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CHARACTERISATION OF SMALL CELLS NETWORKS DEPLOYMENT OPTIONS AND THEIR IMPACT UPON MACRO-CELULLAR NETWORKS

Cristian ANDRONE Tudor PALADE
Communications Department, Technical University of Cluj-Napoca, 26-28 G. Baritiu Street, Cluj-Napoca, Romania
[cristian.androne, tudor.palade]@com.utcluj.ro

Abstract: This paper investigates the effect of small cells networks deployment in a typical traditional macro-cellular mobile communications network. The main deployment options are presented and their impact is shown for the case of a typical residential environment. Through simulation and modeling the effect of small cells deployment is studied mainly at the macrocell users site, considering different options for the characteristic radio parameters and deployment density of the small cells. The results show which are the feasible implementation options for the small cells within macrocells, and give essential guidelines for operators when deciding to introduce small cells .

Keywords: *Small Cells, Femtocells, Interference, Open Access, Closed Access, Coverage.*

I. INTRODUCTION

With the ever-increasing data traffic demand in mobile communication networks, operators encounter difficulties in assuring the quality of services. The situation is more problematic in indoor environments, where very often the radio coverage is poor. Recent studies show that up to 60% of all voice calls and 90% of all data calls are originated from indoor environments [1]. That is why providing a good level of the received signal in these areas is extremely important in order to meet the network KPI.

Several recent papers like [1] and [2] present the difficulties encountered, by the traditional approach, in assuring a good indoor coverage. The issues relate especially to dense urban areas where it is very costly to obtain a good indoor coverage due to the geometry of the environment. Also, the capacity of the network is a sensitive problem, given the fact that using a strictly macro-cellular approach, a large number of base stations would be needed, rising once again the costs. Plus, the planning and optimizations of the network would be hard to manage.

Due to all of these, small cells are considered by operators as a possible solution to enhance the network's coverage and capacity, through spatial reuse of wireless resources.

According to [3] the actual deployment of small cells can take many shapes, as a direct consequence of their application. Therefore, one possible implementation would be as a residential femtocell. In this case, the base station acts as a cellular network access point which has the role of connecting the users to the mobile operators network. It is similar in concept to the wireless access point used in local area networks, and it is designed to be implemented by the user, at the desired location . It has a low transmit power of maximum 24 dBm [4], and allows a number of up to 5 simultaneous calls and data sessions [5].

Another deployment option consists in implementing the small cells as enterprise femtocells. In this case the base stations have a maximum transmit power of up to 30 dBm [4] and can support a maximum number of up to 16 simultaneous calls and data sessions [5]. The last deployment option considers outdoor small cells, which are often called picocells. According to [4] they have a maximum transmit power of 37 dBm, and can support a higher number of users. The work carried out and presented in the paper considers strictly the residential femtocell case, and the terms small cell and femtocell will be interchangeably used.

In terms of spectrum usability the femtocells can be implemented in three distinct ways as illustrated in Figure 1.

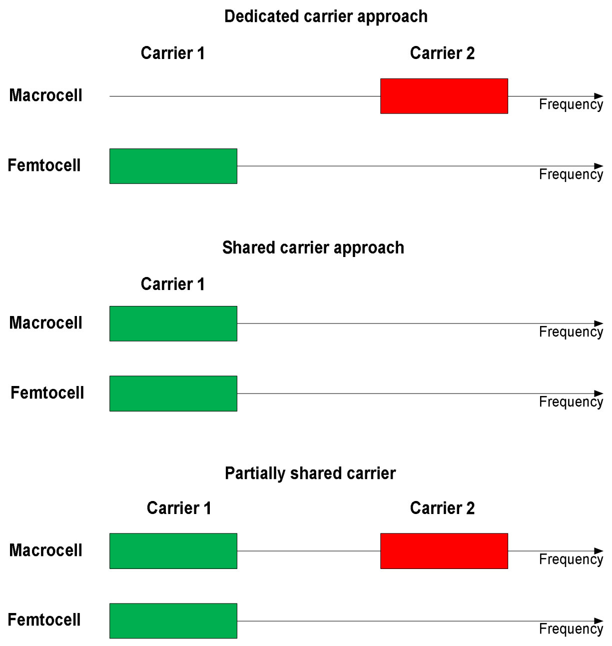

Figure 1. Spectrum allocation possibilities

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The dedicated carrier approach considers different carriers for both macrocell and femtocell. The main advantage in this case is that there is no interference between the two layers, which are acting like two distinct networks, from the radio spectrum usage point of view. The big disadvantage here is the low spectral efficiency and the need for the operator to have at least two carriers available.

The shared carrier approach, on the other hand has great spectral efficiency, considering that only one carrier is used for both macro-cellular and femto-cellular layers, but the main problem is related to the fact that there exists cross-layer interference, which can negatively affect the macrocell users.

As a compromise between the first two cases, the partially shared carrier approach considers at least two carriers, out of which one is strictly dedicated for the macrocell layer, and one which is shared between the macrocells and femtocells. In this way network outage is avoided, but in the same time having a better spectral efficiency.

Another important issue which needs to be taken into account when considering small cells deployment is related to the femtocell access mode, more specifically to the way that users may connect to the femtocell. In this sense, two access modes are defined: open access and closed access [4]. In open access permission to connect is given to all users, and the femtocell acts like an extension of the macro-cellular network, enhancing both coverage and capacity. For the closed access or Closed Subscriber Group mode, access is permitted to only a predefined list of users, for all the others the femtocell acts like an interference source, which may cause a degradation in macrocell network performance. The access modes selection is closely related to the spectrum allocation choice, as we will present later in the paper.

The rest of the paper is organized as follows: in section II the simulation scenario considering the environment with the macro-cellular layer and femto-cellular layer is described ; in section III the simulation parameters considered for this work are presented; section IV presents the obtained simulation results regarding the impact of femtocell deployment for the indoor and outdoor users, respectively; while section V concludes the paper and draws final remarks.

II. SCENARIO DESCRIPTION

The simulation environment consists of a typical residential area in the Transylvania area, Romania, with a street like scenario consisting of houses placed on both sides of the street. The houses have one floor with the rooms mainly aligned one after the other, and multiple entrances positioned on one side. The footprint of the house has a length of about 30 meters and width of about 6 meters. There is a distance of about 20 meters between the houses positioned on one side and the other of the street. For a larger scale scenario an additional area corresponding to back yard and garden must also be taken into account. The attenuations introduced by the materials, when considering perpendicular incidence angle of the waves, used in the construction of the houses, are presented in Table 1.

Wall type (Material used)	**Attenuation (dB)**
External wall (concrete)	15
Internal wall (concrete)	10
Light internal walls (sheetrock)	7
House gate (Thick wood)	5
Doors (Wood)	3
Windows (glass)	1

Table 1. Attenuations introduced by materials used for the construction of the houses.

The street like simulation environment is presented in Figure 2. In this scenario a variable number of femtocell base stations are deployed, with the condition that there can not be more than one base station per house. The houses in which the base stations are deployed as well as the position inside each house are randomly generated. To average the impact of these positions multiple simulation runs have been carried out.

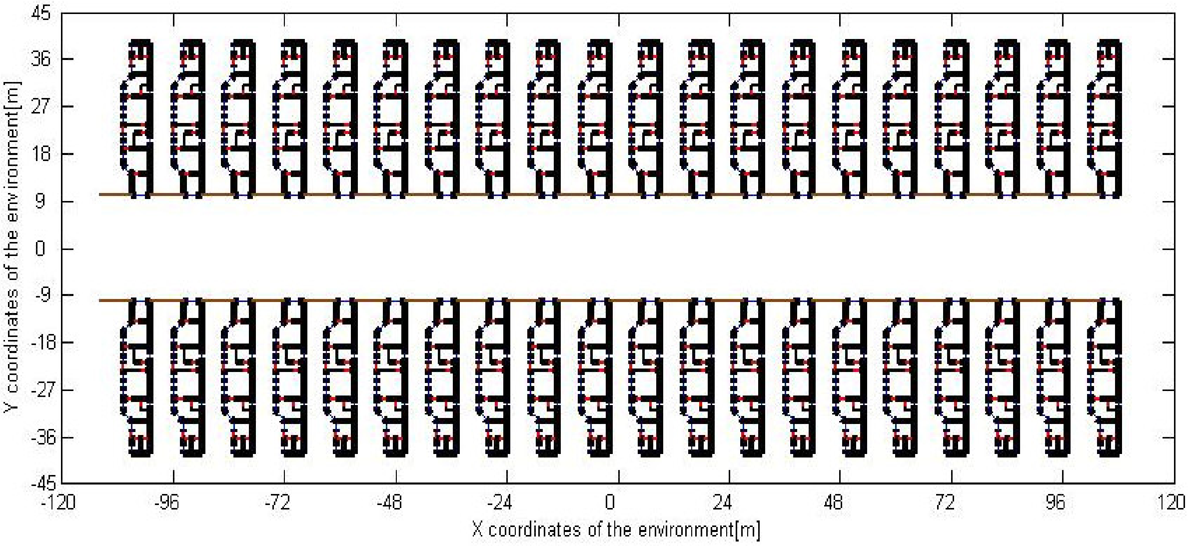

Figure 2. Residential simulation environment

The macrocell tier considered in the simulation consists of 19 macrocells with three sectors each. In one of the center macrocell's sectors the simulation environment presented above is considered. The macrocells' Inter Side Distance is considered to be 1732 meters [4], as for a typical residential environment. Figure 3 presents the considered macro-cellular system model.

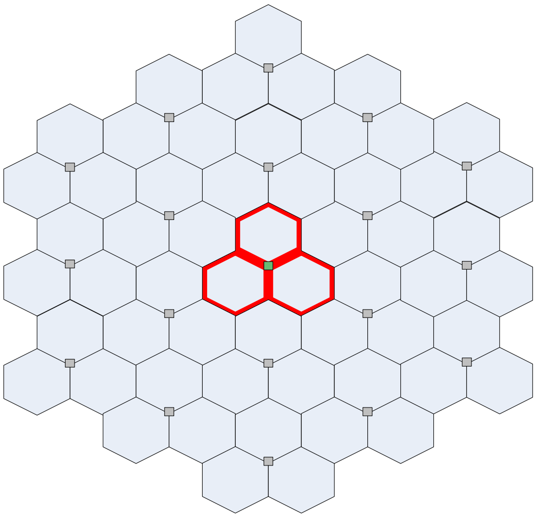

Figure 3. Macrocell system model.

The transmit power of the macrocell base station is considered to be fixed at 43 dBm [4], while the transmit powers of the femtocells, as well as their density is varied throughout the simulation. The default value for the transmit power of the femtocell is considered to be 20 dBm, while the default small cell density is 220 $smallcells \ / \ km^2$, which is equivalent to the case when one in every four houses has a femtocell implemented.

III. SIMULATION PARAMETERS

In order to investigate the impact of small cells deployment we need to simulate the above described scenario. Simulations are an accurate substitute for the real measurements if the correct simulation parameters are chosen. Therefore, Table 2 summarizes the parameters of the simulation model used in this study.

The propagation model considered in the simulation is characterised by a log-distance path loss model which uses the fixed and exponential coefficients from [4]. The amplitude change caused by shadowing is often modelled using a log-normal distribution with a standard deviation according to the log-distance model. The shadow fading maps were generated based on the method in [7] with the standard deviation parameters taken from [4].

Computer simulations were carried out in order to analyze the different deployment options that were described in the first section of the paper. In this sense, the street like environment was placed 500 meters away from the central macrocell base station. The simulation parameters were taken from Table 2, and if there is no otherwise mentioned they will be the same for all the simulations carried out in the paper.

The received signal strength on the downlink direction is calculated as:

$$P_{Rx} = P_{tx} + P_{loss} + P_{shadow} + P_{antenna} + P_{environment} \quad (1)$$

Where P_{tx} is the transmit power of the base station, femtocell or macrocell; P_{loss} is the path loss component calculated according to Table 2; P_{shadow} is the shadow fading component at the user location; $P_{antenna}$ is the antenna gain component specific for each type of antenna used: omnidirectional for femtocells and sectorial for macrocells, calculated according to Table 2; $P_{environment}$ is the attenuation caused by the environment objects, according to the values defined in Table 1.

Path-loss	Path-loss is modelled as $11.81+38.63\log_{10}(d)$ for macrocell users and $29.94+36.70\log_{10}(d)$ for small cell users where d is the distance from the base station in meters.
Shadow fading	Shadow fading is modelled as spatially correlated random process with log-normal distribution (6 dB standard deviation for the macrocell signal, 4 dB standard deviation for the femtocell signal, spatial correlation $r(x) = e^{x/20}$ for distance x.
Receiver noise power	The receiver noise power is modelled as $10\log_{10}(kT\ NF\ W)$ where the effective noise bandwidth is given as $W = 3.84 \times 10^6$ Hz, and $kT = 1.3804 \times 10^{-23} \times 290$ W/Hz. The noise figure at the UE is $NF_{[dB]} = 7$ dB.
Macrocell antenna gain	The macrocell antenna gain is calculated as $G(\theta)dB = G_{max} - \min\left[12\left(\frac{\theta}{\beta}\right)^2, G_s\right], \quad -\pi \le \theta \le \pi$ with $\beta = 70\pi/180$ angle where gain pattern is 3dB down from peak $G_s = 20$dB sidelobe gain level in dB $G_{max} = 16$dB maximum gain level in dB

Table 2. Simulation parameters overview.

Furthermore, in order to analyze interference limited networks, the signal to interference and noise ratio (SINR) parameter is taken into account, obtained at the user position and defined as

$$SINR = P_{Rs\_max} - (P_{interference} + P_{noise}) \quad (2)$$

Where P_{Rx_max} is the received signal strength from the best server; $P_{interference}$ is the sum of the contributions of all the other base stations; P_{noise} is the receiver noise power defined according to Table 2.

IV. SIMULATION RESULTS

Considering the equations given in the previous section, in this part of the paper we will analyze the impact of small cells deployment for both indoor and outdoor positioned users. Figure 4 presents a sample snapshot of the map of the received signal strength for the scenario described in the previous section. The results in Figure 4 are conducted considering a 20 dBm transmit power for all femtocell base stations, and a density of 440 $smallcells\ / km^2$, as can be seen from the figure.

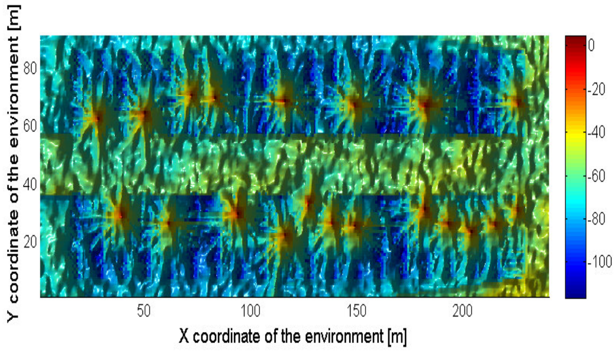

Figure 4. Snapshot of the received signal strength map

The results are presented for random locations within the environment and for random placements within the houses, of the femtocell base stations. The values of received signal strength are given in dBm, according to the color bar on the right hand side of the figure.

A. Indoor users

Femtocells are used in order to enhance the user experience, by providing a better coverage for the indoor environment and by growing the total capacity of the network. Therefore, Figure 5 presents the CDF of the received signal strength for the indoor users in the cases that we have only macrocells, and macrocells and femtocells with variable transmit powers with the values of 50 mW, 100 mW, 150 mW and 250 mW.

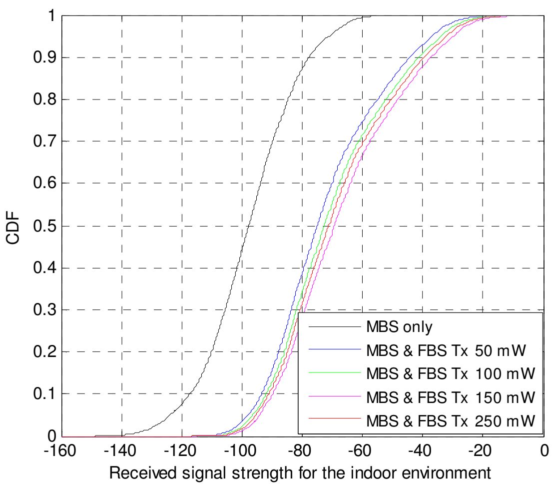

Figure 5. CDF of received signal strength for indoor users.

There is an obvious enhancement in the received signal strength for the indoor users, which was expected in some sense, given the fact that putting a new base station in close proximity of a receiver will surely increase the level of the received signal. Given the map displayed in Figure 4, we can see that there are leakages from the femtocells base stations, but they mainly affect the outdoor users, because due to the high attenuations introduced by the external walls of the houses, the influence of the neighboring femtocells upon the indoor users inside other houses is very low. Therefore, in next part of the paper we will concentrate on the effect that femtocells have on the outdoor users, which are connected to macrocells.

B. Outdoor users

Two very important factors which influence the impact of the femto-cellular layer upon the macro-cellular layer are the femtocell access mode and the spectrum allocation mode, defined earlier in the paper. In our analyses we have considered the shared carrier approach, in which all transmitter base stations use the same carrier. Therefore, we will have two major discussion points related to the femtocell access mode. The major difference between the two cases consists in the fact that using open access the outdoor macrocell users are able to connect to the femtocells, while in close access mode, the camping on femtocells is forbidden, this transforming the femtocells into very important interference sources.

Considering open access mode, we will investigate the influence of the femtocells upon macro-cellular users, in terms of the received signal strength obtained at the user positions.

First, we will investigate the influence of the femtocell density upon the macrocell users. The default transmit power is considered to be 100 mW and the positions of the femtocells inside the environment and within the houses is random. Multiple simulation runs have been made in order to eliminate the position dependency of the results. Figure 6 displays the CDF of the received signal strength for the outdoor users, in terms of the femtocells deployment density.

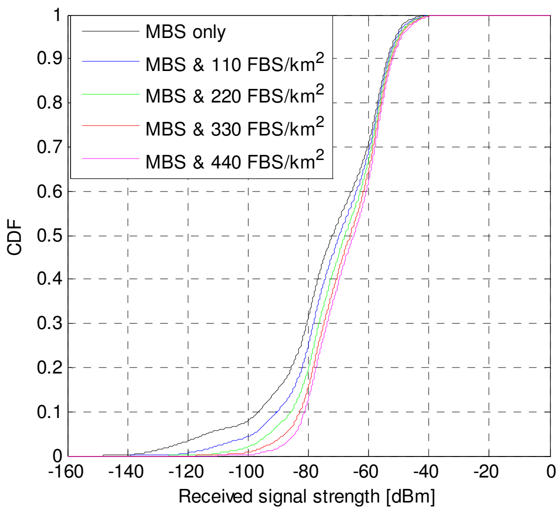

Figure 6. CDF of received signal strength as a function of femtocell density.

Because the open access mode is implemented, the femtocells become an extension of the traditional macro-cellular network. Therefore, if we have a higher density femtocell deployment, the received signal strength will be better. The highest femtocell density considered corresponds to having a femtocell base station in every two houses, which could be a feasible implementation in the near future. But, from the operators point of view, having a high density femtocell network, and considering a user moving along the street, the handover overhead will increase accordingly, taking a lot of resources. That is why solutions like the one proposed in [8] may be implemented with success.

Another analyses option that we considered in the paper is related to the influence of the femtocell base station transmit power. According to [4], the maximum allowed transmit power for residential femtocells is 250 mW, more than enough to assure coverage in a regular house. If we consider open access, this could be beneficial if the femtocell base station becomes the best server. However, a passing user situated outside of the houses will bounce from one base station to the other, leading again to a rise in mobility requests which could be problematic for operators. Figure 7 presents the CDF of the received signal strength for the outdoor users as a function of the femtocell base station transmit power.

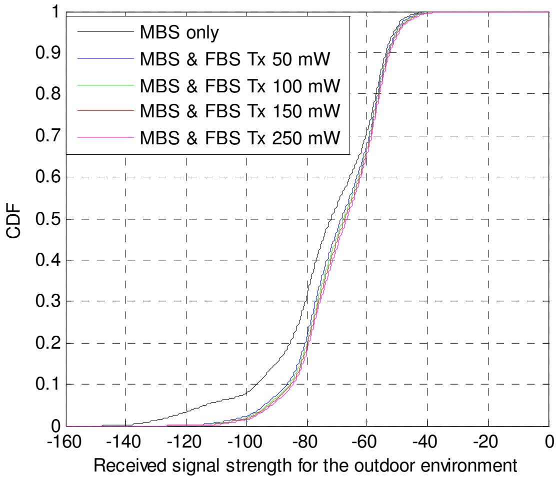

Figure 7. CDF of received signal strength as a function of femtocell transmit power.

For the results in Figure 7, the femtocell density was set to a default value of 220 $smallcells\ / km^2$. We can see that there is an enhancement in the global level of the received signal strength , but it is not that dependent on the transmit power of the femtocell. The difference in the level of received signal considering 50 mW transmit power and 250 mW transmit power, respectively for the femtocell base station, is of only 2 dBm.

Given the obtained results we can say that the predominant factor when it comes to the impact of femtocells upon the macrocell layer is consisted by the femtocell density, rather than the base stations transmit power. This is due to the fact that the houses provide a good isolation of the femtocell signal, making the transmit power of the femtocell base stations to have little impact from one value to the other.

If using open access mode the femtocells network can be considered as an extension of the macrocellular network, while when using the closed access mode, the femtocells become an important interference source. Practically, each femtocell base station has its own access list which contains the IMSIs of the user terminals that are allowed to connect to it. If an outdoor user is listed in the access list of the femtocell, then it has permission to handover to the femtocell, once this becomes the best server. Otherwise, the user will experience great interference because it will not be served by the strongest server, but by the one that it is subscribed to, in most cases a macrocell [5], which is far away.

In the next part of the paper we will investigate the impact of closed access femtocells upon the macrocell users when considering co-channel deployment. As for the open access mode, first we analyze the influence of the femtocell density. Given the fact that the most important issue when considering the closed access mode is the interference, as a reference parameter we will work with the signal to interference plus noire ratio (SINR), which will be calculated at the macro-cellular outdoor user positions.

Using equation (2) we have determined the CDF of the SINR in terms of the femtocell base station density. In Figure 8 results are displayed considering a strictly macro-cellular approach, and other different approaches which involve both macrocells and femtocells implemented with variable densities: 110, 220, 330 and 440 $smallcells\ / km^2$. The transmit power of the femtocell base stations is considered to be fixed to 100 mW, irrespective of their position.

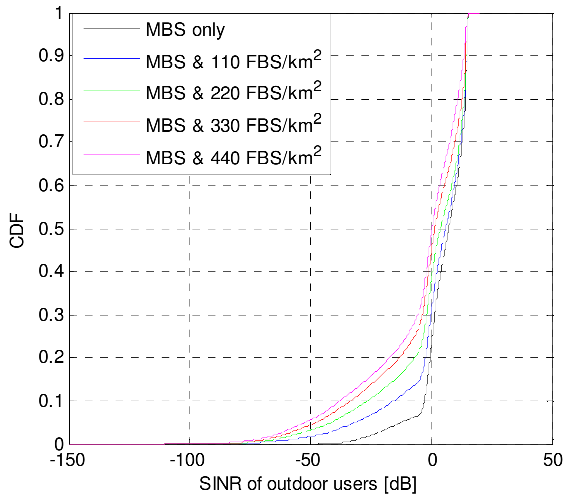

Figure 8. CDF of SINR as a function of femtocell density.

As can be seen from the figure, femtocells have a great impact on macrocell users when considering closed access mode within a co-channel deployment. The higher the density of the femtocell base stations, the higher the interference caused upon macrocellular users, which is reflected in the low level of the SINR value.

Considering the minimum SINR threshold of -6.5 dB below which the call session is dropped, the results shown in Figure 8 reveal the fact that there are areas in the environment in which the service can not be guaranteed. The size of the areas with coverage holes is directly proportional with the level of interference generated by the femtocell layer. For low density deployments, corresponding to an implementation of a femtocell in every eight houses, the results are acceptable considering that only about 15% of the outdoor environment is affected by the high interference which causes network outage. The percentage of outage grows to about 30% of the total area when the deployment density grows to one femtocell in every two houses.

Another simulation case that we considered in the paper refers to investigating the influence of the femtocell layer in terms of the SINR level obtained, as a function of the transmit power of the femtocell base stations. We consider a femtocell deployment density of 220 $smallcells\ / km^2$, with base stations randomly deployed throughout the environment and within the houses. In order to limit the position dependency, multiple simulations were carried out.

Figure 9 displays the results of the analyses which was done. As we can see from the figure, the femtocell layer has a negative impact upon the macrocell users when considering closed access within a co-channel deployment. As for the open access scenario, we consider the case when no femtocells are deployed and when macrocells and femtocells co-exist with a variable transmit power of the femtocell base stations of 50 mW, 100 mW, 150 mW and 250 mW. The macrocell transmit power is set to the default value of 43 dBm [4].

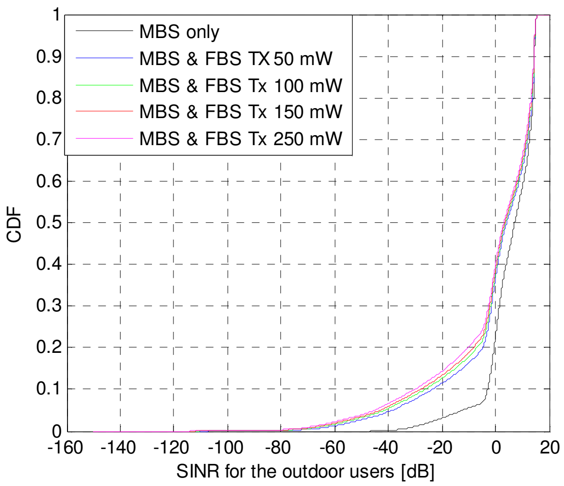

Figure 9. CDF of SINR as a function of the femtocell transmit power.

As for the case of the open access mode, the influence of the transmit power of the femtocell does not change significantly from one value to the other. Considering the same minimum threshold value of -6.5 dB below which the service is not offered, for the case of using a 50 mW transmit power of the femtocell base station, the outage percentage is about 18%, while in the worst case of using a 250 mW transmit power, the outage percentage is about 22%. This is due to the good isolation provided by the house environment.

Because residential femtocells are user deployed, the operator can not interfere in order to optimize the network performances, therefore self-optimization mechanisms are absolutely mandatory. That is why, it is very important, especially when using closed access, that the femtocell base station will have a power control algorithm implemented , as described by the authors of [9].

V. CONCLUSIONS

The authors of the paper managed to investigate the impact of femtocell base stations deployment in a typical residential environment, upon the traditional macrocellular network.

After conducting the simulation experiments a few conclusions can be clearly drawn: from the point of view of the indoor users situated in houses in which femtocell base stations have been deployed, there is an obvious enhancement in the level of the received signal strength, offering in this way a better level of the quality of experience; from the point of view of indoor users which are located in houses without femtocells, the impact of small cells deployment is very limited because of the good isolation of the walls of the buildings.

Considering outdoor users which are mostly connected to the macro-cellular layer, the influence of the small cells is mainly dependent on the access mode implemented. In the case of open access the femtocells network practically becomes an extension of the macro-cellular network enhancing the coverage not only indoors, but outdoors as well. In the case of closed access mode, the outdoor users which are listed in the access list of the femtocells are allowed access to the network through handover to the small cell, while for the ones that are not in the access list, the small cell acts like an important interference source which can seriously degrade the performances of the macrocell users, unless there are self-optimization capabilities implemented at the small cell base stations. Considering the obtained results, we can argue that the predominant factor in terms of the impact that femtocells produce upon the macro-cellular layer is the femtocell density, rather than the femtocell transmit power.

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