

1xEV-DO Femtocell Performance and Capacity Analysis

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ABSTRACT

Femtocell is a miniature base station installed in subscriber's residence and office for providing cellular service within the local home/office environment. Femtocells extend the coverage of an operator's existing macro network and thereby improve a user's voice and data experience. In addition, femtocells offload traffic from the macro network, which helps to solve the capacity crunch faced by operators due to exploding data demand on their macro networks. While femtocells improve a user's coverage and throughput, they also cause interference to existing macro networks. Qualcomm has developed a suite of techniques to manage interference on both forward link (FL) and reverse link (RL) for robust performance in 1xEV-DO femtocell deployments. For example, algorithms for self-calibration of femtocell transmit power, autonomous carrier selection and PN offset selection are developed to mitigate FL interference issues. For the RL, adaptive attenuation algorithm is presented to handle large out-of-cell interference. An overview of these interference management techniques is provided in this paper. Performance of these techniques is analyzed using detailed system level simulations. Results show that in addition to coverage enhancements, significant capacity improvements are achieved when 1xEV-DO femtocells are deployed.

1. INTRODUCTION

Femtocell is the term generally used for personal miniature base stations installed in subscriber's residence/office for providing cellular service within the local environment. Typically femtocells are connected to the Internet and the cellular operator's network via DSL router or cable modem. Key benefits of femtocells are: excellent user experience at home through better coverage for voice and higher data throughput; offloading traffic load from macro cellular network and reduction of infrastructure deployment costs. However femtocells can suffer from RF interference issues due to restricted access (i.e., femtocell access is limited to only certain users), unplanned deployment without RF planning and low isolation between apartments [1], [2].

This paper analyzes performance of 1xEV-DO femtocells with a focus on RF and interference management issues. Algorithms for interference management are presented and performance is analyzed under various conditions. It is shown that high quality user experience can be achieved with femtocells when interference between femtocells and macrocells is carefully managed. The main interference mitigation techniques discussed in this paper are:

- Autonomous Forward Link (FL) Transmit Power Self Calibration: Provides good femto coverage with minimal impact on macro network and neighbor femtocells.
- Autonomous Carrier and PN Code Selection: Ensures effective resource partitioning.

- Adaptive Reverse Link (RL) Attenuation Algorithm: Desensitizes out-of-cell interference to limit impact on femtocell users.

The remainder of the paper is organized as follows. In Section 2, we describe the propagation and simulation models used to evaluate the performance of femtocell deployments. Section 3 focuses on FL, where FL interference mitigation algorithms are described followed by outage and capacity analysis. In Section 4, RL interference mitigation algorithm is presented. This is accompanied by system level simulation results. Finally, conclusions are provided in Section 5.

2. RF Propagation and System Simulation Models

In this paper we use a "simple" link level interference model as well as a system simulation model to analyze the performance of femtocells. The link level interference model is used to motivate the need for femtocell power calibration. In addition, a model that captures system-level femto-femto and macro-femto interactions is used for accurate study of interference issues in femtocell deployments. Before delving deeper into femtocell performance issues, these models are discussed below.

2.1 Femto-Macro Interference Model

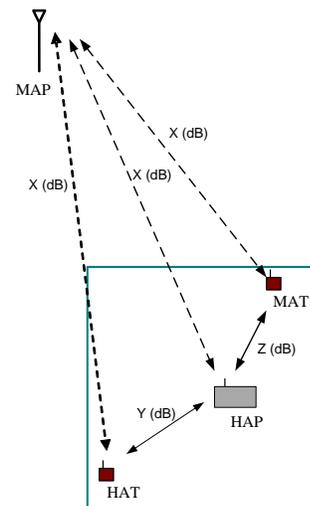


Figure 1 Simple Femto-macro Interference Model

The femto-macro interference model illustrated in Figure 1 consists of a macro access point (MAP) and a home, i.e., femto, access point (HAP). It also consists of a home (femto) access terminal (HAT) that is served by the HAP and a macro access terminal (MAT) that is served by the MAP. The MAP is in the vicinity of the HAP and is restricted from using HAP. Path losses

(PL) between different elements are shown in Figure 1. Different parameter settings are summarized in Table 1 for two different HAP locations with respect to the MAP: cell edge – HAP is at the edge of MAP coverage (large PL between HAP and MAP) and near cell site – HAP is near the MAP site (small PL between the two).

Table 1 Parameters for simple femto-macro interference model

Parameter	Location	
	Cell Edge	Near Cell Site
X = PL between MAP and HAP	140 dB	105 dB
Y = PL between HAP and HAT	80 dB	80 dB
Z = PL between HAP and MAT	80 dB	80 dB
Received signal strength (RSS) at MAT and HAT (excluding HAP contribution)	-92 dB	-60 dB

2.2 Dense Urban Model

A large number of apartment blocks are dropped in a macro layout such that there are 2000 apartment units per macro sector with 1 km inter-site distance as shown in Figure 2. 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 (Figure 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 one-meter-wide balcony. The minimum separation between two adjacent blocks is 10 m. The probability that a HAT is in the balcony is assumed to be 10%.

Assuming a wireless penetration of 80%, operator penetration of 30% and femtocell penetration of 20%, one can say that 4.8% of the units will have femtocells from the same operator. This corresponds to 96 apartments with femtocells, which are randomly picked among the 2000 units. Out of the 96 femtocells in each sector, 12 are assumed to be active at the same time and the rest are inactive (transmitting only pilot and MAC bursts). MATs are also dropped randomly into the three center sectors of the 57-sector macro layout such that 30% of the MATs are indoors. In addition, a minimum path loss of 38 dB (i.e., 1 m separation) is enforced between ATs and femtocells.

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

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

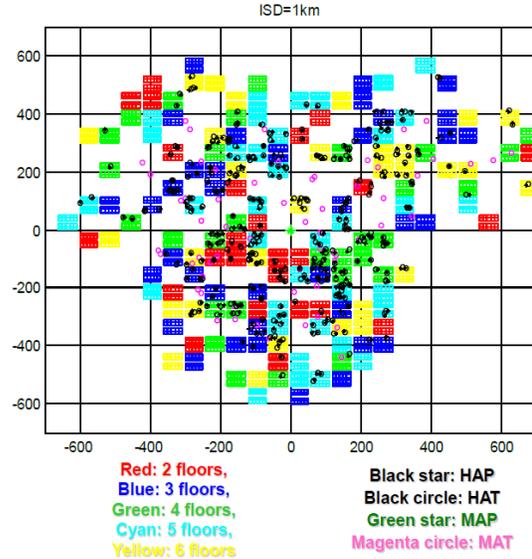


Figure 2 Dense-urban model layout

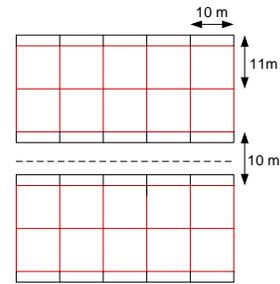


Figure 3 Top view of apartment block in dense-urban layout

where d (in meters) is the separation between transmitter (Tx) and receiver (Rx), 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 Tx and Rx, represented by q , is assumed to be random and is chosen from the set $\{0, 1, \dots, [d/d_w]\}$ with equal probability. Here, d_w represents the minimum wall separation (set to be 2m). In (1), n is the number of floors separating Tx and Rx. For outdoor propagation model, the 3GPP micro propagation model [4] is utilized:

$$PL_{micro}(dB) = 28 + 40 \log_{10} d - G_{ant_pattern} + L_{shadow} + L_{add} \quad (2)$$

where $G_{ant_pattern}$ is the gain due to antenna pattern, L_{shadow} is lognormal shadowing with 10 dB standard deviation, and L_{add} consists of 14 dBi macro sector antenna gain, 0 dBi AT/femtocell antenna gain and 10 dB other losses. When tx is outdoors and rx is indoors or vice versa, a combination of (1) and (2) is used to model the path loss.

3. Forward Link Analysis

Due to unplanned deployment, femtocells can cause interference on the FL for both - the macro network and other neighboring femtocells. For example, a femtocell installed near a window of a residence can cause significant FL interference to the ATs served

by the macrocell. Similarly in a multi resident apartment, femtocells installed near a wall separating two residences can cause significant interference to the neighbor.

3.1 FL Interference Management Techniques

In order to limit coverage holes created around a femtocell home for restricted mobiles, certain FL interference management techniques are required such as selecting an appropriate transmit power level and selecting a carrier frequency with minimal interference. PN code selection is also critical to prevent PN collision with neighbors.

3.1.1 Femtocell FL Transmit Power Self-Calibration

Femtocell transmit power level needs to be adjusted carefully depending on the particular deployment scenario. For example, for dense urban deployments low transmit power level may be appropriate due to smaller apartment sizes and close proximity to neighbors, whereas for suburban deployments a higher transmit power level could be more suitable to provide sufficient coverage within a large house. Furthermore, femtocells need to adjust their power based on their location within a macrocell (e.g., cell edge vs. cell site). When a femtocell is located at the edge of a macrocell, even a small amount of RF leakage can significantly reduce Ecp/Io of nearby MATs, since macro signal levels are already quite low. This would result in large coverage holes for MATs. Therefore, it is desirable to have a method to adapt the femtocell transmit power depending on the desired coverage region and the surrounding macrocell signal levels. Note that apart from the FL service channel, femtocell may also transmit beacons for attracting nearby mobiles to it. In such a case, power calibration is necessary for both femtocell and beacon FLs.

A femtocell can use the following design metrics for power calibration algorithm:

- *HAP_Link_Budget* [dB] = Maximum path loss within which femtocell coverage is expected.
- *HAP_MAT_Min_Pathloss* [dB] = Minimum path loss allowable between HAP and MAT, such that the MAT still achieves acceptable service from a macrocell on an adjacent channel.
- *Ecp/Io_min_MAT* [dB] = Minimum pilot strength, i.e., Ecp/Io, value required to provide acceptable service for the MAT (e.g., -6 dB).
- *Ecp/Io_min_HAT* [dB] = Minimum Ecp/Io value required to provide acceptable service for the HAT (e.g., -5 dB).

Based on these criteria, the femtocell FL transmit power self-calibration algorithm can be described as follows: Each femtocell measures the total signal strength (Io) from all the other macro sectors. It also measures the pilot strength from the best macrocell. Based on these measurements, the femtocell determines the transmit power such that

- 1) For a co-channel MAT located *HAP_Link_Budget* path loss away from the femtocell, a macro Ecp/Io of *Ecp/Io_min_MAT* is maintained.
- 2) For an adjacent channel MAT located *HAP_MAT_Min_Pathloss* away from the femtocell, a macro Ecp/Io of *Ecp/Io_min_MAT* is maintained.
- 3) For a HAT located *HAP_Link_Budget* path loss away from the femtocell, a pilot Ecp/Io of *Ecp/Io_min_HAT* is enforced in order to prevent unnecessary interference to others.

The above algorithm requires femtocell to listen to the macro network FL channel quality. This can be accomplished by equipping femtocell with a Network Listen Module (NLM), which has mobile station like capabilities that allow it to sniff FL macro signals. The fundamental assumption in this NLM based algorithm is that the measurements made by the femtocell are representative of the RF environment experienced by mobiles in the femtocell vicinity. In practice, there can be a mismatch between the RF conditions measured by the femtocell and those experienced by HAT and MAT, which can result in inaccurate estimation of femtocell coverage/interference. However, performance can be improved further by using HAT measurement feedback to complement the NLM measurements since HAT could sample different locations around the femtocell with slightly different RF characteristics. At the same time, idle-mode registration attempts to the femtocell by nearby MATs can also be used to adapt Tx power. For example, if the femtocell observes too many registration attempts from MATs, it can reduce its Tx power to limit interference to MATs. The interested reader is referred to [6] for more details on these advanced methods.

3.1.2 Femtocell Autonomous PN Code Selection

Each femtocell needs to be configured with a particular PN code on the forward link. If neighboring femtocells use the same PN code, significant problems can arise since HATs may not be able to associate with the correct femtocell. In macro networks, PN code selection for base stations is carefully managed through RF engineering. Since RF planning is not practical for femtocells, an autonomous method is desired. The following algorithm is recommended for autonomous PN code selection by a femtocell.

- 1) Certain set of PN offsets are reserved for femtocells: $PN_{Femto} = \{PN_1, PN_2, \dots, PN_N\}$. If the femtocells operate on a dedicated carrier, all the available PN offsets can be reserved, i.e., $N=128$ assuming pilot offset of $4*64 = 256$ chips. If femtocells operate on a shared carrier with macro network, a certain subset of available PN offsets should be reserved only for femtocell use.
- 2) During self calibration, a femtocell scans for all PN offsets and constructs a set of offsets which have pilot energy (Ecp/Io) above a detection threshold: $PN_{DETECTED} = \{PN_i, PN_j, \dots, PN_k\}$.
- 3) If all femto-reserved PN offsets are being used by neighbors, femtocell picks a PN offset in PN_{Femto} with lowest amount of detected energy (i.e., lowest Ecp/Io). Otherwise, the femtocell picks a PN offset randomly from the set of PN offsets that are members of PN_{Femto} but not a member of $PN_{DETECTED}$.

3.1.3 Femtocell Autonomous Carrier Selection

Each femtocell needs to be configured to operate on a certain carrier frequency. If macrocells operate on the same carrier as femtocells then femto-macro interference may result in outage and performance degradation for both femto and macro ATs. One solution would be to make sure the carriers used by femtocells are not used by macrocells. This is a viable option for many cdma2000 operators who have the flexibility of allocating a dedicated carrier(s) to femtocells due to availability of unused spectrum. In general, only a few of all available carriers should be allocated to femtocells, which leaves most of the macro carriers free from femtocell interference. Neighboring femtocells can use different frequencies to minimize inter-femto interference. A

femtocell autonomous carrier selection algorithm is described below in order to achieve these goals.

If an operator has N carrier frequencies: $F = \{f_1, f_2, \dots, f_N\}$, then femtocells can use certain subset (F_{femto}) of these while macrocells can use a certain subset (F_{macro}). Without loss of generality, we assume $F_{\text{femto}} = \{f_1, f_2, \dots, f_K\}$ and $F_{\text{macro}} = \{f_M, f_{M+1}, \dots, f_N\}$ where $1 \leq K \leq N$ and $1 \leq M \leq N$.

- 1) Femtocell makes received signal strength measurements (I_o) of all femto allowed frequencies F_{femto} as $I_{o_{f1}}, I_{o_{f2}}, \dots, I_{o_{fK}}$.
- 2) Femtocell finds the carrier with least interference as $I_{o_{\min}} = \min[I_{o_{f1}}, I_{o_{f2}}, \dots, I_{o_{fK}}]$.
- 3) If I_o of any femto-preferred carrier is within *Frequency_RSS_margin* of $I_{o_{\min}}$, the carrier decision is made as the femto-preferred carrier (i.e., f_1) with the least I_o . If not, then carrier with minimum I_o within F_{femto} is picked.

The parameter *Frequency_RSS_margin* adjusts the tradeoff between the desire to select a carrier with least interference versus the desire to concentrate femtocells on certain carriers so that coverage holes created for macrocell users are minimized. As *Frequency_RSS_margin* is reduced, each femtocell picks the carrier with least interference, whereas larger values of margin increase bias for carrier f_1 .

3.2 Coverage Results

3.2.1 Simple Femto-Macro Interference Model

To analyze femtocell DL Tx power requirements for different femtocell locations in a macrocell, we use the simple femto-macro interference model described in Section 2.1. Assume the following macro and femtocell settings: Macro Tx power = 43 dBm, 50% loading, femto loading = 100%, and Ecp/Ior (pilot to total power ratio) = 0 dB for both MAPs and HAPs.

The HAT and MAT FL performance for macro cell edge and cell site scenarios are provided in Table 2 and Table 3, respectively, assuming fixed and calibrated Tx power levels.

These results show that at cell edge low Tx power is needed to limit interference to MATs. On the other hand, near cell site a larger femto Tx power is needed to ensure good coverage for HATs. Tx power calibration allows a femtocell to autonomously adapt the power level to provide good coverage to home users and at the same time minimize interference to macrocell users.

Table 2 Cell edge macro and femto coverage for the simple femto-macro interference model

Coverage	Cell edge location		
	Ptx _{HAP} = -10 dBm	Ptx _{HAP} = +10 dBm	Ptx _{HAP} Calibrated (-10 dBm)
MAT Ecp/Io[dB]	-9	-27	-9
HAT Ecp/Io[dB]	-2	0	-2

Table 3 Cell site macro and femto coverage for the simple femto-macro interference model

Coverage	Near cell site location		
	Ptx _{HAP} = -10 dBm	Ptx _{HAP} = +10 dBm	Ptx _{HAP} Calibrated (+17 dBm)
MAT Ecp/Io [dB]	-2	-2	-4
HAT Ecp/Io [dB]	-30	-20	-5

3.2.2 Dense-urban System Simulation Model

This section provides coverage results for the dense-urban system simulation model described in Section 2.2. MAP transmit power is assumed to be 43 dBm. HAPs self-calibrate their Tx power in the range [-10, 20] dBm. Signaling-only association is assumed for the HAPs, which means that any AT can camp (i.e., be idle) on any HAP, but can get service only from authorized HAPs. However, an AT can set up a call/session only through a permitted femtocell. A pilot Ecp/Io threshold of -10 dB is used to declare an AT in outage since below this level it is not able to acquire the system.

For idle mode analysis, an AT that is not in acquisition outage, camps on either a HAP or a MAP based on their relative signal strength. A 2 dB hysteresis value is used for determining the candidate for camping in idle mode. In this manner, this analysis incorporates cell selection procedures that would normally be carried out by the ATs. Based on where the AT is camped in idle mode, its coverage/outage in active mode is computed. A MAT camping on HAP is required to acquire the MAP to get service. Similarly, if a HAT is camping on an alien HAP, it will be re-directed to a MAP for service and therefore needs to be able to acquire a MAP as well.

Assuming an operator has two carriers (adjacent carriers f_1 and f_2), we present coverage/outage results for the following deployment scenarios in order to study the optimal deployment strategy. The deployment scenarios considered are:

- 1) Shared f_1/f_2 : Both carriers are shared between HAPs and MAPs.
- 2) Share f_1/f_2 , HAPs prefer f_1 : Both carriers are shared. HAPs give higher preference to f_1 (6 dB margin in the carrier selection algorithm).
- 3) HAPs on f_1 , MAPs on f_2 : Carrier f_1 is dedicated to HAPs, carrier f_2 is dedicated to MAPs.
- 4) HAPs on f_1 , MAPs on f_1/f_2 : Carrier f_1 is shared by HAPs and MAPs. Carrier f_2 is dedicated to MAPs.

Idle mode and active mode coverage/outage statistics for these different scenarios are provided in Table 4 and Table 5, respectively.

Table 4 Idle Mode Coverage/Outage Statistics (%)

Category	Shared f1/f2	Shared f1/f2, HAP prefer f1	HAPs on f1, MAPs on f2	HAPs on f1, MAPs on f1/f2	No HAPs
MAT in outage	0	0	0	0	1
HAT camping on own HAP	95	95	96	92	NA
HAT in outage	0	0	0	0	2

Table 5 Active Mode Coverage/Outage Statistics (%)

Category	Shared f1/f2	Shared f1/f2, HAP prefer f1	HAPs on f1, MAPs on f2	HAPs on f1, MAPs on f1/f2	No HAPs
MAT in outage	4	3	2	2	1
HAT served by macro	5	5	3	7	98
HAT in outage	0	0	1	1	2

The following main conclusions can be drawn from the above results:

- Femtocell deployments reduce HAT outage compared to no femtocell deployment. When no femtocells are deployed, 2% of “would be HATs” are in outage due to poor macrocell coverage indoors. Results also show that ~92-95% of HATs are camped, i.e., connected in idle mode, on their home HAP, while the rest are camped either on neighboring MAP or a neighboring HAP due to strong coverage from these neighboring cells.
- MAT outage increases with femtocell deployments. However, this outage can be controlled by femtocell Tx power calibration and proper carrier allocation. When both the carriers are shared between femto and macrocells, MAT outage is higher due to HAP interference on both the carriers. Better performance can be achieved by restricting femtocell interference to one of the carrier (e.g., HAPs on f1, MAPs on f2 or HAPs on f1, MAPs on f1/f2) and using the other carrier for femtocells only when needed.
- One would expect that MAT outage when HAPs are on f1 and MAPs are on f2 (dedicated femtocell frequency deployment) should be similar to the case with no femtocell deployment. However, even with dedicated HAP frequency, MAT outage is higher. This is primarily due to HAP interference leakage from frequency f1 to the adjacent frequency f2. An ACIR of 18 dB, which is typical for 1xEV-DO systems, is assumed in this analysis. Therefore, the results show that this ACIR level is not sufficient to reject

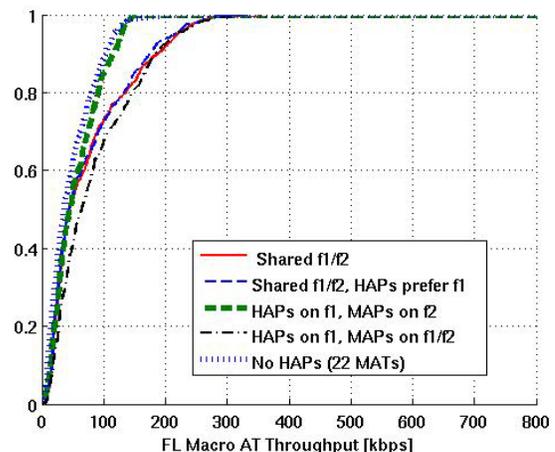
inter-carrier interference. Performance can be improved by re-directing the ATs to a cleaner (interference free) carrier frequency, if available.

3.3 FL Capacity Results

In this section, FL system level performance is analyzed with and without femtocells for the dense urban system simulation model. We assume a Rician channel with $K = 10$ and 1.5 Hz Doppler frequency. When femtocells are deployed, we assume 12 HATs per sector and 20 MATs per sector. The 20 MATs are distributed on the two carriers except for the case when HAPs are on frequency f1 and MAPs are on frequency f2, for which all 20 MATs are on frequency f2. For the case when there are no HAPs, the 12 ATs (referred to as HATs) are served by MAPs, and hence there are a total of 22 (10+12) ATs per sector, which are served by a macro sector. Based on the coverage analysis presented in Section 3.2.2 (Table 5), users in outage are excluded from system level simulations, but included in throughput curves as having zero throughputs. HAPs self-calibrate their power in the range [-10, 20] dBm. Best Effort (BE) traffic is assumed and FL throughputs of users are compared.

Figure 4 shows throughput experienced by MATs. It can be seen that without HAPs (i.e., with 22 MATs per sector) MAT peak throughput is less than 150 kbps due to heavy load on the macro sector. In contrast, when HAPs are deployed MAT performance improves due to traffic offloading from MAPs to HAPs. Comparing different frequency deployment scenarios, we observe the following:

- Compared to other frequency deployment scenarios, MAT performance is worse when HAPs are on f1 and MAPs are on f2 because all MATs are on frequency f2 and thus the resources per user and therefore throughput decreases.
- MAT performance is slightly better when HAPs are on f1 and MAPs are on f1/f2, because MATs on f2 experience better geometries since all HAPs are on f1. Although the MATs on f1 experience higher interference from the HAP on f1, they do not suffer significant degradation in geometries. This is due to load balancing where users experiencing low geometry on f1 are shifted to f2.
- More noteworthy is the improvement in HAT performance as illustrated in Figure 5. By introducing HAPs, much higher


Figure 4 Forward Link MAT Throughput CDF

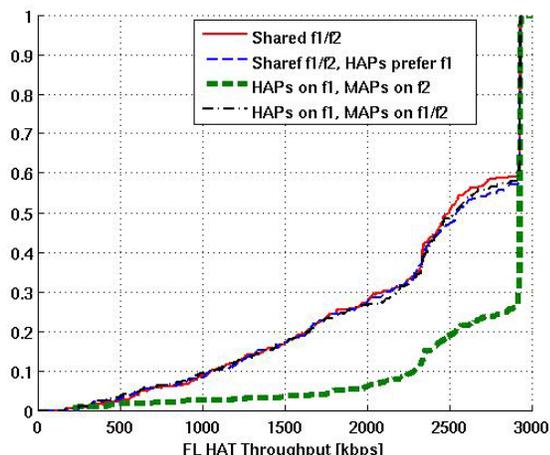


Figure 5 Forward Link HAT Throughput CDF

throughput values (peak rate of ~2.8 Mbps) are observed since some of the users that were otherwise being served by MAPs, are now being served by their indoor HAPs that provide excellent coverage. When HAPs are on dedicated frequency (HAPs on f1, MAPs on f2 case), HAT performance is significantly better compared to other frequency deployment scenarios since there is no macro interference on f1.

The results presented in this section clearly highlight the benefit of femtocells. Home users enjoy high throughput and macro users also experience performance improvement due to traffic offloading from macrocells to femtocells.

4. Reverse Link

There are several causes of concern for RL operation in femtocell deployments. One reason is the fact that a HAT can get arbitrarily close to the femtocell. In such case, it can not obey the power control (PC) down commands due to reaching its minimum transmit power capability. Such a HAT transmitting higher than the required power may desensitize the femtocell receiver and/or also lead to high Rise-over-Thermal (RoT).

Another concern is nearby high power users who are not associated with the femtocell (due to restricted association). These users may cause significant RL interference and lead to very high RoT levels. When the RoT is above a threshold, the sectors set their loading indicator which in turn results in the HATs to reduce their data rates in order to control the loading. This leads to poor femtocell performance. There is also the possibility that the total received signal strength at the femtocell may be beyond the receiver dynamic range. Proper RL interference management techniques are required to alleviate these concerns and ensure satisfactory RL performance.

4.1 RL Interference Management Techniques

One simple solution to deal with the high RoT problem is to raise the RoT threshold. However, this solution has some instability implications. When operating at high RoT levels, burstiness in the interference will cause very high pilot 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. As a result interference

becomes more comparable to thermal noise, leading to low RoT operation. Another advantage is that the attenuation pulls nearby HATs to a power controllable range and solve the saturation problem. A potential problem with applying fixed uniform attenuation across all femtocells results in all HATs to transmit at higher power levels which may affect the macro network. The solution is to use attenuation only when high out-of-cell interference (Ioc) or receiver desensitization is detected at the femtocell.

4.1.1 RL Adaptive Attenuation Algorithm

Adaptive RL attenuation algorithm is designed to ensure good femtocell RL performance while minimizing the effect on the macro network performance. The algorithm results in the RL signal to be attenuated only when the total received signal level is saturating the receiver, or the RL is being jammed by a nearby non-associated AT. It is composed of two main loops: Jammer Control Loop and Interference Control Loop. The Jammer Control Loop is designed to detect signal levels beyond the dynamic range and increase attenuation to bring it down. The Interference Control Loop reacts to high out-of-cell interference (Ioc) as well as HATs that can not PC down due to minimum tx power limitation. The two main loops provide their required RL attenuation values, and the maximum of the two 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 in the sense that the attenuation is mostly maintained when the next burst arrives, ensuring stability.

Consider the simple case of a bursty MAT located at the macro cell-edge (135 dB PL), which is also 80 dB away from a femtocell. In Figure 6, femtocell RoT and received Ecp/Nt of the HAT is plotted with and without the proposed adaptive attenuation algorithm. As seen in the figure, the algorithm ensures stable RL operation and good user experience by significantly reducing the RoT and Ecp/Nt fluctuations due to incoming interference bursts. Thus, adaptive RL attenuation algorithm is recommended for managing RL interference at femtocells.

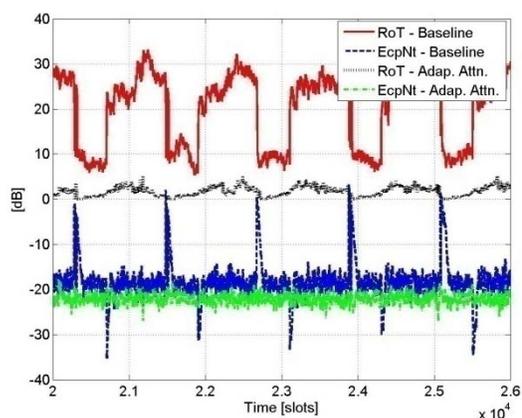


Figure 6 RL Femtocell Performance with Bursty Interference

4.2 RL Capacity Results

In this section, RL system level performance of deployments with and without femtocells is analyzed. Dense urban layout is assumed with 10 MATs per sector and 12 HATs per sector. RL

throughput of users are compared assuming BE traffic. Based on the coverage analysis presented in Section 3.2.2 (Table 5), the users that are in outage are excluded from system level simulations. Performance is presented with adaptive RL attenuation algorithm at the HAPs.

Figure 7 and Figure 8 provide the MAT and HAT RL throughput distributions, respectively. Results show that when there are no HAPs present, AT throughput is very low because only the macro resources are utilized to serve the 22 ATs in each sector. Due to high system loading, no AT is able to get high throughput. When the HAPs are introduced, the ATs that are now served by the HAPs, i.e., HATs, are able to get higher throughput (~600 kbps). The MAT performance also improves with the introduction of femtocells due to few users sharing macro RL resources.

Comparing different frequency deployment scenarios, the MAT performance is similar for most cases except for the dedicated carrier case (HAPs on f1, MAPs on f2). In the dedicated

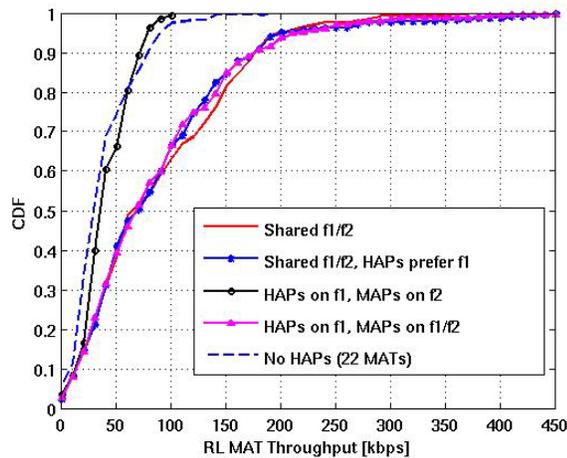


Figure 7 Reverse Link MAT Throughput CDF

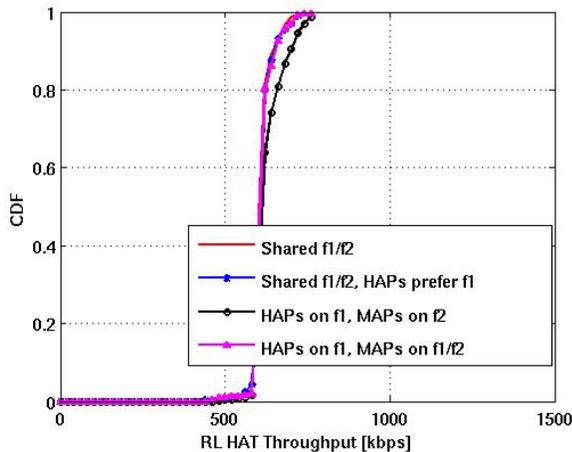


Figure 8 Reverse Link HAT Throughput CDF

carrier case, all 20 MATs in each sector are served by the same carrier making the RL very loaded. This high load leads to lower throughput values for each MAT.

5. Conclusion

In this paper, we have analyzed the performance of 1xEV-DO femtocells with a focus on interference management. We demonstrated that high quality user experience can be achieved with femtocells by properly managing inter-femto and femto-macro interference. Autonomous transmit power, carrier and PN code selection are proposed as primary interference management techniques for the FL. On the RL, adaptive RL attenuation algorithm provides robust femtocell performance in the presence of uncontrolled, out-of-cell interference, especially bursty interference. It is shown that femtocells improve indoor coverage for home users without significant impact to macrocell users. We also demonstrated significant capacity improvement on both FL and RL with 1xEV-DO femtocell deployments. Home users experience very high data rates due to improved indoor coverage and availability of femtocell resources because very few users are served by a typical femtocell. At the same time, macro users benefit from capacity offload to femtocells since more macro network resources are available for them.

6. REFERENCES

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