Limited Access to OFDMA femtocells

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***Abstract*—Femtocells are a promising solution for the provision of high indoor coverage and capacity. Furthermore, OFDMA-based femtocells have proven to be highly versatile when dealing with cross-layer co-channel interference thanks to the allocation of frequency subchannels. However, concerns still exist related to the impact of the different access methods to femtocells in an overlayed network. Femtocells based on a Closed Subscribers Group, where only device owners are allowed connectivity introduce severe interference to macrocell users. On the other hand, Open Access femtocells where any user can connect, does not bring many advantages to the femtocell owner. In this paper, an intermediate access method based on a limited access is proposed. The performance of the model is evaluated throughout system-level simulations and it is shown that limited access contributes to seriously reduce cross-layer interference while guaranteeing a minimum performance to the femtocell subscribers.**

I. Introduction

It is a known fact that nowadays nearly 60% of phone calls take place indoors [1]. Hence the provision of high indoor coverage and capacity at low costs is of high interest for network operators. Femtocells or HNBs (Home NodeBs) [2] have been proposed in recent years as a possible solution to this problem. They are cellular base stations designed for indoor usage, including also some Radio Network Controller functionalities and self-organization techniques.

However, femtocells deployed in the same frequency band as the overlayed macrocell, introduce interference between the femto and macrocell layers. Moreover, interference between neighboring femtocells is also likely to occur. On the other hand, OFDMA (Orthogonal Frequency Division Multiple Access) is a medium access technique where different users are allocated different frequency sub-channels. As reported in [3], by assigning correctly the different OFDMA sub-channels, co-channel interference can be significantly reduced in the femto and macrocell layer.

Another main concern regarding femtocells is the definition of the access method, which controls what users are authorized or not to connect to the femtocell. Usual approaches are:

- CSG (Closed Subscriber Group): Only certain users (the subscribers) are allowed to connect to the femtocell.
- Open Access: All users are considered equal and allowed to connect to the femtocell.

A. Related work

In [4], the impact on the downlink capacity of CSG and Open Access OFDMA femtocells was analyzed. This concluded that CSG leads to higher throughputs in the downlink for femtocell subscribers while creating high levels of interference to unsubscribed users in the proximities of the HNB. On the other hand, Open Access mitigates interference and provides a better overall network performance in terms of QoS (Quality of Service) and throughput [5], mainly because all available resources are shared between users. However, the number of handovers and signaling in the network is heavily increased. Furthermore, indoor users might be discouraged from buying a femtocell if their backhaul connection is to be shared with unknown outdoor users.

In [6], an alternative to CSG and Open Access was proposed and evaluated for HSDPA femtocells. This approach suggested the use of a hybrid method with different levels of Open Access where non-subscribers are allowed to connect to the femtocell according to a fixed probability (0% corresponding to the CSG case and 100% to Open Access). However, it was shown that allowing only one non-subscriber into the femtocell decreases significantly the performance of subscribers.

B. Contribution

In order to overcome the drawbacks of the previously described methods, this paper proposes an approach for the access to OFDMA femtocells and analyzes its impact on the performance of femtocell registered and non-registered users. By exploiting the frequency management techniques offered by OFDMA, a limited number of sub-channels is reserved for access to non-subscribers. This way, users unable of connecting to the macrocell due to the lack of coverage or because of interference can still make use of a small amount of the femtocell resources. In addition and due to the sporadic nature of the traffic coming from non-subscribers (outdoor users passing by do not camp for long periods of time on the femtocell), network operators can rely on randomly distributed femtocells to provide coverage outdoors in regions close to the macrocell edge.

In section II the access method to the femtocell is presented and section III describes the settings of the realistic simulation scenario to be used for benchmarking. Finally, section IV shows several simulation results confirming that this approach benefits non-subscribers while guaranteeing reasonable levels of performance to femtocell owners. Final conclusions and remarks are discussed on section V.

II. Limited Access Method

In contrast to CSG femtocells, this paper proposes to allow non-subscribers of a femtocell the use of a limited amount of the femtocell resources. This is done in order to minimize the impact on femtocell subscribers. Each OFDMA femtocell is then configured to allocate at most v subchannels from a total of K for the access of non-subscribers.

Let us define a non-subscriber user $u \in \Pi_\chi$ where $\Pi_\chi = \{1, ..., U_\chi\}$ is the subset of non-subscribers for which femtocell χ is the best server. Furthermore, $\Theta^\chi_{\phi_u} = \{i_1, ..., i_{\phi_u}\}$ is the set of ϕ_u subchannels to be assigned to user u by femtocell χ and $1 \leq i_1 < ... < i_{\phi_u} \leq K$. Moreover, R^u_{min} and R^u_{max} denote the throughput range of the service desired by user u[1].

First of all, user u tries to connect to the macrocell. If this is not possible due to interference from the surrounding femtocells or lack of macrocell resources, u requests access to femtocell χ and specifies a throughput range $[R^u_{min}, R^u_{max}]$.

The achievable throughput $R(s^k_u)$ in subchannel k for user u depends on the state s^k_u of that subchannel, which is defined by the received signal level and the $SINR$ (Signal-to-Interference-and-Noise-Ratio). Following its own strategy for scheduling and resource allocation, the femtocell selects non-subscribers following the order provided by the scheduler and checks if v or less subchannels are enough to provide them with the minimum requested throughputs. This might require the reduction of the subchannels in use by femtocell subscribers. Then, a non-subscriber $u \in \Pi_\chi$ can be denied access due to insufficient subchannels if

$$\nexists \Theta^\chi_{\phi_u} : \sum_{\forall k \in \Theta^\chi_{\phi_u}} R(s^k_u) \geq R^u_{min} \tag{1}$$

where $\phi_u \leq \varphi_u$ and $\varphi_u = v - \sum_{j=1}^{u-1} \phi_j$ is the amount of remaining subchannels to share with a non-subscriber $u > 1$. Note that if $u = 1$ then $\varphi_u = v$. After all non-subscribers have been assigned resources to guarantee their minimum throughputs, the femtocell increasingly allocates them more subchannels until, for a given user $u \in \Pi_\chi$

$$\sum_{\forall k \in \Theta^\chi_{\phi_u}} R(s^k_u) \geq R^u_{max} \tag{2}$$

in which case u is not assigned more subchannels, or

$$\sum_{\forall u \in \Pi_\chi} \phi_u = v \tag{3}$$

This algorithm can be applied not only on a subchannel basis, but also to slots (WiMAX) or resource blocks (LTE) to increase the granularity of the resource allocation.

III. Simulation Procedure

A. Scenario and coverage prediction

The proposed access method is to be tested in a residential area with 33 houses, some of which will contain femtocells according to femtocell penetrations between 12% and 52%. Each house hosting a femtocell contains 3 simultaneous *subscribers* with the right for making full use of the femtocell resources. A total of 5 simultaneous outdoor users are distributed randomly across the street. These are *non-subscribers* and they always try to connect first to the macrocell. If the connection is unsuccessful, they request access to the best femtocell server as long as $v > 0$. If this connection attempt undergoes failure, they are considered to be in outage.

[1]For instance, a video service could have throughput requirements that vary between $R_{min} = 80kbps$ (10 fps with 160x120 resolution) and $R_{max} = 450kbps$ (15 fps with 320x240 resolution) [7].

TABLE I
Simulated Services

Name	$[R_{min}, R_{max}]$ [kbps]
Data 1 (P2P)	$[0, 20000]$
Data 2 (FTP)	$[0, 1000]$
Video	$[80, 450]$
Voice	$[12.2, 24]$

TABLE II
Simulation sets

Sets	Subscribers Service	Non-subscribers Service
1	Data 1	Voice
2	Data 2	Voice
3	Video	Voice
4	Data 1	Video
5	Data 1	Data 2

The spectral occupation of OFDMA subchannels depends on the traffic load at each femtocell, which is related to the type of service being used at the femtocell. Therefore, the method will be tested under different traffic conditions to analyze the impact on the subscribers throughput and the outage probability of non-subscribers. In Table I, the throughput requirements of different services are shown, and Table II displays the network configurations that will be simulated.

The coverage area of the base stations (both macro and femtocells) has been predicted using the FDTD (Finite-Difference Time-Domain) propagation model described in [8] (see Figure 1). This model has been particularly calibrated for indoor transmitters in the 3.5 GHz frequency band, which is licensed for WiMAX (Worldwide Interoperability for Microwave Access) in Europe. The prediction error of such a model is close to $RMSE = 6.2dB$ and it is thus assumed as a reasonably accurate prediction of the real propagation conditions.

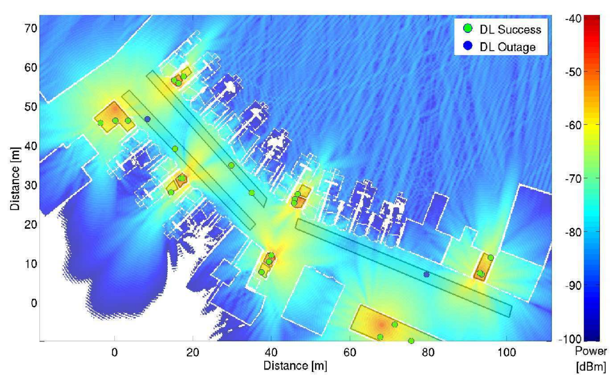

Fig. 1. Coverage prediction for a femtocell penetration of $p = 21\%$ and random snapshot of Simulation Set 4.

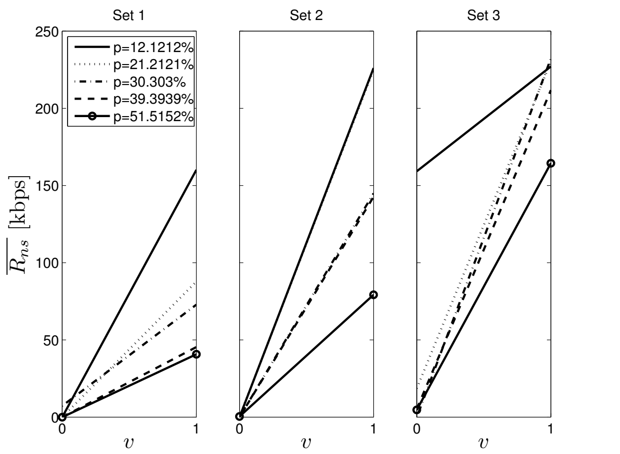

Fig. 2. Average total throughput of $N_{ns} = 5$ non-subscribers requesting a voice service. p represents the femtocell penetration.

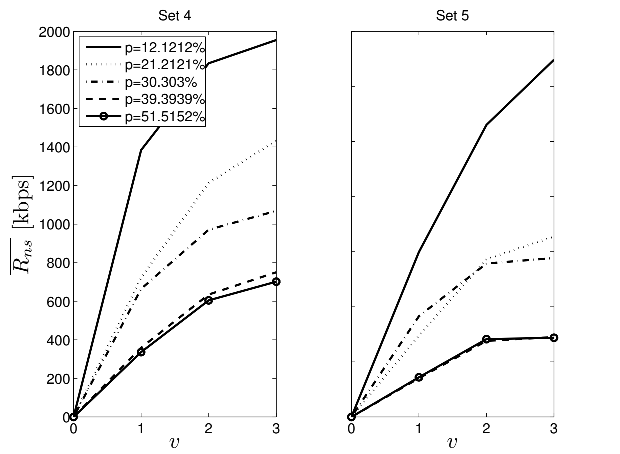

Fig. 3. Average total throughput of $N_{ns} = 5$ non-subscribers requesting a video or data service.

B. System-level simulation

The system-level simulation used in this work to carry out different experimental evaluations is based on a Montecarlo approach, where multiple and independent snapshots are used to assess the performance of a large network over long periods of time. In each snapshot, several users with different services and QoS requirements are spread over the area of study. Then, the simulator takes different steps to compute the final performance of the network. The MAC (Medium Access Control) and PHY (Physical) layer have been modeled according to the WiMAX (IEEE 802.16e) standard, supporting features such as QoS differentiation, adaptive modulation and coding, power control, channel quality feedback, ...

IV. Simulation Results

A. Throughput of non-subscribers

The metric used to measure the improvement in the data rate of non-subscribers is the total throughput. This is defined as $R_{ns}^t = \sum_{u=1}^{N_{ns}} r_u^t$, where r_u^t is the throughput achieved by an individual non-subscriber user u in snapshot t and N_{ns} is the number of non-subscribers in the whole scenario.

In Figure 2, the average total throughput $\overline{R_{ns}}$ achieved under different spectral occupations is shown. Each of the plotted values is the mean R_{ns}^t, averaged over $N_t = 100$ independent snapshots. In the simulation sets shown here, non-subscribers request always a voice service according to Table I. The output of the simulations show that the minimum data rate required by these users is achieved for $v = 1$ in most of the cases. Hence, little improvement is observed for $v > 1$ and the displayed values are limited to the range $v \in [0, 1]$.

Since in order to provide a voice service to non-subscribers $v = 1$ is typically enough, an increase of this parameter would only be noticed when using other services. To guarantee a variety of services for non-subscribers while keeping the disturbance to femtocell owners at a minimum, the v parameter could be dynamically selected depending on the specific service requirements of non-subscribers. It is however up to the network operators to decide what data rates they want to guarantee to their users and how to configure their femtocells.

Regarding the impact of v in services other than voice, Figure 3 shows the obtained $\overline{R_{ns}}$ for cases where non-subscribers request video and data services. It is thus clear from this figure that the throughput increase achieved by non-subscribers varies with v in a way that depends on the type of service requested. One last observation of Figures 2 and 3 reveals that higher throughput is achieved by non-subscribers for lower femtocell penetrations p. The reason for this is the reduced interference from surrounding femtocells affecting outdoor users. However, this effect is less noticeable in Sets 2 and 3 because subscribers do not fully occupy all the subchannels and hence non-subscribers are less interfered.

B. Outage probability of non-subscribers

A user is said to be in outage when, for whatever reason, it can not perform the desired communication. This can occur because of two situations:

1) The user can not be assigned the lowest Modulation and Coding (MC) due to an extremely low $SINR$.
2) The user is assigned an MC, but errors occur during transmission resulting in a communication failure.

After having performed a total of $N_t = 100$ snapshots for different simulation sets and femtocell penetrations, the average fraction of non-subscribers in outage has been extracted. This is presented in Figure 4, where it is shown that by sharing $v = 1$ subchannel, a substantial reduction of the outage probability $\overline{P}_{outage}$ can be achieved. These results also show that Set 1 presents a higher outage probability than others. This is due to the fact that all femtocells in the scenario occupy all the available subchannels because of the high traffic demands of their subscribers (see Tables I and II). As a result, higher interference occurs to outdoor non-subscribers than in other Simulation Sets, thus increasing the chances of outage. Note that the location of users in the scenario is random and so

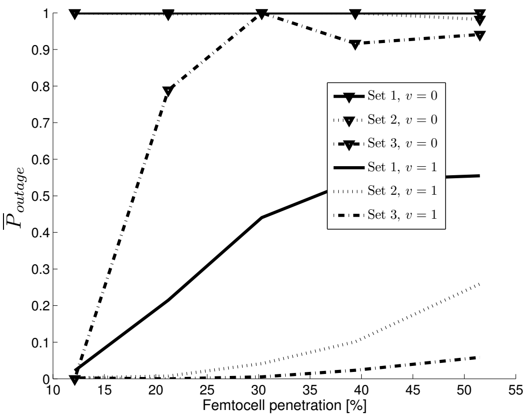

Fig. 4. Average probability of outage for non-subscribers.

only the general tendency of the curves presented must be considered.

Furthermore, it is also seen that the outage probability increases with the femtocell penetration. The spectral occupation is higher when there are more femtocells and hence, the interference suffered by non-subscribers augments and the chance of outage is raised once again. Sets 4 and 5 are not shown here because they are subject to the same interference burden as Set 1 as a result of the high subchannels load introduced from subscribers. The outage probability of non-subscribers in those cases has thus been found equal to that of Set 1.

Additionally, the results obtained for $v > 1$ show no variation with respect to $v = 1$ due to the invariance of the spectral occupation and have been also excluded from this graph. This means that, when femtocells are transmitting at full capacity in downlink to their subscribers, changing v will not change the fact that all OFDMA subchannels are occupied. The interference levels will remain the same for all v and also the outage probability of non-subscribers.

C. *Throughput of subscribers*

When a femtocell F_1 shares v of its subchannels with a non-subscriber, it can happen that the subscribers of F_1 making use of the femtocell resources at that moment, perceive a reduction of their instantaneous throughput. However, this throughput reduction will only be observed when there are less than v unused subchannels in the femtocell. If that is the case, the subscribers will notice a cutback in their data rates only when using data intensive applications such as for instance Peer-to-Peer or FTP (File Transfer Protocol) services. Subscribers using services that do not require all available subchannels (e.g. voice or video calls) for functioning would not feel any impact at all, mostly because the shared subchannels were already unoccupied in the first place. Due to these reasons, the analysis of the throughput reduction presented here, is restricted to the case where femtocell subscribers use data intensive applications with high spectral occupation as described in the Simulation Sets 1, 4 and 5 of Table II.

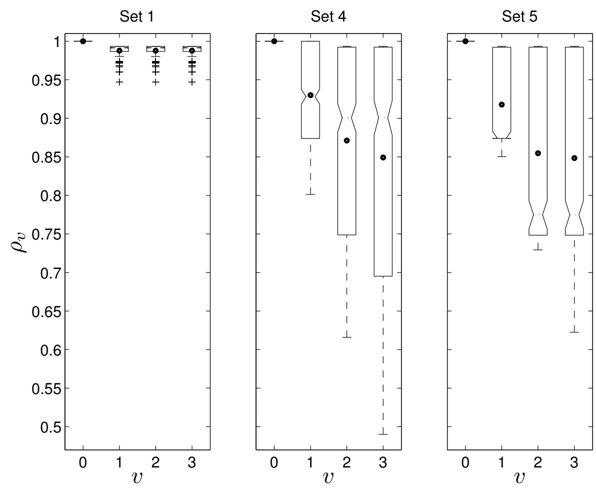

Fig. 5. Distribution of the Throughput Reduction Factor of sharing femtocells for a penetration of $p \approx 30\%$. The data contained in each box corresponds to 100 snapshots of the WiMAX system-level simulator.

In order to quantify the cutback of the data rate in femtocells that share their subchannels, the Throughput Reduction Factor is defined as

$$\rho_v = \frac{R_v}{R_0} \tag{4}$$

where R_0 is the data rate achieved by a CSG femtocell and R_v is the data rate available to the subscribers of the same femtocell when v subchannels are shared. Typically, $R_v < R_0$ and hence $\rho_v < 1$ represents the fraction of throughput still available to the subscribers after sharing v subchannels. To analyze the relationship of ρ_v with v, a total of 100 snapshots have been performed for $v \in [0, 3]$, under 5 different femtocell penetrations and for 5 Simulation Sets (see Table II), accounting for a total of 10000 simulations. At each snapshot, users are randomly distributed throughout the scenario in order to account for different network states.

Since the number of macrocell users is limited, in each snapshot only some femtocells will receive connection requests from non-subscribers. Such femtocells are called *sharing femtocells*. The obtained Throughput Reduction Factors of the sharing femtocells are presented on Figure 5 as box plots to facilitate a visual analysis of the ρ_v distribution. The lower and upper box limits are located at the lower and upper quartiles, and the horizontal dotted line signals the median value. The whiskers extending the boxes indicate the values of the rest of the data until a maximum of 1.5 times the interquartile range. Any ρ_v value outside of this range is considered an outlier and displayed as a cross. The average value $\overline{\rho}_v$ is also displayed as a circle.

It is seen in Figure 5 that when one subchannel is shared ($v = 1$), the highest throughput reduction for a sharing femtocell is 20%, being the average lower than 10% and regardless of the service requested by non-subscribers. If the network operator decides to share more than one subchannel to increase the user experience of non-subscribers, ρ_v will be further reduced until an average value of 85% for $v = 4$.

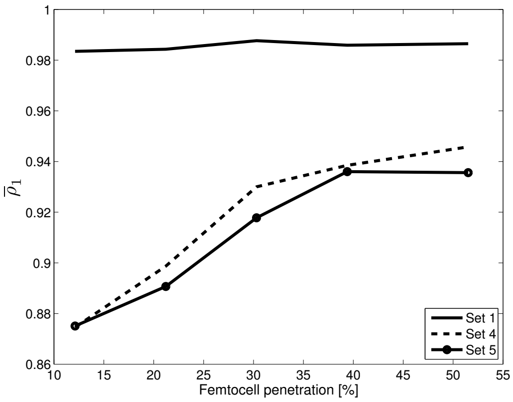

Fig. 6. Average Throughput Reduction Factor of sharing femtocells when $v = 1$.

Then, it is up to the femtocell owners to decide how much of a throughput reduction they are willing to accept in exchange for having a femtocell. In general, it can be said that subscribers will be more affected when non-subscribers request access to services that have unbounded or high data rate requirements.

Furthermore, it has also been observed that the impact of sharing on ρ_v is reduced for higher femtocell penetrations. To illustrate this, Figure 6 presents the obtained Throughput Reduction Factor averaged over 100 snapshots as a function of the femtocell penetration. This increase of ρ_v is due to the fact that when there are more femtocells, non-subscribers have a broader choice of Base Stations to connect to. Hence, the number of non-subscribers requesting access to a given sharing femtocell decreases and less subchannels and time slots have to be shared.

V. Conclusions

By limiting the number of shared subchannels in OFDMA femtocells to v, the following occurs:

Conclusion 1: The throughput of non-subscribers increases (see Figures 2 and 3). In addition, it is even possible for non-subscribers and for low values of v, to achieve throughputs higher than with single macrocell coverage.

Conclusion 2: The probability of outage for non-subscribers notably decreases from 100% ($v = 0$) to the values indicated in Figure 4 for $v = 1$. Furthermore, it has been observed that the outage probability depends mainly on the occupation of OFDMA subchannels. This will hence increase for high femtocell penetrations as well as for situations in which subscribers have high throughput requirements.

Conclusion 3: The impact of sharing subchannels on the femtocell subscribers appears in the form of a throughput reduction. However, limited access helps to control this decrease (see Figures 5 and 6). The values of ρ_v presented here are extracted only from sharing femtocells and show that by sharing a limited amount of subchannels, the cutback for femtocell owners is not dramatic in terms of throughput.

Furthermore, it must also be taken into account that the chances of having to share depend on the density of non-subscribers in the vicinity of the femtocell. The simulations have been run with $N_{ns} = 5$ outdoor non-subscribers distributed within a 140 meters long residential street, which is already a high value for this type of environments even at peak hours. It is thus easy to see that the chances of a femtocell being asked for access by non-subscribers are low. Thus, the limitation imposed to the number of shared subchannels helps to guarantee a reliable service for femtocell subscribers, while reducing the outage probability of non-subscribers.

Conclusion 4: $v = 1$ is enough in most of the cases to guarantee a voice service to non-subscribers. The decision of sharing more subchannels contributes to improving the user experience of non-subscribers. However it may be detrimental for femtocell owners. The v parameter must thus be carefully adjusted by the network operator before deploying femtocells. Another approach would be to have it configured dynamically by the femtocell depending on the throughput requests of non-subscribers, time of the day, etc.

The access method to OFDMA femtocells presented in this paper fills in the gap between *Open Access* and *CSG* femtocells. It has been shown that femtocells do not need to be open for all network users, thus providing little advantage to their owners. Moreover, they do not need to be closed to non-subscribers, introducing severe interference in the existing macrocell network. Hence, the intermediate solution presented here solves the problems of CSG femtocells while guaranteeing a minimum performance to the femtocell owner and contributing to increase the overall network throughput.

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