Interference Behavior of Integrated Femto and Macrocell Environments

Antonios Alexiou[†], Christos Bouras[*†], Vasileios Kokkinos[*†], Konstantinos Kontodimas[*†], Andreas Papazois[*†]

[*] Computer Technology Institute & Press "Diophantus", Patras, Greece

[†] Computer Engineering and Informatics Dept., University of Patras, Greece

alexiua@ceid.upatras.gr, bouras@cti.gr, kokkinos@cti.gr, kontodimas@ceid.upatras.gr, papazois@ceid.upatras.gr

***Abstract*—Femtocells are data access points installed by the subscribers to provide better indoor voice and data coverage and to increase system capacity. The integrated femtocell/macrocell networks offer an efficient way to increase access capacity by improving coverage and quality of service while on the other side the deployment cost for the service provider is kept in extremely low levels. One of the major technical challenges that femtocell networks are facing is their interference behavior when they are placed within macrocells. The study presented in this paper focuses on the impact of integrating femtocells in macrocell networks in terms of adjacent cell interference that the macrocell environment adds to users served by a femto base station and vice versa. To this direction, we have designed and implemented a simulation testbed that estimates the cross-tier interference and the throughput in every point of an integrated femtocell/macrocell Long Term Evolution-Advanced (LTE-A) network.**

I. Introduction

The demand for higher data rates in mobile networks is unrelenting and has triggered the design and development of new data-minded cellular standards. A large wireless capacity gain can be achieved by reducing cell sizes and transmit distance and, to this direction, a recent development that responds to the need of increased mobile user experience is femtocells, also called femto or home Base Stations (BSs) or Home Node-Bs (HNBs). Femtocells are short-range, low-cost, low-power BSs installed by the consumer [1]. A femtocell allows service providers to extend service coverage indoors, especially where access would otherwise be limited or unavailable. Compared to other techniques for increasing system capacity, such as distributed antenna systems and microcells, the key advantage of femtocells is that there is very low upfront cost to the service provider. Another major benefit of femtocell networks is that due to their short transmit/receive range, the power consumption can be kept in low levels and this in turn means that a higher Signal-to-Interference-plus-Noise Ratio (SINR) can be achieved, offering improved user reception experience and higher capacity compared to micro deployments.

Prior research in femtocell networks has mainly focused on the investigation of one of the major technical challenges that femtocell networks are facing, i.e., the interference behavior when they are placed within macrocell environments. An analysis of the interference between macrocells and femtocells is presented in [2] for the case of open access, in which interference problems for co-existing macro and femtocell BSs will not appear, except when too fast passing by terminals are unable to handover to the nearest femtocell. A 3GPP technical report [3] provides an extensive analysis of the different interference scenarios (including femto-to-macro) considering open and closed access for WCDMA systems. The utility-based non-cooperative femtocell SINR adaptation presented in several works, such as [4] and [5], is related to existing game theory literature on noncooperative cellular power control. The adaptation forces stronger femtocell interference to obtain their SINR equilibria closer to their minimum SINR targets, while femtocells causing smaller cross-tier interference obtain higher SINR margins. This is similar to the Utility-Based Power Control (UBPC) scheme presented in [6], where users vary their target SINRs based on the prevailing traffic conditions.

In this paper we study the cross-tier interference behavior of femtocells when they operate within the macrocell underlay. In order to estimate the adjacent cell interference, we create through analytical process a model that takes into account the path and propagation losses in order to estimate the SINR and therefore the adjacent cell interference due to femtocells. Three different scenarios are examined. In the first scenario, we are interested in examining the interference that a femto BS adds to a user served by a macrocell and how this interference affects the achieved throughput, while in the second scenario we examine the opposite deployment: the examination of adjacent cell interference that the macrocell environment adds to a user served by a femto BS. The third scenario simulates the movement of a user that is served by a macro BS, so as to calculate the user's throughput throughout the followed route. For our analysis, we propose a simulation model that estimates the cross-tier interference and the throughput in every point of an integrated femtocell/macrocell LTE-A network.

The remainder of this paper is structured as follows: in Section II, we describe the modeling and analysis used for the cross-tier interference estimation, based on which our simulation testbed described in Section III is designed and implemented. In Section IV, we present the experiments that we have conducted and their results. Finally, our conclusions and planned next steps are described in Section V.

II. Analysis & Modeling

This section presents the simulation model that estimates the cross-tier interference and the throughput in every point of a

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two-tier LTE-A network integrating femto and macrocells.

A. Path Loss Model

In order to estimate the SINR, first we have to calculate the path loss between a macro BS and a User Equipment (UE) and between a femto BS and a UE. The path loss for the first case and for a macro user that roams outdoor in an urban area, can be determined as follows [7]:

$$PL(\text{dB}) = 15.3 + 37.6\log_{10} R \quad (1)$$

whereas, for the case of an indoor macro user the path loss is given by:

$$PL(\text{dB}) = 15.3 + 37.6\log_{10} R + L_{ow} \quad (2)$$

Also, the case that the UE is outside where R is the distance between the transmitter (Tx) and the receiver (Rx) in meters and L_{ow} the penetration loss of an outdoor wall.

The path loss between a femto BS and a UE that are in the same apartment stripe is calculated by the following equation (3) [7]:

$$\begin{aligned} PL(\text{dB}) \quad = \quad & 38.46 + 20\log_{10} R + 0.7d_{2D,indoor} + \\ & 18.3n^{((n+2)/(n+1)-0.46)} + q^{*}L_{iw} \end{aligned} \quad (3)$$

where n is the number of penetrated floors, q is the number of walls separating apartments between the femto BS and the UE, and L_{iw} is the penetration loss of the wall separating apartments. Also, the term $0.7d_{2D,indoor}$ takes account of penetration loss due to walls inside an apartment and is expressed in m.

Finally, we consider the case of an outdoor femto user associated to an indoor femto BS. In this case we assume that the BS is on the ground floor of an apartment stripe, and there are no other barriers between the BS and the user, that might cause signal degradation:

$$\begin{aligned} PL(\text{dB}) \quad = \quad & max(15.3 + 37.6\log_{10} R, 38.46 + \\ & 20\log_{10} R) + 0.7d_{2D,indoor} + \\ & 18.3n^{((n+2)/(n-1)-0.46)} + q^{*}L_{iw} + L_{ow} \end{aligned} \quad (4)$$

B. SINR Estimation

For the estimation of the SINR, our analysis is based on the femtocell dynamic system level simulator presented in [8]. SINR is calculated by using the “attenuated and truncated Shannon bound” mapping method [9], in which the obtained SINR at each snapshot is mapped to the throughput.

Following the analysis in [8], the post-processing SINR is calculated for each user and each subcarrier n. For different downlink transmission modes different post-processing SINR calculation methods are implemented. The post-processing SINR of the desired user i with the power $P_{i,n}$ on the n-th subcarrier for Single-input Single-output (SISO) transmission mode is given by the following equation:

$$SINR_{i,n} = \frac{P_{i,n}(|h_{i,k(i),n}|^2)}{(\sum_{l=1,l\neq i}^{N} P_{l,n}|h^{H}_{i,k(l),n}|^2) + \sigma_n^2} \quad (5)$$

where

- $h_{i,k(i),n}$: channel frequency response on the n-th subcarrier between the i-th user and k-th BS
- k: BS index
- N: total number of users
- σ_n^2: variance of the white Gaussian noise on the n-th subcarrier

We assume that $\sigma_n^2 = 1$ for every subcarrier n.

C. Throughput Calculation

After the SINR estimation, we proceed with the throughput calculation. The capacity of macro user i on sub-carrier n can be given by equation (5) [10]:

$$C_{i,n} = \Delta f \cdot \log_2(1 + \alpha SINR_{i,n}) \quad (6)$$

where, α is a constant for target Bit Error Rate (BER), and defined by $\alpha = -1.5/\ln(5BER)$. In this analysis BER is set to 10^{-6}.

Finally, the overall throughput of serving macrocell M can be expressed as follows:

$$T_M = \sum_i \sum_n \beta_{i,n} C_{i,n} \quad (7)$$

where, $\beta_{i,n}$ represents the sub-carrier assignment for macro users. When $\beta_{i,n} = 1$ means that the sub-carrier n is assigned to macro user i. Otherwise, $\beta_{i,n} = 0$. From the characteristics of the Orthogonal Frequency-Division Multiple Access (OFDMA) system, each sub-carrier is allocated only one macro user in a macrocell in every time slot. This implies that:

$$\sum_{i=1}^{N_i} \beta_{i,n} = 1 \quad (8)$$

where N_i is the number of macro users in a macrocell.

III. Simulation Testbed

The above mathematical analysis has been the basis for the implementation of a simulation testbed that applies for the interference and, therefore, the maximum throughput estimation in macrocell environments that integrate femtocell overlay. This testbed receives as input the macrocell environment dimensioning, the femtocell positions as well as other parameters like the macro and femto BS transmission power. By making use of the (1) to (3) above, and based on the defined macro and femto BS transmission power, the implemented testbed is able to calculate the received power from serving as well as from the interfering cells. Based on these figures and by taking into account the white Gaussian noise, the simulation testbed is able to make an estimation of the SINR and throughput at any given position of the examined LTE-A network.

The simulation testbed has been implemented as a simulation tool that runs on MATLAB environment and has been used for conducting the simulation experiments. It can also consist a useful tool for experimentation over the impact of cross-tier interference in next generation mobile networks that integrate femtocells.

IV. Experimental Results

The selection of the simulation setting values that we use during the experimental evaluation has been based on [8]. TABLE I provides an overview of the simulation parameters along with the selected values.

TABLE I
System Level Simulation Parameters

Parameter	Value
Cellular Layout	Hexagonal grid
Mecrocell Radius (R_m)	250 m
Femtocell Radius (R_f)	20 m
Number of Macro BS	7
Frequency	2 GHz
Multipath channel	vehA (3 km/h)
Macro BS Power	46 dBm
Femto BS Power	20 dBm
Minimum Distance Between Macro BS and Mobile User	10 m
Noise Figure	9 dBm
Outdoor Walls Loss (L_{ow})	20 dB
Indoor Walls Loss (L_{iw})	5 dB
Bandwidth	20 MHz
Subcarrier Spacing	15 kHz

The remainder of this section presents the conducted simulation experiment along with their results.

A. Throughput of Macro User

Based on the simulation model, in this section we calculate the throughput for a macro user (served be the macro BS) that is also located in the coverage area of a femtocell and therefore experiences cross-tier interference. In order to better reveal the affect of cross-tier interference, the throughput is calculated for different distances from the macro BS that vary from 10 m to 250 m. Since the cross-tier interference also depends on the distance of the user from the femtocell, the throughput is also calculated for three different positions inside the femtocell coverage: at distance 1 m from the femto BS, at a distance equal to R_f / 2 from the femto BS (R_f = 20 m, is the radius of the femtocell) and at the femtocell edge. The results are presented in Figure 1 and Figure 2. Figure 1 corresponds to the case of an indoor macro user and Figure 2 of an outdoor one. In both cases, the user is served by the macro BS; however, in the first case the user is located inside the building with the femtocell equipment and therefore, the macrocell signal is attenuated by the exterior wall.

The examination of Figure 1 reveals that the throughput of an indoor macro user decreases as the distance from the macro BS increases, irrespectively of the distance between the user and the femto BS. Specifically for the case of 20 m distance between the user and the femto BS, the throughput of the macro user decreases from 1.5 Mbps to almost 1.1 Kbps (99.93% decrement) as the user moves towards the macrocell edge. Indeed, this movement causes the SINR to consecutively decrease, which in turn, leads to a decrement in the achieved throughput.

For an outdoor user (Figure 2) the results are similar. In this case there is no exterior wall between the macro BS and the user. This fact increases the experienced SINR and may provide a maximum user's throughput of almost 2.1 Mbps (distance: 10 m from macrocell and 20 m from femto BS). When the user is at the macrocell edge, the throughput falls to 10.2 Kbps (99.51% decrement).

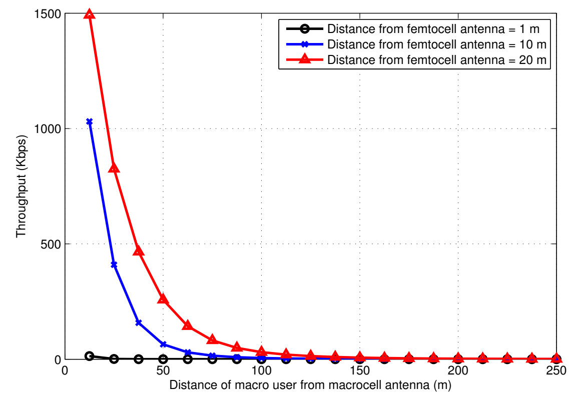

Fig. 1. Throughput for an indoor macro user against the distance from the macro BS when femtocell interference exists.

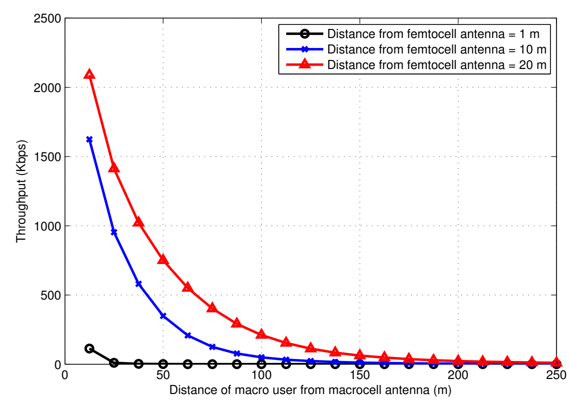

Fig. 2. Throughput for an outdoor macro user against the distance from the macro BS when femtocell interference exists.

The effect of cross-tier interference can be better revealed by examining the achieved throughput for different distances between the macro user and the femto BS. In general, small distances (1 m) result in increased cross-tier interference and therefore in high SINR values and low throughput. As presented in Figure 1 and Figure 2, when the user is 1m from the femto BS, the achieved throughput is very low even for small distances from the macro BS. For larger distances (10 m and 20 m), the cross-tier interference is attenuated leading to an increase in the experienced throughput.

B. Throughput of Femto User

This section performs a similar analysis. However, in this case the user is connected to the femto BS (femto user) and the macrocell transmission acts as interference. In order to calculate the achieved throughput in this case, we examine three different distances between the femto and the macro BSs: at distance 10 m from the macro BS, at a distance equal to R_m / 2 from the macro BS (R_m = 250 m, the radius of the macrocell) and at the macrocell edge. As in the previous section, the experiments are conducted for both indoor and outdoor femto users. Regarding the case of indoor user, we assume that both the user and the femto BS are in the same apartment. However, contrary to the macro user case, an indoor femto user experiences less cross-tier interference than an outdoor femto user because the macrocell transmission (that acts as interference) in the first case is attenuated by the exterior wall. The simulation results for an indoor and an outdoor femto user are presented in Figure 3 and Figure 4 respectively.

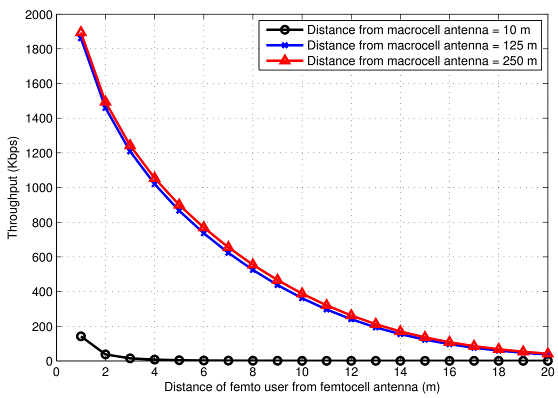

Fig. 3. Throughput for an indoor femto user against the distance from the femto BS when macrocell interference exists.

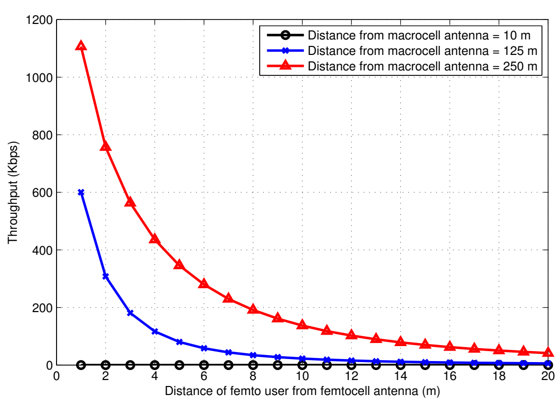

Fig. 4. Throughput for an outdoor femto user against the distance from the femto BS when macrocell interference exists.

The examination of both figures reveals that the throughput of the femto user decreases as the user moves towards the femtocell edge. However, contrary to the macro user case, the decrease is smoother and even at the femtocell edge the throughput is high enough to serve the user. More specifically, for the case where the distance between the indoor user and the macro BS is 250 m, the achieved throughput decreases by 97.83% (from 1.9 Mbps to 41.3 Kbps). For an outdoor user the decrement reaches 96.2% (from 1.10 Mbps to 41.75 Kbps). The achieved throughput at the femtocell edge is low; however, the corresponding throughputs for a macro user are even lower (1.1 Kbps for an indoor and 10.2 Kbps for an outdoor macro user at the macrocell edge). This fact indicates that the cross-tier interference has bigger impact on macrocell transmissions.

Another aspect that we examine is the case of the outdoor femto user. In this case, the throughput is affected by the user's distance from the femto BS in terms of intermediate apartments and floors. TABLE II presents the throughput values when the user roams in a distance of 10 m from the femto BS. The user is interfered by a macro BS which is located in a distance of 125 m. The rows of the table represent the apartments among the femto BS and the user, while the columns represent the floor difference between them. At this point it should be noted that in our previous experiment, the achieved throughput of an indoor femto user in the same distance from the corresponding femto BS, is 361.87 Kbps.

TABLE II
THROUGHPUT OF AN OUTDOOR FEMTO USER AGAINST THE NUMBER OF INTERMEDIATE FLOORS AND APARTMENTS

		# of Floors			
		1	**2**	**3**	**4**
# of Apts.	**0**	22.59 Kbps	7.36 Kbps	2.34 Kbps	0.74 Kbps
	1	0.35 Kbps	0.11 Kbps	0.03 Kbps	0.01 Kbps
	2	0.01 Kbps	0.00 Kbps	0.00 Kbps	0.00 Kbps

It is obvious that the existence of intermediate structures has a great impact in the femtocell performance.

C. *Throughput of Moving User*

This experiment simulates the movement of a user that is served by a macro BS, with main target to calculate the user's throughput during his route (Figure 5). As shown in Figure 5, the user moves from the Start point towards the End point. During his route, the user experiences the cross-tier interference from different number of femtocells (1 to 30), randomly located inside the macrocell sector where the examined user roams.

The results of the simulations are presented in Figure 6. In this 3D plot, the x-axis shows the number of femtocells that actually transmit and contribute in increasing the interference. In order to make clear which femtocells transmit at any instance, we have numbered the femtocells in Figure 5. For example, if the number of interfering femtocells in Figure 6 is one, in Figure 5 only femtocell 1 transmits and acts as source of interference. For two interfering femtocells, only femtocells 1 and 2 transmit, etc.

As depicted in Figure 6, the throughput of the macro user decreases drastically when the user moves towards the cell edge (End point in Figure 6). However, it is clear that the decrement is more abrupt when the number of transmitting femto BSs is higher. Indeed, the increment in the number of transmitting femtocells results in increasing the cross-tier interference, which in turn results in decreasing the achieved throughput.

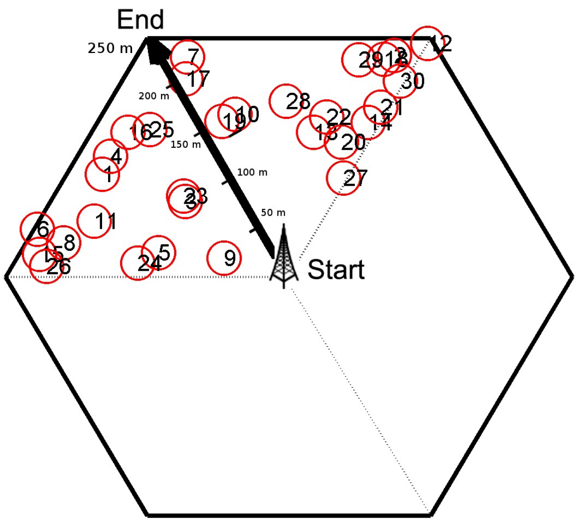

Fig. 5. Simulation topology and route of macro user.

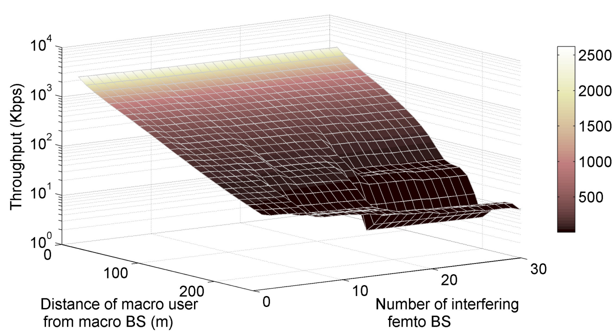

Fig. 6. Throughput for a moving user against the distance from the macro BS and the number of femtocells.

The 3D plot in Figure 6 shows two abrupt decrements in the achieved throughput for 150 m distance (when the number of interfering femto BS is 10 and 19), and two abrupt decrements for a distance of 200 m between the macro BS and the user (when the number of interfering femto BS is 7 and 17). These decrements can be better explained after noticing the user's route in Figure 5. Let us examine the last decrement that appears for 17 femtocells (x-axis) and at a distance of 200 m from macro BS (y-axis). The fact that the number of cells is 17 indicates that femtocells 1-17 are activated. As presented in Figure 5, femtocell 17 is located near the user's route. Thus, when the user passes close to femtocell 17 (at distance 200 m from the Start point) the increased – due to small distance – interference leads to an abrupt decrement in the achieved throughput. From the above experiment, it is obvious that the cross-tier interference between macro and femtocells may affect the overall performance of the system and therefore should be taken into account during the system configuration.

V. Conclusion & Future Work

In this paper, we have examined the cross-tier interference of LTE-A macrocell networks that integrate femtocells. Our investigation includes both types of cross-tier interference, i.e., the femtocell interference to users attached to macrocell and the macrocell interference to users attached to femtocell. Additionally, we have evaluated the interference in the above scenarios in cases where random clusters of femto BSs are located in the examined macrocell and act as sources of interference towards a macro user. Our experiments have examined the throughput that can be achieved for each case based on the distance from the serving and the interfering BSs and they have provided an overview of the impact that cross-tier interference has on LTE-A macrocell networks that integrate femtocells.

An interesting future step that could follow this work is the investigation of radio allocation strategies that reduce the interference and therefore increase the total throughput in the topology. These strategies could include fractional frequency reuse or self-organizing methods for the frequency allocation in the femtocell overlay.

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