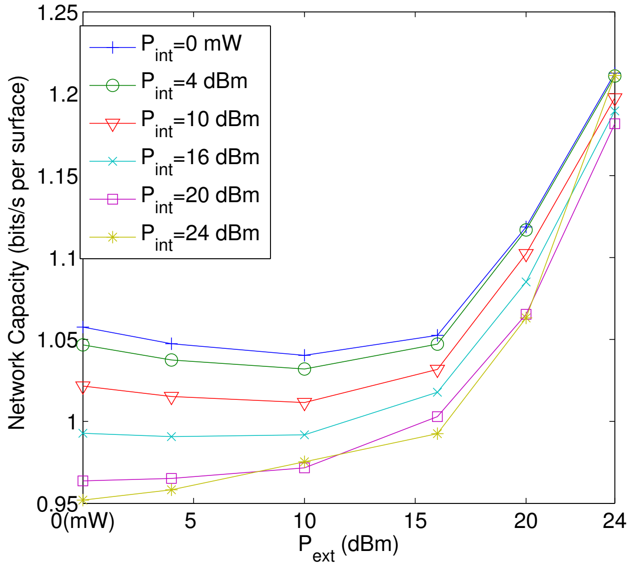

Fig. 2. Network capacity vs. P_{ext} for 4 femtos per macrocell

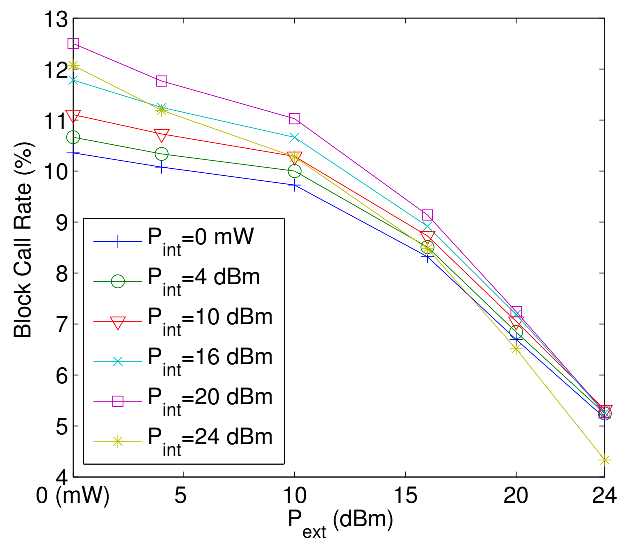

Fig. 3. Network Blocking rate vs. P_{ext} for 4 femtos per macrocell; $\lambda = 3, \mathbb{E}[\sigma] = 10Mbits$

pilot power of femtocells close to the macro station depends on the femtocell density, while femto stations far from the macro station always set the pilot power to the maximum.

Taking these numerical results into account, we obtain our self-configuration offload functionality. The functionality takes the following information as the parameters: (i) the density of femtocells, (ii) the threshold between the two regions int and ext. These values can be broadcasted by macro BS whenever an update is needed. Each femtocell calculates the strongest pilot power it receives from the neighboring macrocells and decides to which region it belongs. Based on this information as well as the density of femtocells, the femto station sets its pilot power at the optimal value.

The increase of femtocells coverage creates additional interferences which can considerably limit the off-loading performance. We next demonstrate the impact of the self-optimizing ICIC for the solution of $P_{ext} = 20dBm$ and $P_{int} = 4dBm$ in the first (sparse) deployment scenario with 80 femtocells. To this end, we evaluate the self-optimizing ICIC scheme (denoted as FFR (Fractional Frequency Reuse) in the figures) of Section IV using a semi-dynamic LTE network simulator [11]. The simulator performs correlated Monte-Carlo snapshots with time resolution of a second. We add the reference case which does not use interference coordination, and is denoted by “no ICIC” in the figures.

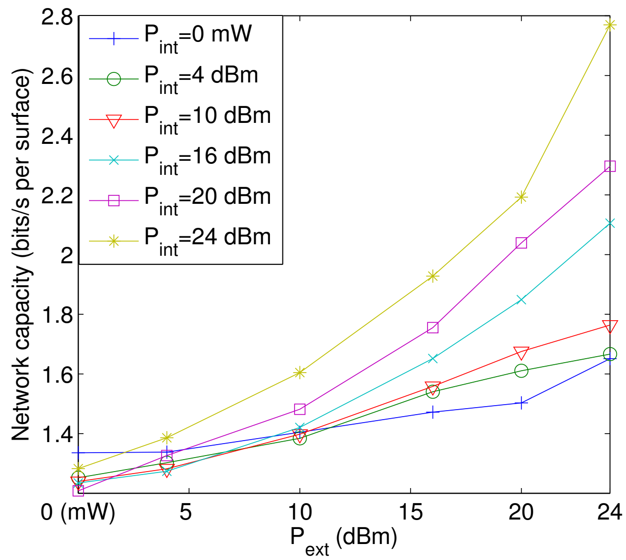

Fig. 4. Network capacity vs. P_{ext} for 20 femtos per macrocell

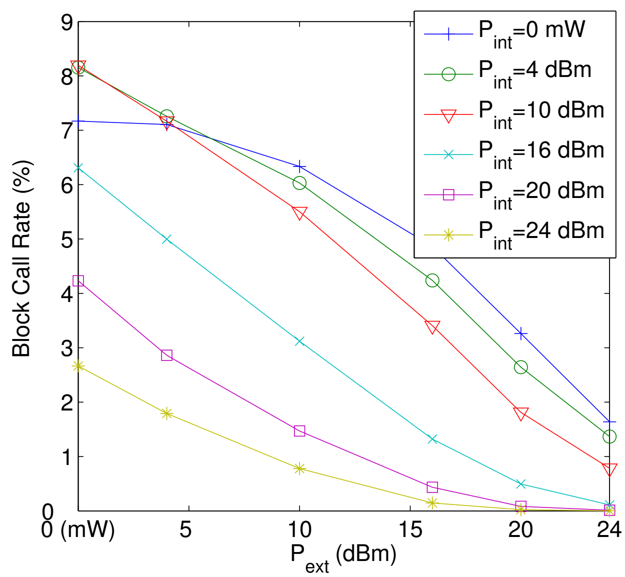

Fig. 5. Network Blocking rate vs. P_{ext} for 20 femtos per macrocell; $\lambda = 3, \mathbb{E}[\sigma] = 10Mbits$

We set $N_{max} = 20$ to evaluate the blocking rate of the network. Figures 6 and 7 represent the results for blocking rate and mean transfer time respectively. We observe that the ICIC algorithm significantly improves both network KPIs. The importance of the ICIC functionality will be critical in a dense femtocell deployment where interference among femtocells is significant. In this case the performance of the self-configured off-loading will be more relevant as well and the performance gains can be achieved with lower transmitted power. Finally it is noted that in open access femtocells deployment, one could expect that only part of the femtocell bandwidth will be "open" to macrocell users to provide priority to the femtocells owners. Hence the power increase will only be applied to a part of the frequency bandwidth, resulting in a decrease of the total femto transmit power.

VI. Conclusion

This paper has described a self-organizing femtocell off-loading mechanism. The off-loading process is performed in two steps: first the femtos' pilot powers are configured as a function of the received macrocell pilot power and femtocells' density. Through a queuing theory evaluation and simulations, it has been shown that the optimal pilot power of femtocells close to the macro station depends on the femtocell density, while femto stations far from the macro station always set the pilot power to the maximum. The gain brought about by the off-loading procedure

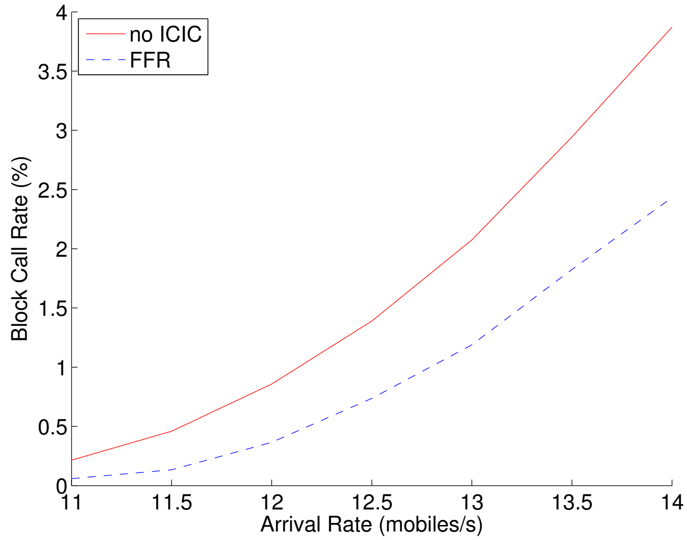

Fig. 6. Blocking Rate

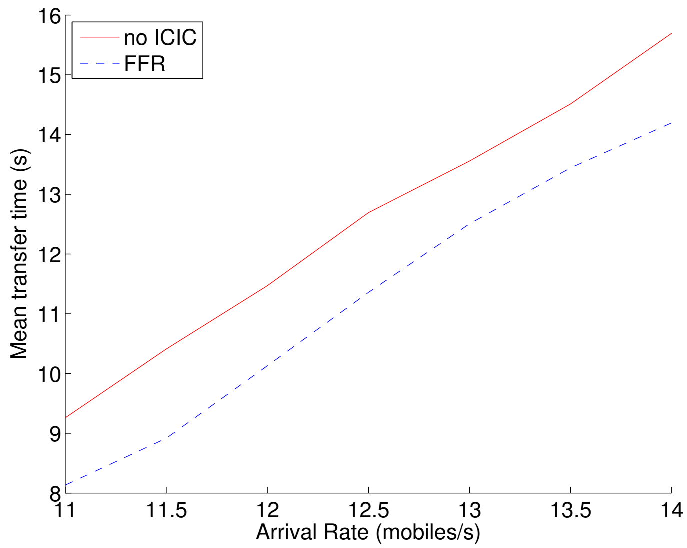

Fig. 7. File transfer time

is significant, and can be achieved with lower femto's pilot power as the femtocell density increases. It has been shown that the self-optimizing ICIC can further increase the off-loading gain, which is expected to be crucial in a dense femtocell deployment.

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