Sensitivity of OFDMA-Based Macrocellular LTE Networks to Femtocell Deployment Density and Isolation

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***Abstract*—In this paper, we investigate the impact of femtocell deployment density and femtocell isolation on the downlink-performance of Orthogonal Frequency Division Multiple Access (OFDMA)-based macrocellular Long Term Evolution (LTE) networks by system level simulations. Femtocell isolation is defined as the separation between macro- and femto tiers by wall penetration loss. We evaluate the relation between user throughput and femtocell density for highly-isolated and non-isolated deployments. The system model is based on a Poisson Cluster Process and simulations are carried out with the Vienna LTE system level simulator. We provide results for Signal-to-Interference-Plus-Noise Ratio (SINR), throughput, fairness and gain over non-femtocell-enhanced networks. Our investigations indicate a femto-network's high sensitivity to varying wall penetration loss and we observe that in dense deployments, average user throughput conceals the severe performance degradation of macrocell-attached users. The whole simulation environment together with the fully reproducible results of this paper are made available for download on our homepage.**

***Index Terms*—Femtocells, Femtocell Access Point, Deployment Density, Fairness, Fairness Index, System Level Simulation, OFDMA Femtocell Network, Stochastic Geometry**

I. Introduction and Contributions

A. Motivation

One of the most straightforward methods to increase capacity in cellular networks is the reduction of cell size. Smaller cell sizes increase spatial reuse but come at the expense of additional interference and required infrastructure.

An economical way to achieve small cell sizes in existing macrocellular networks are user-deployed home base stations, also termed *femtocells*. These low-power, low-cost base stations have attracted a lot of research interest, concerning questions like [1]:

- *How will a femtocell adapt to its surrounding environment and allocate spectrum in the absence of coordination between macrocells and femtocells?*
- *What will be the impact of cross-tier interference on the macrocell network?*
- *Which system models can be applied for cellular systems with femtocell overlay?*

In this paper, we evaluate the downlink-performance of a femtocell-enhanced, Orthogonal Frequency Division Multiple Access (OFDMA) based Long Term Evolution (LTE) network by system level simulations [2, 3]. The femto- and macrocell tiers are assumed uncoordinated and employ universal frequency reuse (i.e., reuse-1), thus, representing a worst-case scenario in terms of interference.

Our work is particularly motivated by two facts:

- Although numerous system level simulation studies with femtocell networks have been carried out [4, 5], the utilized system models (e.g., the dual stripe- and the 5×5 approach [6]) are mostly too specific to systematically investigate the joint impact of femtocell deployment density and femtocell isolation.
  On the other hand, analytical work on this issue, as found in [7–10], is commonly evaluated in terms of capacity and can not directly be transfered to achievable throughput due to highly idealistic setups.
- Resource allocation techniques are usually benchmarked by average-based metrics, e.g., average user throughput [10, 11]. These metrics conceal the distribution of the values among the users, and thus, their validity cannot be assured until complementing measures are taken into account.

B. Contributions

- Our system model employs a simple Poisson Cluster Process and allows us to explicitly analyze the effects of varying femtocell density and isolation in a sophisticated simulation environment.
- Users of a femtocell-enhanced network experience highly heterogeneous channel conditions. We show that overall average user throughput steadily improves with increasing femtocell density, even when macrocell users are downgraded severely. Therefore, we provide means to measure the single users' performance, which would otherwise be concealed.

C. Outline

The remainder of this paper is organized as follows: First, Section II specifies the system model, significant assumptions and simulation parameters. Then, the achieved Signal-to-Interference-Plus-Noise Ratio (SINR) of macrocell- and femtocell users is evaluated in Section III. Section IV provides simulation results for throughput and fairness, and explains significant properties. Finally, Section V concludes the paper.

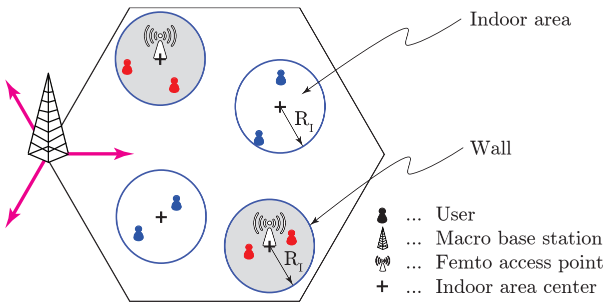

Fig. 1: User distribution in macrocell sector. Users are spread uniformly within homogeneously distributed indoor areas of radius R_I. FAPs are positioned exactly at centers of the indoor areas (denoted by '+') and attach only the users of the corresponding area.

II. Simulation Setup

A. Preliminary Assumptions

In our setup, macrocell Base Stations (BSs) and Femtocell Access Points (FAPs)[1] do not jointly coordinate their transmission, i.e. they act completely autonomously. Proportional fair scheduling is applied in all cells, macro and femto, for resource allocation [12].

B. Macroell Geometry

A hexagonal grid layout is utilized, composed of a central site and two tiers of neighboring sites. Each macrocell site is equipped with three BSs, each one employing a tilted directional antenna with 15 dB maximum antenna gain. The applied horizontal/vertical antenna radiation patterns correspond to realistic antennas[2].

C. User Distribution

Users are distributed according to a Poisson Cluster Process [8], as shown in Figure 1:

1) A parent point process Φ models the position of circularly shaped *indoor areas* of radius R_I by spreading them homogeneously over a macrocell BS's coverage area. The *number of femtocells per macrocell BS* is denoted as *femtocell density*.
2) A set of N_u users is distributed uniformly within each indoor area.

We assume the indoor area to be isolated from the outdoor environment by a wall, which is modeled as a penetration loss. The model is chosen for the following reasons: (i) FAPs are most effectively employed at user hot-spots [14]. Therefore, we generate scenarios, where users exclusively appear in clusters in order to explicitly work out the impact of the femtocell enhancement. (ii) Indoor areas are spread homogeneously over the macrocell-area. The indoor areas which are covered by a FAP are chosen randomly. This reflects the fact that femtocells belong to the unplanned part of the network.

D. Femtocell Access Point Employment

FAPs are equipped with omnidirectional antennas of 0 dB gain. In our simulations, they are added to the network one by one: First, a non-femto-covered indoor area is selected randomly. Then, a FAP is placed at the center of this area (denoted by '+' in Figure 1). Therefore, with increasing FAP count, an increasing number of users is covered by a FAP, while the total number of users is kept constant.

In our setup, Access Points (APs) operate in Closed Subscriber Group (CSG) mode: Only users of the according indoor area are allowed to attach to the FAP, while users in the close vicinity of the femtocell experience strong interference. This setting aims at mimicking a non-working hand-over between macrocell- and femtocell tier, which is the current situation in femtocell deployments.

E. Path Loss Models

Depending on whether a signal originates from a macrocell BS or a FAP, we choose between two propagation path loss models, denoted as ℓ_m and ℓ_f:

- *Macrocell Base Station (ℓ_m)*: The path loss model is referred from [15] subclause 4.5.2 [3] (dashed line in Figure 2).
- *Femtocell Access Point (ℓ_f)*: A dual-slope model is applied (solid line in Figure 2):
  - Within the indoor area, the propagation model as specified in [6] subclause 5.2[4] is employed.
  - At distance R_I the signal is attenuated by the wall penetration loss.
  - For distances larger than R_I, as for the signal from a macrocell BS, the propagation loss model according to [15] subclause 4.5.2 is utilized.

III. Wideband-Signal-to-Interference-Plus-Noise Ratio Distribution

When we combine our assumptions about user distribution, FAP employment and path loss models (Sections II-C–II-E), two user-types can be distinguished:

- The indoor area is *covered* by a FAP. Then, the achieved wideband-SINR of a femtocell-attached user can formally be written as:

$$\mathrm{SINR_F} = \frac{\overbrace{P_\mathrm{f}\ell_f(R_0)G_0}^{\mathcal{S}_\mathrm{Femto}}}{\underbrace{\sum_j P_\mathrm{m}\ell_m(R_j)G_j\, L_{OI}}_{\mathcal{I}_\mathrm{Macro}} + \underbrace{\sum_k P_\mathrm{f}\ell_f(R_k)G_k\, L_{OI}}_{\mathcal{I}_\mathrm{Femto}} + N}, \quad (1)$$

[1]The terms *Macrocell Base Station (BS)*, *Femtocell Access Point (FAP)* and *User* refer to the terms *Evolved Node B (eNodeB)*, *Home Evolved Node B (HeNB)* and User Equipment (UE), as respectively used in the LTE standard.

[2]Antenna gain patterns were kindly supplied by KATHREIN-Werke KG, correspond to a 742215 panel antenna [13], and are also included with the released code.

[3]Exemplifying from [15], for a carrier frequency of 2 GHz and a base station antenna height of 15 m above average rooftop level, $PL = \max(G_{[\mathrm{dB}]} + 128.1\,\mathrm{dB} + 37.6\,\log_{10}(R), 70)$, where $G_{[\mathrm{dB}]}$ is the antenna gain and R is the distance in kilometers.

[4]Exemplifying from [6]: $PL = \max(98.46\,\mathrm{dB} + 20\log_{10}(R), 45)$, where R is the distance in kilometers.

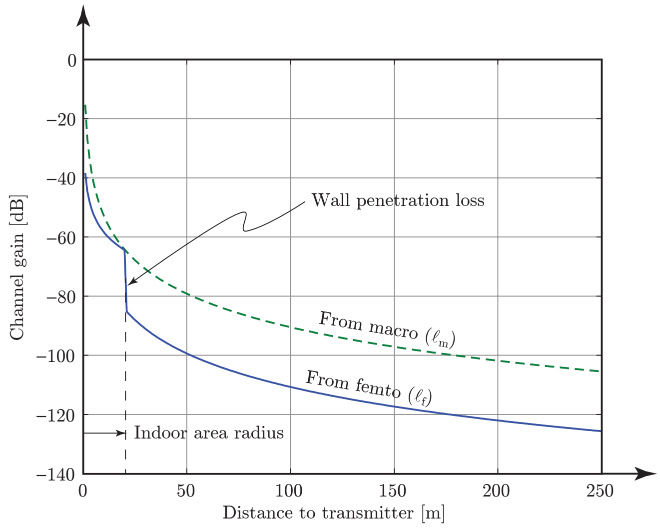

Fig. 2: Channel power gain of model according to [15] (dashed line) and dual slope propagation model (solid line). Simulation parameters are listed in Table I.

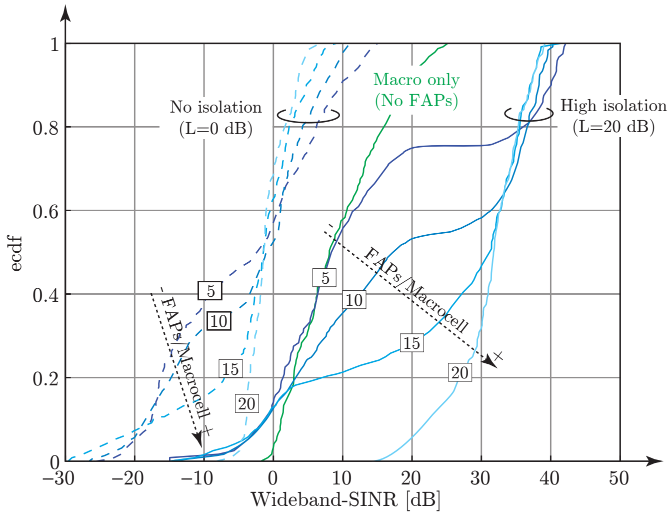

Fig. 3: Wideband-SINR distributions of various femtocell densities (the boxed numbers denote the number of femtocells per macrocell sector) for No Isolation- and High Isolation scenario (dashed and solid lines, respectively). The reference case is denoted as "Macro Only".

Bandwidth		20 MHz
Center frequency		2.14 GHz
Tx × Rx antennas		1×1
Tx power of macrocell BS	P_{m}	46 dBm
Tx power of FAP	P_{f}	20 dBm
Minimum coupling loss macro		70 dB
Minimum coupling loss femto		45 dB
Inter BS distance		500 m
User clusters per macrocell		40
Indoor area radius	R_I	20 m
Users per cluster		2
Wall penetration loss	L	20 dB (0 dB)
Shadow fading	G_i	$\sim \mathcal{LN}(0\,\mathrm{dB}, 8^2\,\mathrm{dB})$
Noise power density		−174 dB
Traffic model		Full buffer
Scheduling		Proportional fair
Femto backhaul		Unlimited, no delay

TABLE I: Simulation Parameters

where P_{f} and P_{m} denote the transmit power of a femtocell AP and a macrocell BS, respectively. The terms $\ell_m(\cdot)$ and $\ell_f(\cdot)$ refer to the macroscopic path loss, as formulated in Section II-E, at distance R_i from transmitter i. The factors G_i account for the shadow fading and L_{OI} is the outdoor-to-indoor penetration loss. Note that the corresponding indoor-to-outdoor loss L_{IO} is already contained in the dual-slope model (ℓ_f). The term N denotes the noise power.

- The indoor area is *not covered* by a FAP. Users are attached to the macrocell BS and their wideband-SINR is formulated as

$$\mathrm{SINR_M} = \frac{\overbrace{P_{\mathrm{m}}\ell_m(R_0)G_0}^{\mathcal{S}_{\mathrm{Macro}}}\,L_{OI}}{\underbrace{\sum_j P_{\mathrm{m}}\ell_m(R_j)G_j\,L_{OI}}_{\mathcal{I}_{\mathrm{Macro}}} + \underbrace{\sum_k P_{\mathrm{f}}\ell_f(R_k)G_k\,L_{OI}}_{\mathcal{I}_{\mathrm{Femto}}} + N} \tag{2}$$

Note the factor L_{OI} in the enumerator. It stems from the fact that the desired signal from the macrocell BS also experiences penetration loss. However, in an interference limited scenario (i.e., $N \ll \{\mathcal{I}_{\mathrm{Macro}}, \mathcal{I}_{\mathrm{Femto}}\}$), L_{OI} can be neglected in (2) and we simply obtain

$$\mathrm{SINR_M} = \frac{\mathcal{S}_{\mathrm{Macro}}}{\mathcal{I}_{\mathrm{Macro}} + \mathcal{I}_{\mathrm{Femto}}}, \tag{3}$$

which is equivalent to the situation where a user is located outdoors. In the remainder of this paper, we set $L_{IO} = L_{OI}$ and briefly denote it as L.

Figure 3 shows wideband-SINR distributions for two types of scenarios: High Isolation (HI) scenarios (solid lines), where FAPs are separated from the outdoor environment by a wall penetration loss of $L = 20$ dB, and No Isolation (NI) scenarios (dashed lines) with $L = 0$ dB, i.e., the worst-case assumption. The distributions are depicted for various FAP densities.

Two characteristics are of particular interest: 1) The large gap between HI and NI scenarios emphasizes the system's sensitivity to fluctuations of the femtocell-isolation. 2) The step-like behavior of the curves indicates a severe imbalance between users with good- and users with bad channel conditions. As shown in the next section, the first group refers to femtocell- and the second group to macrocell users, respectively.

IV. Throughput and Fairness

In this section, we investigate the impact of the observed SINR characteristics on the throughput. We evaluate a HI scenario and compare it to the worst case of non-isolated femtocells.

Figure 4 depicts the average user throughput $(\mathrm{Mbit/s})$ plotted versus the FAP-density. The results for a HI scenario show

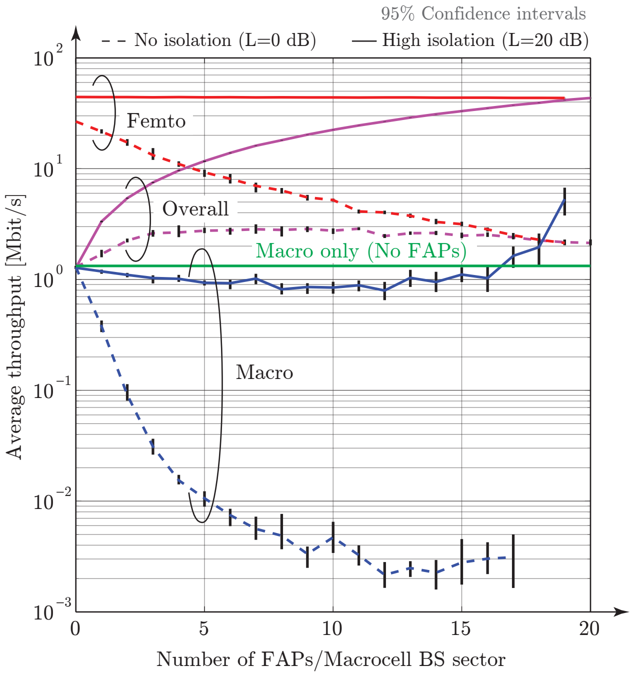

Fig. 4: Average user throughput versus FAP density. 'Macro' refers to macrocell-attached users in a femtocell-enhanced network. 'Macro only' is the reference case without FAP employment.

that the overall average throughput increases monotonically with the number of FAPs (middle solid line) and reaches its maximum at full femtocell coverage, i.e., all indoor areas are covered by a FAP.

Next, we drop the assumption of isolated femtocells by setting the wall penetration loss to $L = 0\,\mathrm{dB}$. In comparison to the HI case, overall average throughput is severely lower, and has a maximum at 9 FAPs/Macrocell BS, as shown in Figure 4 (middle dashed line).

However, performance evaluation in terms of overall average can be misleading, since the value is not achieved by any user, as seen in Figure 5. The figure depicts the scattering of individual user throughput versus SINR for a femtocell density of 10 FAPs/Macrocell BS and high femtocell isolation. The values are either much higher or much lower than the overall average throughput of $22.5\,\mathrm{Mbit/s}$, where the first group is identified as femtocell- and the second group as macrocell-attached users.

In this paper, the imbalance between macrocell- and femtocell users is quantified by the widely used Jain's Fairness Index (JFI). It is formulated as

$$f(\mathbf{T}) = \frac{\left(\sum_{i=1}^{N} T_i\right)^2}{N \sum_{i=1}^{N} T_i^2}. \tag{4}$$

where N is the total number of users in the network, and T_i denotes the throughput achieved by user i.

Fairness is lowest for a small number of femtocells and

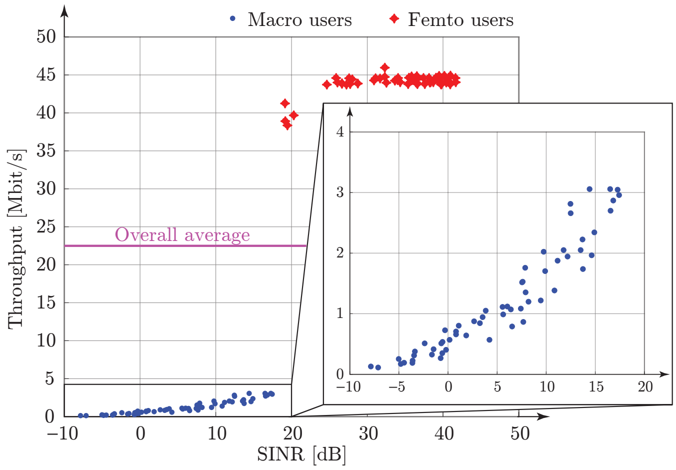

Fig. 5: Individual throughput values: Blue dots in the lower left corner correspond to macrocell-attached users, red dots in the upper right corner denote the femtocell users.

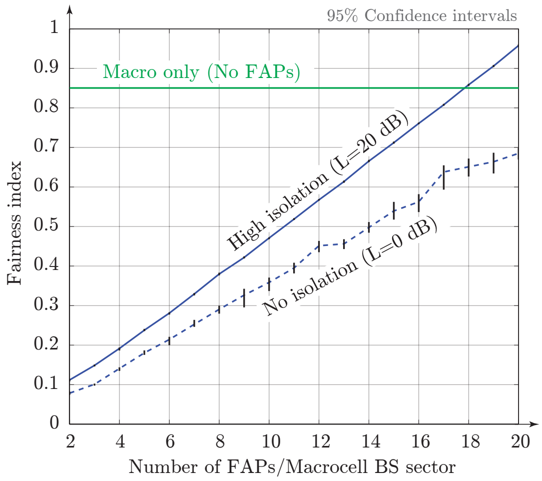

Fig. 6: Jain's Fairness Index plotted versus the femtocell density for HI- and NI scenario (solid and dashed line respectively).

monotonically increases with higher femtocell density, as depicted in Figure 6. The latter results from enhanced spatial reuse: On the one hand, an increasing number of users is attached to a FAP and experiences well-conditioned channels (see Figure 3), and on the other hand, users are handed off from the macrocell BS so that the available resource is shared among less users.

Maximum fairness, i.e., most balanced user performance, is achieved with full femtocell coverage in a HI scenario. In the NI case ($L = 0\,\mathrm{dB}$), however, the reference-network without femtocells outperforms the femto-enhanced system.

The network's sensitivity to absent penetration loss is particularly confirmed by the degraded macrocell user performance: Figure 7 depicts macrocell- versus overall throughput gain related to a network without femtocells.

Although femtocell-enhancement always improves the overall performance, i.e., $T_{\text{Overall}}/T_{\text{Macro Only}} > 1$, the resources,

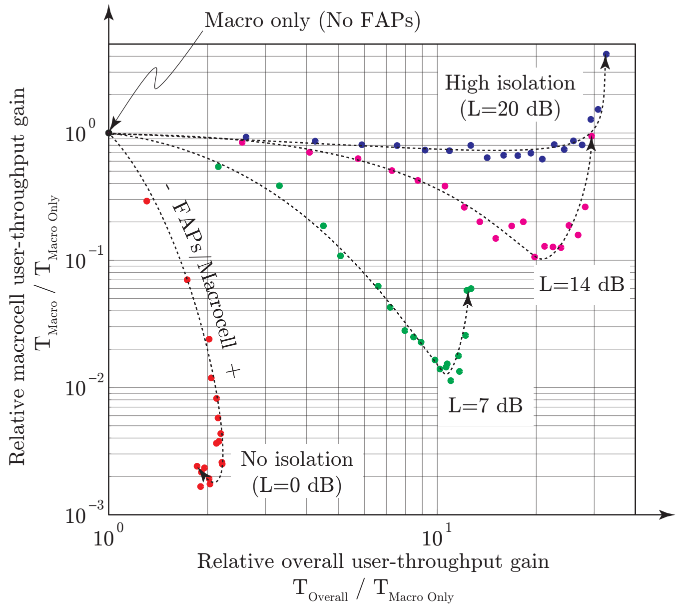

Fig. 7: Macrocell- and overall average user throughput gain related to the 'Macro Only' scenario. Dashed arrows point in the direction of increasing FAP density (ranging from 0 to 20 FAPs/Macrocell BS).

which are released by off-loading the macrocell BS, can mostly not compensate for the harm caused by additional interference, i.e., $T_{\text{Macro}}/T_{\text{Macro Only}} < 1$, except for very high femtocell isolation and almost full femtocell coverage.

Note that the simple geometry of a spatial Poisson cluster process is applied in all simulations. The model accurately captures the effects as obtained in measurement campaigns and highly complex models.

V. Conclusion and Outlook

We evaluated the performance of femtocell-enhanced macrocellular LTE networks with the Vienna LTE system level simulator. We set up a system model by means of stochastic geometry and verified its potential to render the behavior of complex scenarios. The model allowed us to explicitely analyze the effects of increasing femtocell density and fluctuating femtocell isolation in an elaborated simulation environment.

We showed that a femtocell enhancement improves overall average user throughput in both high-isolation- and no-isolation scenarios. However, in scenarios without isolation, femtocell-deployments are outperformed by non-enhanced networks in terms of fairness. Our results confirmed that this is mainly caused by the severe degradation of macrocell-user performance. We thus emphasize to optimize interference mitigation schemes not only in terms of overall sum-, peak- or edge throughput, but also to account for the individual users' performance by means of fairness.

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