Abstract—Deployment of femtocells represents a promising solution to increase cost-capacity benefits for network operators and provide higher data rates to end-users. Femtocells are conceived to provide indoor wireless access to a cellular network through a Home Base Station, which is connected via internet to the operator’s core network, helping to improve coverage in indoors, offload the macrocell and reduce costs for operators. However, large scale deployment of femtocells can severely interfere with the existing macrocell within which they are deployed, particularly when operating in co-channel or in immediate adjacent channels with respect to the macrocell and when using a closed access policy. For instance, macrocell coverage holes in the downlink will appear, i.e. zones in the vicinity of a home base station where interference from home base station signals will prevent macrocell users to receive the desired service from the macrocell network. In this paper, we estimate macrocell coverage holes produced by closed access femtocells when both, macro and femto networks operate FDD WCDMA-based technologies. We investigate the case when the home base station transmits at constant power and when uses a power adjustment mechanism, and for different values of separation in the frequency domain. Results show that coverage holes at the edge of the macrocell can have a radius up to 30 meters when the same carrier is used and up to 5 m when carriers separated 5 MHz are used. Finally, we analyze and discuss how coverage and spectrum allocation are influenced by varying the carrier separation.

I. INTRODUCTION

New wireless standards such as 3GPPs High Speed Packet Access (HSPA) and Long Term Evolution (LTE), and IEEEs WiMax achieve considerable advancements in system capacity and throughput, but the deployment of macro cells results in high operational and capital expenditures. A way to increase cost-capacity of the networks is to deploy a large number of smaller and cheaper cells, i.e. femtocells. Femtocells will improve coverage in indoors, contributing to offload the macro network, yet very important considering that a large amount of wireless traffic is originated in indoors [1]. In addition femtocells will use a cheaper backhaul connection: internet. Not surprisingly, the case of femtocells has gained enormous support from the industry since it can represent a more cost-effective solution for wireless network operators than traditional deployments [2] [3].

Femtocells are conceived to provide indoor cellular access using licensed spectrum. It consists of a wireless access point referred here as Home Base Station (HBS), a low-power and short-range device which is connected to the operator’s core network via internet. The access policy to a femtocell is considered in two ways: open access, where any user belonging to the operator’s network can connect to the HBS and closed access, where only a group of authorized users can privately connect to the HBS. Open access to femtocells is suitable for public places and hot spots while closed access, is more suited for home and small-office scenarios. However, the use of closed access results in interference problems for user terminals connected to macro base stations (MBSs) if they are “close enough” to a HBS. Users connected to a macrocell will, in the downlink, experience a “coverage hole” around the femtocell, both for co-channel and immediate adjacent channel operation. Coverage holes refer to areas in the vicinity of a HBS where interference from HBS signals prevents macro users to receive the desired service from the macro network. The size of the coverage hole increases with the distance between the MBS and the HBS. Therefore, the situation becomes worse at macrocell edges. In this work, we study the impact of the interference from closed access femtocells to the macro cell network. Coverage holes are computed for indoor scenarios when the HBS transmits at constant power and when uses power adjustment. Moreover, we investigate coverage holes for different carrier separations between macro and femto carrier frequencies. The last case may be of interest for spectrum allocation and under spectrum regulation based on technology and service neutrality, see for instance [4].

The remainder of this paper is organized as follows. In Section II, we give an overview of previous studies on femtocells and interference analysis in cellular systems. Section III, describes the methodology used to calculate coverage holes in the different scenarios studied and also the assumptions considered for the simulations. In Section IV, we present and analyse the numerical results. Finally, we conclude this work in Section V.

II. RELATED WORK

Cellular systems have been deployed for many years using a layered approach with macro, micro and pico cells. The vendors also have a multitude of product offers with macro, micro and pico base station equipment. The radio resources management and handover issues using a hierarchical cell structure (HCS) are well known and researched for both GSM and WCDMA type of systems. Analysis of interference in hierarchical cellular systems is described in [5] with focus
on split spectrum and co-channel operation. The analysis of adjacent channel interference is usually performed for cases where the interfering and victim cells belong to the same cells layer. In our paper, we will focus on interference between cells belonging to different layers. Analysis of interference between macrocells and femtocells are presented in [6] [7], for the case of open access, in which coverage hole will not appear, except when too fast passing by terminals are unable to handover to the nearest femtocell. The situation is different for closed access and this is analysed in [8], which describes a similar deployment scenario as the one presented in our paper. Interference management and power control for macro-femto interference are described in some 3GPP reports. The need of power control for adjacent channel protection is discussed in [9] and a power control scheme is described in [10], however, without any details. Interference management through time hopped TH-CDMA and directional antennas are described in [11] with an analysis of the uplink performance. In summary, no previous work has looked into coverage holes as a function of the carrier separation and its implications. Moreover, power adjustment mechanisms have not been evaluated against coverage hole size.

III. METHODOLOGY AND ASSUMPTIONS

A. Scenario

We study a femtocell deployment in a large indoor area assuming a single-storey building. An area of 100×100 m² is considered and within which 9 non-overlapping HBS are deployed. The HBS is assumed to have a maximum transmission power of 20 dBm and an omni-directional antenna. It is also assumed that the coverage area of the HBS is circular shaped. The macrocell network consists of an hexagonal grid of 19 macrocells with a radius of 577 m each. MBSs are placed in the center of the hexagons and have an omni-directional antenna. Statistics are collected from the cell in the center of the hexagonal grid. The serving MBS transmits at its maximum power of 43 dBm, while neighboring MBSs transmit at an average of 41.76 dBm. In all the cases, the transmission power of the macro pilot signal, P-CPICH in 3GPP terminology, is 33 dBm and constant [10]. P-CPICH is the downlink pilot signal broadcasted by the MBS in WCDMA FDD systems with constant power and used for initial identification of scrambling codes. Both MBSs and HBSs transmit with 100% activity.

B. Carrier Separation Analysis

Co-channel and adjacent channel deployments are the cases currently being subject of a lot of studies, but considering other separation distances, less than 5 MHz, may be of interest for spectrum allocation. Of course by reducing carrier spacing the adjacent channel interference will increase and larger coverage holes will be produced. The amount of adjacent channel interference is modelled by means of the Adjacent Channel Interference Ratio (ACIR) which is given by:

$$ACIR_{DL} = \frac{1}{ACLR_{BS} + \frac{1}{ACSR}}$$

where ACLR stands for Adjacent Channel Leakage Power Ratio and is associated with filters and imperfections at the transmitter. On the other hand, Adjacent Channel Selectivity (ACS) accounts for the characteristics of the receiver. In this study we consider the ACIR in the downlink of a macrocell user terminal (UE). Current values according to the state of the art of the filter technology for these quantities are ACLR = 45 dB and ACS = 33 dB [9] [12]. The greater these values the lower the adjacent channel interference. Note that the asymptotic behaviour of Eq. (1) leads to ACIR=min(ACLR, ACS), hence for a carrier spacing of 5 MHz ACIR=ACS=33 dB. For carrier spacings lower than 5 MHz we model the adjacent channel interference as the integral of the total in-band power divided by the integral of the total power leaking in the adjacent channel. Within this model we consider two cases: 1) when the power spectrum of the transmitter is shaped by the spectrum mask [9] and 2) when the power spectrum of the transmitter is shaped by a root raised cosine (RRC) spectra. For the co-channel case, 0 MHz carrier spacing, the ACIR is 0 dB. ACIR values for the different carrier separations are (5 MHz, 4.8 MHz-spectrum mask, 4.8 MHz-RRC, 4.6 MHz-spectrum mask, 4.6 MHz-RRC, 0 MHz) which corresponds to ACIR = (33, 27, 14, 24, 11, 0) dB.

C. Coverage Hole Calculation

Macrocell coverage holes are computed taking into consideration minimum requirements for voice services. An approximation of this requirement is that the pilot carrier to interference ratio (P-CPICH $E_c/I_o$) is larger or equal to -18 dB [10]. Being $R$ the distance between the nearest macro BS and the serving HBS, $D$ the distance between the nearest BS and the macro UE, and $d$ the distance between the HBS and the macro UE, $E_c/I_o$ is calculated at a test macro UE, playing the role of a potential victim, which is placed at different distances ($d$) from a HBS following a path such that $D$ remains constant, and only the distance to the HBS, $d$, varies. The test UE starts at zero distance from the HBS and then moving away until averaged $E_c/I_o$ is above or equal to -18 dB. Then the largest distance from the victim to the HBS for which the averaged $E_c/I_o$ is below -18 dB, corresponds to the coverage hole radius (size), under the assumption that the coverage hole is circular shaped. Computations are also performed for different $R$s.

D. Downlink Model

We consider a WCDMA FDD based network for both macrocells and femtocells. In the downlink, at each snapshot we calculate the $P$-CPICH $E_c/I_o$ at a macro UE (victim) and then we take the average over all samples. Instantaneous $E_c/I_o$ in the downlink is obtained as:

$$\frac{E_c}{I_o} = \frac{RSCP}{RSSI} = \frac{c_k P_{CPICH_k}}{I_{M_k}} + \sum_{i \neq k} c_i P_{F_i} \frac{L_{F_i}}{L_{M_i}} + \sum_{j=1}^{H} \frac{s_j P_{HBS_j}}{L_{F_j} \text{ACIR}_j} + \frac{P_B}{L_{M_k}}$$

(2)
where RSCP is, in 3GPP terminology, the Received Signal Code Power, which in this case correspond to the pilot signal P-CPICH (RSCP\textsubscript{P-CPICH}). RSSI is the Received Signal Strength Indicator and is the total power sensed at the receiver that includes the power received by the serving MBS, the interference power from neighboring MBSs, the interference power from neighboring HBSs and the noise power at the receiver (\(P_{Bk}\)). ACIR is the amount of adjacent channel interference. \(P_{Tk}\) and \(P_{Fj}\) are the transmitter powers of the serving MBS and the neighboring MBSs, respectively. \(P_{HBSj}\) corresponds to the total transmitted power by the serving HBS and neighboring MBSs; \(c_i\) and \(s_j\) are log-normal shadow fading components for outdoors and indoors, respectively. \(N\) and \(H\) are the number of neighboring MBSs and HBSs, respectively. Finally \(L_{Mi}\) and \(L_{Fj}\) are pathloss models for the macro and femto networks for a frequency operation of 2 GHz (Table I). The carrier to interference ratio (CIR) for a data channel of a femtocell UE is modeled as follows [14]:

\[
CIR = \frac{c_i P_{Tk}}{L_{M} ACIR} + \sum_{i \neq k}^{N} \frac{c_i P_{Tk}}{L_{Mi} ACIR} + \sum_{j=1}^{H} \frac{s_j P_{HBSj}}{L_{Fj}} + P_{B} 
\]

(3)

For the CIR of the HBS pilot signal the amount of power assigned is 0.1\(P_{HBS}\).

\subsection*{E. HBS Power Adjustment}

We evaluate a mechanism for power control in the HBS based on measurements of the macro RSCP\textsubscript{P-CPICH} in adjacent channels. Since P-CPICH signals are available all the time, it is feasible to estimate if even if the adjacent channel belongs to a different operator. Moreover, estimation of RSCP\textsubscript{P-CPICH} is facilitated by the fact that is transmitted at constant power (33 dBm) which makes it easier the computations at the HBS. The RSCP\textsubscript{P-CPICH} is averaged over 100 transmissions slots and then the output power adjustment at the HBS is executed as follows:

\[
P_{HBS} = \min (\max (P_{HBSmin}, RSCP_{P-CPICH} + L_{F}), ACIR - Ec/IoTarget, P_{HBSmax}),
\]

(4)

where \(P_{HBSmin} = 0\) dBm, \(P_{HBSmax} = 20\) dBm, \(Ec/IoTarget = -18\) dB, \(ACIR = 33\) dB and \(L_{F} = 47\) dB (target coverage hole, see Table 6.3 in [9]). The estimation of the macro RSCP is affected by the tolerance of the sensor at the receiver. For instance a user terminal can have a tolerance of about 7 dB in its macro RSCP measurements (see Section 9.1 in [15]). We consider the case of perfect measurement and the case when the measurement error is log-normally distributed with standard deviation \(\sigma = 7\) dB.

\section*{IV. NUMERICAL RESULTS AND ANALYSIS}

In this section we present and discuss the simulation results. In the first subsection we compute coverage holes for different carrier spacing between femto and macro frequency carriers when the HBS transmits at constant power. Next, we look into macrocell coverage holes compared to femtocell coverage for adjacent channel (±5 MHz) operation and finally, we estimate coverage holes when the HBS is using a power adjustment mechanism and operates in adjacent channel.

\subsection*{A. Carrier Separation and Coverage Holes}

We consider four different carrier separations and two spectrum shapes: (5 MHz, 4.8 MHz-spectrum mask, 4.8 MHz-RRC, 4.6 MHz-spectrum mask, 4.6 MHz-RRC, 0 MHz) which corresponds to the following ACIR values = (33, 27, 14, 24, 11, 16, 0) dB. In Fig. 1, when the transmission power of the HBS is fixed to 20 dBm, the resultant coverage hole for a carrier separation of 4.8 MHz is considerably large at cell edge: ~18 m when using spectrum mask and ~8 m when using RRC. For co-channel operation (ACIR=0 dB), the coverage hole size might be even larger up to ~31 m. Results show enormous interference problems in co-channel operation. In general, reducing carrier separation leads to a considerable increment in the size of coverage holes. The adjacent channel interference modeling indicates significant differences when comparing the spectrum mask and the RRC models.

\subsection*{B. Macrocell Coverage Holes and Femtocell Coverage}

Fig. 2 shows the coverage hole size and the corresponding femtocell coverage area for a given macro RSCP. When HBS transmits at 20 dBm, its coverage area is about 6 m more than when it transmits at 10 dBm. In both cases the femtocell coverage area is highly affected when the HBS is close to the MBS (RSCP = -56.5 dBm), highlighting the macro to femto interference as major issue as well. Results confirm the need for a power adjustment even when femtocells operates in adjacent channel in order to reduce macrocell coverage holes at the cell edges.

\subsection*{C. HBS Output Power and Macrocell Coverage Holes}

We analyze the case when the serving HBS is transmitting at constant power of 10 and 20 dBm, and when uses the power adjustment method described in Section III-E. Also

\begin{table}[h]
\centering
\caption{Simulation Parameters}
\begin{tabular}{|c|c|}
\hline
Macrocell PL, \(L_{M1}\): & 128.1 + 37 log_{10}(R\text{[km]}) \\
\hline
& + W_{ex} + 15 log_{10}(m) dB \\
\hline
Femtocell PL, \(L_{Fj}\): & 38.5 + 20 log_{10}(d[m]) + 0.7[d[m]] dB \\
\hline
Shadow fading: & \sigma = 4 dB, indoors \\
\hline
& \sigma = 8 dB, outdoors \\
\hline
External walls, \(W_{ex}\): & 15 dB \\
\hline
Internal walls, \(W_{in}\): & 10 dB \\
\hline
Macro cell radius: & 577 m \\
\hline
Macro BS Tx. power (max.): & 43 dBm \\
\hline
Macro BS Ant. Gain: & 16 dB \\
\hline
Number of Macro BS: & 19 \\
\hline
Noise Figure (NF): & \\
\hline
Macro BS: & 4 dB \\
\hline
Home BS: & 7 dB \\
\hline
UE: & 7 dB \\
\hline
Noise Power (\(P_{Bj}\)) : & \mathcal{N}\mathcal{F}_{T/W} \\
\hline
Home BS Tx. power: & 20 dBm (max.), 0 dBm (min.) \\
\hline
Home BS RSCP accuracy: & ±7 dB \\
\hline
\end{tabular}
\end{table}
we compare it against the same power control mechanism but when taking into account an error measurement with a deviation standard \( \sigma = 7 \text{ dB} \). Fig. 3 evidences the advantage of the power adjustment over fixed power and maintaining coverage hole size less than 3 m for all macro received signal power values. However, this mechanism was designed to keep a coverage hole no larger than 47 dB, equivalent to 2.2 m according to the path loss model assumed here. The reason for this is that the mechanism only considers the strongest macro RSCP and there are indeed other interference sources such as neighboring MBSs. Nevertheless, the adjustment can be compensated to comply with the 2.2 m coverage hole. An improvement for the power adjustment mechanism will be to include a functionality in the HBS for detecting potential victims in its vicinity, such that it can transmit at full power if there are no macro UEs nearby. Figures 3 and 4 show the tradeoff that power control mechanism produces: macro UE protection and femtocell coverage. It provides high femtocell coverage (high CIR) and reasonable protection for potential victims (2-3 m coverage hole at cell edge) than fixed power transmissions. The correspondent levels of HBS output power are also showed, for instance for RSCP values less than -75 dBm the output power remains at 20 dBm while at the cell edge the power is adjusted to 13 dBm. Finally, the introduced error in the measurements of the macro RSCP at the HBS does not produce significant differences when compared to error-free measurements and the reason is that the algorithm takes the average of the RSCP and not instantaneous measurements; thus for good accuracy in the RSCP estimations an average of these values is needed to overcome measurements errors.

V. CONCLUSIONS AND IMPLICATIONS

We have studied the interference caused by femtocell deployments towards the macro network in the downlink. We estimated coverage holes by means of computer simulations demonstrating that, with constant power transmission, coverage holes can be up to 5.5 m large for adjacent channel operation and up to 31 m for co-channel operation. In general, when the separation between macro and femto carriers is less than 5 MHz the level of interference increases considerably. In adjacent channel operation a power adjustment based on macro RSCP measurements can offer macrocell users protection and high CIR levels for femtocell users. The power adjustment mechanism in the HBS could also use other inputs such as the list of surrounding user terminals such that if there are no potential victims in the vicinity, the HBS can transmit at maximum power and hence improve further the femtocell
coverage.

Figures 1 and 2, together, depict the implications for operators of the carrier separation and the respective size of the macrocell coverage hole. For co-channel and adjacent channel it assumes that the operators make use of allocated spectrum. These cases are illustrated by the two upper left pictures in Fig. 5, as an example of when the operators make use of all the allocated spectrum. However, for the cases where not all operator carriers are used the system performance can be improved by separating the carriers used for macro and femtocells. With this kind of usage of the allocated spectrum, see the upper right part of Fig. 5, the size of coverage holes can be reduced substantially. However, the target for operators would be to use all allocated spectrum. If the macro UEs are used for voice services, one possibility is to hand over to GSM at 900 or 1800 MHz. Of course this requires that the operator has GSM services but it also requires that the femtocells can be identified and distinguished from macro or micro base stations.

This feature is currently not supported by 3GPP but will most likely be introduced in future releases. Another possibility is that specific femtocell bands are introduced, possibly for all operators. Since the femtocells create interference in adjacent macrocell bands, a natural strategy would be to use one of the carriers next to another operator. Hence, only one of the “own” bands would be interfered. However, by using this strategy the adjacent band of the adjacent operator would be interfered. One possible way to mitigate this effect could be for operators to cooperate and to create “internal” guard bands, see lower part of Fig. 5. The created guard band between the own femtocell carrier and the adjacent macro carrier of the adjacent operator would result in a situation with almost no coverage hole in one of the macro carriers. The price to be paid is that more interference is introduced in the adjacent “own” macro carrier due to the decreased carrier separation. This is of course not an optimum solution but it provides some flexibility to operators to use the allocated spectrum. One possible application of this strategy could be when the farthest (in frequency) macro carrier is used in areas with the densest femtocell deployments.

**REFERENCES**


[9] 3GPP, “Universal Mobile Telecommunications System (UMTS); Base Station (BS) radio transmission and reception (FDD) 3GPP TS 25.104 version 8.5.0 Release 8”, 3GPP 2009.


