Interference Management and Performance Analysis of UMTS/HSPA+ Femtocells

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ABSTRACT

Femtocells are low-power cellular base stations that operate in licensed spectrum. They are typically deployed indoors to improve coverage and provide excellent user experience, including high data rates. Cellular operators benefit from reduced infrastructure and operational expenses for capacity upgrades and coverage improvements. Femtocells also bring unique challenges, such as unplanned deployment, user installation, restricted access, and interoperability with existing handsets and network infrastructure. Although femtocells may cause some interference to other users in the network, with the use of proper interference management techniques, this can be well controlled. We present interference management techniques for both downlink and uplink of femtocells operating based on 3GPP Release 7 standards (also known as HSPA+). Femtocell carrier selection and femtocell DL Tx power self-calibration are proposed as key interference management methods for downlink. For uplink interference management, adaptive attenuation at the femtocell and limiting the Tx power of the femtocell users are proposed. Different interference models and their analysis are presented. In addition, coverage performance and capacity results are presented to quantify the benefits of femtocells. We demonstrate that in addition to coverage enhancements, significant capacity improvements are achieved on both downlink and uplink when femtocells are deployed in 3G UMTS/HSPA+ networks.

INTRODUCTION

Femtocells are low-power base stations installed on the subscriber's premises for providing cellular service within the home or enterprise environment [1]. Typically femtocells are connected to the Internet and the cellular operator's network via a digital subscriber line (DSL) router or cable modem. Femtocells offer benefits for both subscribers and operators. Subscribers experience better voice service coverage and higher data throughput. Special service plans can provide additional incentives for home use (e.g., free calls from home). Operators are able to offload traffic from the macrocellular network, thus reducing infrastructure cost. Moreover, indoor coverage problems can be resolved without deploying expensive macro base stations. Operators also have an interest in ensuring that their mobile devices are used in the home despite the availability of other technologies (e.g., Wi-Fi). Such "stickiness" of their features and services helps reduce churn. Finally, it supports a transition from wire line service to exclusive use of wireless devices at home.

Recognizing these benefits, different operators, vendors, and content providers founded the Femto Forum, which is a membership organization to promote femtocell deployments worldwide [2]. Also, recently some cellular operators have launched commercial femtocell products or have been conducting trials with femtocells.

In addition to their benefits, femtocells also introduce a set of basic challenges due to the following factors:

- *User installation*: Femtocells are installed by subscribers without special training or knowledge regarding antenna placement and system configuration. Because of this, the femtocell should be capable of self-configuration.
- *Unplanned deployment*: Unlike a macro network, femtocells are deployed without network planning; no special consideration is given to traffic demand or interference to/from other cells.
- *Restricted association (or restricted access)*: To protect the use of limited resources (femtocell capacity, DSL/modem connection), femtocells may be configured to limit access to only a few authorized subscribers (e.g., family members or hotel guests).
- *Legacy system support*: Currently available handsets are femto-unaware; femtocells need to support these handsets as well as femto-aware handsets. Moreover, they need

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to interface with existing access and core networks.

Since radio frequency (RF) coverage of femtocells is not manually optimized by the cellular operator and deployment is generally ad hoc, RF interference issues may arise unless appropriate mitigation methods are utilized. Furthermore, due to the limited spectrum available to operators, macrocells and femtocells can share at least one frequency in order to increase efficiency of spectrum use. In the following we outline potential RF interference issues related to femtocell deployments.

Interference between macro and femto cells: Due to the restricted access requirement, femtocells can cause interference on both the uplink (UL) and downlink (DL). For example, a femtocell installed inside near a window of a residence can cause DL interference to handsets outside the house (i.e., macrocell handsets) that are not served by the femtocell. Home handsets that are served by a certain femtocell can also cause interference to the uplink of macrocell handsets.

Inter-femto Interference: Femtocells can also create interference to each other due to unplanned deployment. For example, in a multi-apartment structure femtocells installed near a wall separating two apartment units can cause interference to neighboring apartment units. In such a case, the strongest femtocell for a home handset (in terms of RF signal strength) may not be the serving femtocell due to the restricted access requirement described above.

In this article we describe the main interference management techniques for femtocells that use Third Generation Partnership Project (3GPP) Release 7 standards, also known as high-speed packet access (HSPA) evolved, or HSPA+. The focus is on frequency-division duplex (FDD) systems. To achieve the desired performance, the following interference and mobility management methods need to be employed as part of the femtocell design:

- Calibration of femtocell downlink transmit power to limit interference to the macro network while providing good coverage for the femtocell user
- Adaptive UL attenuation at the femtocell to mitigate interference caused by a nearby interfering macro and/or femto user not controlled by the femtocell
- Carrier selection for femtocells combined with inter-frequency handover for macrocell users to avoid inter-femto and femto-to-macro interference
- Limiting a femtocell user's uplink transmit power to minimize the interference caused to the uplink of the macro network

Furthermore, we present detailed system-level simulation results to quantify the coverage performance and capacity with and without femtocells.

In terms of prior work in this area, the Femto Forum published a study analyzing different interference scenarios between femtocells and macro networks [3]. 3GPP also published a technical recommendation document on interference management [4]. Lastly, [5] presents an analysis of call drop probability for femtocells.

The remainder of the article is organized as follows. We introduce the terminology used in the article. We describe the propagation and simulation models. We describe the proposed interference management methods for downlink and uplink, respectively. Interference analysis for simple interference models are presented. We present coverage and capacity performance based on system-level simulations. Finally, conclusions are given.

Femtocells can cause interference both on the UL and DL. For example, a femtocell installed inside near a window of a residence can cause DL interference to the handsets outside the house (i.e., macrocell handset) that are not served by the femtocell.

Terminology

In this section we define the terminology used throughout the article. For consistency, we mostly use the 3GPP terminology in this article [4]. A femtocell is denoted as a home NodeB (HNB) whereas a macro base station is called a macro NodeB (MNB). Femtocell users are referred to as home user equipment (HUE). Similarly, a macro network user served by an MNB is macro user equipment (MUE). Due to the restricted access requirement, MUE is not allowed to be served by femtocells. Also, conforming to 3GPP terminology, a macro sector is referred to as a cell.

RF Propagation and System Simulation Models

In this article we use both basic interference models as well as system simulation models to analyze the performance of HNBs. The basic interference models are intended to demonstrate interference under simple scenarios. In addition, to study interference issues at the system level, a dense urban model is developed to capture system-level femto-femto and macro-femto interactions.

Basic Interference Models

The Femto Forum recently published a report [3] that evaluates extreme cases of macro-femto interference based on both co-channel and adjacent channel deployment. Some of the considered co-channel interference scenarios are provided in Table 1.

The downlink and uplink interference is also studied in [4] using a "simple" model, shown in Fig. 1. For this model, two scenarios are considered: cell edge and cell site. This simple model captures the DL interference from HNB to nearby MUE and the uplink interference from the MUE to HNB. The assumption is that the femto and macro are on the same carrier frequency.

Dense Urban System Simulation Model

For system-level simulations, we consider a dense urban deployment scenario corresponding to densely populated areas. We simulate multiple cells in the macrocell network and drop multiple apartment buildings in the macro network where each building has multiple floors with 10 apartment units per floor. Each apartment unit is 10 m × 10 m and has a 1-m-wide balcony. The probability that HUE is on the balcony is assumed to be 10 percent. We drop 2000 apartment units in each cell; 96 of them have HNBs installed, and 12 HNBs are simultaneously active. If an HNB is active, it will transmit at full power

To limit the impact of femtocells on existing macrocell networks, it is desired to minimize the amount of interference created by the HNB. On the other hand if the HNB Tx power level is too small, proper femto coverage cannot be maintained inside the home.

Scenario	Description
Macrocell downlink interference to the femtocell UE receiver	A femtocell UE receiver, located on a table next to the apartment window, is in the direct bore sight of a rooftop macrocell (approximately 30 m distance). The macrocell becomes fully loaded while a femtocell UE is connected to the femtocell at the edge of its range.
Macrocell uplink interference to the femtocell receiver	A femtocell is located on a table within the apartment. Weak coverage of the macro network is obtained throughout the apartment. User device UE1, which does not have access to the femtocell, is located next to the femtocell and has a call established at full power from the UE1 device. Another device, UE2, has an ongoing call at the edge of femtocell coverage.

Table 1. *Examples of macro-femto interference scenarios investigated recently by the Femto Forum [3].*

on DL; otherwise, it will transmit only the pilot (CPICH) and overhead channels. MUE is also dropped randomly into the macro cell such that 30 percent of the MUE is indoors. Details of the dense urban model and corresponding propagation models can be found in [6] and [7].

Downlink Interference Management for HNBs

Due to restricted association, unplanned deployment and low isolation, HNBs can cause downlink interference to the macro network and neighboring HNBs. The following key interference management techniques are used to limit the downlink interference of HNBs to the macro network and other HNBs while providing good coverage for the HNB users. As part of these methods the HNB needs to have a "sniffing" function that enables the HNB to perform RF measurements such as received signal strength indicator (RSSI), which is the total received power spectral density (also called Io), and CPICH Ec/Io, which is the ratio of the received pilot energy to the total received power spectral density at the UE on the macro and femto DL channels.

HNB Autonomous Carrier Selection and Inter-frequency Handover for Macrocell Users

Each HNB needs to be configured for a certain carrier frequency or Universal Mobile Telecommunications System (UMTS) terrestrial radio access (UTRA) absolute radio frequency number (UARFCN) for operation. Such a carrier selection mechanism depends on the particular deployment configuration. Our analysis with the dense urban model described above shows that single carrier allocation to HNBs would be sufficient for most cases. However, for very dense deployments there could be certain amounts of inter-HNB RF interference. One solution for addressing the inter-femto interference issue would be to use multiple carriers for HNBs. For example, HNBs in neighboring apartments can be assigned to different frequency carriers to mitigate the potential interference problems. To achieve this goal, one carrier can be assigned as the "preferred" carrier for femtocells, and during self-calibration the HNB can pick this particular carrier unless there is significant interference detected on this carrier. Otherwise, HNB can choose to operate on the "secondary" carrier designated for HNBs.

When a macrocell network operates on the same carrier as HNBs, HNB-macrocell interference can result in a certain amount of outage and performance degradation for MUE. One solution for mitigating the HNB-macro interference would be to make sure the carrier(s) used by HNBs are not used by the macrocell network. Although this method reduces HNB-macro interference noticeably, it is not efficient in terms of spectrum utilization, especially if HNB deployment density is not high. For most operators with limited carriers (e.g., two or three carriers), sharing the carriers between HNBs and macrocell network would be preferable. In this case, HNBs can be deployed on the least used macrocell carrier(s), and if a mobile MUE still experiences significant interference from an HNB, the macrocell network can perform inter-frequency handover of that MUE to another macrocell carrier frequency.

Coverage and capacity results in this article focus on the case where one carrier is shared by femtocells and macrocells. Other available carriers are used by macrocells only.

HNB DL Tx Power Self-Calibration

To limit the impact of femtocells on existing macrocell networks, it is desired to minimize the amount of interference created by the HNB. On the other hand, if the HNB transmit (Tx) power level is too small, proper femto coverage cannot be maintained inside the home. For example, when a femtocell is close to a macro NodeB, larger Tx power levels would be required to provide adequate femto coverage. Thus, it is desirable to have a method to adaptively adjust the HNB Tx power level depending on macrocell signal levels.

For this purpose, as design metrics, the following quantities can be used by HNBs:

HNB_Link_Budget = Maximum path loss within which HNB coverage is expected (e.g., 80 dB)

HNB_MUE_Min_Pathloss = Minimum path loss allowable between HNB and MUE, such that the MUE still achieves acceptable service on an adjacent carrier (e.g., 47 dB)

Ecp/Io_min_MUE = Minimum CPICH Ec/Io value required to provide acceptable service for the MUE (e.g., –18 dB)

Ecp/Io_min_HUE = Minimum CPICH Ec/Io value required to provide acceptable service for the HUE (e.g., –15 dB)

Each HNB measures the total received signal strength (RSSI or *Io*) from all the other NodeBs (including MNBs and HNBs). It also measures the pilot strength from the best MNB. Based on these measurements, the HNB can determine its transmit power as follows [4, 6]:

- To maintain CPICH Ecp/Io value of *Ecp/Io_min_MUE* for MUE located *HNB_Link_Budget* away from the HNB on the same channel (i.e., protect the co-channel macro user)
- To maintain an Ecp/Io value of *Ecp/Io_min_MUE* for a MUE located *HNB_MUE_Min_Pathloss* away from the HNB on the adjacent channel (i.e., protect the adjacent channel macro user)
- To make sure that HNB is not causing unnecessary interference by enforcing a cap on Ecp/Io value of the HUE of *Ecp/Io_min_HUE* at *HNB_Link_Budget* away from the HNB

Note that the above algorithm can be achieved by DL RSSI and CPICH Ecp/Io measurements performed by the HNB, assuming these measurements are representative for UE RF experience in the vicinity of the HNB. In practice, there can be a mismatch between the RF conditions measured by the HNB and those experienced by the HUE and MUE, which could result in inaccurate estimation of HNB coverage/interference. However, performance of the algorithm can be further improved by using HUE measurement feedback to complement the HNB measurements since HUE could sample different locations around the HNB with slightly different RF characteristics. At the same time, idle-mode registration attempts to the HNB by nearby MUE can also be used by the HNB to adjust its transmit power. For example, if the HNB observes too many registration attempts by nearby MUE, it can reduce its transmit power to limit the interference to MUE. In addition, if measurements from nearby MUE are made available to the HNB by the macro network, the measurement reports could be used by the HNB to fine-tune its transmit power.

If a unit of MUE still experiences interference from a nearby HNB, the MUE can be moved to another frequency by the macro network.

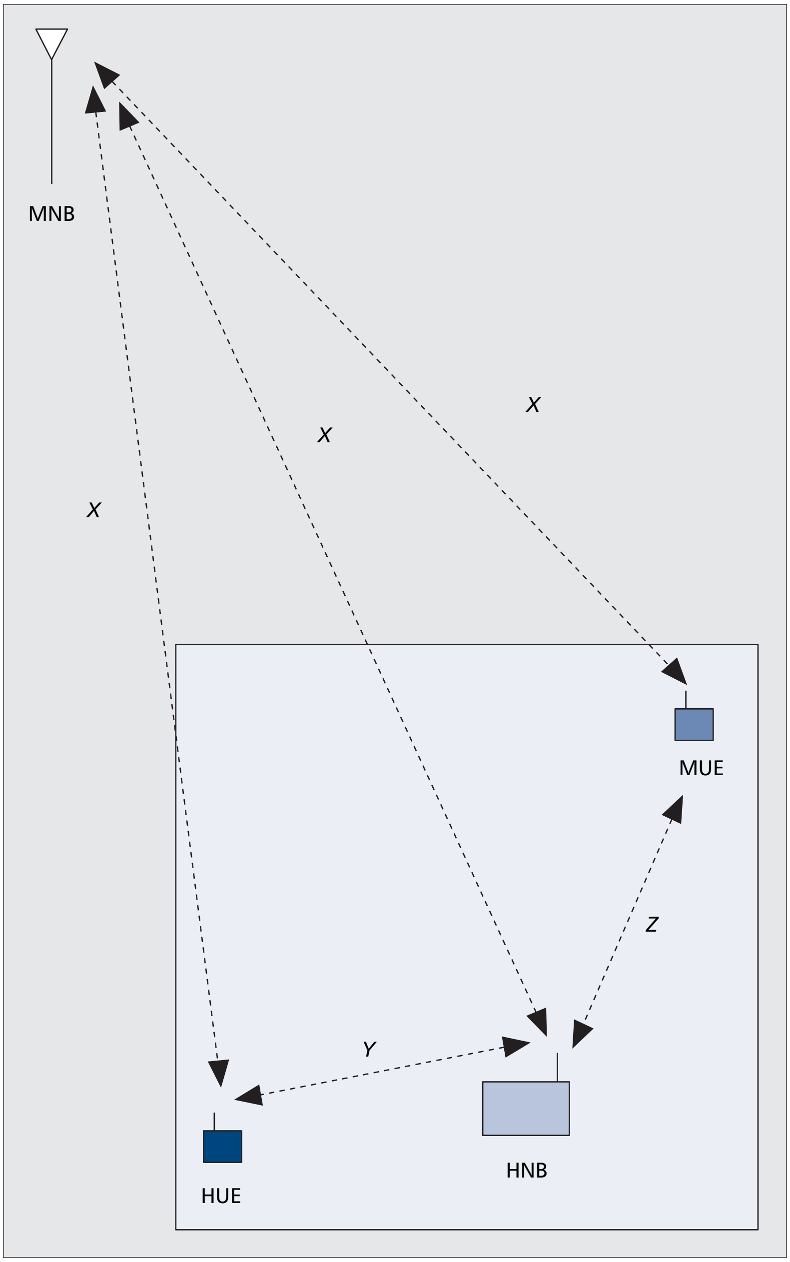

Figure 1. *Simple femto-macro interference model.*

Uplink Interference Management for HNBs

Due to restricted association, unplanned deployment and low isolation, HNBs can experience significant uplink interference from nearby uncontrolled UE (MUE or HUE). In addition, HUE can cause uplink interference to the macro network and neighboring HNBs. The following key interference management techniques are needed to mitigate the uplink interference at the HNB and to limit the uplink interference caused by HUE to the macro network and other HNBs.

Adaptive UL Attenuation

Since the minimum coupling loss between UE and an HNB can be as low as 30–40 dB, UE can cause very high signal levels at the HNB, from both HUE that cannot be power controlled down due to minimum UE Tx power limitation and out-of-cell (restricted) HUE and MUE. One solution for this would be to use a large noise figure value (or attenuation) at the HNB front-end to bring the signal to the appropriate level for further processing. However, as a result of the high noise figure, HUE transmit power values will increase even when there is no interfering MUE, and this will result in unnecessary UL interference to MNBs. This is particularly important if the HNB happens to be close to a macrocell. Thus, instead of simply increasing the noise figure to a constant level, it is more desirable to adjust HNB UL attenuation adaptively only when needed. Another scenario is when HUE is near a neighbor's wall and causes significant interference to the neighbor's HNB. In this case, applying fixed attenuation at both HNBs will not

Parameters	Cell edge	Cell site
X: PL to MNB (dB)	140	100
Y: PL_HUE_HNB (dB)	80	80
Z: PL_MUE_HNB (dB)	80	80
RSSI (dBm)	–95	–60
MNB RSCP (dBm)	–107	–67
MNB maximum Tx Power (dBm)	43	43
MNB Tx CPICH Ec (dBm)	33	33
HNB CPICH Ec/Ior (dB)	–10	–10
MNB load factor (%)	50	50
HNB load factor [%]	100	100

■ **Table 2.** *Parameters for the simple femto-macro interference model.*

	P_{HNB} = –10 dBm	P_{HNB} = +10 dBm	Calibrated HNB power (P_{HNB} = –10 dBm)
MUE Ecp/Io (dB)	–18	–37	–18
HUE Ecp/Io (dB)	–11	–10	–11

■ **Table 3.** *Cell edge macro and femto coverage with fixed and calibrated HNB Tx power. Power calibration results in desired performance for both MUE and HUE.*

	P_{HNB} = –10 dBm	P_{HNB} = +10 dBm	Calibrated HNB power (P_{HNB} = 17 dBm)
MUE Ecp/Io (dB)	–7	–7	–9
HUE Ecp/Io (dB)	–40	–20	–15

■ **Table 4.** *Cell site macro and femto coverage with fixed and calibrated HNB Tx power. Power calibration results in desired performance for both MUE and HUE.*

solve the UL interference problem. Instead, we only need to increase the UL attenuation at the "victim" HNB. To manage the UL interference, we propose an adaptive UL attenuation algorithm that applies just enough attenuation only when needed to react to high out-of-cell interference as well as high signal level due to HUE that cannot be power controlled down. An HNB can compute out-of-cell interference by first summing up the energy of all the in-cell users tracked by the HNB. Out-of-cell interference will be obtained by subtracting the in-cell energy and noise floor from the total received energy on the uplink. In the presence of high out-of-cell interference, attenuation is applied at the HNB UL receiver to bring the out-of-cell interference level down to be comparable to the thermal noise level. This allows the HUE to be power controlled up to overcome the interference. In addition, fluctuations of the received signal levels must also be considered. For example, if an MUE with bursty UL traffic is in the vicinity of HNB, it can create large variations in the UL signal-to-interference ratio (SIR) of HUE connected to the same HNB. The usual power control loops are not designed for this situation, and unstable system operation can result. We propose to decay the attenuation slowly when the jammer/interference source disappears. This slow decay provides robustness against bursty interferers in the sense that the attenuation is mostly maintained when the next burst arrives and the served HUE already transmits with sufficient power. More details on the method can be found at [7]. The simulations reported below use this method. Alternatively, the attenuation can be reduced when the interference disappears while the HUE power control loop still temporarily maintains the power levels of the served HUE.

LIMITING HUE TX POWER

As a safety mechanism and to limit the uplink interference caused by HUE to the macro network (or neighbor HNBs), the HNB can estimate the path loss to the nearest MNB (and/or HNB) and use this estimate to limit the maximum Tx power of the HUE. The path loss to the nearest MNB (and/or HNB) can be estimated by the HNB by measuring the other cell's DL signals.

ANALYSIS OF SOME INTERFERENCE SCENARIOS

This section considers two main problems: the setting of the HNB DL power and the impact of bursty UL interference from MUE on HNBs. To analyze femtocell DL Tx power requirements for different femtocell locations in a macrocell, we use the simple model described in Fig. 1. We focus on two specific locations: the macrocell edge and macrocell site as shown in Table 2. The corresponding HUE and MUE Ecp/Io for fixed and calibrated HNB Tx power are given in Tables 3 and 4 for the cell edge and cell site, respectively. It is seen from the table that at the cell edge, low HNB Tx power is needed to limit the coverage hole for the macro user. On the other hand, at the cell site, larger HNB Tx power is needed to provide good HNB coverage for the home user. The HNB Tx power calibration proposed earlier autonomously adjusts the HNB Tx power to an appropriate level so that both MUE and HUE achieve acceptable performance.

To analyze the UL interference impact of MUE on HNBs, we focus on the cell edge case and consider the scenario where MUE has bursty traffic. The MUE traffic model is such that every 2 s, a burst of 38 packets arrive. In Fig. 2 rise over thermal (RoT, i.e., noise rise) at the HNB and received Ecp/No (received DPCCH energy per chip over the total noise power spectral density) of the HUE is plotted with and without the proposed adaptive attenuation algorithm. As seen in the figure, the algorithm ensures stable

UL operation and good user experience by significantly reducing the RoT and Ecp/No fluctuations caused by incoming interference bursts.

Coverage and Capacity Analysis

In this section we provide coverage analysis and DL and UL throughput results with and without HNB deployment for the dense urban model described earlier.

Coverage Analysis

In this section we obtain coverage statistics for the HUE and MUE of a two-frequency deployment in which one frequency (*f1*) is shared by macro and femtocells, and the other frequency (*f2*) is used by macro users only. The two frequencies are assumed to be adjacent with an adjacent channel interference ratio (ACIR) of 33 dB. We assume that out of the 96 HNBs per cell, 12 are active and hence transmit at full power, while the remaining ones transmit pilot and overhead only (i.e., 20 percent of total power). Restricted association is assumed throughout. We assume an Ecp/Io threshold of –20 dB to declare UE in outage. MNBs are assumed to be 50 percent loaded, which means they transmit at 50 percent of full power (i.e., 40 dBm). It is also assumed that 10 percent of full power is allocated to CPICH for both MNBs and HNBs. In addition, we take into account the idle-mode cell reselection procedure to determine whether HUE is camped on its HNB or an MNB, or is in outage (or moved to a third frequency). The idle-mode cell reselection parameters are set such that priority is given to HNBs over MNBs when UE is performing idle cell reselection. However, a minimum Ecp/Io of –12 dB is enforced for HNBs so that idle-mode cell reselection to an HNB happens only when the HNB signal quality is good. MUE is said to be in outage if it does not have macro coverage on both *f1* and *f2*. HUE is said to be in outage if it is not able to get coverage from either its own HNB on *f1* or MNBs on *f1* and *f2*. Table 5 summarizes the coverage statistics with and without HNBs. The HNBs are assumed to use the DL Tx power self-calibration algorithm described earlier with min and max HNB Tx power of –10 dBm and 20 dBm, respectively. For the no-HNB case, the so-called HUE, located inside apartments, need to get coverage from the MNB.

It is seen from the coverage statistics in Table 5 that HNBs eliminate outage for indoor users without any noticeable impact on the macro coverage. When no HNBs are deployed, almost 5 percent of the "would-be HUE" is in outage since it is indoors and does not have macro coverage. When HNBs are deployed, these users are able to get coverage from their own HNB. When indoor outage was larger due to poor macro coverage (e.g., different deployment scenarios than the dense urban model used in this article), deploying HNBs would again eliminate outage for indoor users. The results also show that about 96 percent of the HUE is camped on its own HNB. The remaining 4 percent has very good macro coverage and hence camp on the macro (either on *f1* or *f2*), similar to the case described earlier using the basic interference model. Moreover, MUE whose coverage is affected by the HNBs can get macro coverage on *f2*; hence, the overall MUE outage does not change when HNBs are deployed. The results in Table 5 highlight the benefits of HNBs in terms of improving UE coverage indoors. More important, this UE coverage improvement can be obtained without any adverse effect on the macro network.

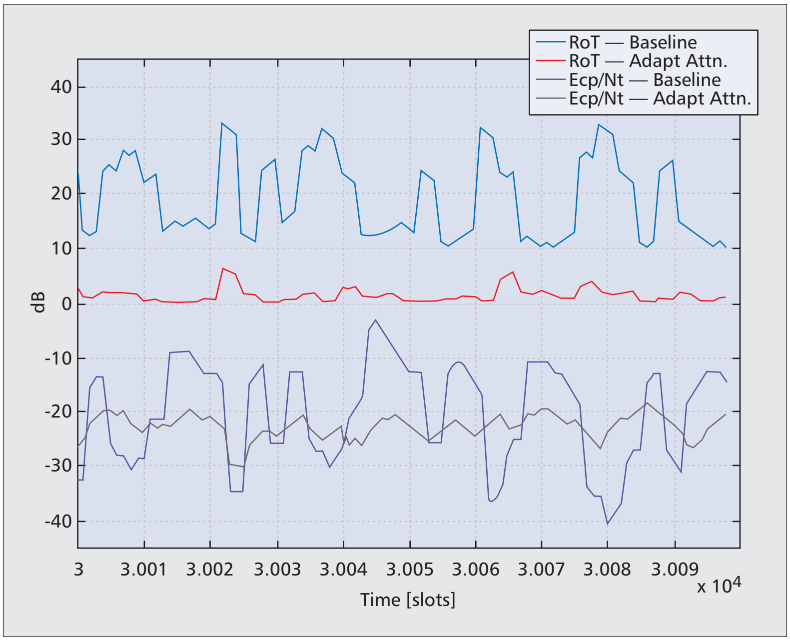

Figure 2. *HSPA+ HNB UL performance with bursty interference. The adaptive UL attenuation algorithm ensures stable UL operation and good user experience in the presence of strong bursty interference.*

Category	With HNB deployment	Without HNB deployment
MUE in outage	2.7%	2.7%
HUE camping on own HNB	96%	N/A
HUE in outage	0%	4.9%

Table 5. *Coverage statistics for dense urban two-frequency deployment. HNBs eliminate outage for indoor users without any noticeable impace on the macro coverage.*

Capacity Analysis

To demonstrate the benefits of HNBs in terms of capacity improvements, in this section we present system-level simulations and compare the HSPA+ UE throughput performance on both DL and UL with and without HNBs for the two-frequency deployment scenario under consideration.

We use a detailed slot-level system simulation tool to obtain the HSPA+ UE DL and UL throughput distributions on the frequency shared by femto and macro users (i.e., *f1*). The system simulator captures all the data and overhead channels, and models DL and UL scheduling, hybrid automatic repeat request (H-ARQ) transmissions as well as fading channels. We assume

[1] *Note that the indoor users drain significant portion of RF resources due to relatively poor RF environment. Offloading these users to HNBs provide disproportional gains for remaining users in the macrocell.*

a Rician channel with Rician factor $K = 10$ and 1.5 Hz Doppler frequency. There are 96 HNBs per macro cell on carrier *f1*, out of which 12 have active HUE (i.e., in CELL_DCH state). There are also 10 active units of MUE per macro cell on carrier *f1*. For the case where HNBs are deployed, there are 12 units of HUE and 10 of MUE per macro cell. For the case where there are no HNBs, the 12 units of UE (previously referred to as HUE) are served by the macro, and hence there are a total of 22 (10 + 12) UE units per cell, which are served by macro. Only UE that is not in outage are included in the simulations (Table 5). The UE in outage is included in the cumulative distributed functions (CDF)s as zero throughput.

On the DL a maximum modulation of 64-quadrature amplitude modulation (QAM) is assumed with one receive (Rx) antenna at the UE. On the UL, the minimum and maximum transmit power for the UE are set to –50 dBm and 24 dBm, respectively. Also, adaptive UL attenuation is assumed at the HNBs.

Figures 3 and 4 show the HSPA+ throughput CDFs on the shared frequency with and without HNB deployment for the DL and UL, respectively. It is observed from Figs. 3 and 4 that very significant capacity gains are achieved when HNBs are deployed. The capacity offload benefits both HUE and MUE since:

- The HUE units achieve very high data rates since they are the only users served by the HNB.
- Since some users are now served by HNBs, the remaining MUE units can receive more resources from the macro network and hence achieve better DL throughput.[1]

Further details on the simulations and results can be found at [6, 7].

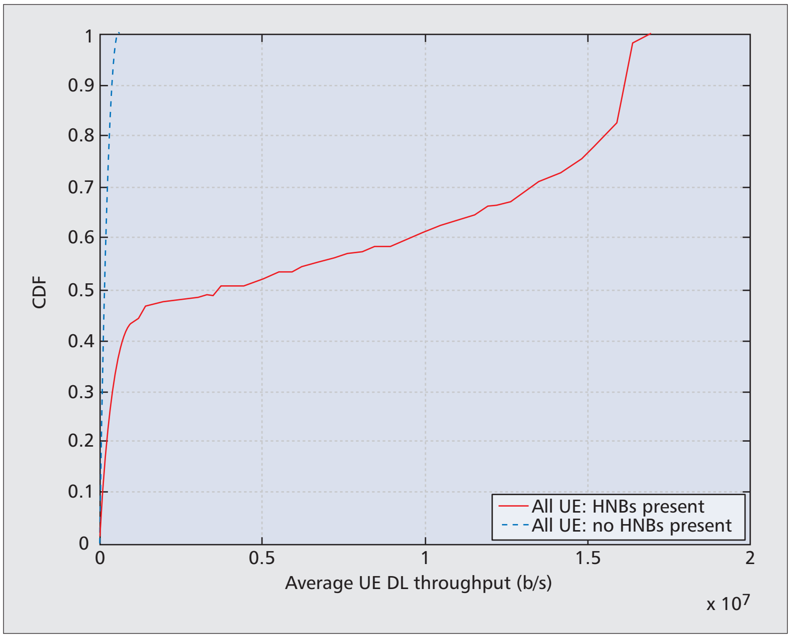

Figure 3. *HSPA+ DL user throughput distributions on f1 (shared frequency between femto and macro). There are 10 units of MUE and 12 of HUE per macro cell when HNBs are present. There are 22 (10 + 12) UE units per cell served by the macro when HNBs are not present.*

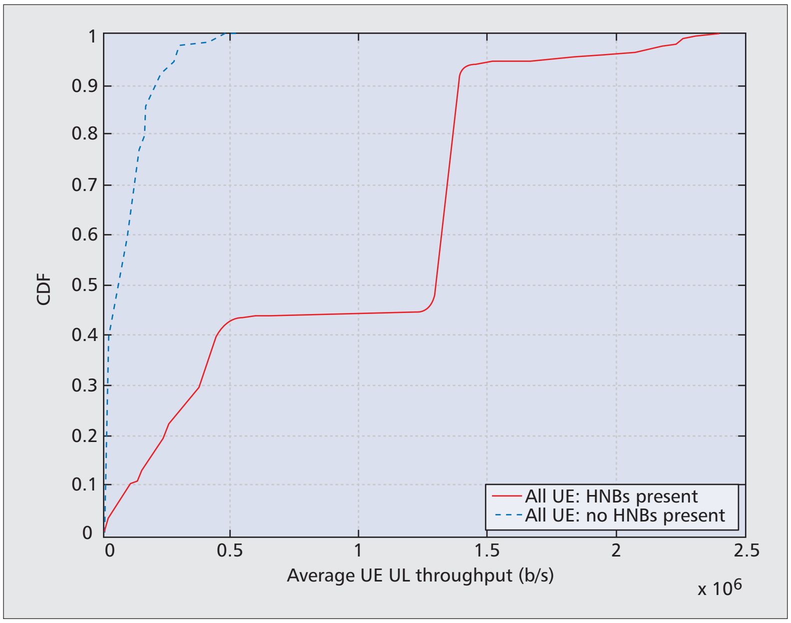

Figure 4. *HSPA+ UL user throughput distributions on f1 (shared frequency between femto and macro) with and without HNBs. There are 10 units of MUE and 12 of HUE per macrocell when HNBs are present. There are 22 (10 + 12) UE units per cell served by the macro when HNBs are not present.*

Conclusions

In this article we have shown that although a femtocell can cause interference to other users in the system, the interference can be well controlled on both the downlink and uplink if proper interference management techniques are used. Downlink HNB carrier selection and HNB DL Tx power calibrations are proposed as key interference management methods for the downlink. On the uplink, we have shown that adaptive UL attenuation at the HNB is an effective method for overcoming the uplink interference caused by nearby macro user or home user not allowed to use HNB, especially if the interference is bursty. Different interference models and analysis have been presented to demonstrate the interference scenarios for downlink and uplink. In addition, we have provided coverage and capacity analysis through system-level models and simulations for a two-frequency deployment in which one frequency is shared by the macro and femto, and the other one is dedicated to the macro. It is shown that HNBs eliminate indoor outage without any noticeable impact on the coverage for macrocell users. Furthermore, we have demonstrated that in addition to coverage benefits, significant capacity improvements on DL and UL are achieved when femtocells are deployed in 3G HSPA+ networks. The capacity benefits of HNBs are due to two factors. On one hand, the HUE served by HNBs can achieve very high data rates since they are among the few users served by that HNB. At the same time, macro users benefit from the capacity offload since more macro network resources are available for them.

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Additional Reading

[1] 3GPP TR 25.896 v6.0.0, "Feasibility Study for Enhanced Uplink for UTRA FDD."

Biographies

MEHMET YAVUZ is a principal engineer and manager in Corporate Research and Development (CR&D) at Qualcomm, where he is currently working on interference and mobility management for femtocells. He received a B.Sc. degree in electrical and electronics engineering from Middle East Technical Universiyt, Turkey, in 1994, and M.S. and Ph.D. degrees in electrical engineering: systems from the University of Michigan, Ann Arbor in 1996 and 1999, respectively. From 1997 to 1999 he was a full-time research scientist at General Electric Global Research Center, and from 1999 to 2003 he was with the CDMA System Research and Development group at Nortel Networks. Since 2003 he has been with CR&D at Qualcomm, where he has worked on system design and performance analysis of wireless networks such as 1xEVDO, WCDMA/HSPA+, and femtocells. In 2009 he received the Distinguished Contributor Award from Qualcomm CR&D for his technical contributions to the department.

FARHAD MESHKATI received a B.A.Sc. degree in engineering science (electrical option) and an M.A.Sc. degree in electrical engineering from the University of Toronto, Canada. He received his Ph.D. in electrical engineering from Princeton University in 2006. He is currently with CR&D at Qualcomm, where he is involved in design, optimization, and performance analysis of current and future wireless systems.

AKHILESH POKHARIYAL [M] received his M.Sc.EE. and Ph.D. degrees in 2002 and 2007, respectively, from Aalborg University, Denmark. His Ph.D. work involved design and system-level performance analysis of multidimensional link adaptation and packet scheduling algorithms for the Evolved Universal Terrestrial Radio Access (E-UTRA). His Ph.D. was co-sponsored by Nokia Networks. Since 2007 he has been working for ip.access Ltd., United Kingdom, focusing on air interface performance optimization including design of radio resource management (RRM) algorithms for WCDMA-based femtocells. His technical areas of interest are RRM, cross-layer optimization, MIMO, and modeling of cellular communication systems. He has made a number of conference and journal contributions, and has several pending patent applications.

BALAJI RAGHOTHAMAN has been with Airvana Inc. since 2006, where he is currently a consulting engineer in the Advanced Technology Group, with a focus on system architecture and algorithm design for femtocell networks for 3G and 4G. He received his B.E. degree in electronics and communication engineering from Coimbatore Institute of Technology in 1994, and his M.S. (1997) and Ph.D. (1999) degrees from the University of Texas at Dallas. During his graduate studies, he spent two summers in the Wireless Products Group, Texas Instruments. From 1999 to 2006 he worked at the Nokia Research Center in Dallas and San Diego in various roles, including principal scientist and research manager in the CDMA Radio Systems Group. At Nokia he conducted research and standardization efforts in the CDMA and 4G physical layers, multi-antenna algorithms including MIMO and beamforming, and advanced receiver design. He continues to serve on the technical committees of various conferences, and participates in the peer review process for various IEEE journals. He has more than 25 journal and conference publications and more than 20 patent applications to his credit.

Andy Richardson has been involved in the digital mobile communications industry since the early 1980s. He has worked for a number of notable mobile communications companies, including Philips and Nokia, before setting up his own training and consultancy company, Imagicom. He has been actively involved in the definition of 2G, 3G, and 4G standards throughout his career. He is the author of an industry text, *The WCDMA Design Handbook*. In 2004 he was a cofounder of a small startup company, 3Way Networks, established to develop and promote femtocell technology, which was acquired by Airvana Inc. in 2007. Since 2007 he has been the vice president of systems at Airvana based in Cambridge, United Kingdom. He has authored numerous papers and has more than a dozen patents either filed or pending.

SANJIV NANDA is a senior director with CR&D, Qualcomm, where he currently leads the fembocell systems engineering program. At Qualcomm he has previously worked on systems engineering and standardization of 3G/WiFi interworking and IEEE 802.11n. During 2001–2002 he was director of systems engineering at Narad Networks, Westford, Massachusetts, designing switched Ethernet backhaul over hybrid fiber coax networks. Prior to Narad, he spent over 10 years with the Performance Analysis Department at Bell Laboratories and at WINLAB, Rutgers University, working on many aspects of cellular system design, including system architecture, protocol design, system performance, and link performance. He received a B.Tech. degree from the Indian Institute of Technology, Kampur, and M.S. and Ph.D. degrees from Rensselaer Polytechnic Institute.

NICK JOHNSON is the chief technology officer if ip.access Ltd. and Chairman of the Radio & Physical Layer Working Group in the Femto Forum. He has a Ph.D. in microwave scanned imaging techniques from University College London and an M.A. in physics from the University of Cambridge.