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 information and communication technology (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 3rd generation (3G) long-term evolution (LTE) and its advanced (LTE-A) networks. It will be shown that, to increase the spectral efficiency, operators envisage to utilize 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 networks overlaying femtocells. Complete downlink system-level simulations corroborate exposed analysis and thus confirm the performance effectiveness of femtocell deployments.

Index Terms— femtocell, interference management, LTE-A.
I. INTRODUCTION

A femtocell is a cellular base station (BS) typically installed by the end-user and transmitting with minimal transmission powers to serve residential or small business environments. It connects to the service provider’s network via broadband such as Digital Subscriber Lines (DSL) or cable, and typically supports only a few user equipments (UEs) [1]. A femtocell allows service providers to extend service coverage indoors, where data rate requirements are typically highest but the access due to heavy propagation losses limited. Due to its advantages such as low cost and high energy efficiency, femtocell technology has been proposed and applied in the 3rd Generation Partnership Project (3GPP) for its Universal Mobile Telecommunications System (UMTS), long-term evolution (LTE) networks and its advancement (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, equipments for backhaul transmission from macrocell BSs to their core network, among others; this essentially greatly diminishes cost and power consumption. From the customer’s viewpoint, the femtocells can be conveniently deployed as wanted, providing sufficient radio signals to the UEs whilst consuming less/least 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 by at least an order of magnitude less than that of macrocell BSs. Moreover, one other benefit of femtocells is that they help 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 the 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, i.e., the MeNB and HeNB. The network can thus be divided into two tiers, i.e., the Macro-tier with macrocells and Femto-tier with femtocells. The interference between macrocell and femtocell, i.e., inter-tier 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., intra-tier interference. Without proper interference management methods, significant power is likely to be wasted in order to maintain an acceptable user performance. For example, usually the high transmit power is radiated by a macrocell BS to provide the services for outdoor UEs. If no proper downlink power control method is applied at the macrocell BS, interference is possibly generated to indoor UEs connected to the femtocell BS in case that the whole or a part of frequency band is shared between the femtocell and macrocell. Thereupon, the femtocell BS has to increase its transmission power to maintain the communication with its indoor UEs. In this situation, the overall energy efficiency of the network becomes even worse after deploying the femtocells. Interference management is therefore a key issue to being able to capitalize on the potential energy efficiency in 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 interference management schemes are discussed in details, including power control and radio resource coordination. Note that an exhaustive state-of-art on interference management schemes is out of scope. Finally, the throughput performance of LTE-A cellular networks with femtocells and interference strategies are compared extensively.

II. INTERFERENCE ANALYSIS WITH FEMTOCELL DEPLOYMENT

The HeNBs are deployed with the MeNBs 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 (OSG) or closed subscriber group cells (CSG). OSG deployment enables the HeNBs to serve all the UEs of an operator; whilst 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 RF-requirements.
HeNBs give a high level of uncertainty in the deployment of LTE-A cellular networks due to being privately owned by the end users. Some particular characteristics of HeNBs can be summarized as follows:

- **Location Uncertainty.** Since the HeNBs can be moved around as the HeNB owners like, the location of the HeNB is randomness 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 could 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 the backhaul connection of the HeNB could be the bottleneck. In CSG deployment, the HeNB provides services only for users pre-configured by its owner.

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

Introducing femtocells should not significantly degrade the performance of other/prior deployed networks. Co-existence between HeNB and MeNB 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 I. All the interferences can be classified into inter-tier or intra-tier interferences and dealt with by different interference management schemes.
### TABLE I
**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>
</table>
| 1    | HUE→ Macro UL          | Inter-tier     | - Orthogonal radio resource partition between femtocell and macrocell  
                                              - Uplink power control  
                                              - Semi-static resource coordination |
| 2    | HeNB→Macro DL          | Inter-tier     | - Orthogonal radio resource partition between femtocell and macrocell  
                                              - Downlink power control  
                                              - Semi-static resource coordination |
| 3    | MUE→Femto UL           | Inter-tier     | - Orthogonal radio resource partition between femtocell and macrocell  
                                              - Uplink power control  
                                              - Semi-static resource coordination |
| 4    | MeNB→ Femto DL         | Inter-tier     | - Orthogonal radio resource partition between femtocell and macrocell  
                                              - Downlink power control  
                                              - Semi-static resource coordination |
| 5    | HUE→Femto UL           | Intra-tier     | - Semi-static/dynamic resource coordination  
                                              - Centralized/distributed resource coordination |
| 6    | HeNB→ Femto DL         | Intra-tier     | - Semi-static/dynamic resource coordination  
                                              - Centralized/distributed resource coordination |

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

### III. INTERFERENCE MANAGEMENT FOR FEMTOCELL NETWORKS

It is paramount to mitigate the co-channel interference which 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 LTE-A cellular networks with femtocells are presented in this section.

#### A. 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-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 cellular LTE-A network with femtocells. There are usually few HUEs with very low or even no mobility in the home or office environment, so that only one HUE is assumed to be connected to the HeNB per cell for simplicity [4]. Let the binary matrix $A = \{a_{m,n}|a_{m,n} \in \{0, 1\}\}_{M \times N}$ 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 the 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, i.e.,

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

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

- **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], i.e.,

$$\max_{A,P} \sum_{n=1}^{N} \log \left( \sum_{m=1}^{M} a_{m,n} \cdot \eta_{m,n} \right). \quad (2)$$

W can easily find that the optimization problem as shown in (1) and (2) are non-concave because the Hessian matrix is not always negative semi-definite to $P$ [6]. Meanwhile, such problems are also the mixed binary non-linear 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, radio resource coordination, have been proposed to provide the promising energy-efficient performances.

**B. Power Control**

The current power control schemes in femtocell networks usually require no signaling between MeNB and HeNB or between HeNBs. As seen above, power control (PC) is necessary to mitigate the interference not only in the downlink but also in the uplink.
1) **Downlink Power Control:** In order to mitigate the interference to outdoor macro UE (MUE) and maintain good HeNB coverage for indoor HUEs, the downlink (DL) transmit power of HeNBs should be set appropriately when HeNB and MeNB share the whole or a part of the frequency band. Firstly, the HeNB measures the Reference Signal Received Power (RSRP) from the surrounding neighboring MeNBs via a DL receiver function. RSRP is the average power of cell-specific reference signals during the measurement frequency bandwidth. Then, the largest RSRP corresponding to the nearest MeNB is used as one of the parameters for downlink power control [7].

As the RSRP decreases, which means that the HeNB is located close to the edge of the macro cell, the transmit power should be small in order to mitigate the downlink interference to the MUE. In addition, the pathloss (PL) between the HeNB and an outdoor MUE including penetration losses can be estimated to calculate the power offset. If a HeNB is close to a MUE, lower transmit power should be set to mitigate its interference to the MUE.

With the knowledge of the largest RSRP and power offset, the HeNB selects the transmit power of the reference signal as the median values of the sum of the largest RSRP and power offset, the lower and the upper limit value of transmit power. The downlink transmit power of other signals is set in proportion to that of the reference signal.

2) **Uplink Power Control:** In the uplink (UL), the interference from the outdoor HUE to the MeNB becomes a serious problem when the HUE is located close to the MeNB. In this case, the transmit power from HUE has to be reduced in order to mitigate such interference. On the other hand, the indoor HUE, which is close to its serving HeNB and far from the MeNB, can increase transmit power with quite little or even no interference to MeNBs. Therefore, it is necessary to apply the uplink power control in femtocell networks.

The basic UL open-loop power control is to adjust the HUE transmit power only based on the PL from the HUE to its serving HeNB, which can be estimated from the difference between the received power and the transmit power of the signals from the HeNB. The former can be measured by the HUE through the reference signal from HeNB while the latter is known by means of decoding the given variable in the system message broadcasted.
However, if this simple power control method is applied in the uplink, a too strong signal transmitted from the outdoor HUE possibly can cause interference to nearby MeNB(s). In order to deal with this problem, the PL between HUE and its nearest neighbor MeNB has to be estimated for additional actions. Here, we present two advanced methods developed for uplink power control [8], i.e.,

- **Power-Cap-Based PC.** In this method, the maximum transmission power density (i.e., power cap) of the HUE is restricted in order to avoid heavy interference to MeNB(s). The power cap of the HUE is calculated as a function of the estimated PL between HUE and its nearest neighbor MeNB. Then, the HUE is power-controlled based on the PL from the HUE to its serving HeNB, up to the level of the power cap.

- **PL-difference-based PC.** With the knowledge of the difference between the PL from the HUE to its serving HeNB and its nearest neighbor MeNB, the HeNB calculates the power offset as a non-decreasing function of the PL difference. Then, this offset value is sent to the HUE via a radio resource control message to further adjust the uplink transmission power.

C. 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 which differ in the choice of communication interval as well as control strategy.

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

- **Semi-Static Schemes.** The semi-static interference management schemes can adapt to the slow variation of different components in the network such as the density of HeNB, the number of UEs and their corresponding traffic types. One of the typical semi-static interference management schemes for the downlink transmission in femtocell networks, using soft frequency reuse (SFR), is exemplified
In traditional LTE cellular networks, SFR has been largely accepted to be used 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 the 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.

The 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 link or through the wired interface between MeNBs and HeNBs. The HeNB thus knows which sets of resource blocks are used for macrocell center users (CCU) and macrocell edge users (CEU), respectively. Then, in order to avoid the 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 a HeNB is located at the edge or center of the MeNB, the HeNB will give high scheduling priority to resource blocks used by the macro CCU or macro CEU 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 in the case that high-priority resources are not sufficient for transmission in one cell.

- **Dynamic Schemes.** Compared with macrocell deployment, there are usually significantly less numbers of UEs 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 in the first subframe but not the second subframe. However, no other HeNBs can use these given subchannels although it is empty in the second subframe because of the pre-partition, which causes inefficient spectral reuse. Thus, for better resource utilization, the radio resource allocation between HeNBs is desirably dynamically adjusted at the cost of control information between HeNBs at, ideally, 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 tradeoff between performance and implementation feasibility.

2) Different Control Strategies: The interference coordination can be performed either through the centralized or distributed control strategies. From the overall performance point of view, the networks with centralized control can achieve better performance than that with distributed control. However, the distributed control avoids the bottleneck effect of a centralized control entity, which is quite advantageous from the implementation point of view.

- **Centralized Control Strategies.** By measuring the control channel and reference signal transmitted by the neighboring HeNBs, a HeNB can know the cell ID of each neighboring HeNB and the pathloss between it and neighboring HeNB(s). All this information can be delivered to the centralized coordinator via S1 signaling to form an interference graph of all HeNBs. In this interference graph, each vertice 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 UEs. These requirements are also collected at the centralized coordinator. Given the interference graph and the requirements, the centralized coordinator determines the specified transmission pattern, i.e., which subframes and subchannels is 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 graph
theoretical coloring algorithm, i.e., graph-based method. All the HeNBs can be first 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 pathloss 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 be easily 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 the centralized coordination schemes, a HeNB does not have to inform the centralized
coordinator about the cell identification (ID) and the 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.

IV. PERFORMANCE COMPARISON

In this section, the performances in LTE-A cellular networks with and without HeNBs are com-
pared through system-level simulations. We consider the dense-urban scenario corresponding to densely-
populated areas, where there are multi-floor apartment buildings with small size apartment units as
described in Section III. Detailed simulation parameters including channel model and system assumptions
are summarized in Table II [4].
TABLE II
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 per cell</td>
</tr>
<tr>
<td>Inter-site distance (ISD)</td>
<td>500m</td>
</tr>
<tr>
<td>Macro UE Density</td>
<td>24 UEs / sector</td>
</tr>
<tr>
<td>Macro cell shadowing standard deviation</td>
<td>8 dB</td>
</tr>
<tr>
<td>Macro cell 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 dBi</td>
</tr>
<tr>
<td>Min/Max HeNB transmit power</td>
<td>0/20 dBm</td>
</tr>
</tbody>
</table>

Pathloss

<table>
<thead>
<tr>
<th>Pathloss</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<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>$127 + 30 \log(R/1000)$, $R$ in m</td>
</tr>
</tbody>
</table>

A. Simulation Configuration

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

- **Case 1 - No HeNB Deployment.** All the UEs are served by the MeNB per sector, where no HeNB is deployed. All the radio resources are evenly allocated to each UE.

- **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 assigned to each MUE in each macrocell and fully reused by all the HUEs in femtocells.

- **Case 3 - Dedicated Channel HeNB Deployment.** Half of the whole frequency band is assigned to HeNBs deployed in femtocells while another 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 HUEs.

There are two typical environments of femtocells deployed within a macrocell coverage area, i.e., urban and suburban environments.
1) Urban: In the cellular networks with only macro sites, the 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 significant coverage/capacity shortage with conventional macro-only solutions. In these cases, femtocells result in the UEs being able to be used in a better way, allowing users to rely on their mobiles at home in an ubiquitous manner.

Figure 3(a) presents the typical dense-urban femtocell modeling for performance evaluation of LTE-A cellular networks. One or more femto blocks can be placed uniformly within a macro cell area. Each block represents two stripes of apartments, each stripe has 2 by $N_A$ apartments. For instance, $N_A$ is 10 in the example illustrated in Figure 3(a). Each apartment is of size $10 \text{m} \times 10 \text{m}$. There is a street between the two stripes of apartments, with width of $10 \text{m}$. It is assumed that the femtocell blocks are not overlapping with each other. Each femtocell block has $L$ floors, where $L$ is chosen randomly ($L$ is selected to 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.

2) Suburban: 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. As shown in Figure 3(b), each femto cell can be modeled as a two-dimensional rectangular house for performance evaluation. Within each house, the HeNBs and Home UEs (HUEs) 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 homogenous deployment with only MeNBs and the heterogeneous deployment with both MeNBs and HeNBs. The UE placement is as follows: 24 MUEs are located uniformly while one femto block/ 10 femtocell in 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, it will transmit with suitable power over the traffic subchannels; otherwise, it will keep silent. Only
Fig. 3. Femtocells deployment in an LTE-A wireless networks; a) urban; b) suburban environments.

one UE is placed in an apartment with an active HeNB, where both HeNB and UE are located uniformly at random in the apartment.

B. Simulation Results

Figure 4 (a), (b) and (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; e.g., the area with the red color has higher
throughput than that with the green or blue color. It is clear that there are much more areas with the red color in Fig. 4 (b) and (c) than that in Fig. 4 (a). 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. III compares the average throughput of LTE-A networks with and without HeNBs in urban and suburban environments. Compared with Case 1 without HeNB deployment, significant gains in terms of average throughput per user are achieved by femtocell deployment in Case 2 and Case 3, in particular for HUEs. Since fewer femtocells are deployed with larger distant between each other in the suburban environment than in the urban environment, the interference in the former is quite smaller in the latter. So, the HUE average throughput is much higher in the suburban environment than in the urban environment.
TABLE III
COMPARISON OF AVERAGE THROUGHOUT IN LTE-A CELLULAR NETWORKS WITH OR WITHOUT HeNBs.

<table>
<thead>
<tr>
<th></th>
<th>Suburban</th>
<th></th>
<th>Urban</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MUE</td>
<td>HUE</td>
<td>All UE</td>
<td>MUE</td>
</tr>
<tr>
<td>Case 1</td>
<td>–</td>
<td>–</td>
<td>0.53</td>
<td>–</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.51</td>
<td>112.90</td>
<td>33.56</td>
<td>0.33</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.37</td>
<td>83.20</td>
<td>24.74</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Notes: Unit=Mbps.

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, i.e., for frequency reuse factor (FRF)=1, FRF=1/2 and graph-based method with Proportional-Fair (PF) objective through centralized control. Figure 5 (a) shows the complementary cumulative distribution function (CCDF) of the throughput of HUEs 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 with ensuring the proportional rate fairness among femtocells. Then, compared with the cases of FRF=1 and FRF=1/2, the performances of cell edge HUEs are improved. For instance, in 90 % of operational cases, FRF=1 achieves a throughput of only close to zero bits per second, whereas the graph-based method yields at least 2 Mbps. However, with the decreasing percent of operational cases, the case of FRF=1...
can achieve the 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. 5 (b), where the cumulative distribution function (CDF) of the General Proportional Fairness (GPF) index are collected with different schemes. We observe that the graph-based method with PF scheme has larger GPF index than others, which means it has better fairness performance [10].

V. CONCLUSIONS

Femtocells are meant to form an integral part of the LTE(-A) landscape as corroborated by numerous standardization activities. Whilst being the same technology, they differ w.r.t. the overlaying 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; and 4) ensure viable control of a large amount of dense femtocells. This paper 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 to realize the system’s true potential w.r.t. energy efficiency, interference management has been shown to be essential for femtocell networks. We thus presented various power control and radio resource coordination methods, which 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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