ENERGY-EFFICIENT WIRELESS IN-HOME: THE NEED FOR INTERFERENCE-CONTROLLED FEMTOCELLS

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ABSTRACT

Fostering growth in provisioning of wireless data at the same or even reduced energy expenditure levels, is crucial to society and thus one of the most important goals of the ICT sector. Femtocells, installed at customer premises, have emerged as a promising energy-efficient solution as connectivity is provided where and when needed. This article thus first overviews femtocell deployments in the context of 3G LTE and its advanced (LTE-A) networks. It is shown that to increase spectral efficiency, operators envisage utilizing the same spectrum for femtocells as well as overlaying macrocells. This in turn leads to significant interference between macro and femto as well as adjacent femtocells, the mitigation of which yields some major power gains. We therefore present various recent interference management schemes and quantify their throughput in the context of an LTE-A cellular network overlaying femtocells. Complete downlink system-level simulations corroborate exposed analysis and thus confirm the performance effectiveness of femtocell deployments.

INTRODUCTION

A femtocell is a cellular base station (BS) typically installed by the end user and transmitting with minimal transmission power to serve residential or small business environments. It connects to the service provider's network via broadband such as digital subscriber line (DSL) or cable, and typically supports only a few user equipment units (UE) [1]. A femtocell allows service providers to extend service coverage indoors, where data rate requirements are typically highest but access is limited due to heavy propagation losses. Due to its advantages, such as low cost and high energy efficiency, femtocell technology has been proposed and applied in the Third Generation Partnership Project (3GPP) for its Universal Mobile Telecommunications System (UMTS), and Long Term Evolution (LTE) networks and their advanced form (LTE-A) [2, 3]. Note that the macrocell BS and femtocell BS are usually referred to as macro evolved NodeB (MeNB) and home evolved NodeB (HeNB) in 3GPP.

From the operator's viewpoint, a significant amount of traffic can be moved from the macrocell network to femtocell networks, thus reducing the number of macrocell BSs, equipment for backhaul transmission from macrocell BSs to their core network, and other equipment; this essentially greatly diminishes cost and power consumption. From the customer's viewpoint, femtocells can be conveniently deployed as wanted, providing sufficient radio signals to the UE while consuming less/easest power in indoor environments. It may also not be powered at all times of the day for further energy savings. The typical power consumption of a femtocell is likely to be in the range of a few watts, which is at least an order of magnitude less than that of macrocell BSs. Moreover, one other benefit of femtocells is that they help a user's battery last longer indoors where data rate requirements are often highest. This is because less power is required to transmit a signal over the short distance to the femtocell rather than over the long distance to a macrocell BS.

As femtocell networks are customer-deployed without proper network planning, their interference environment tends to be much more complicated than those of traditional cellular networks. Thus, interference problems in femtocell networks cannot be handled by existing schemes typically used for macrocell deployments. There are two types of access points in femtocell networks, the MeNB and HeNB. The network can thus be divided into two tiers: the macro-tier with macrocells and the femto-tier with femtocells. The interference between macrocell and femtocell (i.e., intertier interference) arises from the fact that femtocells may utilize the spectrum already allocated to the macrocell. Meanwhile, all the femtocells can share the same radio resources for improving the spectrum efficiency, which may cause the interference between femtocells themselves (i.e., intratier interference). Without proper interfer-
Interference conditions in relation to HeNB deployments.

Interference management methods, significant power is likely to be wasted in order to maintain acceptable user performance. For example, usually high transmit power is radiated by a macrocell BS to provide the services for outdoor UE. If no proper downlink power control method is applied at the macrocell BS, interference is possibly generated to indoor UE connected to the femtocell BS if the whole or a part of the frequency band is shared between the femtocell and macrocell. Therefore, the femtocell BS has to increase its transmission power to maintain the communication with its indoor UE. In this situation, the overall energy efficiency of the network becomes even worse after deploying femtocells. Interference management is therefore a key issue in being able to capitalize on the potential energy efficiency of femtocell networks.

The scope of this article is hence to examine how users in LTE-A cellular networks with femtocell deployment can share the available radio resources efficiently in order to mitigate co-channel interference and thus enhance the spectral efficiency of the networks. We briefly present the femtocell deployment in LTE-A cellular networks under both suburban and urban environments. Then, with the introduction of the fundamental issues of optimizing the spectral efficiency in femtocell networks, typical radio resource coordination schemes are discussed in detail. Note that an exhaustive state of the art on interference management schemes is beyond the scope of this article. Finally, the throughput performance of LTE-A cellular networks with femtocells and interference strategies are compared extensively.

Interference Analysis with Femtocell Deployment

The HeNBs are deployed with the McNBs in an overlay, overlapping, or disjointed area in LTE-A cellular networks as an energy-, performance-, and cost-efficient solution. These deployments could be open subscriber group cells (OSGs) or closed subscriber group cells (CSGs). OSG deployment enables the HeNBs to serve all the UE of an operator; while CSG permits access to the HeNB to a specific user group only. The options can be chosen by the operator considering not only the business case, but also the technology and radio frequency (RF) requirements.

HeNBs give a high level of uncertainty in the deployment of LTE-A cellular networks due to being privately owned by end users. Some particular characteristics of HeNBs can be summarized as follows.

Location uncertainty: Since HeNBs can be moved around as the HeNB owners like, the location of an HeNB is random and unpredictable.

Configuration variation: Some HeNB configuration parameters might be adjusted by the HeNB owners for operation and performance. The degree of uncertainty in the deployment increases if the HeNB configuration can be set differently for each HeNB.

Access control: Different access control mechanisms for femtocells may result in different interference environments. OSG deployment is simple, and no additional configuration is needed. However, the capacity and backhaul connection of the HeNB could be the bottleneck. In CSG deployment, the HeNB provides services only for users preconfigured by its owner.

Such uncertainty makes the interference of femtocell networks much more complicated than that of conventional wireless cellular networks.

Introducing femtocells should not significantly degrade the performance of other/prior deployed networks. Coexistence of HeNB and McNB networks in orthogonal channels is simple but leads to low spectrum efficiency from a system point of view. In order to achieve higher spectral efficiency, femtocells can be deployed in the same channel as an existing overlay macrocell network, leading to a shared channel deployment. However, there will be an increased level of interference relative to orthogonal channel deployment, especially in the case of CSG. Figure 1 illustrates possible interference conditions in relation to CSG HeNB deployments with a corresponding analysis given in Table 1. All the interference can be classified into intertier or intratier interference and dealt with by different interference management schemes.

Interference Management for Femtocell Networks

It is paramount to mitigate the co-channel interference that arises when femtocells are deployed in a network typically based on macrocells and ensure that their spectral efficiency is better than that of the macrocell only network. Therefore, several interference management schemes for
Interference scenario
• Semi-static/dynamic resource coordination
• Semi-static/dynamic resource coordination

MUE
Classification
Intertier
Intratier
HeNB
Classification
Intertier
Intertier
MeNB

Table 1. Interference analysis for femtocell with macrocell.

<table>
<thead>
<tr>
<th>Case</th>
<th>Interference scenario*</th>
<th>Classification</th>
<th>Possible solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HUE→macro UL</td>
<td>Intertier</td>
<td>• Orthogonal radio resource partition between femtocell and macrocell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Uplink power control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Semi-static resource coordination</td>
</tr>
<tr>
<td>2</td>
<td>HeNB→macro DL</td>
<td>Intertier</td>
<td>• Orthogonal radio resource partition between femtocell and macrocell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Downlink power control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Semi-static resource coordination</td>
</tr>
<tr>
<td>3</td>
<td>MUE→femto UL</td>
<td>Intertier</td>
<td>• Orthogonal radio resource partition between femtocell and macrocell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Uplink power control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Semi-static resource coordination</td>
</tr>
<tr>
<td>4</td>
<td>MeNB→femto DL</td>
<td>Intertier</td>
<td>• Orthogonal radio resource partition between femtocell and macrocell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Downlink power control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Semi-static resource coordination</td>
</tr>
<tr>
<td>5</td>
<td>HUE→femto DL</td>
<td>Intratier</td>
<td>• Semi-static/dynamic resource coordination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Centralized/distributed resource coordination</td>
</tr>
<tr>
<td>6</td>
<td>HeNB→femto DL</td>
<td>Intratier</td>
<td>• Semi-static/dynamic resource coordination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Centralized/distributed resource coordination</td>
</tr>
</tbody>
</table>

* A→B: transmission of interferer A onto the reception of link B.

interference scenario
• Centralized/distributed resource coordination

LTE-A cellular networks with femtocells are presented in this section.

**OPTIMAL RESOURCE ALLOCATION**

In networks with HeNBs, many wireless links potentially interfere with each other. An increase in the transmit power of one cell results in larger received signal-to-interference-plus-noise-ratio (SINR) and hence higher throughput. However, this reduces the throughput of many neighboring cells.

Consider the downlink transmission with $N$ users and $M$ subchannels in a cellular LTE-A network with femtocells. There are usually a few home UE (HUE) units with very low or even no mobility in the home or office environment, so only one HUE is assumed to be connected to the HeNB per cell for simplicity [4]. Let the binary matrix $A = \{a_{m,n}\} a_{m,n} \in \{0,1\}$ describe the channel assignment among the users, where $a_{m,n} = 1$ denotes that subchannel $m$ is assigned to user $n$; otherwise, $a_{m,n} = 0$. $P = \{P_{m,n}\} P_{m,n} \in [0, P_T]_{M \times N}$ represents the transmit power matrix, where $P_{m,n}$ denotes the transmit power of the $n$th user on the $m$th subchannel and $P_T$ is the maximum transmit power per subchannel. According to Shannon’s theorem, the maximum achievable rate on subchannel $m$ in femtocell $n$ (i.e., $\eta_{m,n}$) depends on the allocated bandwidth and received SINR, which is a function of channel path loss attenuation, $A$ and $P$.

The interference management problem is to find $A$ and $P$ such that an objective function is optimized. Usually, the following optimization problems with different objectives are needed to be solved for interference coordination:

- **Maximize throughput (Max-TP):** Assuming the goal is to achieve the highest system spectrum efficiency, the objective function of this problem can be formulated as

$$
\max_{A,P} \sum_{n=1}^{N} \sum_{m=1}^{M} a_{m,n} \cdot \eta_{m,n}.
$$

- **Maximize proportional-fair (Max-PF):** Assuming the goal is to achieve the highest system throughput while ensuring proportional fairness among femtocells, the sum of the logarithmic average cell throughput needs to be maximized [5], that is,

$$
\max_{A,P} \sum_{n=1}^{N} \log \left( \sum_{m=1}^{M} a_{m,n} \cdot \eta_{m,n} \right).
$$

We can easily find that the optimization problem as shown in Eqs. 1 and 2 are non-concave because the Hession matrix is not always negative semi-definite to $P$ [6]. Meanwhile, such problems are also the mixed binary nonlinear programming (MBNLP) problem with binary variables $A$. To find its optimal solution, exhaustive search over all the possible solution set is needed, which has prohibitively high computational complexity.

Therefore, considering the implementation feasibility, it is necessary to deal with the interference management problem in LTE-A cellular networks with femtocells by other methods. Various interference management techniques, such as power control and radio resource coordination, have been proposed to provide promising energy-efficient performance. Here, only typical resource coordination is discussed due to its importance.

**RADIO RESOURCE COORDINATION**

The coordination of radio resources in energy-efficient wireless networks with HeNBs is realized by allocating different resources between...
neighboring eNBs in the time or frequency domains in order to mitigate co-channel interference. The main challenge lies in the fact that the location and coverage areas of HeNBs are uncertain. This yields solutions that differ in the choice of communication interval as well as control strategy.

**Different Communication Intervals** — The coordination requires communication between different network nodes in order to (re)configure radio resources. Based on the needs of the intersite communication interval, most interference coordination schemes can be categorized into two classes, semi-static and dynamic.

**Semi-static schemes:** Semi-static interference management schemes can adapt to the slow variation of different components in the network such as the density of HeNBs, the number of UE units, and their corresponding traffic types. One of the typical semi-static interference management schemes for DL transmission in femtocell networks, using soft frequency reuse (SFR), is exemplified in [7].

In traditional LTE cellular networks, SFR has been largely accepted for use to minimize/solve the inter-cell interference problem. It utilizes frequency resources and radiated power to coordinate MeNB transmissions with predefined resource constraints for different user types. The coordination of macrocells for SFR operation is not affected by the introduction of femtocells. Instead, the SFR between macrocells may be utilized by femtocells to coordinate the interference from the HeNB to the MeNB.

SFR related information, such as frequency partition pattern and power profile of the neighboring macrocells, can be obtained at the HeNB by measuring the air interface or through the wired interface between MeNBs and HeNBs. The HeNB thus knows which sets of resource blocks are used for macrocell center users (CCUs) and macrocell edge users (CEUs), respectively. Then, in order to avoid interference to the nearby MUE as much as possible, the HeNB schedules first the resource blocks not used by the nearby MUE. For example, when an HeNB is located at the edge of MeNB, the HeNB will give high scheduling priority to resource blocks used by the macro CCUs or macro CEUs for downlink transmission.

When SFR patterns of neighboring macrocells are changed, the coordination in femtocells should also be adjusted correspondingly. The definition of different priority to resource blocks does not exclude the scheduling of the resource blocks with low priority by the HeNB. The resource blocks with low priority can be used with lower power should the high-priority resources be not sufficient for transmission in one cell.

**Dynamic schemes:** Compared with macrocell deployment, there are usually significantly fewer UE units in a femtocell. Each user may have bursty data services, such as HTTP traffic, for which semi-static coordination schemes are often not efficient. For example, in some given subchannels, one HeNB may have data to transmit to a UE unit in the first subframe but not the second subframe. However, no other HeNBs can use these given subchannels although the second subframe is empty because of prepartitioning, which causes inefficient spectral reuse. Thus, for better resource utilization, it is desirable that the radio resource allocation between HeNBs is dynamically adjusted, at the cost of control information between HeNBs, ideally on the timescale of one subframe. Such dynamic approaches hence need to be designed properly so as to avoid large control overheads. In general, the more information is exchanged between HeNBs, the better the interference coordination. However, more signaling overhead and implementation complexity are needed. Therefore, a well designed dynamic approach should satisfy the trade-off between performance and implementation feasibility.

**Different Control Strategies** — The interference coordination can be performed through either centralized or distributed control strategies. From the overall performance point of view, networks with centralized control can achieve better performance than those with distributed control. However, distributed control avoids the bottleneck effect of a centralized control entity, which
Centralized control strategies: By measuring the control channel and reference signal transmitted by the neighboring HeNBs, an HeNB can know the cell ID of each neighboring HeNB and the PL between it and neighboring HeNB(s). All this information can be delivered to the centralized coordinator via SI signaling to form an interference graph of all HeNBs. In this interference graph, each vertex denotes an active HeNB, and an edge represents the jamming condition between two HeNBs. The edge exists only when the channel gain difference between the interfering and serving links exceeds a certain threshold. On the other hand, each HeNB estimates the required radio resource for transmission according to the varying traffic load and channel conditions of its serving UE. These requirements are also collected at the centralized coordinator. Given the interference graph and requirements, the centralized coordinator determines the specified transmission pattern (i.e., which subframes and subchannels are allowed for each HeNB's transmission) and thus increases the overall performance of the network. The transmission pattern can be determined by different algorithms. For example, we can deal with the problem of establishing the transmission pattern for different HeNBs with the help of a graph theoretical coloring algorithm (i.e., a graph-based method). All the HeNBs can first be grouped into different clusters by applying the greedy graph coloring algorithm in the interference graph. The HeNBs in the same group can share the same subchannels, while those in different groups must use orthogonal subchannels. In this way, the same subchannel can be used simultaneously in two or more HeNBs only with acceptable interference. Next, it needs to be determined how to allocate all the subchannels into different groups. Assuming that the subchannels are fully reused between HeNBs in the same group, their SINRs have no difference when only the PL of links is mainly considered in femtocell networks. The channel allocation problem is therefore reduced to finding how many subchannels should be assigned to each cluster, which can easily be solved by means of the convex optimization theory. Figure 2 gives an example of the centralized channel allocation between HeNBs.

Distributed control strategies: Different from centralized coordination schemes, an HeNB does not have to inform the centralized coordinator of the cell identification (ID) and PL of each neighboring HeNB. It instead constructs its own local interference graph, which only contains the vertices that denote its neighboring HeNBs. Distributed graph coloring algorithms can then be used by each HeNB to choose its resources. Furthermore, resource negotiation between HeNBs can be performed based on a utility function that enables nodes to quantify the benefit or loss due to each resource coordination action. These utility values can then be used at each HeNB to decide whether to send the resource coordination requests to its neighbors, or to accept/reject the requests based on the quantified benefits to the network.

**PERFORMANCE COMPARISON**

In this section, the performances in LTE-A cellular networks with and without HeNBs are compared through system-level simulations. We consider the dense urban scenario corresponding to densely populated areas where there are multifloor apartment buildings with small apartment units as described earlier. Detailed simulation parameters including channel model and system assumptions are summarized in Table 2 [4].

**SIMULATION CONFIGURATION**

In LTE-A cellular networks with/without HeNBs, there are several scenarios in our simulations for comparison.

**Case 1 — No HeNB deployment:** All the UE is served by the MeNB per sector, where no HeNB is deployed. All the radio resources are evenly allocated to each UE unit.

**Case 2 — Co-channel HeNB deployment:** HeNBs are deployed and the whole frequency band is shared between the macrocell and femtocells. The radio resources are orthogonally

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### Table 2. Parameters assumption in femtocell networks.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular layout</td>
<td>19 cells, 3 sectors/cell</td>
</tr>
<tr>
<td>Intersite distance (ISD)</td>
<td>500m</td>
</tr>
<tr>
<td>Macro UE density</td>
<td>24 UE units/sector</td>
</tr>
<tr>
<td>Macrocell shadowing standard deviation</td>
<td>8 dB</td>
</tr>
<tr>
<td>Macrocell shadowing correlation</td>
<td>Between cells 0.5</td>
</tr>
<tr>
<td></td>
<td>Between sectors 1</td>
</tr>
<tr>
<td>Max MeNB transmit power</td>
<td>46 dBm</td>
</tr>
<tr>
<td>BS antenna gain after cable loss</td>
<td>14 dBi</td>
</tr>
<tr>
<td>UE antenna gain</td>
<td>0 dBi</td>
</tr>
<tr>
<td>Noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td>HUE number per active HeNB</td>
<td>1</td>
</tr>
<tr>
<td>Deployment ratio * Activation ratio</td>
<td>0.2 * 0.5</td>
</tr>
<tr>
<td>HeNB antenna gain</td>
<td>0 dB</td>
</tr>
<tr>
<td>Min/max HeNB transmit power</td>
<td>0/20 dBm</td>
</tr>
<tr>
<td>Path loss</td>
<td></td>
</tr>
<tr>
<td>MeNB to MUE</td>
<td>Outdoor: 15.3 + 37.6 log(R), R in m</td>
</tr>
<tr>
<td></td>
<td>Indoor: 35.3 + 37.6 log(R), R in m</td>
</tr>
<tr>
<td>MeNB to HUE</td>
<td>35.3 + 37.6 log(R), R in m</td>
</tr>
<tr>
<td>HeNB to HUE</td>
<td>&amp; 127 + 30 log(R/1000), R in m</td>
</tr>
</tbody>
</table>
assigned to each MUE in each macrocell and fully reused by all the HUE in femtocells.

Case 3 — Dedicated channel HeNB deployment: Half of the whole frequency band is assigned to HeNBs deployed in femtocells, the other half to MeNBs in each sector. The resources assigned to the macrocell are orthogonally allocated to each MUE, while those in femtocells are fully reused by all the HUE.

There are two typical environments of femtocells deployed within a macrocell coverage area, urban and suburban.

Urban — In cellular networks with only macro sites, indoor coverage is not always reliable (e.g., perhaps available only on upper floors or close to windows). In some urban areas with UE densities above a certain level, there will be signifi-

The coordination of radio resources in energy-efficient wireless networks with HeNBs is realized by allocating different resources between neighboring eNBs in the time or frequency domains in order to mitigate co-channel interference.

Figure 3. Femtocells deployment in an LTE-A wireless networks; a) urban; b) suburban environments.
cant coverage/capacity shortage with conventional macro-only solutions. In these cases, femtocells result in the UE being able to be used in a better way, allowing users to rely on their mobiles at home in a ubiquitous manner.

Figure 3a presents the typical dense urban femtocell modeling for performance evaluation of LTE-A cellular networks. One or more femtocell blocks can be placed uniformly within a macro-cell area. Each block represents two stripes of apartments; each stripe has \(2 \times N_A\) apartments. For instance, \(N_A = 10\) in the example illustrated in Fig. 3a. Each apartment is of size \(10 \times 10\) m. There is a street between the two stripes of apartments, 10 m wide. It is assumed that the femtocell blocks are not overlapping with each other. Each femtocell block has \(L\) floors, where \(L\) is chosen randomly (\(L = 6\) in our simulations). If more than one femtocell blocks are deployed, each femtocell block can have a different number of floors. The HeNB and HUE are assumed to be randomly placed in each femtocell.

**Suburban** — The user benefit of femtocell deployment in suburban areas is the provision of reliable coverage throughout the home. With the limitation of a minimum distance to MeNBs, HeNBs can be deployed within or on the edge of the macro coverage area. As shown in Fig. 3b, each femtocell can be modeled as a two-dimensional rectangular house for performance evaluation. Within each house, the HeNBs and HUE units are randomly deployed within a specified distance to the center point of the house.

In order to have a fair comparison, the same UE distribution is assumed in both homogeneous deployment with only MeNBs, and heterogeneous deployment with both MeNBs and HeNBs. The UE placement is as follows: 24 MUE units are located uniformly, while one femto block/10 femtocells in a house are deployed per sector randomly under the urban/suburban environment. To simulate the realistic case where an apartment may not have a femtocell, a parameter of deployment ratio is used to show the probability of deploying an active HeNB in an apartment or a house. Since femtocells are not always on, we defined another parameter of activation ratio to describe the percentage of active femtocells. Only when a femtocell is active will it transmit with suitable power over the traffic subchannels; otherwise, it will keep silent. Only one UE unit is placed in an

**Figure 4. Geometry of throughput performances in LTE-A cellular networks with or without HeNBs in urban environments.**
apartment with an active HeNB, where both the HeNB and UE are located uniformly at random in the apartment.

**Simulation Results**

Figures 4a–c present the spatial characteristics of the throughput in LTE-A networks under different scenarios in the urban environment, where the block is assumed to be located at the center of the sector. Different colors represent different throughput values; for example, the red area has higher throughput than the green and blue areas. It is clear that there are many more red areas in Figs. 4b and 4c than in Fig. 4a. So the throughput is dramatically increased, especially in the femto block area when HeNBs are deployed. Such improvement is more obvious in case 2 than in case 3. Similar results can be achieved in the suburban environment.

Table 3 compares the average throughput of LTE-A networks with and without HeNBs in urban and suburban environments. Compared to case 1 without HeNB deployment, significant gains in terms of average throughput per user are achieved by femtocell deployment in cases 2 and 3, in particular for HUE. Since fewer femtocells are deployed with larger distances between each other in the suburban environment than in the urban environment, the interference in the former is much smaller in the latter. Thus, the HUE average throughput is much higher in the suburban environment than in the urban one. Then we apply the interference coordination schemes to improve the throughput performance in the urban environment in the next steps.

Assuming the whole frequency band is evenly allocated to the macrocell and femtocells as in case 3, we compare different radio resource allocation schemes between HeNBs in order to show the effects on system throughput in the urban environment. That is, for frequency reuse factor (FRF) = 1, FRF = 1/2, and the graph-based method with PF objective through centralized control. Figure 5a shows the complementary cumulative distribution function (CCDF) of the throughput of HUE in the network with different radio resource allocation schemes. When the graph-based method with PF is applied, the interference between HeNBs can be well coordinated while maximizing the system throughput by ensuring proportional rate fairness among femtocells. Then, compared with the cases of FRF = 1 and FRF = 1/2, the performance of cell edge HUE is improved. For instance, in 90 percent of operational cases, FRF = 1 achieves a throughput of only close to 0 b/s, whereas the graph-based method yields at least 2 Mb/s. However, with the decreasing percentage of operational cases, the case of FRF = 1 can achieve higher throughput because the channels are reused more frequently by this scheme, even with more interference generated. Next, the fairness of channel allocation schemes is also measured in Fig. 5b, where the cumulative distribution function (CDF) of the general proportional fairness (GPF) index is collected with different schemes. We observe that the graph-based method with PF scheme has a larger GPF index than others, which means it has better fairness performance [8].

**Conclusions**

Femtocells are meant to form an integral part of the LTE(-A) landscape, as corroborated by numerous standardization activities. While being the same technology, they differ regarding the

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**Table 3.** Comparison of average throughput in LTE-A cellular networks with or without HeNBs.

<table>
<thead>
<tr>
<th></th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MUE</td>
<td>HUE</td>
</tr>
<tr>
<td>Case 1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.51</td>
<td>112.90</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.37</td>
<td>83.20</td>
</tr>
</tbody>
</table>

Notes: Unit = Mb/s.
The user benefit of femtocell deployment in suburban areas is the provision of reliable coverage throughout home. With the limitation of a minimum distance to the MeNBs, HeNBs can be deployed within or on the edge of the macro coverage area.

overlying macrocell rollouts in reduced transmission powers, unplanned deployment strategy, and ownership. The most important problems arising due to this are:
1. Be able to provide sufficient backhauling capacity for femtos to offload their traffic
2. Ensure that interference from femtos to macro is minimal (ideally negligible)
3. Ensure that interference between femtocells is minimal
4. Ensure viable control of a large amount of dense femtocells

This article has mainly concentrated on points 2 and 3, leaving 1 and 4 as future work.

In essence, we have corroborated that femtocell technology is an energy-efficient solution for indoor coverage in LTE-A cellular networks. In order to solve the problem of co-channel interference and realize the system’s true potential for energy efficiency, interference management has been shown to be essential for femtocell networks. We thus presented various power control and radio resource coordination methods that are applicable in LTE-A cellular networks with femtocells. Our simulation results have demonstrated that femtocell deployment can significantly improve throughput performances of LTE-A cellular networks. When a good radio resource coordination scheme is applied in femtocell networks, not only the effectiveness but also the fairness of the network can be improved.

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REFERENCES


BIographies

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