Impact of Three-Dimensionality of Femtocell Deployments on Aggregate Interference Estimation

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***Abstract*—Accurate estimation of aggregate interference is crucial for understanding the potential capacity gains from densification of cells. In this paper we study the impact of three-dimensionality of femtocell deployments on both cross-tier and co-tier aggregate interference using realistic building data and accurate propagation models. Our results show that the three-dimensional character of urban femtocell deployments can result in significantly higher interference effects compared to typically used two-dimensional evaluation scenarios. Further, we also show that *heterogeneity* in building heights plays an important role in the amount of aggregate interference, and should be considered more carefully when specifying standard topologies for interference studies.**

I. Introduction

Mobile data traffic is growing at a rapid pace and several techniques have been proposed to increase the capacity of the network, including physical layer enhancements such as higher order modulation schemes, increased sectorization of cells, and use of multiple antenna techniques. Of the various proposals, densification of cells is the most promising one with the potential to improve the network capacity while also addressing the problem of indoor coverage. The potential benefit of cell densification to increase capacity can be also seen from the Cisco prediction that more than half the traffic originating from mobile devices will be offloaded to Wi-Fi access points or femtocells by 2018. However, the capacity gains arising from network densification are limited by aggregate cross-tier and co-tier interference, making the accurate estimation of this interference crucial for reliable estimation of the performance gains. Modeling the interference in heterogeneous networks has been studied extensively in the literature (see, for example, [1]–[5]). In all these studies, the interference environment is typically modeled as a two-dimensional plane, either completely flat or with homogeneous network structure in terms of deployment heights. The interference itself is estimated using a homogeneous log-distance path loss model around the interference source. Using a two-dimensional model has the advantage of simplicity, but also comes with significant limitations in accuracy.

In this paper we study in detail the impact of the three-dimensional character of urban femtocell deployments on aggregate interference in heterogeneous networks. Using realistic propagation models and actual building data from different regions of New York City we show that the three-dimensional character of urban femtocell deployments can result in significantly higher interference effects compared to typically used two-dimensional evaluation scenarios. Our studies also show that a macro base station (MBS) from a neighboring cell could strongly interfere with a co-channel femtocell at a higher floor, even at a far distance, due to the presence of a low-loss path between them. A two-dimensional approach would not account for such increased interference. A comparison of co-tier interference situation among femtocells was evaluated at 2.6 GHz and 3.5 GHz, and the latter was found to be more suitable from an interference standpoint owing to the higher penetration and propagation losses in the 3.5 GHz band.

The rest of this paper is structured as follows. In Section II we discuss our simulation model and scenarios in detail. Results on cross-tier interference to the MBS downlink are then presented in Section III, followed by the discussion on the cross-tier interference on the femtocell downlink in Section IV. Impact of three-dimensional deployments on co-tier femtocell downlink interference is then discussed in Section V. Finally, we draw our conclusions and outline future work in Section VI.

II. Modeling and Simulation

In order to study interference in a three-dimensional context, we need a 3D model of an urban and suburban region, and simulation tools with propagation models that provide increased accuracy by capitalizing on the details in the 3D model. In this section we discuss the building models used, propagation estimation tools employed, and the simulation scenarios for the heterogeneous networks studied in more detail.

A. Scenarios and Data Sources

In order to accurately simulate a network scenario in a target region, we need a 3D model of the region at hand to be able to reliably estimate the signal propagation and interference arising in comparison to two dimensional approaches. Commercial vendors of course provide 3D models of cities, but these models tend to be prohibitively expensive for academic research. Several cities are now taking transparency initiatives to make an increasing amount of city data available to the public for free. Some of the participating cities include New York City, Chicago, London etc. The databases made available by New York City includes building footprints and building height

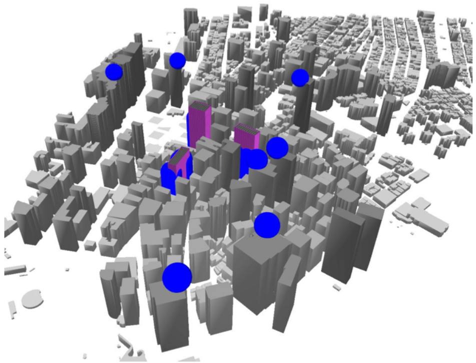


Fig. 1. An illustration of the 3D building data set used in the study, with high risers used for femtocell deployments shown in purple, and macrocellular antenna sites shown in blue.

information, provided by Department of Information Technology and Telecommunications [6]. For simulation scenarios two regions were chosen, one in Manhattan with significant height differences between buildings, and one in Brooklyn with more homogeneous suburban building landscape. An illustration of a typical simulation scenario is shown in Figure 1.

B. Propagation Modeling and Choice of Tools

In studying aggregate co-tier and cross-tier interference, the log-distance path loss model is often assumed or statistical models are used. However, these models could work accurately for one scenario and could be misleading for the other. Recent work in [7], [8] shows that the errors induced by such propagation models could be in the range of 8 to 10 dB. Thus emploing sophisticated models like dominant path model and ray tracing to predict the propagation more accurately using the 3D models of the cities would be more appropriate.

The ray tracing approach is very powerful, but is also very sensitive to the accuracy of the vector database [9] and requires very large computation time [10]. The dominant path model provides a good trade off between the accuracy of the received power estimate and computation time. As it computes only the most dominant diffraction path, the computation time is much smaller compared to the ray tracing approach. Accounting for diffraction makes the dominant path model more accurate than the empirical models, and was thus chosen as the basis of our work. Regarding the concrete implementation of the propagation model, the WinProp suite from Awe Communications was used. WinProp suite facilitates the creation of models with buildings modeled as polygonal cylinders, with courtyards, vegetation and terrain information. The indoor models can be created with fine indoor details, including wall materials, furniture, and so on.

C. Simulation Parameters

LTE uses a wide range of channel bandwidths, ranging from 1.4 MHz to 20 MHz, and wider if carrier aggregation is implemented. In this work, simulations were performed at the smallest and largest bandwidths to calculate the SINR. We focused on the 2.6 GHz band for the downlink, although we also studied the impact of the carrier frequency on aggregate interference. Other simulation parameters are summarized in Table I.

TABLE I
MODELLING PARAMETERS.

Parameter	Value
MBS Transmit power	40 dBm
FAP Transmit power	20 dBm
Floor height	5 m
Outerwall for buildings with FAP	20 cm concrete
Innerwall for buildings with FAP	10 cm concrete
Windows	5 mm glass
Ceiling wall	20 cm concrete

In addition to the baseline scenario with frequency reuse of one, the effect of fractional frequency reuse (FFR) was modeled by considering a region around the FAP where the interference or coverage is not computed. This marks the region at which the frequency allocation schemes assign a different frequency for the FAP compared to the MBS and hence the FFR alleviates the cross-tier interference within this region. The region is modeled as a disk with a defined radius controlling the distance between the FAP and the macrocellular UE (MUE) using the same frequency bands.

The model is obviously an approximation, as the location of the FAPs is not ideally located to fit the circular borders assumed. Thus the experiments were repeated for different values of the radius and choices of the frequency reuse regions so as to ensure that the results are not highly sensitive to such modeling assumptions. Together with studying the impact of the overall femtocell deployment density, this simple approach allows approximation of the results of more complex frequency management schemes such as [11], [12].

III. CROSS-TIER INTERFERENCE FROM FAPS TO MUES

We shall now present the results from our studies, first focusing on the aggregate interference from multiple FAPs in the same building to the MUE. Here it is interesting to look at how much the impact varies by varying different parameters like femtocell deployment density, wall material, and so on. The results of those scenarios are listed below.

A. Study of 3D Deployments Compared to 2D Study

Before investigating the different parameters, we first illustrate that the study of femtocell deployments in 3D space gives a stronger interference than what the 2D analyses would estimate and that it adds more value than a scaled 2D estimate. Note that 3D deployments not only increase the number of interferers but also modify the pattern of the interference. For example, a FAP in the top floor does not cause identical interference as a FAP in the ground floor, as it can have a line of sight path to larger area than the FAP at the ground floor. Thus the SINR degradation caused to a macrocell by a single FAP in a building at the ground floor is compared with the SINR

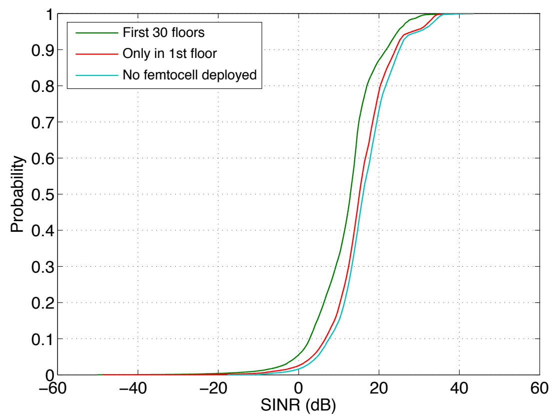


Fig. 2. Comparison of the CDF of SINR estimates from 2D and 3D deployment scenarios.

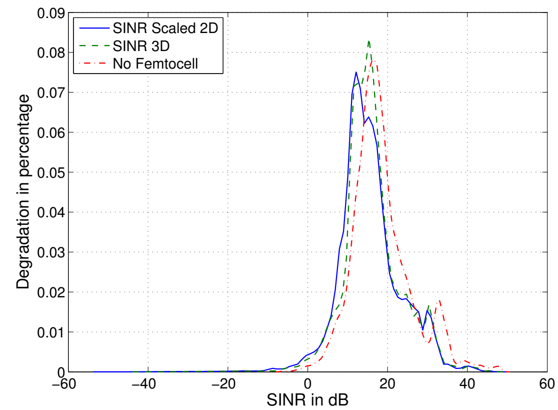


Fig. 3. Comparison of the PDF of SINR estimates for scaled 2D model and 3D model.

degradation caused by the aggregate interference of all the interfering FAPs in the building. As can be seen from Figure 2, a 2D analysis strongly underestimates the interference that can arise from femtocell deployments, particularly in urban areas with tall buildings, as they can host more interfering FAPs.

Now, let us consider the case of scaling up the 2D deployment. For example, instead of modeling deployment in, say, 30 floors of a building, we could construct a model that describes the scenario as 30 FAPs in the ground floor. The latter case permits a 2D model for studying interference towards the MUE (although for co-tier interference in the femtocell network such model would obviously be insufficient). Hence if such an approximation would work, the 2D models could be modified to imitate the study of 3D deployments. To study this scenario, we used a model that includes buildings with FAPs in the first 30 floors, with one FAP per floor. The SINR degradation for MUE by the aggregate interference from these FAPs is calculated. For comparison, the interference from the FAP at ground floor is scaled up by a factor of 30, and the effective SINR degradation is computed.

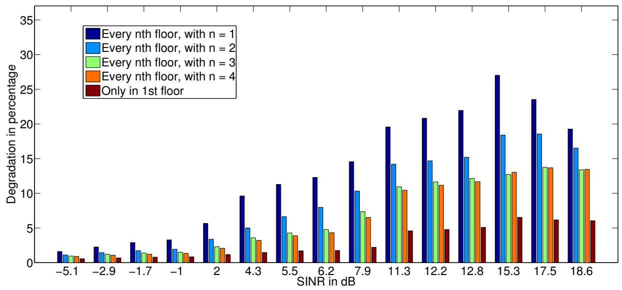
The SINR PDF curves based on the 3D model and the scaled 2D model are compared in Figure 3. As can be seen from the figure, the scaled 2D model does not perform close to the true 3D model, with some 5 dB errors in the mode of the SINR distribution. However, such large difference is not present in all cases. Scaling the 2D model could work if the path loss from the FAP at the ground floor to the MUE is close to the path loss from the FAP at other floors. Unfortunately this does not usually happen. The signal from the FAP at ground floor is strongly attenuated by the adjacent buildings, while the FAP at a higher floor can have line of sight path to a large area of the macrocell and hence create a stronger interference. Hence a scaled 2D model will underestimate the interference power in the case where there are different channel conditions existing between the interferer at ground floor and those at higher floors.

B. Influence of Bandwidth of Operation

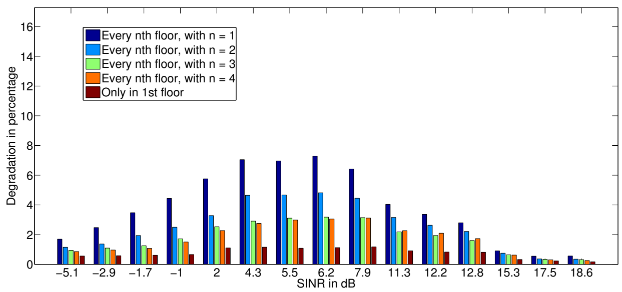
The effect of interference with a given transmit power varies according to the bandwidth used. Hence a comparison was made between the effect of interference in the lowest bandwidth of 1.4 MHz and the highest bandwidth of 20 MHz. As can be seen from Figure 4, the SINR degradation is stronger in the case of lower channel bandwidth than in the higher bandwidth. This is because, in the 20 MHz case, the EIRP of 100 mW is spread over a larger bandwidth, resulting in increased noise power, and the SINR for MUE is limited more by the noise power than the interference power. On the other hand, in the lower bandwidths, the transmit power is spread over a smaller bandwidth and also the thermal noise power is less in comparison. The SINR of the MUEs is not limited by the noise floor, as much as it was in the case of a large bandwidth. In this case, the interference from FAPs has a stronger potential to degrade the SINR of the MUE and hence the effects of interference are more pronounced. Deployment of femtocells on every floor of a building can result over 4 times the SINR degradation compared to the flat deployment with femtocells on the first floor only.

C. Effect of Frequency Reuse

In order to study the impact of frequency reuse on aggregate interference, the effect of the interference caused is evaluated for different distances from the FAP to the region with co-channel MUEs. Using different radii models different reuse zones and, proportionally, the cell sizes. As can be seen from Figure 5, for distance of 200 m, the reduction in interference is very small. However, with larger radii the interference drops faster, falling to less than half as a radius of 1 km is reached. Hence, fractional frequency reuse is more beneficial if the co-channel regions are larger, as is the case for large cell sizes. In urban scenarios, where the cell sizes are small, the benefits of FFR are also minimal, especially when no power control is used for FAP. When power control is used, the magnitude of the impact is determined by the power level that is active at the given moment. When the femto UE (FUE) is at the far end of FAP coverage region, the FAP transmit power will be



(a) Bandwidth of 1.4 MHz.



(b) Bandwidth of 20 MHz.

Fig. 4. Influence of Bandwidth in SINR degradation. Degradation is computed compared to the case of no interferers.

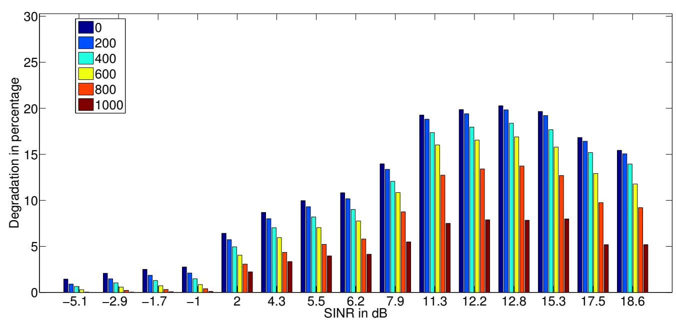


Fig. 5. Impact of FFR as a function of the frequency reuse radius in meters for bandwidth of 1.4 MHz. Radius of zero refers to the case of no FFR being used.

high and will interfere with the neighboring co-channel MUE even when FFR is used. Hence even the use of power control is not a guaranteed measure to limit the interference.

D. Effect of Encirclement of Macrocell by FAPs

The effect of deployment density when four interferer buildings hosting FAPs are present is shown in Figure 6. We can see that even for sparse deployments, the interference is worse by almost 10 dB compared to what the 2D flat deployment models would estimate. Hence being surrounded by interfering FAPs creates a strong degradation in SINR.

The effect of varying number of interferer buildings hosting FAPs is shown in Figure 7. The interference progressively worsens with increasing number of buildings with FAPs. These effects will be often seen in the suburban environment that have a few tall buildings that encircle a valley of relatively low buildings. Impact of such encirclement is severe. Adding

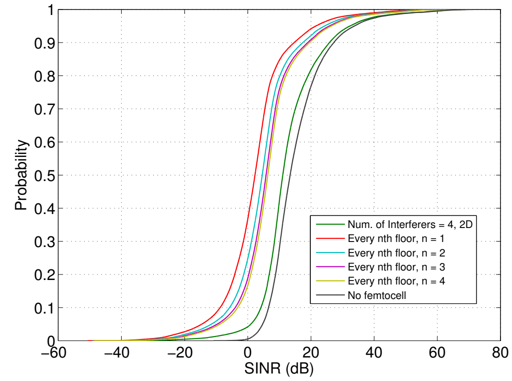


Fig. 6. Impact of density of FAP deployment in surrounding interferers, for FAP to MUE interference.

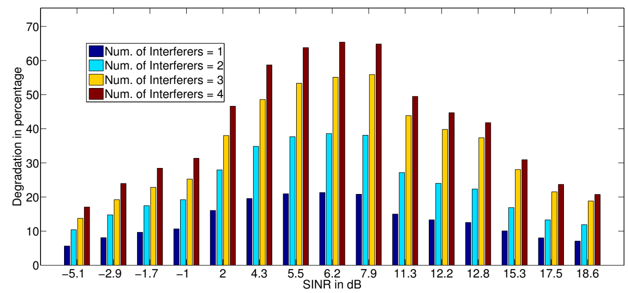


Fig. 7. Impact of number of surrounding interferers for FAP to MUE interference.

the second interfering building almost doubles the degradation. The difference between 3 and 4 interfering buildings is small, because with 3 interferers the coverage is already very strongly degraded. Hence adding any further interferers does not worsen the situation any more.

IV. Cross-tier interference from MBS to FUE

In aggregate interference studies the focus is typically on the downlink of the macro UE, as the femto user is assumed to be strongly shielded by multiple buildings in deployments that are close to ground floor. However, considering elevation effects will result in femtocells being also deployed in higher floors, with potentially very low path loss from macrocell base stations to the femto users. Hence the FUE can receive a high interference power as seen in the Figure 8. This degrades the SINR of the FUE at the higher floor much more than the FUE at the ground floor. Thus the effective service area of the FAP operating at the same power level is smaller in the higher floors than in the ground floor. Hence, either a higher transmit power has to be used, which increases the interference to its neighbors or multiple low power femtocells have to be used, which increases the cost. A trade off between the transmit power and number of femtocells has to be achieved.

V. Co-tier interference in Femtocell layer

We shall now move on to discuss impact of building height differences and deployment densities on aggregate *co-tier* interference, that is, impact of surrounding femtocells on the

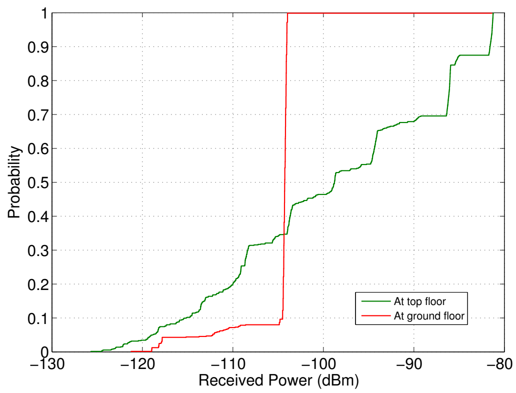


Fig. 8. Received power at the ground floor and at a top floor for a building from a neighboring cochannel MBS.

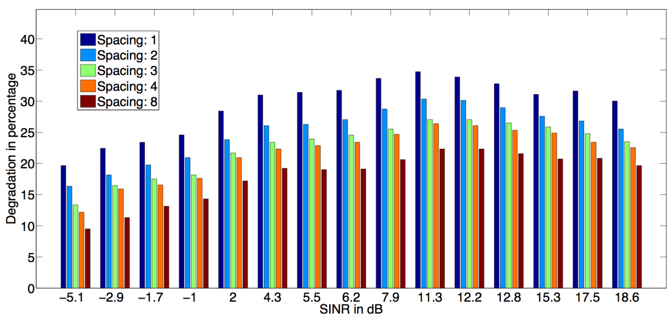


Fig. 9. Influence of density of FAPs in FAP to FUE interference.

downlink of a chosen femto user. We first study the impact of varying the density of the femtocell deployment for a given scenario. We see from Figure 9 that reducing the density of deployment from one FAP per floor to one every 8 floors, reduces the degradation by about 40% and as the density of deployment increases, the degradation increases rapidly. Thus the density of deployment influences the SINR degradation very strongly in three-dimensional deployments.

To study the impact of encirclement by interferers, a scenario where a femtocell deployment in one building receives interference from adjacent buildings from more than one direction was studied. As can be seen from Figure 10, the impact of each additional building is very strong and could significantly limit the coverage of the FAP in the intended building. However, the degradation is strong for the the first building and the impact weakens with each additional building as was also seen for the macro user above. After the 3rd building, the interference impact added by the fourth building is already very small.

A. Evaluation of 3.5 GHz Band for Femtocells

A comparison of the performance was done between femtocells using 2.6 GHz and those using 3.5 GHz band. The coverage area is of course less for femtocells deployed in 3.5 GHz band if the transmit power power is kept the same as 3.5 GHz signals have higher transmission and diffraction losses compared to the 2.6 GHz band. To compute the SINR

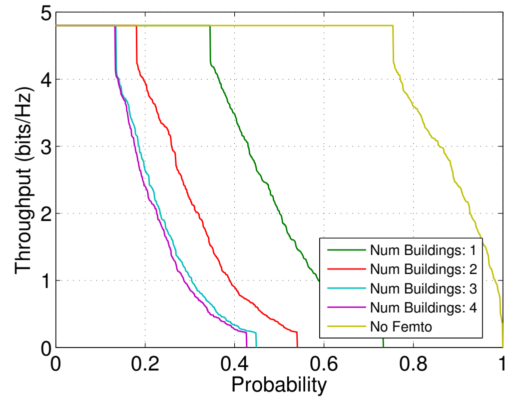


Fig. 10. Influence of encirclement of FAPs in FAP to FUE interference.

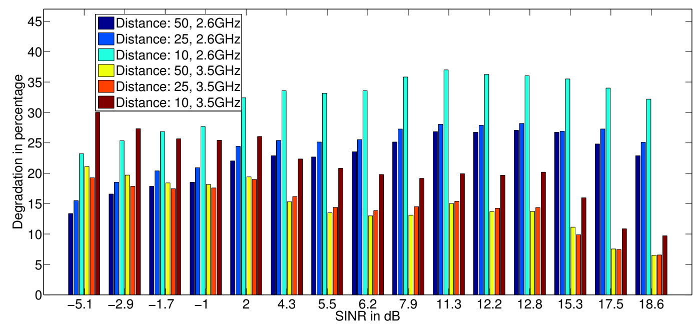


Fig. 11. Degradation charts for normalized CDFs for 2.6 GHz and 3.5 GHz bands. Degradation is computed compared to the case of no interferers.

degradation, it is important to compare degradation in the coverage area and not across the whole floor. Hence the CDF was normalized to the area, where the SINR without interference is more than -6.5 dB, the minimum SINR required for QPSK with coding rate of $1/8$. SINR degradation is evaluated in the normalized CDF. The SINR degradation as a function of distance between interfering buildings can be seen in Figure 11. As seen, the femtocells operating in the 3.5 GHz band are less affected by interference compared to those in the 2.6 GHz band, experiencing less than half the degradation especially in high SINR conditions. This is because of the stronger attenuation that the interfering signals go through. The behavior is consistent over varying distance between the buildings and over varying femtocell deployment density. However, it is important to note that the areas that were receiving very weak signal were more strongly attenuated in the case of 3.5 GHz band. This is because the path loss exponent is higher for 3.5 GHz band and hence the decay is more rapid. The interference can affect the periphery of a femtocell, but the interference decays rapidly thereafter.

From these results we see that the use of 3.5 GHz band for femtocells can be highly beneficial, as it eliminates the cross-tier interference between macrocells and femtocells and also reduces the co-tier interference among femtocells.

VI. Conclusion

In this paper we have studied in detail the impact of the three-dimensional character of urban femtocell deployments on aggregate interference in heterogeneous networks. Using realistic propagation models and actual building data from different regions of New York City we have shown that the three-dimensional character of urban femtocell deployments can result in significantly higher interference effects compared to typically used two-dimensional evaluation scenarios. Depending on the number of high rise buildings in a city, the interference would be strongly influenced by the 3D structure. Merely increasing the number of interferers (densification) in 2D models was found to cause inaccuracies as they cannot account for the complex combination of deployment and propagation effects arising from 3D deployments. The effect of aggregate interference is especially pronounced for small bandwidth deployments. Frequency reuse was shown to mitigate the interference as expected, but even with heavy frequency reuse interference was not negligible and was dependent on the size of the zones used in frequency reuse. The encirclement by multiple high buildings with femto base stations was found to cause very strong degradation in performance of macrocellular users, and hence resource management techniques such as inter-cell interference coordination have to be employed in order to guarantee outage-free performance of the network.

Considering 3D deployments also introduced strong interference effects in scenarios which do not have 2D deployment based counterparts. The potential for tall adjacent buildings hosting FAPs interfering in aggregate with FUEs in other buildings was shown to be high. We inferred that the limitations imposed in the capacity gains of HetNets due to interference was stronger in the case of 3D deployment scenarios than is observed 2D deployment based studies due to the high aggregate interference. Using femtocells in shared access model instead of closed access mode could improve the situation probabilistically based on the location of the MUE and the load of the neighboring femtocell that it can potentially associate with. However the magnitude of such gains should be further investigated as a part of future work.

Studying 3D deployments also showed a stronger potential for co-tier interference among femtocells. Co-tier frequency reuse minimized this, but in dense deployments interference among femtocells in tall buildings was still found to be high. The use of 3.5 GHz frequency band exclusively for femtocells proved to be a promising solution to eliminate cross-tier interference and to mitigate co-tier interference among femtocells due to the high penetration loss.

In summary, our work shows that 3D based models and methods are crucial for accurate estimation of aggregate interference in heterogeneous networks, and thus for accurate evaluation of the wireless network performance. Also the *heterogeneity* in building heights was shown to play an important role in the amount of aggregate interference, and we strongly urge that such inherently 3D effects should be considered more carefully when specifying standard topologies for interference studies in the future.

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