Studying the Performance and Robustness of Frequency Allocation Schemes for LTE HetNets

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***Abstract*—We present results from a detailed comparative study of the performance of three different frequency assignment schemes for interference management in heterogeneous LTE networks. Realistic indoor propagation models are used in order to obtain accurate results. We show that simple graph based frequency assignment schemes yield an excellent compromise between computational complexity and high performance. Static fractional frequency reuse on the other hand is shown to result in highly suboptimal performance at all network densities. We also study the robustness of the graph based approach against uncertainties in the employed radio propagation estimates, showing that even relatively high estimation errors in radio propagation models do not result in significant degradation of performance.**

I. Introduction

Network densification through deployment of femtocells is one of the most promising approaches for sustainably increasing the capacity of cellular networks [1]. Proliferation of small cells poses a serious challenge on the employed interference management techniques, which has resulted in significant interest in studies of co-tier and cross-tier interference as well as development of several advanced interference management schemes (see, for example, [2]–[9]). Unfortunately most of the existing literature has relied on highly simplified propagation models in the evaluation of the proposed schemes, making it difficult to evaluate the reliability of the results due to the complex influence of the indoor propagation environment. Further, almost no comparative studies have been made, making it highly challenging to understand the relative performance of the different proposals for interference management and frequency allocation. Building such understanding is crucial as the various schemes proposed have highly different computational and messaging complexities, making it important for practical network design to find solutions that yield good performance without too high overheads.

In this paper we carry out a detailed comparative study on the performance of three different frequency assignment schemes for interference management in heterogeneous LTE networks using realistic indoor and indoor-outdoor propagation models. Our results show that while the computationally highly complex approaches do result in performance improvements especially in the densest scenarios, simple graph-based approaches can achieve almost as good performance with significantly reduced overhead. We also show that the latter are highly robust against uncertainties in the employed radio propagation estimates. This makes them ideal for use in measurement-based deployment scenarios where data from mobile terminals is used for estimating the coverage of femtocells instead of the network planning tools used for macrocell coverage estimation.

The rest of this paper is structured as follows. In Section II we describe our used system model in detail, and discuss the frequency assignment algorithms chosen for comparison. In Section III we give a baseline comparison of the performance of the three schemes using a variety of metrics. In Section IV we discuss the robustness of the frequency assignment problem to errors in path loss estimates, and show that one of the studied methods based on graph clustering has very good robustness in these terms. Finally, we draw our conclusions in Section V.

II. Scenarios and Frequency Allocation Schemes

A. System Model

We focus on a downlink cross-tier interference scenario in which the femtocells and the macrocellular network operate on the same overall frequency band, and the objective of the frequency assignment method is to choose which subcarriers are used by each of the femto and macro base stations. The deployment scenario considered is illustrated in Figure 1, showing several apartment buildings each potentially hosting a femtocell separated by streets and a small pedestrian area. The region illustrated in the figure is placed within a macrocell,

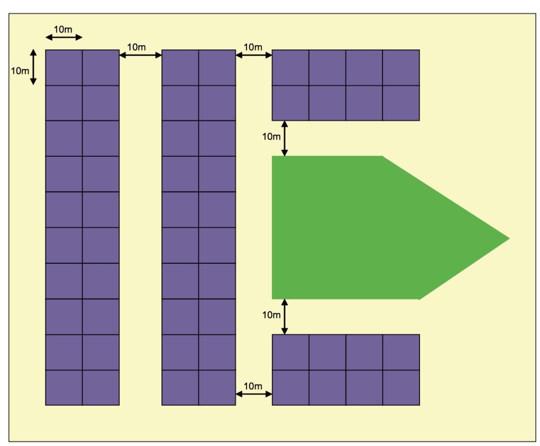


Fig. 1. Illustration of the femtocell deployment scenario.

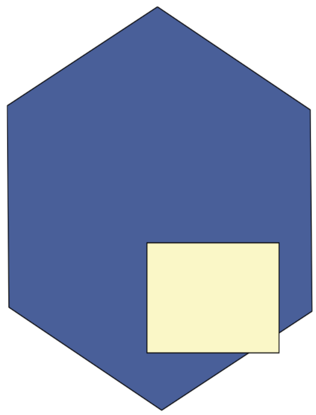


Fig. 2. Placement of the femtocell simulation region in relation to the closest macrocell.

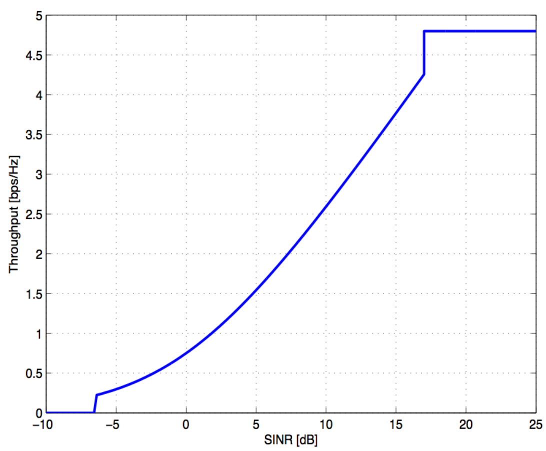


Fig. 3. Truncated Shannon capacity law used to estimated LTE downlink throughput based on the SINR of a resource block.

closer towards cell edge as shown in Figure 2. As we assume an urban deployment, relatively small cells and transmit powers are assumed for the macrocellular network as shown in Table I where the simulation parameters for the macrocellular system are gathered in. For femtocells, the corresponding simulation assumptions are collected in Table II. While no widespread LTE femtocell deployment has yet taken place, we have made conservative assumptions on the used transmit powers, and assume a single antenna terminal as the receiver, such as a typical smartphone or a tablet.

In order to obtain the path loss values needed to evaluate the impact of interference at any given user equipment (UE) location, we use the dominant path model as implemented in the AWE WinProp suite for propagation simulations [10]. This model has been found to be highly accurate in practice, and enables realistic modeling of complexities of the indoor propagation environment. For evaluating the performance of the chosen frequency assignment schemes we compute SINRs for each randomly generated UE locations and for each resource block. In order to obtain throughput estimates these

TABLE I
MACROCELL SYSTEM ASSUMPTIONS.

Parameter	Value
Cellular Layout	Hexagonal grid, 3 sectors/site
Number of transmit antennas	1
Inter-site Distance	500 m
Total Area	1.52 km^2
Carrier Frequency	2.6 GHz
Bandwidth	5 MHz
Transmit Power of BS	31.5 dBm
Antenna Gain	14.5 dBi
Noise Figure of UEs	-174 dBm/Hz
Number of receive antennas	1

TABLE II
FEMTOCELL SYSTEM ASSUMPTIONS.

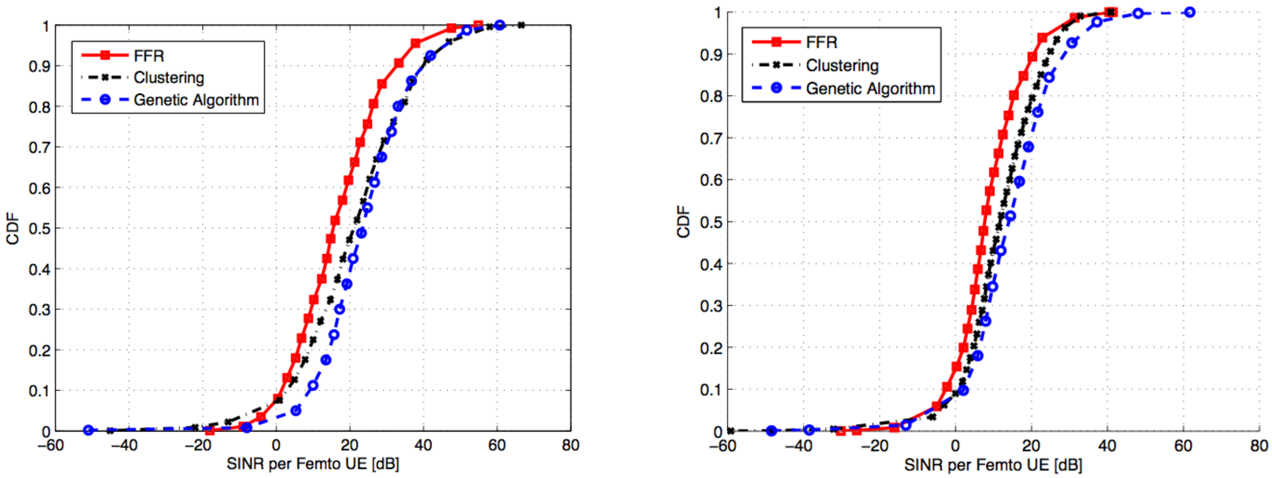
Parameter	Value
Carrier Frequency	2.6 GHz
Bandwidth	5 MHz
Number of transmit antennas	1
Transmit Power of BS	23 dBm
Antenna Gain	0 dBi
Noise Figure of UEs	-174 dBm/Hz
Number of receive antennas	1

are then mapped to downlink throughput using the truncated Shannon capacity curve illustrated in Figure 3. This approach approximates very closely the actual achieved LTE system performance.

B. Frequency Allocation Schemes Considered

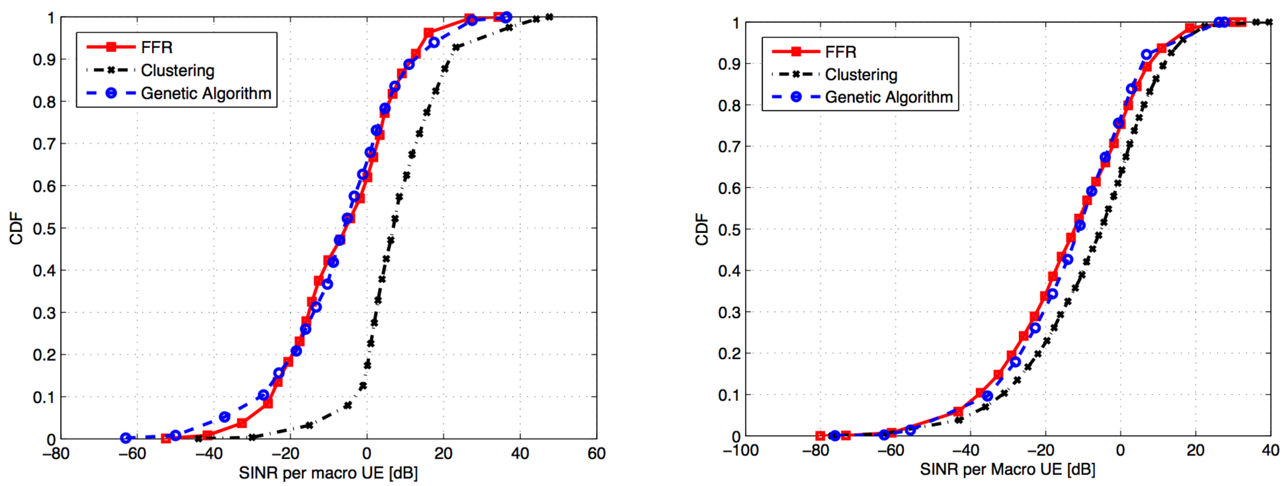
We consider three different frequency allocation schemes in our study, ranging from the highly simplified to very accurate but computationally expensive. The first of these is the simple application of fractional frequency reuse (FFR) to the two-tier LTE network as described in [11]. Here dedicated subbands are assigned to the macro UEs in their respective sectors, with simple geometric reuse of subbands being employed on the femto layer. This FFR approach does not use any information on the estimated propagation environment explicitly, simply relying on the geographic locations of the femtocells for frequency assignment. It is thus simple to implement, but is not expected to result in a good performance compared to alternative methods utilizing path loss data in frequency assignment decisions.

As another extreme, we consider the use of a genetic algorithm (GA) for optimizing the frequency assignment, using SINR distribution as the optimization target as described in [12]. While the SINR maximization problem is very complex, metaheuristics such as the GA can find near-optimal solutions for such problems at the cost of very high computational overhead. In essence, correctly implemented GA with sufficient computational time will find at least as



(a) $D = 0.2$ (b) $D = 0.8$

Fig. 4. Distribution of femtocell downlink SINR for different frequency assignment algorithms and deployment ratios.



(a) $D = 0.2$ (b) $D = 0.8$

Fig. 5. Distribution of macrocell downlink SINR for different frequency assignment algorithms and deployment ratios.

close solutions to the optimum one as any other frequency assignment scheme.

Finally, we consider as an approach of intermediate complexity the graph clustering method for frequency assignment described in [13]. In this method path loss values are not used directly for optimization, but instead they are first quantized, and the quantized values are used to build a graph of "significant" interference relationships. Based on this graph heuristics similar to graph coloring can be applied to find frequency allocations that assign distinct subbands to heavily interfering nodes. Overall the method has much lower computational complexity than the GA, while still benefiting from the use of path loss information unlike the simple FFR approach.

III. Results on Performance Comparison

Figure 4 shows the arising SINR values for the three frequency assignment schemes considered for two different *deployment ratios*, defined as the probability of an individual apartment to house a femtocell. First of these ($D = 0.2$) corresponds to a relatively sparse deployment, with the second ($D = 0.8$) resulting in a very dense interference environment. As expected, the FFR approach performs largely the worst, with the GA resulting in the best overall performance. However, in general the graph clustering approach performs almost as well as the GA, despite the much higher complexity of the latter. In the sparse deployment the GA approach will result better operating conditions for UEs in low SINR conditions, with the clustering approach performing well for high SINR conditions.

The situation for the macro UEs is similar with respect to the performance of FFR and graph clustering approaches as seen in Figure 5. However, the performance results for the GA based approach are relatively poor. The reason for this

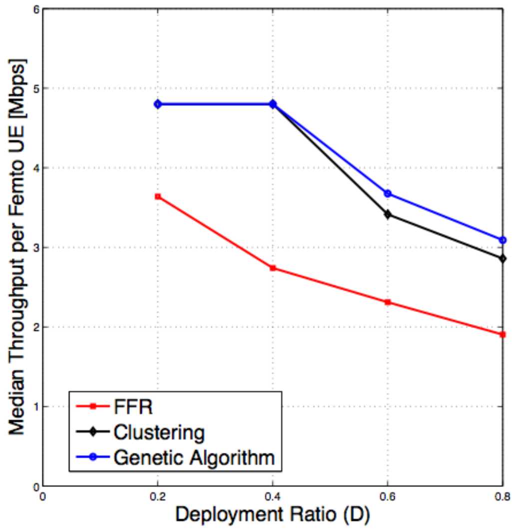


Fig. 6. Median femto UE throughput as a function of the deployment ratio.

turns out to be in the performance objective given for the GA, namely the overall capacity maximization which in this case results in high level of unfairness towards the macro UEs.

We shall next study more closely the resulting UE throughput distributions for the different methods. Figure 6 shows the median femto UE throughput for the three approaches as a function of the considered deployment ratio. Again the performance of the graph clustering method is seen to be close that of the GA approach, with small gap in optimality being visible at the higher deployment ratios. The FFR approach on the other hand performs relatively poorly throughout.

Finally, Figure 7 gives the full CDFs of the femto UE downlink throughputs are achieved by the different approaches for the different deployment ratios considered. The FFR approach provides the worst performance throughout, with the differences being smallest in the low SINR regime in dense deployments. The graph clustering approach is seen to result is good performance when compared against the GA, although the latter yields better performance especially in low SINR conditions for sparser deployments. This is of course expected from the results on the SINR distribution discussed above.

IV. Performance with Inaccurate Pathloss Data

We shall now relax the assumption on the accuracy of the path loss data used for frequency assignment for femtocells and macrocells. Our focus will be on the impact of inaccurate path loss estimates on the performance of the graph clustering approach, as the performance of this method is very close to the near-optimal one provided by the GA approach.

Before proceeding to the results, we shall briefly discuss the realistic modeling of errors in path loss estimates. In outdoor environments it is well accepted that deviations from the large-scale propagation laws (traditionally called *shadow fading*) are well modeled by the log-normal distribution. As shown recently in [14], [15], the errors can be rather large, often reaching 8-10 dB range even for the most well established propagation models. Thus a standard deviation of at least several dBs is needed for the realistic modeling of these errors.

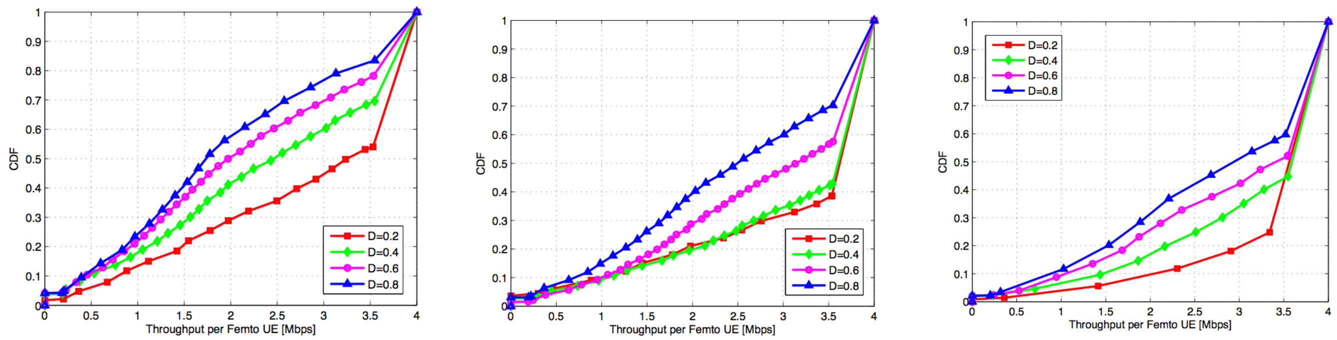
In the indoor case the situation is much more complex, as the traditional large scale path loss models are no longer valid. As shown in [16], tools from spatial statistics can be used for estimating the indoor coverage with small number of measurements (that can be collected by femtocells themselves or through mobile terminals), with errors that are again closely modeled by the normal distribution in the dB-scale. Depending on the propagation environment and the number of measurements, the standard deviations for these errors were shown in [16] to be in the 3–12 dB range. We shall use these values as a basis of our study.

Figure 8 shows the distribution of downlink throughput for both the femto and macro UEs for the dense deployment scenario ($D = 0.8$) in the presence of such normally distributed path loss errors. We see that for the femto clients the errors play only a very minimal role, with the most severe errors causing only a slight degradation in the throughput. This is a highly encouraging result, as it shows that high accuracy of path loss data is in fact *not* needed for successful interference management in femtocell networks as long as a robust optimization algorithm such as the graph clustering approach is used. The reason for this robustness is rooted in the way path loss values are used by the algorithm. The differences in path loss values in indoor environments are inherently very high due to wall losses, making the discretization of path loss values into just few classes used by the algorithm relatively insensitive to errors in these values. From the figure we also see that the impact on the macro UEs is somewhat larger as the standard deviation of the path loss errors becomes high. However, for smaller and more typical error magnitudes the method remains highly robust.

V. Conclusions

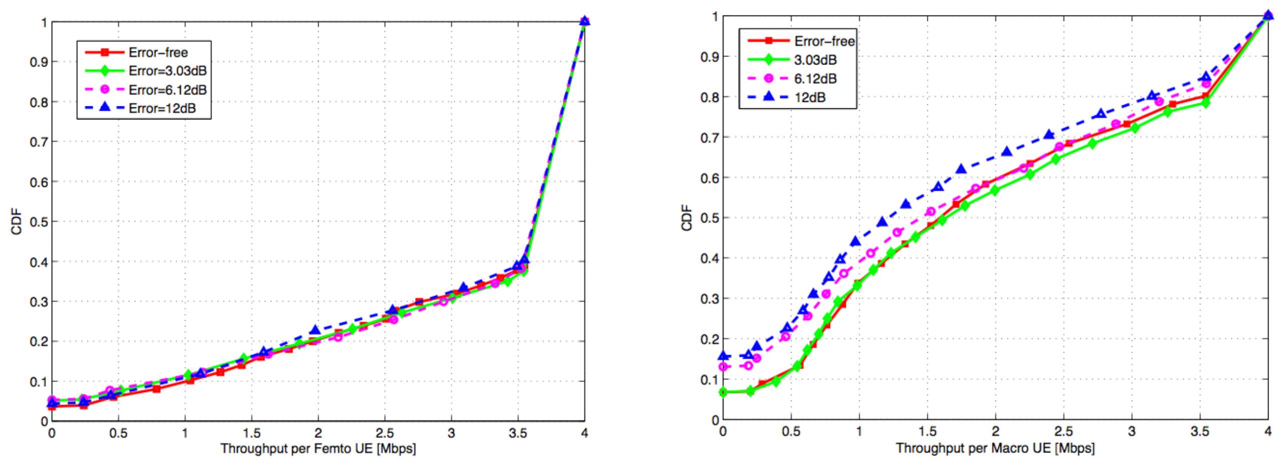
In this paper we have presented results from a detailed comparative study of the performance of three different frequency assignment schemes for interference management in LTE femtocells using realistic indoor propagation models. We have shown that while the computationally highly complex approaches such as the use of genetic algorithms and similar metaheuristic optimization methods do result in performance gains especially in the densest scenarios, simple graph-based approaches can achieve very good performance with significantly reduced computational overhead. We have also seen that the latter are highly robust against uncertainties in the employed radio propagation estimates. Such robustness is highly desirable for actual deployments due to the high inherent errors of indoor propagation estimates.

We are currently extending this work towards a more integrated simulation environment, enabling more realistic and detailed modeling of the path loss estimation errors. Our aim is to enable system level simulations of the entire frequency assignment cycle, including both the measurement-based gathering of path loss data followed by data fusion yielding



(a) FFR (b) Graph clustering (c) Genetic algorithm

Fig. 7. Distribution of femtocell downlink throughput for different frequency assignment algorithms and deployment ratios.



(a) Femtocell downlink (b) Macrocell downlink

Fig. 8. Distribution of femtocell and macrocell downlink throughputs for the clustering method in the presence of estimation errors for link gains.

propagation estimates, and their subsequent application for frequency allocation. Following a comprehensive simulation assessment, we also plan to implement the most promising approaches on actual UEs and small cells emulated using SDR platforms in order to carry out a real world validation of the performance and robustness properties of graph based frequency assignment schemes.

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