# Uplink Interference Management for HSPA+ and 1xEVDO Femtocells

Yeliz Tokgoz, Farhad Meshkati, Yan Zhou, Mehmet Yavuz and Sanjiv Nanda

***Abstract*— Femtocells are low power cellular base stations typically deployed indoors in residential and enterprise environments as well as hotspots in order to improve voice and high rate data coverage and provide excellent user experience. The cellular operator benefits from reduced infrastructure deployment costs for capacity upgrades and coverage improvements. While improving performance, femtocells may cause some interference to other users in the network. However, with the use of proper interference management techniques, this interference may be well controlled. This paper focuses on uplink (UL) interference management techniques for 3G femtocell deployments. On the UL, the challenge is the presence of large uncontrolled interference from nearby users not associated by the femtocell that result in high noise rise (rise-over-thermal, RoT), that may lead to poor femto user experience. Femtocell users that can not be power controlled due to their very close proximity to femtocells may also cause high noise rise levels. An algorithm is proposed for both HSPA+ and 1xEVDO femtocells to desensitize the receiver when uncontrolled interference is detected, ensuring robust UL performance with minimal impact on the macro network. It is demonstrated through system level simulations that in addition to superior performance experienced by femtocell users, the macro users also benefit significantly from offloading traffic load to the femto network.**

***Index Terms*— 3G femtocells, interference, uplink.**

## I. INTRODUCTION

FEMTOCELL is the term generally used for personal low power base stations installed in subscriber's residences, office buildings or hotspots for providing cellular service. Typically femtocells are connected to the Internet and the cellular operator's network via DSL router or cable modem.

Key benefits of femtocells can be outlined as: excellent user experience at home (through better coverage for voice and higher data throughput); offloading traffic load from macro cellular network that leads to improved macro user performance and reduction of infrastructure deployment costs. Femtocells can suffer from RF interference due to: closed subscriber groups (i.e., users allowed to get service from a restricted set of femtocells); unplanned deployment without RF planning and low isolation between residences [1]. However these concerns may be resolved by adopting proper interference mitigation techniques.

This paper analyzes performance of 3G femtocells (HSPA+ and 1xEVDO) with a focus on RF and interference management on the UL. It is shown that reduced outage, improved user performance and robust system operation can be achieved through the use of special UL interference mitigation techniques that adapt to the particular RF conditions of each femtocell. An Adaptive Uplink Attenuation Algorithm is proposed to desensitize femtocells in the presence of strong uncontrolled interference, which effectively reduces the noise rise level, leading to stable UL operation and high throughput for femtocell users.

System performance is evaluated using detailed HSPA+ and 1xEVDO system-level simulations to quantify the performance of macro and femtocell users in both single- and dual-carrier femtocell deployments. The benefits of deploying femtocells for coverage enhancement and offloading traffic are demonstrated. It is shown that high quality user experience can be achieved with femtocells. The macro users are also shown to benefit significantly from femtocell deployments due to the reduction in the macro load.

The remainder of the paper is organized as follows. Section II describes the terminology used in the paper. In Section III, propagation and simulation models are described. In Section IV, UL interference mitigation techniques are described, accompanied by system levels simulation results in Section V. Conclusions are provided in Section VI.

## II. TERMINOLOGY

In this paper, UL performances of HSPA+ and 1xEVDO femtocells are analyzed. For consistence, 3GPP terminology will be adopted throughout the rest of the document. The purpose of this section is to clarify the terminology for readers who are familiar with either of these 3GPP ($3^{rd}$ Generation Partnership Project) or 3GPP2 technologies.

A femtocell user is referred to as a Home User Equipment (HUE) or a Home Access Terminal (HAT). Similarly, a macro network user is a MUE or a MAT. Femtocells are denoted either as Home Node B (HNB) or Home Access Point (HAP), whereas macro base stations are called Macro Node B (MNB) or Macro Access Point (MAP). Total received signal strength to thermal noise ratio is defined as RoT or noise rise. Conforming to 3GPP terminology, a macro sector will be referred to as a cell.

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## III. RF PROPAGATION AND SYSTEM SIMULATION MODELS

This section describes the RF propagation and system simulation models used for performance and capacity analysis of femtocells. In order to isolate various femto and macro interactions, two simple models are developed that represent realistic but harsh interference scenarios. In addition to that, a dense-urban model is developed to capture system-level femto-femto and macro-femto interactions. The dense-urban layout models densely-populated areas where there are multi-floor apartment buildings with small apartment units.

### *A. Simple Interference Models*

Two simple interference models are proposed in this section. Model 1 is a simple two-apartment model which is meant to demonstrate femto-to-femto interference, whereas Model 2 is for demonstrating femto-macro interactions.

#### *1) Inter-Femto Interference Model (Model 1)*

This model demonstrating femto-to-femto interference consists of two adjacent apartments. There is one HNB and a corresponding HUE in each apartment, as shown in Fig. 1. Restricted association is assumed, where a HUE is associated with its own HNB only. The path loss values are chosen based on the indoor propagation model described in Section III.B. On the UL, HUE2 communicating with the 75 dB away HNB2 creates high interference at the close-by HNB1 (60 dB away), which affects HUE1 performance.

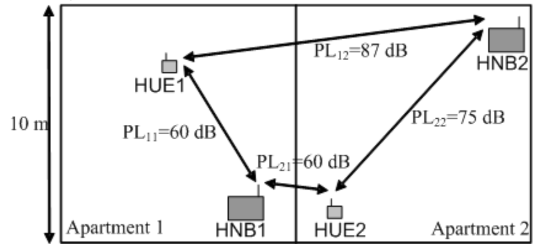

Fig. 1. Inter-Femto Interference Model

#### *2) Femto-Macro Interference Model (Model 2)*

This model consists of a single apartment/house at the edge of the macro cell coverage with a HNB and an associated HUE inside the house. A MUE is located 80 dB away from the HNB as shown in Fig. 2. The MUE is served by the MNB and is not allowed to access the HNB. While this model captures a particularly harsh scenario in terms of femto-macro interference, it is a realistic one.

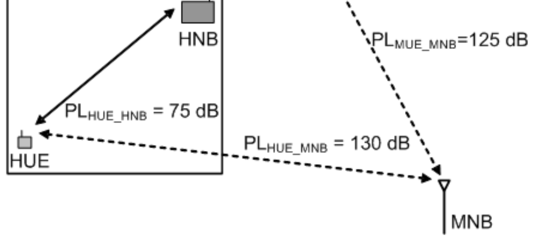

Fig. 2. Femto-Macro Interference Model

### *B. Dense-Urban Model*

For the dense-urban model a large number of apartment blocks are dropped in a macro layout such that there are 2000 apartment units per macro cell with 1km inter-site distance (ISD). Assuming an average of 2.6 persons per household, this population is representative of a dense-urban setting.

Each apartment block is 50 m x 50 m and consists of two buildings and a horizontal street (10 m width) between them (Fig. 3). The number of floors in each building is randomly chosen between 2 and 6. On each floor, there are 10 apartment units of size 10 m x 10 m with a 1 m wide balcony. The minimum separation between two adjacent blocks is 10 m. The probability that a HUE is in the balcony is assumed to be 10%.

Assuming wireless penetration of 80%, operator penetration of 30% and HNB penetration of 20%, one can say that 4.8% of the units will have HNBs from the same operator, which is believed to be representative of medium term deployments. This corresponds to 96 apartments with HNBs, which are randomly picked among the 2000 units. Out of the 96 HNBs in each sector, 12 are assumed to be active at the same time and the rest are inactive (transmitting only pilot and overhead).

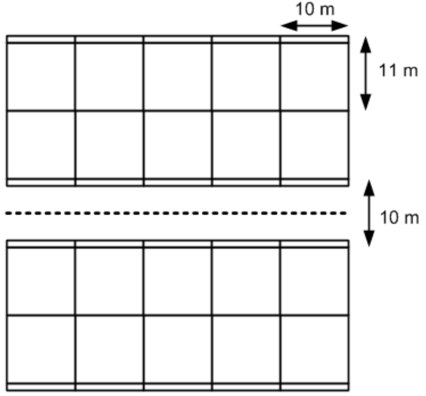

Fig. 3. Dense-urban model: Top view of apartment block

MUEs are also dropped randomly into the three center cells of the 57-cell macro layout such that 30% of the MUEs are indoors. In addition, a minimum path loss of 38 dB (i.e., 1 m separation) is enforced between UEs and HNBs.

For indoor propagation loss (e.g., HNB to HUE), a modified version of the Keenan-Motley model [3] is used:

$$PL(dB) = 38.46 + 20\log_{10} d + qW + Fn^{((n+2)/(n+1)-0.46)} \quad (1)$$

$d$ is the separation between the transmitter and the receiver (in meters), $W$ is the wall partition loss (assumed 5 dB), and $F$ is the floor partition loss (assumed 18.3 dB). The number of walls between transmitter and receiver, represented by $q$, is assumed to be random and is chosen from the set $\{0,1,\ldots,\lfloor d/d_w \rfloor\}$ with equal probability. Here, $d_w$ represents the minimum wall separation (set to 2 m). In (1), $n$ is the number of floors separating the transmitter and receiver.

For outdoor propagation loss, the 3GPP micro propagation model [4] is utilized:

$$PL(dB) = 28 + 40\log_{10} d - G_{ant\_pat} + L_{shad} + L_{add} \quad (2)$$

$G_{ant\_pat}$ is the gain due to antenna pattern, $L_{shad}$ is lognormal shadowing with 10 dB standard deviation, and $L_{add}$ consists of 14 dBi MNB antenna gain, 0dBi UE/HNB antenna gain and 10 dB other losses. When the transmitter is outdoors and the receiver is indoors or vice versa, a combination of (1) and (2) is used to model the path loss.

The various PL Cumulative Distribution Functions (CDF) based on the dense-urban model are shown in Fig. 4. It is observed that the PL from a HUE to its own HNB ranges from 38.5 dB to 95 dB, with only 2% above 80dB. Based on this observation, 80 dB is believed to be an appropriate coverage target for HNBs in dense-urban locations. The path loss from a HUE to the strongest interfering HNB can be as low as 51 dB, which may lead to femto-to-femto interference problems. Since the micro model is used for outdoor propagation, the PL from UEs to the strongest MNB can be as large as 165 dB. This is particularly harsh model and leads to some macro outage since 165 dB is beyond the link budget of typical 3G cells. The difference between the PL CDFs from HUEs to MNBs and MUEs to MNBs is due to the fact that most of HUEs are located indoors and therefore have a larger PL.

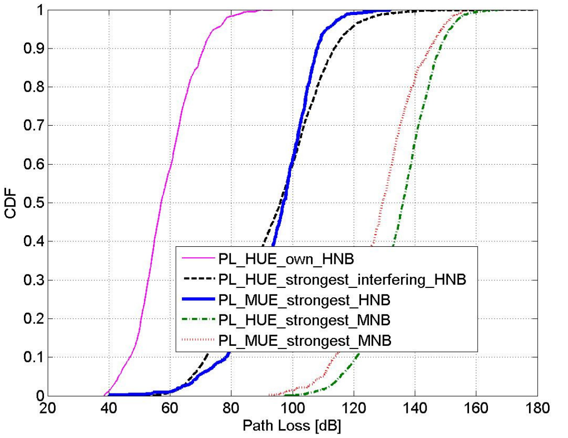

Fig. 4. Dense-urban layout path loss distributions

## IV. UPLINK INTERFERENCE MANAGEMENT TECHNIQUES

There are several concerns that need to be resolved for good UL performance in femtocell deployments. One is the fact that a HUE can get arbitrarily close to the HNB. In such case, HUE can not obey the power control (PC) down commands due to hitting its minimum transmit power capability. Such a HUE transmitting higher than the required power may desensitize the HNB receiver and/or also lead to high noise rise (RoT).

Another concern is nearby high power users that are not associated with the HNB (i.e. due to restricted association). These users may cause significant UL interference and lead to high noise rise levels, resulting in poor HUE performance. There is also the possibility that total received signal strength at the HNB is beyond the receiver dynamic range. Proper UL interference management techniques are required to alleviate these concerns and ensure satisfactory UL performance.

One simple solution to deal with the high noise rise problem is to raise the noise rise threshold. However, this solution has some instability implications. When operating at high noise rise levels, bursty interference will cause very high pilot signal-to-noise ratio (SNR) fluctuations which the PC loop may not be able to keep up with. In this case, error bursts are likely to happen. Also, the receiver saturation issue is not resolved with this approach.

A better solution is to desensitize the interference by attenuating the signal at the receiver, leading to a higher noise figure (NF). This way, interference becomes more comparable to thermal noise, leading to low noise rise operation. Another advantage is that the attenuation pulls nearby HUEs to a power controllable range and resolve the saturation problem. A potential problem with applying a fixed attenuation across all HNBs is that HUE transmit power values will increase even when there are no interfering MUEs, resulting in unnecessary UL interference to macrocells. This is particularly important if the HNB happens to be close to a MNB. The solution is to use attenuation only when high out-of-cell interference (Ioc) or receiver desensitization is detected at the HNB.

### A. *Adaptive UL Attenuation Algorithm*

Adaptive UL attenuation algorithm is designed to ensure good HNB UL performance while minimizing the effect on the macro network performance. The algorithm results in the UL signal to be attenuated only when the total received signal level at the HNB is saturating the receiver, or the UL is being jammed by a nearby non-associated UE.

#### 1) *Analysis of UL Attenuation*

It is crucial to determine the correct amount of padding that will improve the HUE performance without degrading the MUEs. This trade-off is analyzed in more detail using the simple femto-macro interference setup (Fig. 2), focusing on large out-of-cell interference scenario.

The cell edge case is considered first, where the $PL_{HUE_MNB}=PL_{MUE_MNB}=130$dB. HNB transmit power is chosen to maintain a coverage area of 70dB, 80dB or 90dB. Both the HUE and the MUE are assumed to be located at the HNB coverage boundary. Being at macro cell edge, the MUE is assumed to be transmitting at 18dBm. In Fig. 5, the noise rise contribution of the MUE at the HNB is plotted for different HNB UL attenuation values. This noise rise contribution is denoted by Ec/No', where Ec is received signal strength of the MUE at the HNB and No' corresponds to the received signal strength in the absence of HUE or MUE. Assuming that the HUE is transmitting at a power level to maintain -2.4dB Ec/No with a max power limit of 21dBm, the noise rise contribution of the HUE at the MNB is also plotted. The goal of the algorithm is to keep the MUE contribution on the HNB noise rise at a value below the noise rise threshold.

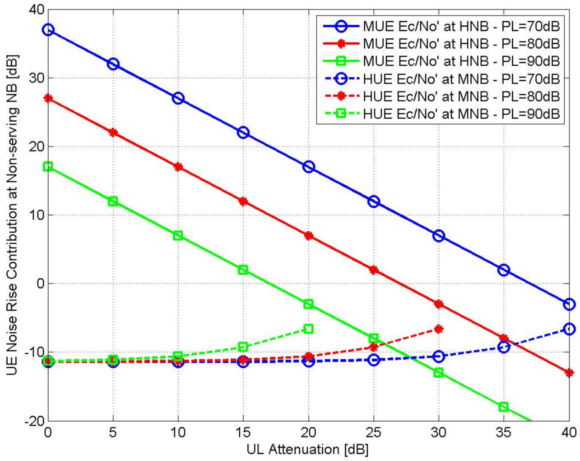

Fig. 5. Cell Edge Scenario: Noise Rise Contribution of Non-associated UEs

A reference algorithm trying to maintain the out-of-cell contribution to the HNB noise rise at 3dB would choose to apply 34dB, 24dB and 14dB UL attenuation for the 70dB, 80dB and 90dB coverage cases, respectively. The corresponding effect of HUE on the MNB noise rise is seen to be negligible.

Next, the cell site scenario is considered where the $PL_{HUE\_MNB}=PL_{MUE\_MNB}=100dB$. HNB transmit power is chosen to maintain a coverage area of 60dB, 70dB or 80dB. (A HNB can not maintain 90dB DL coverage at macro cell edge given that its tx power is limited to 20dBm.) The HUE and the MUE are located at the HNB coverage boundary. Being at macro cell site, MUE tx power is assumed to be -15dBm. In Fig. 6, noise rise contributions of the MUE at the HNB and the HUE at the MNB are plotted with different HNB UL attenuation values. HUE tx power is again determined to maintain -2.4dB Ec/No with a max power limit of 21dBm.

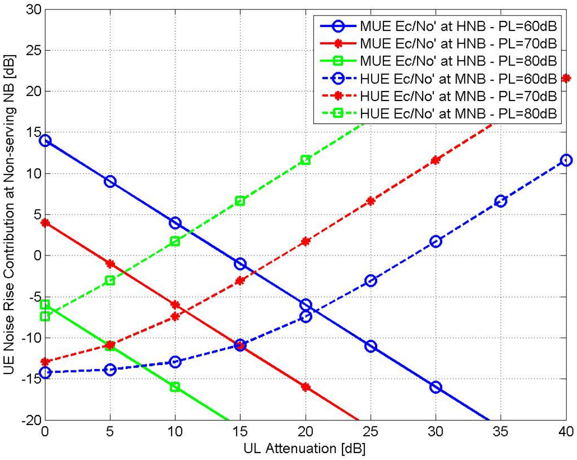

Fig. 6. Cell Site Scenario: Noise Rise Contribution of Non-associated UEs

In order to maintain the out-of-cell contribution to the HNB noise rise at 3dB, one would choose to apply 11dB, 1dB and 0dB UL attenuation for the 60dB, 70dB and 80dB coverage cases, respectively. The corresponding effect of the HUE on the MNB noise rise is negligible. On the other hand, it can be seen that if a HNB was to apply 20dB fixed UL attenuation, the HUE transmission would result in 12dB noise rise at the MNB for the 80dB coverage case, which would certainly affect the MUE performance. Therefore, it is very important to use UL attenuation only as much as needed.

### 2) *Algorithm Description*

DO Adaptive UL Attenuation algorithm is composed of two main loops. The Jammer Control Loop is designed to detect signal levels beyond the dynamic range and increase attenuation to bring it down. The energy at the output of the Analog-to-Digital Converter (ADC) is used as input to this loop to detect high signal levels that saturate the output bits. The Interference Control Loop reacts to high out-of-cell interference (Ioc) as well as HUEs that can not PC down due to minimum tx power limitation.

The first branch of the Interference Control Loop compares the filtered estimate of the out-of-cell interference to noise ratio ($Ioc/N_T$) to a target and proposes an attenuation value to maintain $Ioc/N_T$ within the desired range. In a practical system, the $Ioc/N_T$ can be estimated by subtracting the in-cell users' contribution from the total received signal strength. The second branch looks at the in-cell users' pilot SNR (Ecp/No). The pilot channel of the in-cell users are power controlled to maintain Ecp/No at a required setpoint. If a user's Ecp/No is above typical setpoint values, an UL attenuation value is proposed to make sure no user is received stronger than necessary and therefore prevent high noise rise. The maximum attenuation proposed by the two branches is applied at the receiver front end. The attenuation is decayed slowly when the source of the problem disappears. This slow decay feature provides robustness against bursty interferers. Assume that there is a bursty MUE transmitting at very high power located close to the HNB. In the absence of UL attenuation, the noise rise at the HNB increases very abruptly with every burst of the MUE. All HUEs need to power control up in order maintain their link and may lose a few consecutive packet until PC catches up. With this algorithm, UL attenuation is applied after the first burst and it is mostly maintained until the next burst arrives. This time, the effect of the MUE on the noise rise is much less due to the attenuation already present, leading to more robust UL operation.

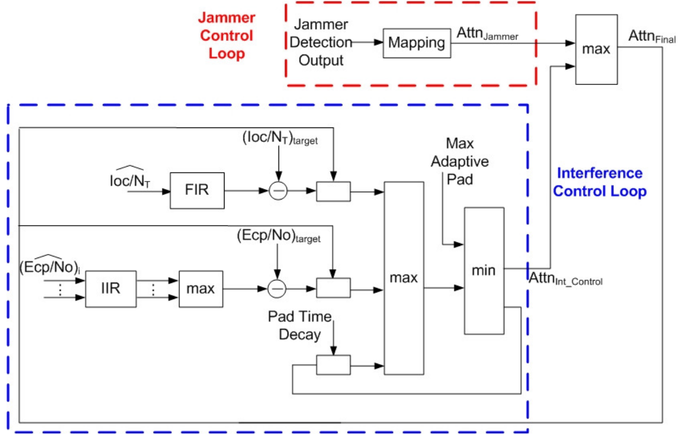

Fig. 7. Adaptive UL Attenuation Algorithm Block Diagram

## B. *Limiting HUE Transmit Power*

As a safety mechanism and to limit the uplink interference caused by a HUE to the macro network (or to neighbor HNBs), the HNB may limit the transmit power of a HUE based on the HNB's proximity to the nearest MNB or an estimate of the UL interference caused at the MNB.

For HSPA+ networks, the path loss to nearest MNB (and/or HNB) can be estimated by measuring the corresponding received common pilot strength (CPICH RSCP) and obtaining the pilot (CPICH) Transmit Power value from the broadcast channel of the cell. Based on this estimate, a maximum HUE transmit power can directly be imposed. In 1xEVDO networks, a HNB can not directly limit the transmit power of a UE. However, indirect mechanisms such as setting the busy bit (loading indicator) or sending more conservative Medium Access Control (MAC) parameters would limit the data rate of a HUE, resulting in lower transmit power levels.

## V. UPLINK CAPACITY RESULTS

In this section, the HSUPA and 1xEVDO UL performance with and without femtocell deployment is evaluated using both the simple interference models, as well as the dense-urban model introduced in Section III.

The case referred to as *macro settings* is when HNBs are deployed using MNB settings i.e., 5-6dB noise rise threshold and 5 dB NF with no UL interference management (0 dB attenuation). *Picocell settings* correspond to the case where HNBs use a higher noise rise threshold of 10 dB and a 19 dB NF, representative of picocell operation. *Adaptive Attenuation* refers to the case where the proposed adaptive UL attenuation algorithm (Section IV.A) is utilized at the HNBs. With this algorithm, attenuation is introduced when the out-of-cell interference to thermal ratio exceeds 3dB, and/or when the HUE pilot SNR exceeds the expected setpoint by 2 dB. A maximum of 40 dB attenuation is applied. Noise rise threshold used is the same as macro settings (5-6 dB). NF is assumed to 13 dB which is higher than MNB to account for lower cost HNBs.

Detailed slot-level system simulation tools are used for both 3GPP and 3GPP2 technologies. These system simulators capture all the data and overhead channels and model UL scheduling/MAC algorithms, Hybrid-ARQ transmissions as well as fading channels. Rician channel with 10 dB K-factor and 1.5 Hz Doppler frequency is assumed. The MUEs and HUEs are assumed to transmit full-buffer traffic. For HSUPA systems, 2ms TTI is assumed and the maximum number of transmissions is set to 4. The minimum and maximum transmit power for the UEs are set to -50dBm and 24dBm, respectively.

### A. *Simple Interference Models*

In this section, results with the two simple interference models are presented. For these models, cell reselection procedures are not taken into account.

#### 1) *Inter-femto Interference Mode1*

Model 1 is a simple two-apartment model which captures the femto-femto interference as discussed in Section III.A. The average HUE throughput and noise rise at the HNBs are provided in Table I for the cases where HNBs use macro or picocell settings, as well as utilize the proposed adaptive UL attenuation algorithm.

TABLE I INTER-FEMTO INTERFERENCE MODEL RESULTS

| | | HUE1 Thrpt (kbps) | HNB1 Noise Rise (dB) | HUE2 Thrpt (kbps) | HNB2 Noise Rise (dB) |
|---|---|---|---|---|---|
| HSUPA | Macro set. | 25 | 10.4 | 1319 | 1.1 |
| | Picocell set. | 296 | 10.7 | 1326 | 1.1 |
| | Adap. Attn. | 1365 | 3.9 | 1318 | 1.2 |
| 1xEVDO | Macro set. | 12 | 12.4 | 459 | 1.7 |
| | Picocell set. | 6 | 12.2 | 459 | 1.7 |
| | Adap. Attn. | 601 | 3.3 | 459 | 1.9 |

As seen in the table, the UL performance of HUE1 is poor with macro and picocell settings due to interference caused by HUE2 at HNB1. It should be noted that the 14 dB higher HNB NF with the picocell settings does not mitigate the inter-femto interference, since the resulting noise rise is still above the threshold. It simply results in approximately 14 dB higher transmit powers for both UEs. On the other hand, adaptive UL attenuation results in good uplink performance for both HUE1 and HUE2. This is because with adaptive UL attenuation, attenuation (higher NF) is applied only when needed. In this case, the signal at HNB2 is not attenuated since noise rise is already low. Therefore, the transmit power of HUE2 does not increase as it did in picocell settings case. At HNB1, large out-of-cell interference is detected and sufficient attenuation is applied such that interference from HUE2 becomes comparable to thermal noise. Consequently, HUE1 is power controlled up to overcome the attenuation. As a result, noise rise is much better controlled.

For the HSUPA system, this leads to HUE1 receiving grants from the scheduler and achieve high uplink throughput (around 1300 kbps) similar to HUE2. In the 1xEVDO system, the low noise rise prevents HNB1 from setting its Reverse Activity Bit (RAB) and therefore HUE1 can now get more UL allocation, resulting in higher UL data rates.

It is shown that even in this harsh femto-femto interference scenario, excellent femto experience can be achieved with the use of proper interference management techniques.

#### 2) *Femto-Macro Interference Model*

Model 2 is a simple model capturing the femto-macro interference as discussed in Section III.A, where a MUE at the cell edge transmitting at high power levels is causing a lot of interference on the UL for a close by HNB. The average HUE throughput and noise rise at HNBs are provided in Table II.

TABLE II FEMTO-MACRO INTERFERENCE MODEL RESULTS

| | | HUE1 Thrpt (kbps) | HNB1 Noise Rise (dB) | HUE2 Thrpt (kbps) | HNB2 Noise Rise (dB) |
|---|---|---|---|---|---|
| HSUPA | Macro set. | 20 | 40.2 | 1321 | 1.1 |
| | Picocell set. | 20 | 26.2 | 1321 | 1.1 |
| | Adap. Attn. | 1362 | 3.6 | 1326 | 1.2 |
| 1xEVDO | Macro set. | 5 | 42.1 | 459 | 1.7 |
| | Picocell set. | 5 | 28.1 | 459 | 1.7 |
| | Adap. Attn. | 600 | 3.0 | 458 | 2.2 |

It is clear from the table that the UL performance of the HUE is poor with macro and picocell settings due to the interference caused by the MUE at the HNB. The interference from MUE (transmitting at high power levels to be heard at the far away MNB) causes a large noise rise at the HNB. As a result, the HUE is able to get very low throughput. The higher noise figure in the picocell settings case is not sufficient to overcome the amount of interference. On the other hand, the adaptive UL attenuation algorithm allows up to 40 dB attenuation at the HNB. (Since only HNBs that need it increase their UL attenuation, one can become more aggressive in terms of setting the maximum allowable attenuation.) In this scenario, this value is sufficient to pull the noise rise at the HNB below the noise rise threshold. This means that the HUE can transmit at higher data rates and observe a significant performance improvement. Meanwhile, this attenuation at the HNB results in an increase in the transmit power of the HUE, which leads to slightly higher noise rise at the MNB. However, the effect is not significant.

It is shown that using interference management techniques, excellent femto experience can be achieved with minimal or no impact on MUEs, even in very severe interference scenarios.

One important feature of the adaptive UL attenuation algorithm is that the attenuation is decayed slowly when interference disappears. This is especially important in the presence of bursty interference. The attenuation is mostly maintained when the next burst arrives, therefore preventing large fluctuations in the noise rise and HUE pilot SNR.

1xEVDO system is used to analyze the HNB performance with bursty interference. Assume that the MUE in the femto-macro model (Fig. 2) has bursty traffic. The traffic model is such that every 2 seconds, a burst of 36 packets arrive. Each packet is 1500 bytes and the inter arrival time between packets within a burst is 16 slots. In Fig. 8, the noise rise (RoT) and the received pilot SNR (Ecp/Nt) of the HUE is plotted for the cases when the HNB is adopting picocell settings and when adaptive UL attenuation algorithm is utilized. As seen in the figure, the algorithm ensures stable UL operation and good user experience by significantly reducing the noise rise and Ecp/Nt fluctuations due to incoming interference bursts. As a result, error bursts due to the sudden declines in the Ecp/Nt (as seen with picocell settings) are prevented. Similar results are observed for HSUPA systems as well.

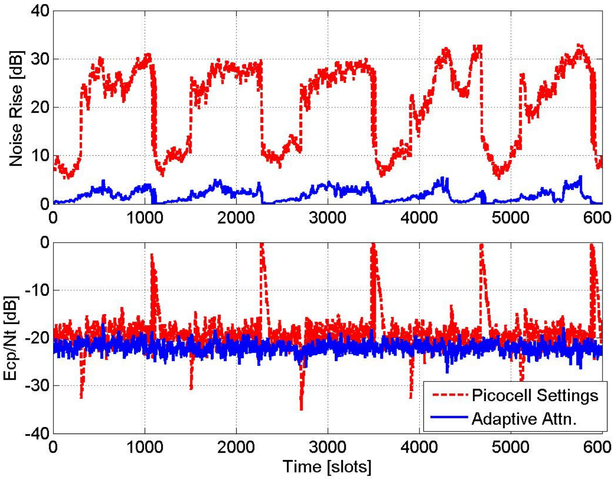

Fig. 8. 1xEVDO UL HNB Performance with Bursty Interference

## B. *Dense-Urban Model*

In this section, UL performances of HSPA+ and 1xEVDO systems are evaluated in the dense urban scenario (Section III.B). Both single carrier and dual carrier macro-femto deployments are considered, where there are 10 and 20 MUEs per cell, respectively. In addition, 12 HUEs are assumed to be present in each cell that would have an active HNB in their apartment. (These users are served by the macro network for the no HNB deployment results.) There are also 84 inactive HNBs that transmit only overhead channels on the DL.

For these simulations, realistic cell reselection procedures are taken into account. The DL transmit power of the femtocells are assumed to be self-calibrated based on the HNB location within the macrocell, as well as deployment scenario, targeting an 80 dB coverage region. More details on the transmit power self-calibration algorithm can be found in [5].

The DL Ecp/Io of all MUEs and HUEs are computed. The outage Ecp/Io threshold is -20 dB for HSPA+ and -10dB for 1xEVDO systems. The MUEs that are in outage according to these DL Ecp/Io acquisition thresholds have been excluded from the system level simulations. The HUEs that are in outage with their own HNB have been switched to the MNB provided that they are within macro coverage. If not, they too have been excluded from the UL simulations. Note that service outage is due to the harsh propagation model adopted which places users beyond the macro link budget. More on outage statistics can be found in [5]. Results for both single and dual frequency deployments are presented.

### *1) Single Frequency Deployment*

In Fig. 9 and Fig. 10, MUE and HUE UL throughput distributions are provided for HSUPA and 1xEVDO systems for the cases with and without HNBs in a single frequency scenario (macro and femto share one carrier). Two HNB deployment options are considered. The first one is with macrocell settings (5-6 dB noise rise threshold, 5 dB NF) and the second one is with the adaptive UL Attenuation algorithm (5-6 dB noise rise threshold, 13 dB NF, up to 40 dB attenuation).

When there are no HNBs present, only the macro resources are utilized to serve the 22 UEs in each cell. Due to high system loading, UE throughput suffers. As seen in the figures, adding HNBs results in significant improvements in the overall system throughput. When the HNBs are introduced with macrocell settings, some of the UEs that are now served by the HNBs are able to get higher throughput. On the other hand, some HUEs experience a reduction in throughput because of the high noise rise at their HNBs. This problem is resolved by utilizing the adaptive UL attenuation algorithm in which case all HUEs experience very good UL performance. The MUE performance also improves significantly with the introduction of HNBs, due to fewer users sharing macro UL resources. Also note that there is no degradation in MUE throughput with the UL attenuation algorithm when compared to the macrocell settings case, despite the much higher NF values at the HNBs.

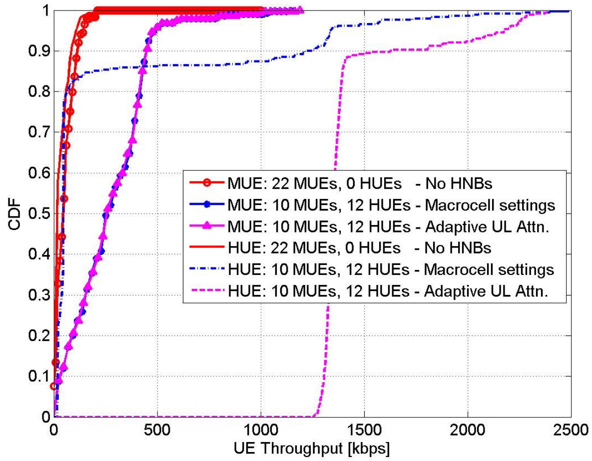

Fig. 9. HSUPA UL UE Throughput CDF - Single Frequency

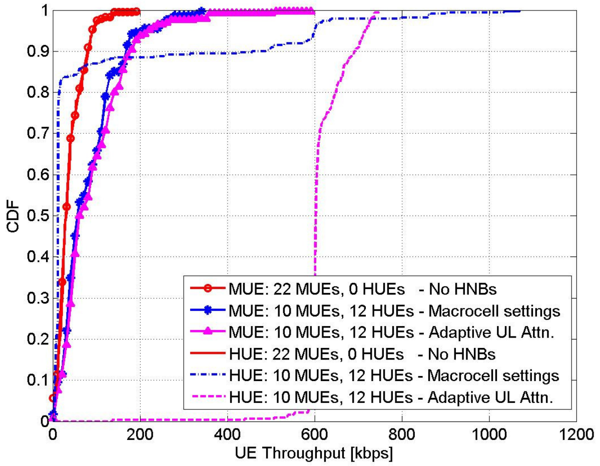

Fig. 10. 1xEVDO UL MUE and HUE Throughput CDF - Single Frequency

### 2) *Dual Frequency Deployment*

In this section, the goal is to analyze the performance of HSUPA and 1xEVDO systems with different carrier allocation strategies, when there are two carriers available for macro and femto operation. The UL performance of HUEs and MUEs are evaluated for the following two-carrier (f1 and f2) deployment scenarios: 1) Both carriers are shared, HNBs give higher priority to f1, 2) f1 is dedicated to HNBs, f2 is dedicated to MNBs, 3) f1 is shared, f2 is dedicated to MNBs. The UE throughput distributions for the two technologies are presented in Fig. 11 and Fig. 12. All HNBs are assumed to use the adaptive UL attenuation algorithm.

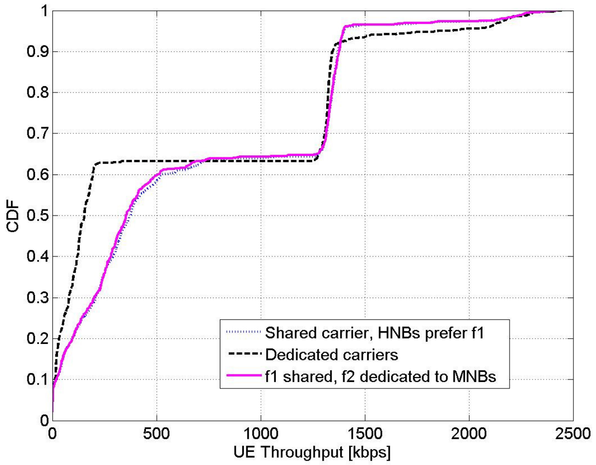

Fig. 11. HSUPA UE UL Throughput CDF - Dual Frequency

For all deployment options, the HUEs experience very high UL throughput (right section of the bi-modal curve). Except for the dedicated carrier case, the MUE performances are very similar. In the dedicated carrier case, all 20 MUEs in each cell are served by the same carrier, making the UL very loaded. This high load leads to lower throughput values for each MUE. From this standpoint, dedicated carrier deployment does not make the best use of system resources. When making deployment decisions, in addition to the UL performance, the outage statistics and the DL performance also needs to be taken into account.

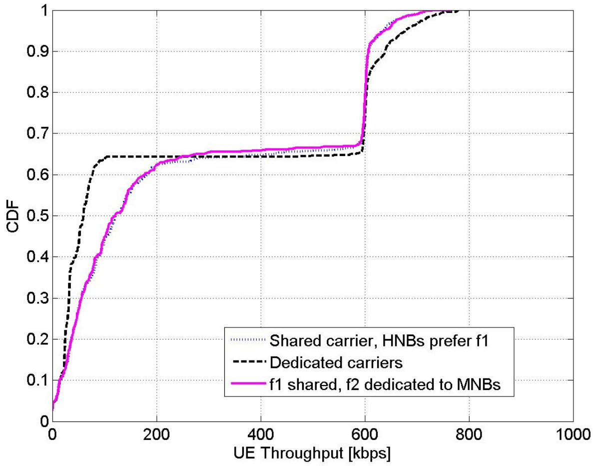

Fig. 12. 1xEVDO UE UL Throughput CDF - Dual Frequency

## VI. CONCLUSION

In this paper, the UL performance of HSPA+ and 1xEVDO systems with HNB deployment is analyzed with a focus on interference management. The key UL interference concerns between HNBs, as well as between HNBs and MNBs are identified. An adaptive UL attenuation algorithm is proposed for UL interference management, ensuring robust system operation by adapting to particular RF conditions of each HNB on the UL.

Performance with and without UL interference management is analyzed using detailed 3G system levels simulators. Simple interference models are utilized to isolate the various UL concerns, whereas dense urban simulations are used to capture the system level perspective. It is shown that high quality user experience can be achieved with femtocells for deployment densities expected in the medium term. To achieve desired performance, some primary interference management methods need to be employed as part of HNBs.

Most significant benefits of femtocells are shown to be coverage extension by providing better performance to users at the cell edge through HNBs and an overall system capacity improvement by offloading some of the macro traffic to HNBs.

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