Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2010, Article ID 142629, 15 pages
doi:10.1155/2010/142629

Research Article

Intracell Handover for Interference and Handover Mitigation in OFDMA Two-Tier Macrocell-Femtocell Networks

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Received 29 August 2009; Accepted 17 December 2009

Academic Editor: Ismail Guvenc

There are two main access policies (open and closed) to Femtocell Access Points (FAPs), being closed access the customers favorite. However, closed access is the root cause of crosstier interference in cochannel deployments of two-tier networks (i.e., macrocells and femtocells). Further, the effect of this problem is remarkably serious in the downlink of outdoor users not subscribed to any femtocell. Open access has been considered as a potential solution to this problem. However, this increases signaling in the network due to the elevated number of HandOvers (HOs) that mobile users have to perform. Therefore, this paper proposes an interference avoidance technique based on the use of Intracell HandOvers (IHOs) in Orthogonal Frequency Division Multiple Access (OFDMA) femtocells. It is shown that a proper combination of IHO and power control techniques reduces the outage probability for nonsubscribers compared with that of closed and open access. In addition, the impact of several network parameters such as the femtocell penetration is also considered in the analysis.

1. Introduction

Open access has been regarded [1] as a feasible solution to the problem of cross-tier interference in two-tier networks. Nevertheless, open access femtocell deployments are hardly practical due to the elevated number of required handovers. Indeed, when outdoor users are allowed to connect to any available cell (i.e., macrocell or femtocell) it is likely that due to the nomadic nature of these users, their connections would be continuously transferred between adjacent femtocells, or between femtocells and the umbrella macrocell. Furthermore, it is also well known [2] that HOs are not always successful and connections might be dropped as a consequence of HO failure. Additionally, the excessive signaling that emanates from an open access femtocell tier increases the complexity of the access network and introduces the need for large and powerful femtocell gateways.

1.1. Terminology. In order to clarify the concepts used throughout this article, the terminology to be applied is presented in the following. First, the main femtocell access policies are described.

(i) *Open access*: all clients of an operator have the right to connect to any of the femtocells of the operator.

(ii) *Closed access* also referred to as *Closed Subscriber Group* (*CSG*): only certain clients (subscribers) of an operator are allowed to connect to the given femtocell. The list of these clients is regulated by the femtocell owner.

(iii) *Hybrid access*: part of the femtocell resources is operated in open access, while the remaining follow a CSG approach [3]. This translates into a preferential access for subscribers and a limited access for other users.

In addition, in a closed and hybrid access, mobile users are classified as follows.

(i) *Subscribers*: these are the rightful users of a femtocell.

(ii) *Nonsubscribers*: these are users that are not registered in any nearby femtocell and therefore, they can only connect through the macrocell tier.

Moreover, the types of interference in two-tier networks are classified as follows.

(i) *Cross-tier interference*: this is caused by an element of the femtocell tier to the macrocell tier and vice versa.

(ii) *Cotier interference*: this takes place between elements of the same tier, for example, between neighboring femtocells.

Finally, note that variables in lower case represent magnitudes in natural units, while upper case indicates logarithmic scale, that is, dB.

1.2. Related Work. In order to cope with the previously mentioned problems, automatic pilot power control has been proposed in [4] as a possible solution for Code Division Multiple Access (CDMA) femtocells. However, this approach could lead to insufficient indoor coverage. In similar way, dynamic antenna patterns have also been suggested in [5], at the expense of a slightly more complex hardware in the FAPs. Furthermore in [6], a decentralized OFDMA resource allocation scheme was presented that optimizes the Area Spectral Efficiency (ASE) by applying spectrum fragmentation. However, this approach limits the maximum achievable instantaneous throughput regardless of the interference.

1.3. Contribution. It is because of the previously described drawbacks of open access that the closed access femtocell approach still seems appealing to most mobile network operators. Hence, novel solutions to the interference problem caused by CSG femtocells are still needed. In this article, a HO and interference mitigation technique based on the use of IHO for OFDMA femtocells operating in CSG mode is proposed. IHOs are widely used in Global System for Mobile communication (GSM) networks, where users are changed from channels with low-signal quality to channels that are in better conditions. The objective of this work is to apply the same concept to OFDMA subchannels, similarly as is done in GSM, in order to mitigate cross-tier interference.

In Section 2, interference is described in the context of two-tier networks. In Section 3, the notation used and several key concepts are presented. In Section 4, the IHO approach proposed in this article is depicted. In Section 5, the dynamic system-level simulation used in order to verify the performance of the IHO approach is summarized. In Section 6, a performance comparison in terms of network outages and throughput between closed, open access and IHO is given. Finally, in Section 7, the conclusions are drawn.

2. Interference in Two-Tier Networks

In two-tier networks, the severity of interference depends on two main factors: the strategy used for allocating the spectral resources to the tiers and the method used for accessing the femtocells [7]. A discussion on this topic follows.

2.1. Impact of the Spectrum Assignment on Network Performance

2.1.1. Assignment of Spectral Bands. Operators having more than one licensed spectral band have the following options for spectrum allocation [8].

(i) *Dedicated spectrum:* in this approach, a spectral band is assigned to the macrocell tier, while a different one is assigned to the femtocell tier. In this way, cross-tier interference is completely avoided, since both tiers operate at different frequencies. However, this results in a low spectral efficiency, since the cells in one tier can only access a subset of the overall frequency resources.

(ii) *Shared spectrum:* this approach reaches a higher spectral efficiency because both tiers access all resources. Nevertheless, in such configuration, cross-tier interference occurs, which could degrade the overall network performance unless interference is efficiently handled.

(iii) *Partially shared spectrum*: this is an intermediate solution. In this approach, the macrocell tier has access to all spectral bands, while femtocells operate only in a given subset. The main advantages of this approach are

  (a) better spectral efficiency than with dedicated spectrum.

  (b) reduction of cross-tier interference, when compared to a shared approach, since macrocell users creating or suffering from large cross-tier interference can be moved to the dedicated macrocell spectrum.

It is to be noticed that deploying a two-tier network using more than one carrier introduces a notable problem of battery drain in the User Equipment (UE), especially in the dedicated and partially shared approaches. In this case, femtocell subscribers connected to the macrocell tier perform a continuous search for the femtocell carrier, which is highly energy-consuming from the radio-interface point of view. Once the femtocell subscribers find the femtocell carrier, they synchronize to it and check, in the case of CSG access, their connectivity rights. Furthermore, if the femtocell subscriber is not allowed to connect to the CSG femtocell, its UE must resynchronize to the macrocell carrier, which supposes a new search, and therefore a further battery consumption.

Since not all operators have more than one spectral band to divide between tiers, and because the shared spectrum approach is more challenging from the technical point of view (it results in a better spectral efficiency, at the expense of having to mitigate cross-tier interference), the rest of this article focuses on the single carrier case.

2.1.2. Assignment of OFDMA Subcarriers. In OFDMA, the spectrum is divided into orthogonal subcarriers that are then

Table 1: Performance comparison.

	Subchannels allocation	
	Orthogonal	Cochannel
Average macrocell tier throughput (Mbps)	2.68	1.71
Average femtocell tier throughput (Mbps)	170.27	190.70
Average network throughput (Mbps)	172.95	192.41

Throughput analysis in a residential area (Figure 3) covered by 64 OFDMA femtocells and 1 macrocell, using a 5 MHz bandwidth. 4 indoor users are connected to each femtocell and 4 outdoor users move freely in the streets.

bundled into groups called subchannels (Wireless Interoperability for Microwave Access (WiMAX)) or resource blocks (LTE). Therefore, operators owning one spectral band and deploying a two-tier OFDMA network have different choices to allocate subchannels to the macrocell and femtocell tiers [9].

(i) *Orthogonal assignment.* A fraction of the subchannels is used only by the macrocells, while the rest of them are used exclusively by the femtocells.

(ii) *Cochannel assignment.* All macrocells and femtocells can access all subchannels.

It must also be mentioned that in [10], a hybrid approach has been proposed in which femtocells far from a macrocell use a cochannel assignment, whereas the close femtocells apply an orthogonal approach.

As explained in the previous section and in a similar way to the shared spectrum approach, a cochannel assignment of subchannels results in a larger spectral efficiency as long as cross- and cotier interference are efficiently mitigated, for example, by using self-organization techniques. To illustrate this, Table 1 shows the results of a system-level simulation of a two-tier OFDMA network (scenario shown in Figure 3) using the self-organization approach presented in [11]. The experiment verifies that the performance of a cochannel assignment in terms of network throughput is better than that of an orthogonal assignment, mainly due to the better frequency reuse.

2.2. Impact of the Access Method on Network Performance

2.2.1. Interference in Closed Access. With closed access, nonsubscribers can receive severe jamming from nearby femtocells. Even if the femtocell pilot power is larger than that of the nearest macrocell, nonsubscribers are not allowed to use the femtocell and are thus interfered in the downlink. Moreover, nonsubscribers transmitting with high power can cause interference in the uplink of nearby femtocells. The most challenging case of cross-tier interference, in this case, occurs when a nonsubscriber enters a house hosting a CSG femtocell. Then, in the downlink, the interference from the FAP is much stronger than the macrocell carrier, thus jamming the visitor. Similarly, the visitor can jam the uplink of the FAP.

2.2.2. Interference in Open Access. With this access method, nonsubscribers can also connect to femtocells. Therefore, the problem of a nonsubscriber passing by or entering a house where a femtocell is deployed is nonexistent. Hence, open access reduces the impact of cross-tier interference, which can be verified by the experiments presented in Table 2. However, open access has two major drawbacks.

(i) Femtocells are paid by subscribers, who are not keen on accepting nonsubscribers as users of their own femtocells. It is thus expected that operators would reduce the fees paid by subscribers or provide them with other advantages to make these type of femtocells more appealing.

(ii) Since all users can make use of the femtocells, the number of HOs and thus signaling increase in the network. It is also to be noticed that there is a chance that a HO will fail. According to [2], there is a 2% probability that a HO results in a dropped call. Therefore and as it is verified in Table 2, open femtocells can create outages.

Furthermore, in large deployments (high femtocell densities) of open access femtocells, even if a nonsubscriber is connected to a femtocell, the aggregate of all cotier interference coming from neighboring femtocells can disrupt its service (Table 2). It is to be noticed that cotier interference is also a problem in closed access.

As a conclusion, it is to be noticed that both access methods have drawbacks: CSG increases cross-tier interference, whereas open access increases the number of HOs [12]. In this article, the use of Intracell Handovers (IHOs) is proposed in order to cope with both issues.

3. Preliminaries

In the following, the notation used in the rest of the article is presented. Moreover, the concepts of neighboring cell list, measurement report, channel quality indicator, and handover are introduced.

3.1. Neighboring Cell List and Measurement Report. In order to select the best serving cell when the UE is idle, or to aid the HO procedure when the UE is active, the UE measures continuously the RSSs of the pilot channels of the neighboring cells. In order to simplify and speed up the task of the UE when monitoring the air interface, the serving cell periodically broadcasts to its UEs the list of cells and pilot channels that they must measure. This list is known as the Neighboring Cell List (NCL). After receiving the NCL, the UE performs (every period of duration T_{MR}) the appropriate measurements, and reports back the results to its serving cell, which then decides whether to start a new HO procedure or to take no action.

In two-tier networks, the NCL of a macrocell not only contains neighboring macrocells, but also open femtocells. Therefore, nonsubscribers must report back the RSSs of the pilot channels not only from all neighboring macrocells, but also from open femtocells.

TABLE 2: Performance comparison.

	Access method	
	Closed	Open
Outages due to HO failure	—	54
Outages due to interference	702	5
Average macrocell tier throughput (Mbps)	2.24	4.62
Average femtocell tier throughput (Mbps)	158.94	169.33

Outage and throughput analysis in a residential area (**Figure 3**) covered by 64 OFDMA femtocells and 1 macrocell using a 5 MHz bandwidth. 4 indoor users are connected to each femtocell and 8 outdoor users move in the streets.

Nevertheless, the case of CSG femtocells is different from open access. In order to minimize the impact of femtocell deployments on the existing macrocell tier, macrocells do not provide information about CSG femtocells in their neighboring cell list to the UEs. However, UEs perform an autonomous search to detect CSG femtocells [13].

3.2. Channel Quality Indicator. By using the Channel Quality Indicator (CQI), a UE can also report periodically, for example, at most every 2 ms in LTE networks, to its serving cell its signal quality in terms of Signal to Interference plus Noise Ratio (SINR), as well as the signal qualities of a given subset of resource blocks (usually the ones with better conditions). This CQI is used by the Medium Access Control (MAC) layer for channel-dependent scheduling and rate control, but it can also be used to trigger a HO when the UE reports a low SINR.

Furthermore, let us mention that in several wireless standards, such as WiMAX and LTE, the user equipment has the capability of estimating the instantaneous SINR in all subcarriers [14, 15].

3.3. Network Definition. Let us define a two-tier OFDMA network as a set of:

(i) $N + M$ cells $\{C_0, \ldots, C_i, \ldots, C_{N+M-1}\}$ with:

  (a) N femtocells $\{F_0, \ldots, F_n, \ldots, F_{N-1}\}$,
  (b) M macrocells $\{M_0, \ldots, M_m, \ldots, M_{M-1}\}$,

(ii) $X + Y$ users $\{\mathrm{UE}_0, \ldots, \mathrm{UE}_z, \ldots, \mathrm{UE}_{X+Y-1}\}$ with:

  (a) X subscribers $\{\mathrm{UE}^s_0, \ldots, \mathrm{UE}^s_x, \ldots, \mathrm{UE}^s_{X-1}\}$,
  (b) Y nonsubscribers $\{\mathrm{UE}^{ns}_0, \ldots, \mathrm{UE}^{ns}_y, \ldots, \mathrm{UE}^{ns}_{Y-1}\}$,

(iii) K subchannels $\{0, \ldots, k, \ldots, K-1\}$,

where the NCL of cell C_i contains J different cells (macrocells and femtocells) and it is denoted by $\mathcal{N}_i = \{N_0, \ldots, N_j, \ldots, N_{J-1}\}$.

3.4. Handover. In cellular networks, a HO is triggered when the RSS ($\mathrm{RSS}^{\mathrm{pilot}}_{i,z}$) of the pilot signal from a serving cell C_i at a mobile UE_z is lower than that of a neighboring cell N_j ($\mathrm{RSS}^{\mathrm{pilot}}_{j,z}$). These signal strength measurements are signal levels averaged over time using measurement reports. This averaging is necessary in order to cope with fading. Moreover, when a mobile user is located in between cells, it could happen that its transmission is ping-ponged from cell to cell. In order to avoid this effect, a hysteresis margin for the HO decision is also used. Furthermore, an umbrella cell system is normally deployed to minimize the large number of HOs incurred by high-speed users.

Then, if the HO condition is met, the serving cell C_i establishes communication with the target cell N_j and a HO is performed. However, in two-tier networks, performing a HO is not always the best choice or a possible option at all, because

(i) in closed access, it is not allowed that a nonsubscriber hands over from its serving cell to a CSG femtocell.

(ii) in open access, it is preferred to keep a mobile user connected to a macrocell than hand it over continuously and repeatedly between adjacent open femtocells. In this case, the mobile user speed must be considered.

In order to overcome these drawbacks, and the limitations imposed by closed and open access (CSG increases cross-tier interference, whereas open access increases the number of HO), the following IHO approach is proposed.

4. Intracell Handover in Femtocell Networks

The IHO is a special type of HO in which the source and target cell is the same one. The purpose of IHO is to transfer a user from a channel, which may be interfered or faded, to a clearer or less-faded channel. IHO is used, for example in GSM networks, where it is triggered when a UE reports a large RSS, but a low Received Signal Quality (RSQ) due to interference and/or fading.

The main idea of the proposed approach is that when a nonsubscriber that is connected to a macrocell suffers from cross-tier interference due to a nearby femtocell, the macrocell itself performs an IHO if possible, or casts an IHO in all interfering femtocells otherwise.

Without loss of generality respect to the IHO approach, the rest of this article focuses only on the DownLink (DL).

4.1. Triggering an IHO. When the SINR of a nonsubscriber UE^{ns}_y connected to macrocell M_m in subchannel k is smaller than a given threshold $\mathrm{SINR}^{\mathrm{IHO}}_y$, the serving macrocell M_m requests a measurement report from nonsubscriber UE^{ns}_y. In this measurement report, nonsubscriber UE^{ns}_y indicates the RSS of its serving macrocell M_m in subchannel k ($\mathrm{RSS}^k_{m,y}$), as well as the RSSs of its neighboring cells N_m in such subchannel k ($\mathrm{RSS}^k_{j,y}$).

Note that the neighboring cells of UE^{ns}_y are identified by the NCL provided by macrocell M_m to nonsubscriber

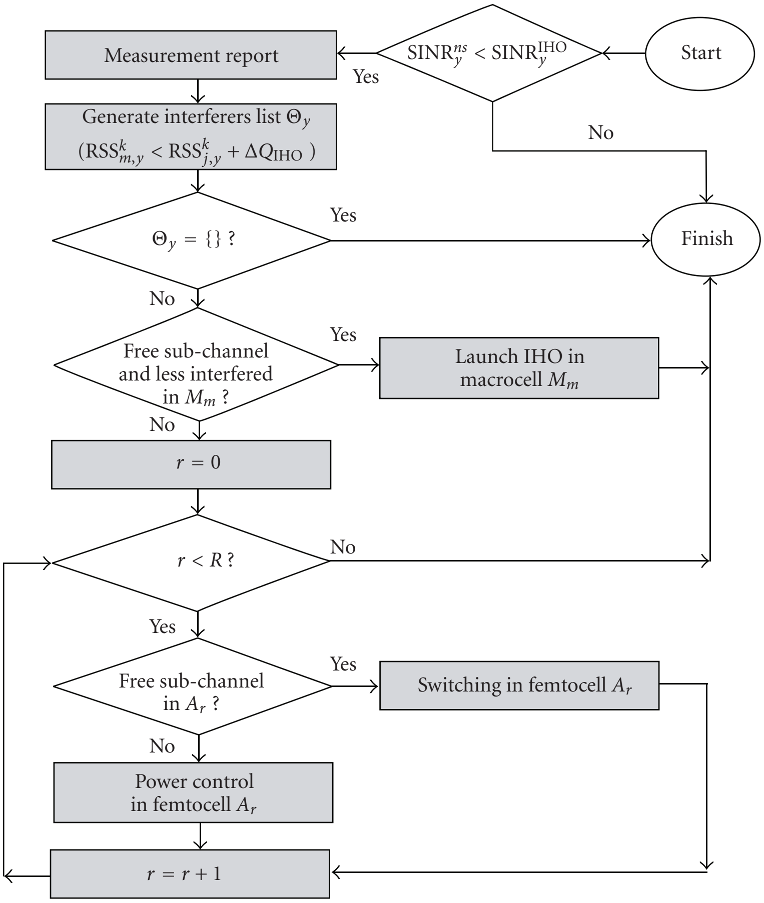


Figure 1: Intracell Handover approach.

UE_y^{ns}, and that they can be both macrocells and femtocells. Nevertheless, for the sake of simplicity it is assumed that the macrocell tier has been deployed using network planning and optimization tools, for example, base station location [16], automatic frequency planning [17], and thus macrocell intercell interference can be disregarded.

After receiving this measurement report, macrocell M_m compares its $\mathrm{RSS}_{m,y}^k$ with the other reported $\mathrm{RSS}_{j,y}^k$. Thereafter, macrocell M_m triggers an IHO only if condition (1) is verified by a neighboring cell N_j, and this neighboring cell is a femtocell F_n.

$$\mathrm{RSS}_{m,y}^k < \mathrm{RSS}_{j,y}^k + \Delta Q_{\mathrm{IHO}} \quad \forall N_j \in \mathcal{N}_m, \tag{1}$$

where ΔQ_{IHO} denotes an interference protection margin. If ΔQ_{IHO} is too low, the nonsubscriber UE_y^{ns} may suffer from interference before the IHO is launched, and its service could be dropped. Contrarily, if ΔQ_{IHO} is too large, the IHO may be triggered to solve a nonexistent problem, thus increasing the signaling overhead in the network. Therefore, ΔQ_{IHO} must be carefully selected in order to launch the IHO before the nonsubscriber falls into outage, while minimizing the signaling overhead.

Thus, if femtocell F_n verifies (1), it is considered as a cross-tier interferer of nonsubscriber UE_y^{ns} in subchannel k, and therefore an IHO is triggered. Note that the set of all interfering femtocells of nonsubscriber UE_y^{ns} verifying (1) is denoted by $\theta_y = \{A_0, \ldots, A_r, \ldots, A_{R-1}\}$.

Thereafter launching the IHO, it can be performed either in the serving macrocell M_m or in all interfering femtocells θ_y. In order to minimize the signaling overhead, it is preferred to perform this IHO in the serving macrocell M_m than in all interfering femtocells θ_y. However, this is not always possible due to traffic load or interference conditions in the macrocell M_m.

In the following, the conditions that are taken into account to decide whether an IHO is performed in the serving macrocell or in all interfering femtocells are presented, as well as the taken actions.

4.2. Performing the IHO in the Macrocell.

An IHO is launched in the serving macrocell M_m only if

(i) there is at least one free subchannel h to which nonsubscriber UE_y^{ns} can be reallocated to (switching),

(ii) and the interference suffered by subchannel h is lower than the one suffered by the assigned subchannel k.

In the case that there are more than one available subchannels in macrocell M_m, nonsubscriber UE_y^{ns} is switched to the subchannel h that suffers the least interference. This subchannel h is selected by macrocell M_m according to the CQIs reported by nonsubscriber UE_y^{ns}. In order to do this, macrocell M_m can instruct nonsubscriber UE_y^{ns} to perform measurements on unused subchannels, and report back their signal quality over the pilot reference symbols using the CQI.

It is to be mentioned that if no subchannel fulfills these requirements, the IHO is not performed in the serving macrocell M_m, but in all interfering femtocells $A_r \in \theta_y$.

4.3. Performing the IHO in the Femtocells.

4.3. Performing the IHO in the Femtocells. If the IHO cannot be performed in the macrocell, it is attempted in all interfering femtocells verifying condition (1). In this case, the macrocell establishes communication with these femtocells (Section 4.4) and initiates an IHO in them. The signaling overhead caused by these communications is analyzed in Section 6.5. Moreover, and according to the availability of subchannels in the interfering femtocell A_r, the IHO procedure differs. When there are available subchannels in femtocell A_r, a subchannel *switching* process is carried out, whereas when there are no available subchannels in femtocell A_r, a *power control* procedure is executed. Figure 1 summarizes this sequence of actions. Both procedures are introduced next.

4.3.1. Switching Approach for IHO in the Femtocells. Switching is only possible when there is at least one available subchannel h in the interfering femtocell $A_r \in \theta_y$. Then, the femtocell subscriber UE_x^s, which is currently connected to subchannel k, is transferred to subchannel h. In this way, subchannel k is liberated, thus avoiding cross-tier interference to nonsubscriber UE_y^{ns}. Note that if there are more than one available subchannels in femtocell $A_r \in \theta_y$, subscriber UE_x^s is switched to the subchannel h with best conditions according to its CQIs. In order to do this, femtocell A_r can instruct subscriber UE_x^s to perform measurements on unused subchannels, and report back their signal quality over the pilot reference symbols using the CQI.

4.3.2. Power Control for IHO in the Femtocells. If there are no free subchannels in the interfering femtocell $A_r \in \theta_y$, then one option would be to disconnect UE_x^s from subchannel k for a period of time ΔT_{IHO} in order to avoid cross-tier interference towards nonsubscriber UE_y^{ns}. However, this would decrease the throughput of femtocell $A_r \in \theta_y$, which is undesired. Note that this approach, called subchannel *forbidding*, is not part of the proposed IHO algorithm, but will be used for comparison in the following.

Then, instead of disconnecting UE_x^s from subchannel k, the power transmitted by $A_r \in \theta_y$ in subchannel k is reduced for a period of time ΔT_{IHO}. In this way, cross-tier interference towards the nonsubscriber UE_y^{ns} is mitigated.

The primary objective of this power control algorithm (illustrated in Figure 2) is to manage cross-tier interference, while the secondary objective is to maximize the femtocell throughput. In this way, the reduction of the throughput of femtocell $A_r \in \theta_y$ is minimized compared to that of the forbidding approach presented above.

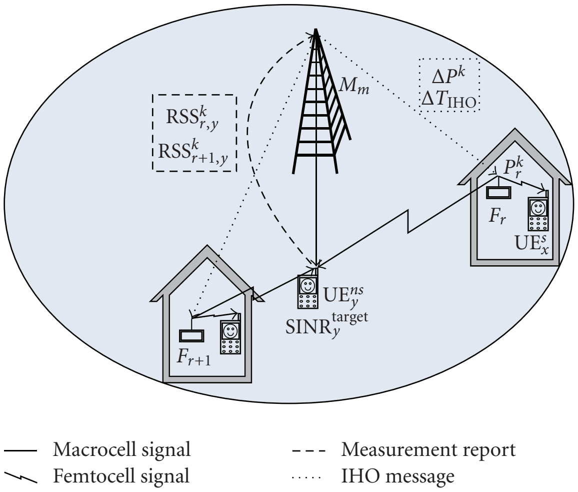


Figure 2: Power control algorithm for IHO.

The target of this distributed power control is to set the power P_r^k, with which all interfering femtocells $A_r \in \theta_y$ transmit in subchannel k, to a value $P_r^{'k}$ that ensures a certain signal quality $\mathrm{SINR}_y^{\mathrm{target}}$ to nonsubscriber UE_y^{ns}.

In order to guarantee such $\mathrm{SINR}_y^{\mathrm{target}}$, the maximum interference $i_y^{\max}$ that nonsubscriber UE_y^{ns} can tolerate is

$$i_y^{\max} = \frac{\mathrm{rss}_{m,y}^k}{\mathrm{sinr}_y^{\mathrm{target}}} - \sigma, \tag{2}$$

where σ denotes the background noise.

Then, macrocell M_m asks all interfering femtocells $A_r \in \theta_y$ to decrease their transmit power in subchannel k from p_r^k to $p_r^{'k}$ so that $i_y^{\max}$ is respected for nonsubscriber UE_y^{ns}. Furthermore and in order to avoid unfair power decrease requests among femtocells, the power decrease is weighted by macrocell M_m using the RSS reported by nonsubscriber UE_y^{ns} from each interfering femtocell $A_r \in \theta_y$ according to

$$p_r^{'k} = \underbrace{i_y^{\max} \cdot \frac{\mathrm{rss}_{r,y}^k}{\sum_{\forall r} \mathrm{rss}_{r,y}^k}}_{i_{r,y}^{\max}} \cdot \underbrace{\frac{p_r^k}{\mathrm{rss}_{r,y}^k}}_{pl_{r,y}^k}, \tag{3}$$

where $i_{r,y}^{\max}$ is the maximum interference that femtocell $A_r \in \theta_y$ is allowed to cause to nonsubscriber UE_y^{ns} and $pl_{r,y}^k$ is the path loss between them. Then, (3) simplifies to

$$P_r^{'k} = P_r^k - \Delta P^k, \tag{4}$$

where

$$\Delta P^k = 10 \cdot \log_{10}\left(\frac{\sum_{\forall r} \mathrm{rss}_{r,y}^k}{i_y^{\max}}\right) \tag{5}$$

being ΔP^k the power reduction in decibels requested for subchannel k, which is computed by macrocell M_m and passed on (Section 4.4) to all interfering femtocells $A_r \in \theta_y$.

Finally, it can occur that if femtocell A_r is already transmitting with too little power in subchannel k or if

$\mathrm{SINR}_y^{\mathrm{target}}$ is too high, the power decrease request ΔP^k might have the same effect as switching off subchannel k. In this case, subchannel k is *forbidden* in femtocell A_r for a period of duration ΔT_{IHO}, avoiding cross-tier interference towards nonsubscriber UE_y^{ns}. However, it must be mentioned that subscriber UE_x^s is only disconnected from subchannel k if it can afford it, that is, UE_x^s has allocated more subchannels or carries a service where delay is not crucial, for example, best effort, nonreal-time service.

Let us also indicate that the decrease in the femtocell throughput when forbidding a subchannel is statistically small, since this type of IHO is performed only from time to time when the femtocell is fully loaded and a nonsubscriber passes by the femtocell proximities.

Moreover, it is worth mentioning that a femtocell can generally afford to liberate a subchannel during a short period of time to avoid the outage of a mobile outdoor nonsubscriber. For instance, a WiMAX femtocell with 5 MHz bandwidth can achieve 12 Mbps in the downlink. Since a femtocell can only be accessed simultaneously by at most 4 users and subchannel forbidding is only triggered when the femtocell is fully loaded (otherwise, there would be available subchannels to switch to), then in order to fully use all available subchannels, it is likely that the femtocell users are not only using VoIP (12.2 kbps) or video (256 kbps), but also other intensive best effort services, for example, peer to peer. Then, they can afford to free a subchannel for a short period of time in favor of avoiding a nonsubscriber outage.

4.4. Macrocell and Femtocell Communication. In order to initiate an IHO in a femtocell, the macrocell needs to communicate with it. This communication could be established over the following.

(i) The backhaul connection using the core network infrastructure, for example, Radio Access Network Application Part (RANAP) in Universal Mobile Telecommunication System (UMTS) and $S1$ in LTE [18].

(ii) A direct interface between macrocells and femtocells. This solution has synergies with LTE, which has defined an $X2$ interface for signaling between eNodeBs.

(iii) The user, who could relay data from a macrocell to a femtocell and vice versa. This solution is suggested by the authors of [9].

Given the state of the art of mobility management in LTE femtocells, and because no $X2$ interface has been standardized yet for HeNodeBs, the exchange of messages between macrocells and femtocells is more likely to be implemented over the backhaul connection. This can be done in a similar way as proposed approaches for macro to femto and femto to macro HOs, using the femtocell Gateway (GW) [19].

Since this communication is out of the scope of this paper, it is not analyzed in detail in the following sections. However, the signaling overhead originated in the system due to the IHO approach is analyzed in Section 6.5.

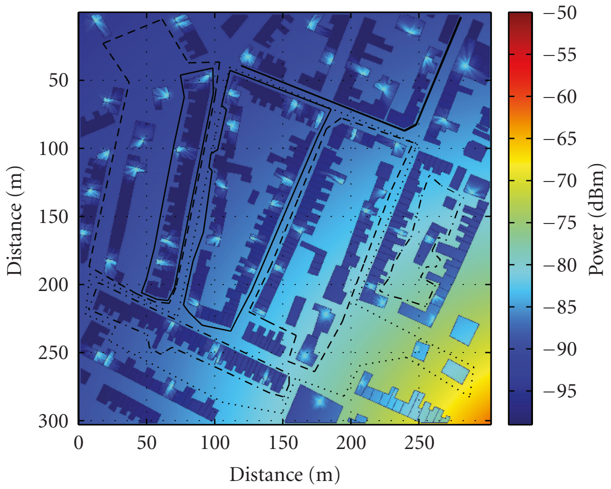


Figure 3: Received power per OFDMA subcarrier (OFDMA-512 system) in a residential area covered by 1 macrocell and 64 femtocells. Each femtocell premises contains several indoor users, while 8 pedestrian users are located outdoors, being their routes also indicated.

5. Experimental Setup

To evaluate the performance of the proposed IHO approach, dynamic system-level simulations have been used.

The scenario under scrutiny is a residential area with a size of 300 × 300 m in the town of Luton (U.K.), containing 438 premises of which around 400 are dwelling houses. 64 of these were selected to potentially host an indoor femtocell. Assuming that 3 operators with equal customer share provide services in this area, these 64 femtocells represents an approximate 50% femtocell penetration. Besides these femtocells, the scenario also contains one outdoor macrocell. Note that experiments were carried out with different femtocell penetrations: 50% (= 64 femtocells), 25% (= 32 femtocells) and 12.5% (=16 femtocells). The setup with 64 femtocells is illustrated in Figure 3, while the parameters of the simulation are shown in Table 3.

In this experimental evaluation, the different types of customers follow a well-defined behavior.

(i) Subscribers are located inside the houses with femtocell and do not move.

(ii) Nonsubscribers are located outdoors and move along predefined paths according to the pedestrian mobility model based on [20].

5.1. Propagation Model. For the path-loss predictions two different propagation models were used

(i) The macrocell coverage prediction was performed using the model proposed in [21]. This is an empirical model based on macrocell measurements in an urban environment at a frequency of 3.5 GHz.

Table 3: Simulation parameters.

Parameter	Value	Parameter	Value
Scenario size	300 m × 300 m	Macro Antenna Gain	0 dBi
Simulation time	800 s	Macro Antenna Pattern	Omni
Macrocells	1	Macro cable loss	3 dB
Femtocells	16, 32, 64	Femto TX Power	10 dBm
Nonsubscribers	4, 8	Femto Antenna Gain	0 dBi
Subscribers	4, 8 per femto	Femto Antenna Pattern	Omni
Carrier	3.5 GHz	UE Antenna Pattern	Omni
Bandwidth	5 MHz	UE Body Loss	0 dB
Duplexing	TDD 1 : 1	UE Noise Figure	7 dB
DL symbols (T_{DL})	19	UE Average Speed	1.1 m/s
UL symbols (T_{UL})	18	T_{MR}	50 ms
Preamble symbols	2		
Overhead symbols	11		
Frame duration	5 ms	$\text{SINR}_y^{\text{IHO}}$	3 dB
Subcarriers (SC)	512	$\text{SINR}_y^{\text{target}}$	10 dB
SC_{pilot}	48	ΔQ_{IHO}	3 dB
SC_{data}	384	ΔT_{IHO}	10 s
Subchannels (K)	8	Outage Threshold	200 ms
Thermal Noise Density	−174 dBm/Hz	Macro Path Loss	Empirical
Macro TX Power	43 dBm	Femto Path Loss	FDTD

(ii) The femtocell downlink coverages were predicted with a Finite-Difference-Time-Domain-(FDTD) based model [22] calibrated with indoor-to-outdoor measurements at a frequency of 3.5 GHz.

The Root Mean Square Errors (RMSEs) of the macrocell and femtocell models are 8 dB and 6 dB, respectively.

5.2. System Level Simulation. An event-driven dynamic system-level simulation is used to model the operation of this two-tier OFDMA network. In this case, the life of the network through time is modeled as a series of events. For instance, an event happens when a user changes its position, when an IHO is launched, and so forth.

Because traffic modeling is out of the scope of this article, it is assumed that a user is allocated in each OFDMA frame to only 1 subchannel having T_{DL} OFDM symbols. Under this assumption, the SINR and throughput per user and other statistics are computed at regular time intervals.

This system-level simulation supports Adaptive Modulation and Coding (AMC). The different Radio Access Bearers (RABs), together with their SINR thresholds and efficiencies are shown in Table 4. Note that a UE cannot transmit when its SINR is lower than the SINR threshold of the lowest RAB defined in the network, that is, 2.88 dB.

Following the behavior of real-time services, a user is considered to be in outage when it cannot transmit for a given period of time. In this case, this period of time is fixed to 200 ms as recommended by [23] for VoIP applications.

Further information about this system-level simulator such as channel modeling, interference modeling, throughput calculation, and so forth. can be found in [11].

Table 4: RABs (Modulation and coding schemes).

RAB	Modulation	Code rate	SINR threshold	Efficiency
1	QPSK	1/2	2.88	1.00
2	QPSK	3/4	5.74	1.50
3	16QAM	1/2	8.79	2.00
4	16QAM	3/4	12.22	3.00
5	64QAM	1/2	15.88	4.00
6	64QAM	3/4	17.50	4.50

5.3. Closed and Open Access Implementation. In the closed access simulations, nonsubscribers are always connected to the macrocell. These are likely to suffer from outage when they pass close to a femtocell that is making use of the same subchannel. It is assumed that after this type of outage, the nonsubscriber reestablishes its connection or call as soon as its SINR is larger than the SINR threshold of the lowest RAB defined in the network.

In open access simulations, outdoor users are always connected to the best server regardless of whether it is the macrocell or a femtocell. This case, outdoor users send a measurement report to their serving cell based on its NCL on a regular basis (T_{MR}). This indicates the RSSs of pilot channels of neighboring cells. Then, a hard HO is performed if the RSS of the strongest neighboring cell is larger than the one of the current server. It is to be noted that the HO procedure is carried out by the network and that there is a 2% probability that it fails, resulting in a dropped call. Then, it is assumed that after this type of outage, a nonsubscriber reestablishes connection immediately.

Table 5: Outages of nonsubscribers.

ΔQ_{IHO} (dB)	−1	0	1	2	3
12.5% penetration	35	1	0	0	0
25% penetration	80	16	2	0	0
50% penetration	356	143	49	6	0

6. Results

First of all, let us mention that the IHO threshold $\text{SINR}_y^{\text{IHO}}$ has been set to 3 dB, which is a value slightly larger than that of the lowest RAB defined in the system, that is, 2, 88 dB. In this way, the IHO is launched before the user cannot achieve any RAB, and it falls into outage, that is, the user cannot transmit for more than 200 ms.

6.1. Effect of Parameter ΔQ_{IHO}. Table 5 summarizes the network performance in terms of the outage of nonsubscribers, when using IHOs with different values of the interference protection margin ΔQ_{IHO}. The simulations have been carried out with different number of femtocells in order to analyze the impact of the femtocell penetration on ΔQ_{IHO}. It has been observed that if ΔQ_{IHO} is low, for example, $\Delta Q_{\text{IHO}} = 0$, a large number of outages occur. The reason is that the IHOs are launched either too late, when the nonsubscriber is already in outage, or they are not even launched. Moreover, when the femtocell penetration grows, the interference protection margin ΔQ_{IHO} needed to fight outages is larger. For example, $\Delta Q_{\text{IHO}} = 2$ is sufficient in the case of a 25% penetration, whereas $\Delta Q_{\text{IHO}} = 3$ is needed in the case of a 50% penetration. This is due to the fact that with larger femtocell penetrations, the aggregate of cotier interference from neighboring femtocells towards a nonsubscriber grows. Therefore, the IHO must be launched when lower increases in interference are detected. Finally, it is worth mentioning that if ΔQ_{IHO} is too large, an IHO will be launched to try to solve a problem (cross-tier interference) that does not even exist, increasing thus signaling, which is undesired.

In view of the results of Table 5, $\Delta Q_{\text{IHO}} = 3$ dB is assumed in the rest of the article because it is seen to guarantee outage avoidance in all cases.

6.2. Effect of Parameter ΔT_{IHO}. Figure 4 shows the sample scenario used to illustrate the performance in terms of SINR of a nonsubscriber, when it moves across the scenario. In this case, the performance of the IHO approach with different values of ΔT_{IHO} is compared to that of closed access.

First of all, let us note that in closed access, when a nonsubscriber moves close to femtocells A or B (Figure 4(a)), it is jammed due to cross-tier interference (Figure 4(b)). This is assuming that femtocells A and B are using all available subchannels. Thus, the nonsubscriber falls into outage, since its SINR is smaller than that of the minimum RAB defined for a period longer than 200 ms.

However, when using the IHO approach and the SINR of the nonsubscriber decreases, an IHO is launched in both femtocells A and B. Then, these femtocells stop using the subchannel used by the nonsubscriber. In this way, cross-tier interference towards the nonsubscriber is mitigated, and the outage is thus avoided.

Moreover, it can be seen in Figures 4(b) and 4(c) that if ΔT_{IHO} is not finely tuned, femtocells A and B begin to use the forbidden subchannel before the nonsubscriber moves out of their coverage area. In this case, new IHO must be launched in the femtocells in order to avoid the nonsubscriber outage, increasing thus the signaling overhead in the network.

However, if ΔT_{IHO} is finely tuned (see Figure 4(d)), femtocells A and B will not use the forbidden subchannel until the nonsubscriber is out of their coverage domain. Since a pedestrian walks at an average speed of 1.1 m/s and because the femtocell radius is estimated to be 10 m [22], $\Delta T_{\text{IHO}} = 10$ s has been proven to be appropriate to force only one IHO per femtocell in a residential scenario with mobile pedestrians.

6.3. Effect of Power Control. Figure 5 illustrates the performance in terms of SINR of the nonsubscriber moving along the route defined in Figure 4(a). The IHO approach with and without power control is compared here to closed access. In this case, the macrocell and femtocells are fully loaded. Therefore, an IHO based on subchannel switching is not possible.

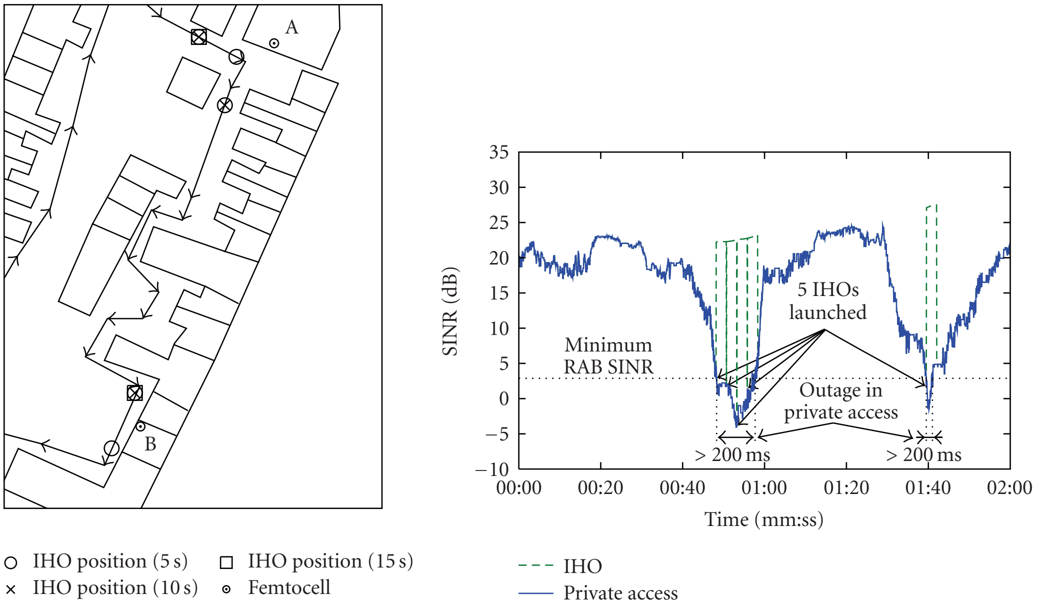
When the IHO approach is applied without power control, that is forbidding interfering femtocells from using the subchannel employed by the nonsubscriber, the SINR of such nonsubscriber grows notably due to the avoidance of cross-tier interference (Figure 5(a)). However, this is at the expense of reducing the femtocell throughput, since a subchannel is forbidden (Figure 5(b)).

Contrarily, when the IHO approach is used with power control, subchannels are not forbidden, but the power applied to it is reduced. This is done in a controlled manner in order to protect the nonsubscriber. As a result, the SINR of the nonsubscriber is not as large as when forbidding the subchannel, but the outage is avoided and the femtocell throughput is enhanced with respect to the forbidding case. Figure 5(b) shows a case in which power control does not recover the full throughput capacity compared to CSG, but provides a gain with respect to the forbidding approach. In this case, this throughput gain is about 250 kbps, which is enough to hold real-time services such as VoIP (12.2 kbps).

6.4. Closed, Open and IHO Comparison. In this section, the performance of the IHO approach compared to that of the closed and open access is analyzed. This has been done under different femtocell penetrations (12,5%, 25%, and 50%), and traffic loads in both the macrocell and femtocells (50% (4 users) and 100% (8 users)). There are 8 subchannels available for transmission.

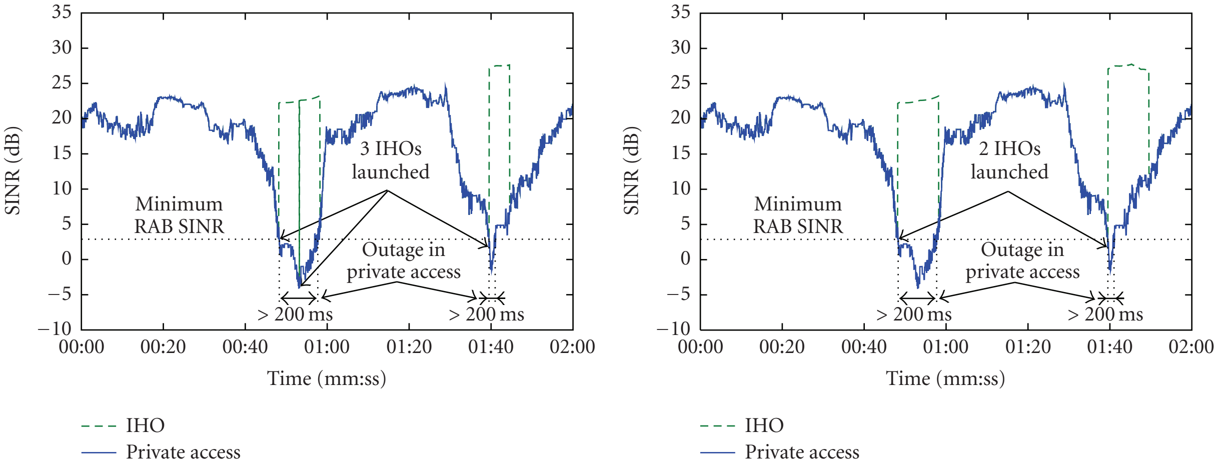
The different setups are as follows.

Setup. Macrocell and femtocells are both half loaded (4 users). Under these conditions, IHOs based on subchannel switching are mostly launched in the macrocell (see Table 6 for results).



(a) Route of the user and locations of IHO launches

(b) $\Delta T_{\mathrm{IHO}} = 2.5\,\mathrm{s}$



(c) $\Delta T_{\mathrm{IHO}} = 5\,\mathrm{s}$

(d) $\Delta T_{\mathrm{IHO}} = 10\,\mathrm{s}$

Figure 4: Performance comparison of CSG and IHO for a mobile nonsubscriber ($\Delta Q_{\mathrm{IHO}} = 3\,\mathrm{dB}$).

Setup. Macrocell is fully loaded (8 users), whereas the femtocells are half loaded (4 users). IHOs based on subchannel switching are mostly launched in the femtocells (see Table 7 for results).

Setup. Macrocell and femtocells fully loaded (8 users) and IHO implemented without power control. This case, subchannels are forbidden in the femtocells (see Table 8).

Setup. Macrocell and femtocells fully loaded (8 users) and IHO implemented with power control under different $\mathrm{SINR}_y^{\mathrm{target}}$ for the nonsubscribers (see Table 9).

The analysis follows next with regard to different performance metrics.

6.4.1. Number of HO and IHO Attempts. First of all, let us note that in the CSG case, HOs are not allowed. Then, this value is neglected in the result tables.

It is to be mentioned that in all setups with open access, the number of HOs increases with the femtocell penetration. The more femtocells a nonsubscriber finds along its route, the more hand-ins and hand-outs must be carried out. Furthermore, the number of HOs also increases with the number of nonsubscribers.

Similarly, the number of IHOs also increases with the femtocell penetration and the nonsubscriber density. However, the number of IHOs launched is significantly less than the triggered HOs for open access in the same period of time. The reason behind this is that a unique IHO is

Table 6: Performance comparison for Setup 1 (800 s simulation).

Femtocell penetration		12.5%			25%			50%	
Access method	Closed	Open	IHO	Closed	Open	IHO	Closed	Open	IHO
HO attempts	—	243	6	—	606	86	—	1084	193
Average HO attempts into femtocells	—	7.63	0	—	9.78	0.03	—	12.36	0.44
HO attempts into macrocell	—	121	6	—	293	85	—	393	165
Outages due to HO failure	—	2	0	—	12	0	—	21	0
Outages due to interference	69	0	0	224	0	0	299	5	0
Total nonsubscribers tier throughput [Mbps]	2.35	2.69	2.66	1.77	2.62	2.44	1.29	2.45	2.13
Total subscribers tier throughput [Mbps]	44.91	47.33	46.08	91.14	93.70	92.71	166.94	172.46	166.33

IHO approach switching subchannels in the macrocell. Handover, outage and throughput analysis in a residential area (300 × 300 m) covered by several femtocells and 1 macrocell, using a 5 MHz bandwidth. Each house hosting a femtocell contains 4 indoor users. Furthermore, 4 users were located outdoors and demanding one OFDMA subchannel each. Note that the system level simulation is dynamic and the users move throughout the scenario.

Table 7: Performance comparison for Setup 2 (800 s simulation).

Femtocell penetration		12.5%			25%			50%	
Access method	Closed	Open	IHO	Closed	Open	IHO	Closed	Open	IHO
HO attempts	—	462	35	—	1090	80	—	2554	178
Average HO attempts into femtocells	—	14.14	2.19	—	17.88	2.50	—	28.03	2.78
HO attempts into macrocell	—	231	0	—	518	0	—	760	0
Outages due to HO failure	—	7	0	—	21	0	—	54	0
Outages due to interference	134	1	0	352	2	0	702	5	0
Total nonsubscribers tier throughput [Mbps]	4.53	5.07	5.09	3.66	4.95	4.95	2.24	4.62	4.59
Total subscribers tier throughput [Mbps]	42.24	43.06	42.24	87.07	90.00	87.99	158.98	169.33	160.18

IHO approach switching subchannels in the femtocells. Handover, outage and throughput analysis in a residential area (300 × 300 m) covered by several femtocells and 1 macrocell, using a 5 MHz bandwidth. Each house hosting a femtocell contains 4 indoor users. Furthermore, 8 users were located outdoors and demanding one OFDMA subchannel each. Note that the system level simulation is dynamic and the users move throughout the scenario.

needed to mitigate the cross-tier interference coming from one femtocell, while in open access two HOs are required (one hand in and one hand out). In addition, the HO is done based on the pilot signal, which is always transmitted, while the IHO only happens if the nonsubscriber and the interferer are utilizing the same subchannel (it does not always occur). Moreover, in this case and due to the multi-path effects, the coverage provided by the femtocells is not continuous. As a consequence, a nonsubscriber moving at low motion can hand over several times from the macrocell to the same open femtocell and vice versa. In order to mitigate this effect, a HO margin, which ensures that the HO is performed only if the neighboring cell is stronger by a given threshold than the server, could be considered. Nevertheless, in this way, the outages due to cross-tier interference would increase. In this case, a perfect HO is considered (as many HOs as needed are done), since the target is to compare open access and the IHO approach based on the number of outages, but not on the signaling overhead.

6.4.2. Outages Due to Interference. In all setups, closed access deployments are severely affected by cross-tier interference, resulting this in a large number of outages. As soon as a nonsubscriber walks near a femtocell using the same subchannel, the nonsubscriber falls into outage. This confirms the need of novel approaches for interference avoidance in two-tier networks.

In the case of open access, the number of outages due to interference are notably reduced compared to that of closed

Table 8: Performance comparison for Setup 3 (800 s simulation).

Femtocell penetration	12.5%			25%			50%		
Access method	Closed	Open	IHO	Closed	Open	IHO	Closed	Open	IHO
HO attempts	—	462	231	—	1090	533	—	2554	1130
Average HO attempts into femtocells	—	14.44	14.44	—	17.88	16.66	—	28.03	17.67
HO attempts into macrocell	—	231	0	—	518	0	—	760	0
Outages due to HO failure	—	7	0	—	21	0	—	54	0
Outages due to interference	284	1	0	746	2	0	1117	5	0
Total nonsubscribers tier throughput [Mbps]	3.60	4.24	4.63	2.15	3.43	4.06	1.07	2.28	3.08
Total subscribers tier throughput [Mbps]	82.40	83.65	80.29	180.05	183.44	175.05	316.48	327.38	307.38

IHO approach without power control, but forbidding subchannels in the femtocells. Handover, outage and throughput analysis in a residential area (300 × 300 m) covered by several femtocells and 1 macrocell, using a 5 MHz bandwidth. Each house hosting a femtocell contains 8 indoor users. Furthermore, 8 users were located outdoors and demanding one OFDMA subchannel each. Note that the system level simulation is dynamic and the users move throughout the scenario.

Table 9: Performance Comparison for Setup 4 (800 s simulation).

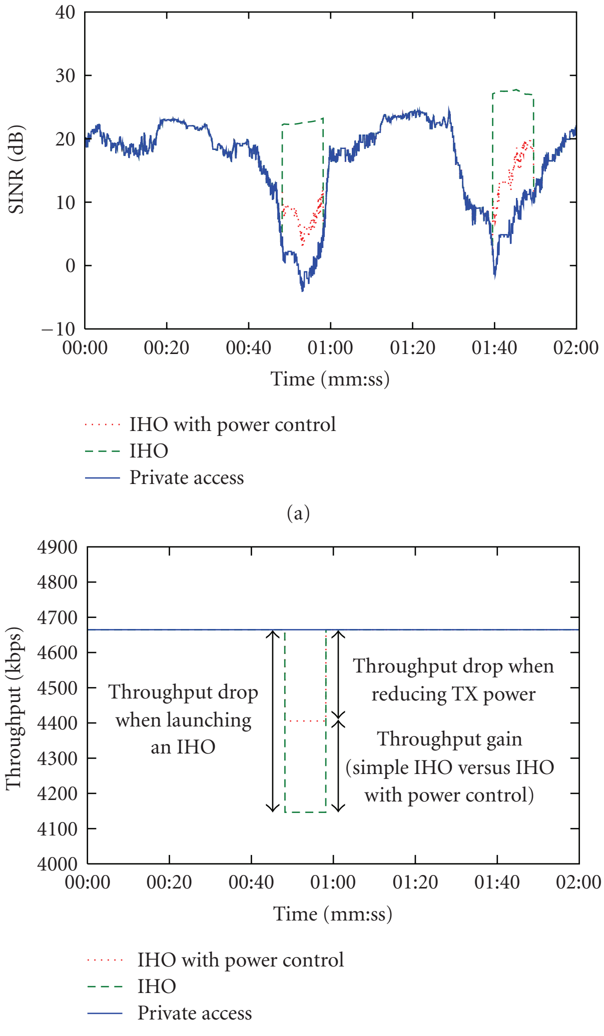
Femtocell penetration	12.5%			25%			50%		
Access method	IHO 10dB	IHO 15dB	IHO Forbid.	IHO 10dB	IHO 15dB	IHO Forbid.	IHO 10dB	IHO 15dB	IHO Forbid.
HO attempts	325	234	231	743	534	533	1491	1135	1130
Average HO attempts into femtocells	20.31	14.63	14.44	23.22	16.69	16.06	23.38	17.77	17.67
HO attempts into macrocell	0	0	0	0	0	0	0	0	0
Outages due to HO failure	0	0	0	0	0	0	0	0	0
Outages due to interference	0	0	0	0	0	0	0	0	0
Total nonsubscribers tier throughput [Mbps]	4.18	4.45	4.63	3.24	3.75	4.06	2.26	2.75	3.08
Total subscribers tier throughput [Mbps]	81.55	80.62	80.29	177.77	175.75	175.05	312.10	308.82	307.38

IHO approach without forbidding subchannels, but with power control in the femtocells. Handover, outage and throughput analysis in a residential area (300 × 300 m) covered by several femtocells and 1 macrocell, using a 5 MHz bandwidth. Each house hosting a femtocell contains 8 indoor users. Furthermore, 8 users were located outdoors and demanding one OFDMA subchannel each. Note that the system level simulation is dynamic and the users move throughout the scenario.

access. This is because nonsubscribers are allowed to connect to the strongest cell, turning the strong interferer into their best server. However, when the femtocell penetration grows, some cases of outage due to interference also appear. This is because even if the nonsubscriber is connected to the strongest femtocell, the aggregate of cotier interference from neighboring femtocells can disrupt its service, thus creating outage. It is to be noted that the signal strength of a femtocell outdoors is in the same order of magnitude as the signal strength of a neighboring femtocell located few meters away and therefore, if the femtocell penetration is large, cotier interference is a problem.

In the case of IHO, however, the number of outages due to interference is always zero. The number of outages, in this case, does not depend on the femtocell penetration, since the IHO approach is able to “switch off” all existing interferers independently of their number and position.

6.4.3. Outages Due to HO Failure. In open access, the number of HO failures increases with the femtocell penetration and the nonsubscriber density. Let us remember that according to [2], there is a 2% probability that a HO attempt results in a dropped call (outage). The more HO attempts,



(a)

(b)

Figure 5: SINR level of a mobile nonsubscriber.

the more HO failures. Nevertheless, the number of outages due to HO failure in open access is much smaller than due to interference in CSG.

6.4.4. NonSubscriber Throughput. In all setups, open access deployments achieve a larger throughput for nonsubscribers than closed access. This is because in open access, nonsubscribers always connect to the strongest cell (macrocell or femtocell), which mitigates cross-tier interference and provides larger RABs. Moreover, the total nonsubscriber throughput in the IHO approach is also always larger than that of closed access due to cross-tier interference mitigation.

When comparing open access and the IHO approach, two issues must be highlighted.

(1) When the IHOs are performed in the macrocell (subchannel switching (Table 6)), the total nonsubscriber throughput in open access is always larger than in the IHO approach.

(2) When the IHOs are performed in the femtocells (subchannel switching (Table 7), forbidding (Table 8) or power control (Table 9)), the total nonsubscriber throughput in open access is always lower than in the IHO approach.

The reason behind this is that in the IHO approach, in the first case, the macrocell just changes the interfered subchannel of the nonsubscriber to another with less interference. However, in the second case, all interfering femtocells stop using such subchannel, thus increasing notably the signal quality and throughput of the nonsubscriber.

It is also to be noticed that in all setups and for all techniques, the larger the femtocell penetration, the lower the total nonsubscriber throughput. This is again due to interference reasons: the more femtocells, the larger the interference, and therefore, the lower the SINR of the nonsubscribers, which is thus translated into a reduction of the nonsubscribers throughput.

6.4.5. Subscribers Throughput. Open access deployments achieve a larger throughput for subscribers than closed access and the IHO approach. This is due to the fact that when a nonsubscriber connects to a femtocell, a subchannel is released in the macrocell. This way, cross-tier interference towards subscribers is reduced, and the throughput of femtocells close to the macrocell is enhanced.

Let us now compare closed access with IHO.

(1) When the IHO is based on subchannel switching either in the macrocell (Table 6) or in the femtocells (Table 7), the total subscriber throughput is slightly better in the IHO approach.

(2) When the IHO is based on subchannel forbidding (Table 8) or power control (Table 9) in the femtocells, the total subscriber throughput is higher in closed access than in the IHO approach.

The reason is that when the IHO is based on subchannel forbidding or power control, the interfering subchannel is either banned from femtocell use or its allocated power is reduced for a period of time. This causes a throughput loss for the subscribers. On the contrary, in closed access, subscribers are always connected to the same subchannel (no power variation) and thus their throughput is not reduced.

It is also to be noticed that in all setups and for all techniques, the larger the femtocell penetration, the larger the total subscriber throughput. This is because the more femtocells, the larger number of connected users in the femtocell tier. However, the average throughput per subscriber does not depend on the femtocell penetration, as it does in the nonsubscribers tier. This is because the effects of cotier interference indoors are smaller than outdoors, namely due to the shield provided by the house walls.

6.4.6. Power Control Behavior. Table 9 presents the performance of IHO with subchannel forbidding compared to that of IHO with power control. Table 9 also shows results for IHO with power control using different $\mathrm{SINR}_y^{\mathrm{target}}$ values.

This experimental evaluation shows, in agreement with the results presented in Figure 5(b), that when power control is used, the reduction of the femtocell throughput is less compared to that of subchannel forbidding. However, it occurs at the expense of decreasing the nonsubscribers throughput, since the interfering subchannels are not turned off.

It is also to be mentioned that the lower the $\text{SINR}_y^{\text{target}}$ value, the lower the reduction of the femtocell throughput. However, it occurs at the expense of reducing the nonsubscriber throughput, since they are only allowed to achieve lower signal qualities.

6.5. Signaling Overhead Due to IHO. The IHO approach implies the following signalin.

(i) A measurement report in order to indicate the RSSs of the neighboring cell in subchannel k, and trigger the IHO.

(ii) An IHO message in order to indicate to the interfering femtocell A_r the reduction of power ΔP^k that has to be applied to subchannel k, and for how long (ΔT_{IHO}).

The size of a measurement report is

$$R \cdot (d_{\text{ID}} + d_{\text{RSS}}), \tag{6}$$

where R denotes the number of interfering femtocells ($|\theta_y|$), d_{ID} indicates the number of bits required to encode the identity of a neighboring cell, and d_{RSS} represents the number of bits required to encode the RSS of a neighboring cell.

The size of an IHO message is

$$d_k + d_{\Delta P} + d_{\Delta T_{\text{IHO}}}, \tag{7}$$

where d_k denotes the number of bits required to encode the identifier of the subchannel, while $d_{\Delta P}$, and $d_{\Delta T_{\text{IHO}}}$ are the number of bits required to encode ΔP^k and ΔT_{IHO}, respectively.

Let us assume that 3 bits are used to encode k (there are 8 subchannels), while 8 bits (256 levels) are used for d_{ID}, d_{RSS}, $d_{\Delta P}$ and $d_{\Delta T_{\text{IHO}}}$. Therefore, the number of required bits per measurement report and IHO message are 512 and 19, respectively. Note that an average of 32 interfering femtocells are considered in this calculation, which is the maximum NCL size in UMTS networks.

The measurement report is triggered when the SINR of a nonsubscriber UE_y^{ns} connected to macrocell M_m in subchannel k is smaller than a given threshold $\text{SINR}_y^{\text{IHO}}$. In the worst case scenario (Setup 4 (Table 9)), when having a femtocell penetration of 50% and using $\text{SINR}_y^{\text{IHO}} = 3\,\text{dB}$ and $\text{SINR}_y^{\text{target}} = 10\,\text{dB}$, an average of 23.38 IHOs have been triggered per femtocell (simulation time = 800 s). Therefore

(i) the average uplink bandwidth required to carry 23.38 measurement reports per femtocell in 800 s is 14.96 bps,

(ii) the average downlink bandwidth required to carry 23.38 IHO messages per femtocell in 800 s is 0.56 bps.

These values are negligible compared to the capacity of the downlink and uplink of current OFDMA standards such as LTE or WiMAX. Therefore, it can be concluded that only a small fraction of the whole available bandwidth is needed for signaling overhead.

Finally, it is to be noted that the signaling required for an IHO is lower than for a HO. When performing a HO, all packets stored in the source cell, which belong to the user that is to be handed over, has to be transferred from the source cell to the target cell (implying a large overhead). However, in the IHO approach, in the worst case scenario, the macrocell has to indicate to the interfering femtocells only the reduction of power that has to be applied to a given subchannel and for how long.

7. Conclusions

The results of the system-level simulations show the following evidence about this type of residential scenarios.

Conclusion 1. The main problems of open access are the risk of outage due to HO failure and the high signaling introduced in the network. On the other hand, CSG femtocells introduce serious jamming problems (dropped call) to macrocell users in the downlink.

Conclusion 2. Open access has always an overall better throughput performance than the one of closed access.

Conclusion 3. When the femtocell penetration is large, the aggregate of the interference of nearby femtocells might be enough to cause outage to outdoor users, who will not be able to take advantage of the open access.

Then, it has been shown that by applying an intracell handover approach to OFDMA two-tier networks, the following occurs.

Conclusion 4. Downlink cross-tier interference to nonsubscribers decreases compared to CSG deployments. This is made evident from the number of outages due to interference shown in Tables 6, 7, 8, and 9 (results).

Conclusion 5. Handover attempts and thus network signaling decrease with respect to the open access case. Furthermore, the risk of outage due to handover failure is removed as it can be seen in the tables of results.

Conclusion 6. In order to avoid macrocell deterioration due to femtocell deployment, FAPs must be flexible when limiting the throughput of their own subscribers. The interference reduction of nonsubscribers should thus have more priority than the maximization of subscribers throughput. Therefore, a trade-off between these two objectives must be always achieved. Moreover, due to the nature of the services used by subscribers, the impact of subchannel forbidding is, in average, not too crucial for femtocell connectivity.

Conclusion 7. In order to reduce signaling, IHOs are attempted in the macrocell before they are attempted in nearby femtocells. However, it has been observed that femtocell-based IHOs result in higher throughput gains than macrocell ones. This is because a femtocell IHO removes fully the cross-tier interference while a macrocell IHO selects a less interfered subchannel which is not necessarily free of cross-tier interference.

Conclusion 8. Power control helps to handle cross-tier interference, while limiting the impact to subscribers when subchannel switching is not possible.

To summarize, the IHO approach presented in this article has better performance than CSG in terms of outage and throughput of nonsubscribers in all tested femtocell penetration conditions. The throughput of nonsubscribers is slightly below than that of open access in most cases, except for large femtocell penetrations, in which the IHO approach outperforms open access (Table 8). However, the network signaling is lower in case of IHO, and thus the risk of HO failure is practically nonexistent, avoiding outage.

Acknowledgments

This work is supported by the EU FP6 project on 3G/4G Wireless Network Design "RANPLAN-HEC" with Grant no. MEST-CT-2005-020958 and EU FP6 "GAWIND" with Grant no. MTKD-CT-2006-042783.

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