From Homogeneous to Heterogeneous Networks: A 3GPP Long Term Evolution Rel. 8/9 Case Study

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Abstract— **Heterogeneous cellular networks (HetNets)—conventional macro base stations overlaid with low-power nodes —are being deployed for reasons of improved spectral efficiency, economy, and scalable network expansion. To optimally realize the benefits of HetNets, it is crucial to factor deployment aspects such as cell association, transmission power, spectrum allocation, and deployment density. This paper presents comprehensive dynamic system level simulations based on the 3GPP Long Term Evolution (LTE) standard modeling spatial, temporal, and frequency domain channel variations and ray-tracing based penetration losses in urban and indoor environments. The simulator takes into account the dynamic (subframe level) modulation and coding scheme and precoder selection, as well as finite rate channel state feedback and transmission aspects intrinsic to LTE. Considering a Rel. 8/9 LTE HetNet, two access schemes are analyzed: first, open access picocells, where results show that a single picocell can double the area spectral efficiency without any impairment of the macro-layer, and second, closed access femtocells, where results show that in typical scenarios, the user throughput is deteriorated on both the macro-layer and the femto-layer. Consequently, open access low-power nodes can be deployed as is, whilst closed access ones require additional interference avoidance mechanisms. These dynamic system level simulations are important for deriving accurate and practically relevant performance trade-offs, while commensurate with the time and frequency granularity of LTE.**

I. Introduction

Over the last decade, vast increases in the data throughput of wireless cellular networks have been achieved, mainly through advancements to the air interface. The 3rd Generation Partnership Project's (3GPP's) Long Term Evolution (LTE) features orthogonal frequency-division multiplexing (OFDM) and multiple input multiple output (MIMO) techniques as examples for the aforementioned enhancements. Recently, however, it has become increasingly difficult to keep up with the data demand novel devices impose on these networks. Multi-user MIMO (MU-MIMO) techniques, for instance, substantially increase the complexity of the scheduler at the base stations, especially at high bandwidths, where up to 100 resource blocks have to be assigned to possibly hundreds of users on a millisecond-by-millisecond basis. Accordingly, standardization bodies have begun to consider upgrades to the infrastructure in support of improvements to the air interface. Coordinated multi-point (CoMP) transmissions by means of base station cooperation are one promising example considered for LTE-Advanced. CoMP lets base stations coordinate their transmissions in order to reduce the impact of intercell interference to out-of-cell users. In this paper, we focus on the deployment of heterogeneous networks (HetNets) as yet another means.

The idea behind HetNets is to overlay existing homogeneous networks with additional infrastructure in the form of smaller low-power low-complexity base stations. The homogeneous tier is commonly named the macro-layer alluding to the extended coverage radius of its legacy "macro" base stations. Similarly, the small form factor base stations in the second tier are referred to as "pico" or "femto" base stations for their coverage area is considerably smaller. This cell splitting can provide large gains in overall system performance both in the physical layer, for the average distance between transmitter and receiver is significantly reduced, and the MAC layer, for the average number of connected users per base station is also substantially lowered.

A. Related Work

A lot of theoretic work has been published on heterogeneous networks within the last couple of years. To name a few, outage probability and capacity analyses were presented for the uplink [1] and downlink [2], respectively. Multi-antenna techniques were the subject of [3], [4] and [5], [6] looked into power control issues. Different access control mechanisms were treated in [7], [8] and a spectrum sharing policy was proposed in [9].

Our contribution focuses less on the theoretical work and more on the practically achievable performance of heterogeneous networks as demonstrated by simulation results. System level simulations have been presented in [10]–[17]. Autonomous resource allocation in time and frequency for co-channel deployments were simulated in [16] using a ray tracing tool. A comparative study on power control, access schemes, and different deployment modes was reported in [14] and the impact of pathloss, network size, base station density and the number of users was assessed in [13]. The outage probability was evaluated in [10] and bit and packet error performance was simulated in [11]. Most publications, though, focus on data throughput and spectral efficiency in the context of 3GPP LTE. The performance of IEEE 802.16e (WiMAX) was analyzed in [17] with special focus on coverage holes. Lastly, field tests were reported in [18].

More similar to our work, [12] simulated the Physical Uplink Shared Channel (PUSCH) in 3GPP LTE and LTE-Advanced, however, the throughputs were obtained by map-

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ping the signal-to-interference-and-noise ratios based on a modified Shannon-type formula. For the downlink, a dynamic system level simulator was presented in [15] which used a link level abstraction mapping to generate throughput results.

B. Contributions

In this paper, we also present system level simulations. Our methodology, however, differs from previous publications in that the presented data rates and spectral efficiencies are not based on long-term channel characteristics [11], Shannon's capacity formula [12]–[14], or link level abstractions [15]. Rather, we opted for the simulation of the actual behavior of the Physical Downlink Shared Channel (PDSCH) in time, frequency, and space. Notably, the observations presented herein model

- the fast fading with different models for indoor and outdoor propagation channels
- the finite rate channel state feedback from the user equipment (UE), i.e., the channel quality indicator (CQI), precoding matrix indicator (PMI), and rank indicator (RI)
- the precoding and link adaptation at the base station
- the frequency-selective proportional-fair scheduling
- hybrid automatic repeat request (HARQ) transmissions
- and the receive signal processing at the UE

compliant to the latest release of the 3GPP LTE standard for cellular wireless networks, namely, Release 9. All results presented in this paper were obtained through dynamic simulation of the adaptive modulation and coding, multi-antenna precoding, HARQ processes, and so forth, i.e., no long-term signal-to-interference-and-noise ratios were used to obtain (estimated) data throughputs.

Two scenarios are of particular interest to network operators:

1) Hotzones such as malls, schools, or stadiums, where users tend to be clustered in a small space. Operators install additional low-power base stations to create *picocells* in a planned manner. Access to these low-power nodes is open to everyone in the coverage zone and the operator is in control of the backhaul connection.
2) Residential or enterprise *femtocells*, where the objective is to increase indoor coverage for a rather small number of users. These low-power base stations are usually installed by the consumer or enterprise directly (operator is not in control of the backhaul connection) and thus operate in closed access, e.g., users have to be on a "whitelist" in order to be able to connect to the femtocell.

Our simulation results provide insights into the gains that heterogeneous networks offer, their impact on the existing macro network performance, and possible challenges that need to be addressed. In particular, we analyze the impact of multiple transmit antennas, deployment densities, and transmit power levels on the performance of the entire network and the existing legacy macro network. The direct comparison of open access picocells and closed access femtocells unveils that the access scheme is of paramount importance in the assessment and deployment of HetNets and entails implications that need to be addressed in the standardization of such networks.

II. Simulation Assumptions

Since the simulations are standard compliant and all standard documents are available online for free, we only provide a brief overview of parameters and assumptions. The reader is referred to [19] for an overview of all parameters and assumptions relevant to heterogeneous networks, especially the spatial channel, pathloss, and shadowing models.

A. Macro Base Stations and User Equipment

We consider a hexagonal grid of 57 3GPP Case 1 urban macro-cells with three sectors per site and universal frequency reuse (10MHz bandwidth at 2GHz carrier frequency). The distance between two sites is 500m and each cell has 60 users moving at 3 km/h. The minimum distance between a base station and a mobile user is 35m. The base stations' antenna gain is 14dBi and the maximal transmit power is 46dBm. The assumed antenna height is 32m. The handsets have two antennas and employ minimum mean squared error (MMSE) equalization with perfect channel estimation and a noise figure of 9dB. Full buffer data traffic is assumed and a maximum of three retransmissions are performed.

B. Picocells

For picocells or hotzones, the low-power base stations are uniformly distributed within one cell maintaining a minimum distance of 40m and 75m to other low-power and macro base stations, respectively. Their antennas are omnidirectional with 5dBi antenna gain. Two thirds of the users within one cell are clustered around the low-power nodes (minimum distance to transmitter is 10m; maximum distance to transmitter is 40m), the remaining users are uniformly distributed within the cell. All users are assumed to be indoor.

C. Femtocells

We use the dual-strip apartment block model, i.e., each cell has one apartment block with 40 apartments. The apartments are arranged into two buildings (20 10m $\times$ 10m rooms each) that are separated by a road (10m wide). See [19] for details. The femto base stations are then randomly placed into the rooms[1] and each femto base station has a single user connected to it (minimum distance to femto base station is 3m and the user is always in the same room as the base station). The minimum distance between a femto and a macro base station is 75m and two apartment blocks are at least 40m apart. The femto base stations have omnidirectional antennas with 5dBi antenna gain. Of the remaining users, 35% are clustered around the apartment block, while the other 65% are uniformly distributed within the cell. The penetration loss for outside and inside walls is 20dB and 5dB, respectively. The number of penetrated walls is determined by ray tracing.

[1] there can be one or no femto base station per room

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III. Simulation Results

A. *Picocells*

The basic motivation behind picocells is the increase of spectrum reuse per area. Traditionally, spectral efficiency is measured in bits/second/Hertz (bits/s/Hz). In the context of HetNets, one often adds area as another dimension, namely, bits/second/Hertz/sector, to measure the area spectral efficiency. The normalization is important as heterogeneous networks may have multiple base stations per sector or cell.

Accordingly, the number of additional low-power base stations (picocells) that share the same resources directly relates to how well these shared resources are reused. As a first study, we thus fix the number of transmit antennas (single antenna) and the transmit power (24dBm) to assess the gains in area spectral efficiency as depicted in Fig. 1. The first bar in each cluster of three represents the spectral efficiency of the homogeneous network, i.e., only macro base stations are present. Similarly, the spectral efficiency for heterogeneous network deployments is shown. However, the results are split into the macro-layer (center bar) and the pico-layer (right bar in each cluster). Hence, the overall spectral efficiency per sector is the sum of the two right bars. Also note that the user distribution in the cell is the same for the homogeneous and the heterogeneous network, viz., a fraction of the users is clustered even for the homogeneous networks. One can then observe that each additional picocell significantly increases the spectral efficiency in the network while at the same time the performance of the macro-layer (two left bars in a cluster) is hardly affected. In other words, smaller less complex and thus cheaper base stations, that are overlaid onto the existing network, facilitate large gains without any changes to the air interface simply by increasing the reuse of available resources both in time and frequency.

These gains can be further increased by additionally changing the air interface, for instance, by employing more transmit antennas as depicted in Fig. 2. For a transmit power level of 24dBm and two picocells per sector, we plot the spectral efficiency per sector as a function of the number of transmit antennas. Similarly to Fig.1, the right bar in each cluster demonstrates the gains in spectral efficiency that multiple transmit antennas offer. Note, however, that the impact on the macro-layer, viz., the difference in height between the two left bars in each cluster, is a little more pronounced for a large number of transmit antennas. This is known as the "flashlight" effect: more transmit antennas result in narrower beams and accordingly, the signal power is more localized in space. If a beam points to an out-of-cell user, the degradation in performance due to larger interference power will be more severe if the energy is more localized. This is exactly what can be observed in Fig. 2.

Lastly, we analyze the impact of different transmit power levels at the pico base stations. For two single-antenna pico base stations per sector, we plot the number of users connected to the macro-layer in Fig. 3. As the transmit power directly relates to the size of the coverage area, larger transmit power

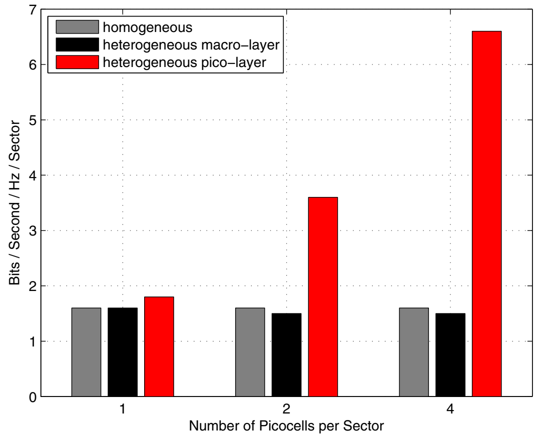

Fig. 1. The spectral efficiency improves as the number of picocells increases due to the larger spectral reuse per area. Picocells can be overlaid without a significant impact on the macro-layer.

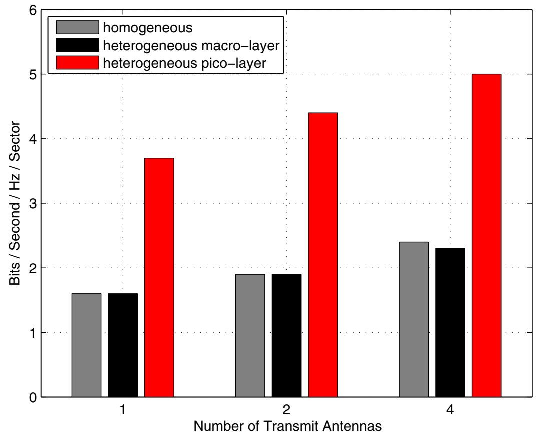

Fig. 2. Increasing the number of transmit antennas can further increase the spectral efficiency of heterogeneous networks. For this plot, closed-loop SU-MIMO was assumed.

constraints lead to larger hotzones and accordingly, more users connect to the pico-layer. This frees up resources at the macro-layer, i.e., macro users have more scheduling opportunities resulting in larger spectral efficiencies (see text in bars). For 24dBm, 24% of all users in a sector are offloaded to the pico-layer; for 30dBm, 37% of all users in a sector are offloaded to the pico-layer improving the spectral efficiency by 0.2 bits/s/Hz/sector. There is a caveat, though, in that with growing transmit power levels the interference power also increases which ultimately will counteract the offloading gains.

B. *Femtocells*

The main difference between picocells and femtocells is that any user can connect to the former if it improves the interference conditions, whereas the latter require a user to be on the whitelist of a base station for it to be able to connect. With respect to the downlink, a user may thus experience a large pathloss to the closest macro base station while at the same time it is not allowed to connect to a nearby femto base

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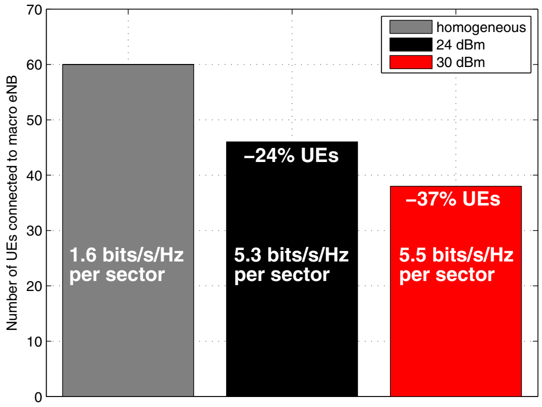

Fig. 3. The transmit power of the pico-layer affects the number of users connected to the macro-layer. This offloading effect increases the spectral efficiency by freeing up resources at the macro-layer (less users to be scheduled).

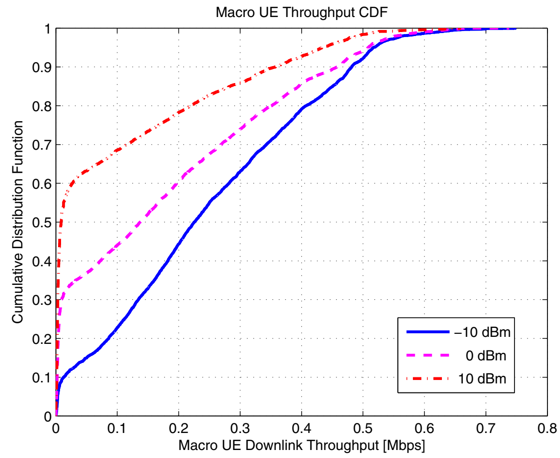

Fig. 4. Femto base stations severely impact the performance of the macro-layer. Since macro users cannot connect to femto base stations, users in the vicinity of an apartment block suffer increased co-channel interference, particularly as the femto base stations increase their transmit power.

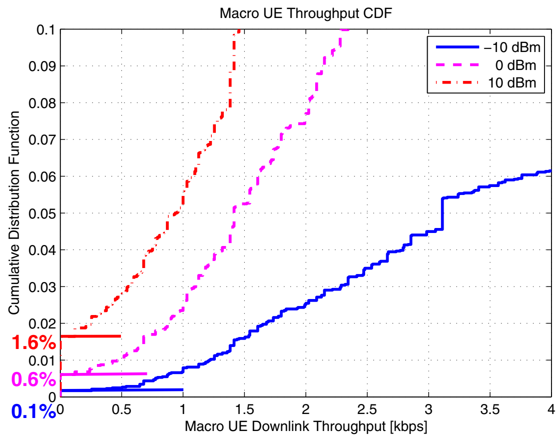

Fig. 5. The macro-layer becomes interference limited, i.e., the curves saturate and an outage probability below a certain threshold cannot be achieved.

station. For the 65% of users that are uniformly distributed over the cell area, femto base stations are sufficiently insulated as they generally have significantly lower transmit power levels and are further encapsulated by the building structure. The 35% of macro users that are clustered around the femtocells, on the other hand, experience exactly the scenario where a low-power (e.g., 0dBm) femto base station masks the received signal of the macro base station (e.g., 46dBm) because of the lower pathloss to the former.[2] This creates the so-called coverage holes in which macro users cannot decode the control channel and consequently do not receive any data at all. Figure 4 plots the cummulative distribution function (CDF) for users connected to the macro-layer. We assume four single-antenna femto base stations per apartment block with varying transmit power levels. One clearly observes the degradation in performance of the macro-layer as the transmit power in the femto-layer increases from -10dBm to 10dBm. Figure 5 reveals that the CDFs actually saturate, i.e., outage probabilities below the thresholds depicted in Fig. 5 are not possible!

For those users connected to the femto base stations, the picture looks completely different. Since each femto base station serves a single user, this user gets allocated most of the resources. As seen in Fig. 6, the data throughput even saturates for some users as they are served on all 50 resource blocks with the highest modulation alphabet of 64QAM.

For the femto-layer, interference originates from nearby femto base stations. Thus, their performance worsens as the number of femto base stations in one apartment block is increased. For the macro-layer, a larger number of femto base stations by and large has the same effect as larger transmit powers, cf. Figs. 4 and 7. For the femto-layer, though, increasing the number of femto base stations in the apartment block deteriorates the performance of the femto users for they now experience larger interference powers from nearby femto base stations transmitting on the same frequencies, see Fig. 8 which compares the performance of the femto-layer for two and four single-antenna femto base stations per apartment block with a transmit power constraint of 0dBm.

IV. Conclusions

We presented dynamic system level simulations for co-channel deployments of heterogeneous networks consistent with the time and frequency granularity associated with 3GPP LTE. The dynamic simulation of adaptive modulation and coding, spatial precoding, finite rate feedback, retransmissions, as well as channel fluctuations are important to ultimately assess the gains of such networks. For picocells such as hotzones, additional low-power base stations sharing the same spectrum offer large gains in terms of area spectral efficiency due to the proximity between transmitter and receiver and the offloading effect that frees up scheduling resources at the macro-layer which is hardly compromised by the overlaid picocells. Femtocells, which, on the other hand, operate in

[2] cell-(re)selection in Rel. 8/9 is based on pathloss measurements

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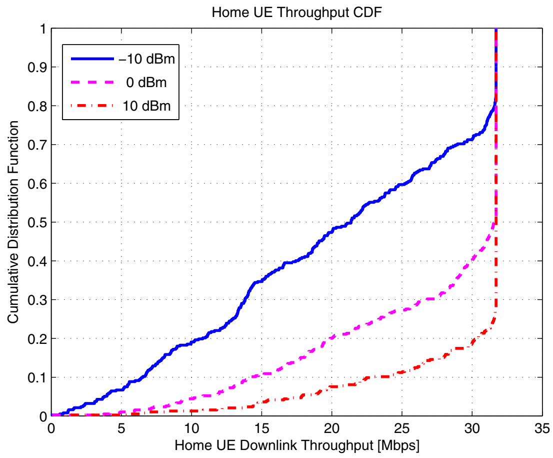

Fig. 6. Since only one user is connected to each femto base station, a huge percentage is allocated the entire available bandwidth at 64QAM. Hence, the throughput saturates for those users. The performance of these users is mainly determined by the transmit power of other nearby femto base stations.

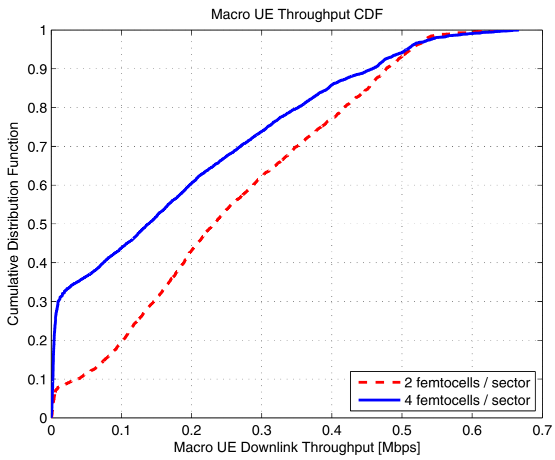

Fig. 7. The performance of the macro-layer significantly depends on the number of femto base stations within that cell.

closed access, considerably impair the performance of both the macro-layer and the femto-layer and thus require coordination between the two layers. This is, however, technically challenging since the femto base stations are typically not connected to the operator's backhaul network as they are consumer deployed and use an Ethernet backhaul connection.

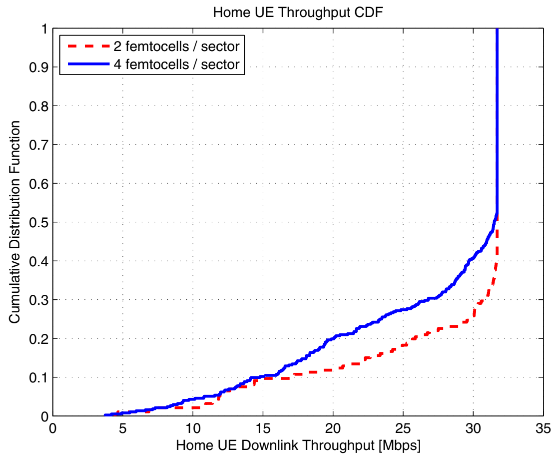

Fig. 8. The more femto base stations are deployed within the apartment block, the more the femto-layer becomes interference limited.

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