Abstract—With considerable interest being garnered in recent years, femto-cells are seen as a major contender to significantly increase capacity and fill coverage holes in 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) cellular networks. User-deployed femto-cells, each exclusively serving a set of registered users and sharing the same frequency spectrum as the overlay macro-cells are already defined in 3GPP specifications. Such a co-channel and random deployment of femto-cells can cause heavy downlink (DL) interference to a user equipment (UE) in the vicinity of one or more femto-cells and not belonging to their closed subscriber groups (CSGs). In this paper, we focus on protection of the most important LTE DL control channel, known as the physical control format indicator channel (PCFICH). Failure to decode this channel correctly results in the loss of the subsequent subframe. A technique which mitigates femto-to-macro PCFICH interference by carefully manipulating the physical cell identity (PCI) of the aggressor femto-cell is presented. It is shown that employing this technique results in a significant improvement of PCFICH effective signal-to-interference-plus-noise ratio (SINR) without the need for any additional network signaling.

I. INTRODUCTION

In the past, increasing capacity demands have been met by increasing the available frequency spectrum. However, bandwidth is an extremely expensive and increasingly scarce commodity which is severely regulated. Therefore, in the future, it will not be possible to arbitrarily increase the bandwidth in order to satisfy growing network capacity needs. In fact, an analysis of the financial impact of femto-cells indicates that for increasing data rates, purely macro-cellular deployment becomes less economically viable [1]. Studies have also revealed that smaller cell sizes enable the efficient spatial reuse of spectrum [2]. While decreasing the cell size generally boosts system capacity, the operator cost involved becomes increasingly prohibitive due to the required installation of new network infrastructure. Furthermore, recent studies have shown that a high proportion of network traffic originates indoors [3]. Considering this, femto-cells, which are low-power, short-range, plug-and-play base stations promise to solve all problems simultaneously, i.e., they increase overall network capacity, fill the coverage holes that typically exist indoors and do not impose a significant additional cost to the operator as they are deployed by end users themselves. Femtocell base stations, known henceforth using 3rd Generation Partnership Project (3GPP) terminology as Home Evolved NodeBs (HeNBs), have a wired connection to the backbone network. HeNBs therefore offload indoor users from the macro-cell, thus potentially enhancing the capacity both, indoors (by bypassing the wall penetration loss problem) as well as outdoors (by freeing up resources). There are several obvious advantages from femto-cell deployment, the most important of which is that macro-cellular radio resources are exclusively available for outdoor users, yielding better user performance (satisfied user criterion) and coverage. Furthermore, high throughput coverage is extended to the indoor environment where it is most needed [3].

Many recent studies [4–8] have found that open-access femto-cells help alleviate the coverage hole problem. However, it has been decided that 3GPP Long Term Evolution (LTE) femtocells should solely operate in the closed-access mode, i.e., each HeNB maintains a list of user equipments (UEs) that are allowed access to it. Any UE which is not a member of this so-called closed subscriber group (CSG) must attempt to maintain communication with its serving macro Evolved NodeB (eNB) despite being in close proximity to the HeNB. While femto-cells promise substantial coverage and capacity gains [3, 9–11], their random deployment introduces additional interference, particularly to macro UEs who are not part of the CSG of the HeNBs in their vicinity. This paper focuses on the performance of such macro UEs.

Existing literature does not contain much study devoted to control channel performance with femto deployment. Yet, the control channel is immensely important in LTE. Each downlink (DL) LTE subframe begins with a control region [12], the correct decoding of which is vital to the successful reception of data contained in the remainder of the subframe by the UE. The authors of this paper have previously studied general femto-to-macro control channel interference mitigation techniques [13]. In this work, we concentrate on the physical control format indicator channel (PCFICH). This control channel is the most important of all the control channels because it informs the UE of the size of the control region.
two OFDM symbols matter. In the frequency domain, for an OFDM symbol carrying CRSs, there is one CRS per transmit antenna port every six REs. With 2 transmit antenna ports the number of CRSs doubles, so that in total there is one CRS every three REs. In order to minimize inter-cell CRS interference, a cell-specific frequency shift, determined as \( N_{\text{cell}} \mod 6 \), is also applied to the CRS sequence.

C. The PCFICH

The PCFICH carries the control format indicator (CFI), indicating the number of OFDM symbols (1, 2 or 3) used for the transmission of DL control channel information in each subframe. The CFI is made robust by adding redundancy. Whereas two bits are sufficient to signal the three possible values of the CFI, the corresponding codeword is 32 bits long, which amounts to a code-rate of 1/16. These 32 bits are mapped to 16 REs using quadrature phase-shift keying (QPSK) modulation. Frequency diversity is achieved by distributing the 16 REs in the frequency domain in four groups of four REs each. The PCFICH always occurs on the first OFDM symbol. The reason for this is simple: the UE should be able to determine the size of the control region before being able to decode the remaining data. The cyclically-rotated location of the PCFICH in each cell is dependent on the PCI of that cell so that PCFICH-PCFICH interference from neighboring cells is mitigated. In addition, a cell-specific scrambling sequence is applied to the CFI codewords so that the UE can preferentially decode the PCFICH from its associated eNB.

Using LTE nomenclature, a resource element group (REG) represents four consecutive REs free of CRS. Let \( z(i) \) represent the symbol quadruplet \( i=\{0, 1, 2, 3\} \). Each of these quadruplets is mapped to one REG [14]. The quadruplet \( z(i) \) is mapped to the REG numbered \( k \), where \( k \) is determined as

\[
  k = \overline{k} + [i \cdot N_{\text{RB}}/2] \cdot N_{\text{RE}}/2, \quad (1)
\]

and

\[
  \overline{k} = (N_{\text{RE}}/2) \cdot (N_{\text{cell}} \mod 2N_{\text{RB}}). \quad (2)
\]

Therefore, (1) and (2) ensure that the PCFICH is evenly distributed in the frequency domain and that it is cyclically rotated depending on the PCI of the cell.

D. The PHICH

The physical hybrid-ARQ indicator channel (PHICH) carries the uplink (UL) hybrid-ARQ ACK/NACK information indicating whether the eNB has correctly received an UL transmission from the UE. The PHICH to RE mapping is somewhat similar to that of the PCFICH with two exceptions: it consists of three redundant repetitions in the frequency domain instead of four and it can occur on any combination of the available OFDM symbols, i.e., it is not restricted to just the first OFDM symbol. If the PHICH is smeared over two or three OFDM symbols, it is known as the extended PHICH configuration. Details on PHICH to RE mapping can be found in [14]. The PHICH undergoes the same frequency shift as does the PCFICH. Therefore, its location is also entirely dependent on the PCI of the eNB in question.
E. The PDCCH

Nine REGs constitute one control channel element (CCE). The physical downlink control channel (PDCCH) carries the DL control information, including UE specific resource assignments. The PDCCH dedicated to any UE occupies any of \( \{1, 2, 4, 8\} \) CCEs depending on the prevailing channel conditions between UE and serving eNB. The REGs still free of PCFICH and PHICH are numbered consecutively and arranged in a matrix with a fixed number of columns and an appropriate number of rows. A known inter-column permutation pattern is applied to this matrix [15] and the resulting matrix is reshaped into a vector that generates the interleaving pattern. This interleaving pattern undergoes the same cell-specific frequency shift as CRSs and PCFICH, so that the PDCCH locations in neighboring cells are pseudo-randomized.

Once the interleaving pattern is determined, the UE-specific PDCCH needs to be assigned. Each UE has a dedicated search space where it looks for its own PDCCH. This is done in order to reduce the number of blind decoding attempts a UE needs to perform [12]. The CCEs available in the system are numbered such that CCE 1 is composed of REGs 1 through 9 and so on. The candidate starting CCE indices in the search space of UE \( u \) in subframe \( k \) are calculated as

\[
L^u \cdot \left\{ Y_k + m \right\} \mod \left[ N_{\text{CCE}, k, L}, k \right] + i, \quad m = 0, \ldots, M(L^u) \\
i = 0, \ldots, L^u - 1
\]

where \( N_{\text{CCE}, k, L} \) is the number of CCEs available in subframe \( k \), \( L^u \) is the aggregation level assigned to UE \( u \), \( m \) is the number of PDCCH candidate locations depending on the aggregation level \( L^u \). The lower the aggregation level, the higher the value of \( M(L^u) \) is. This implies that the UE has to perform more blind decoding attempts for lower aggregation levels. Further details on the above procedure can be found in [16]. The variable \( Y_k \) is calculated as

\[
Y_k = (A \cdot Y_{k-1}) \mod D,
\]

where \( Y_{k-1} = n_{\text{RNTI}} \) \( (n_{\text{RNTI}} \) is the identifier of UE \( u \); more details in [17]), \( A = 39827, D = 65537 \) and \( k = n_s/2 \) \( (n_s \) is the slot number within the LTE radio frame). Therefore, it is seen that changing the PCI of an eNB changes the interleaving pattern used for PDCCH distribution and thus also changes the location of REGs carrying the PDCCH of UE \( u \).

III. STATE-OF-THE-ART INTERFERENCE MANAGEMENT

Fig. 2 shows various existing techniques for femto-to-macro control channel interference mitigation. The subfigures show only the first three OFDM symbols of the subframe since this is the extent to which the control region can extend. It is expected that a macro-cell serves a significantly higher number of users than a femto-cell. Therefore, in this paper, it is assumed that the control channel of the macro layer is always three OFDM symbols long so that the control region can accommodate sufficient control information for all active UEs.

A. No Coordination

Fig. 2(a) shows LTE operation without coordination between the femto and macro layers. Since the number of UEs served by a HeNB is expected to be small, under uncoordinated operation, the HeNB may use one OFDM symbol for the control region, with the rest of the subframe used for data transmission in order to maximize the data throughput. This operation is very detrimental for the trapped macro UE such that a radio link failure is likely to be declared.

B. Sparse Control Region

In Fig. 2(b), the HeNB is forced to use all three OFDM symbols for the control channel (even though this may not be needed due to the low number of UEs served), thus creating a sparse control region [13, 18]. Making the femto control region sparse has the advantage that the probability of collision on the PDCCH, PHICH and PCFICH belonging to the trapped macro UE is reduced. Furthermore, the HeNB may continue to transmit data in the rest of the subframe. The disadvantage of this method is that the data region of the trapped macro UE undergoes interference from the HeNB. However, techniques such as resource partitioning to counter this situation have been proposed [8]. Another advantage is that the sparse control channel possibly reduces the interference among femto-cells, which, however, is beyond the scope of this paper.

C. ABS Configuration

The almost blank subframe (ABS) configuration is depicted in Fig. 2(c) [19]. In such a configuration, the subframe only carries CRSs and is blank otherwise. This technique reduces the interference on all three control channels for the trapped macro UE. However, residual interference from femto-CRS still exists. Moreover, data cannot be transmitted to femto UEs on subframes declared as ABS. Unfortunately, interference management by virtue of ABS mitigates macro-UE control channel interference, at the expense of a significant reduction of femto-cell throughput due to ABS insertion.

IV. PCI MANIPULATION

In LTE a HeNB may arbitrarily be assigned any one of the 504 possible PCIs. In [20], it has been proposed that the HeNB opportunistically switches its PCI between a default CSG PCI and an open subscriber group (OSG) PCI, in such a way that
if a non-CSG UE is in the vicinity of the HeNB, the HeNB adopts the OSG PCI which allows the trapped macro-UE to access that HeNB. However, this method violates the CSG paradigm of LTE femto-cells. Moreover, a large amount of signaling is required to inform the HeNB about nearby non-CSG UEs.

According to Section II, the position of all three control channels depends on the PCI of the eNB. This offers the opportunity to modify the PCI of a HeNB, such that the DL control channel of a HeNB causes least detrimental interference to the DL control channel a UE trapped within the coverage area of that HeNB, without toggling the femto-cell status from closed-access to open-access. To this end, if the HeNB manipulates its PCI at startup, it can minimize the interference it causes from its CRS, PCFICH, PDCCH and PHICH to the PCFICH of the trapped macro UE. This approach, based on PCI manipulation, is therefore fully compliant to CSG femto-cells, and does not require any signaling. The only requirement of the proposed PCI manipulation method is that HeNBs have the ability to detect the PCI of the strongest neighboring macro eNB, which is possible by decoding the eNB’s broadcast channel [12].

PCI Manipulation offers several advantages:

- No additional signaling for the HeNB to acquire knowledge of the PCI of the closest macro eNB, because the HeNB can simply infer it from the primary synchronization signal (PSS) of the macro eNB.
- In LTE, HeNBs are equipped with a DL receiver for power control purposes [20]. Since this receiver also is used to infer the PCI of the closest macro eNB, no additional hardware is required.
- No backward compatibility issues for legacy (Rel.-8/9) UEs, since the HeNB chooses the PCI autonomously, such that there is no additional burden to the UE.

V. System Setup

For performance evaluations, the macro-cellular network is composed of a tessellated hexagonal cell layout, where each eNB employs three sectors. Thus, the eNB is situated at the junction of three hexagonal sectors. The simulation area comprises a one tier of macro-cells around a central eNB sector. Statistics are taken only from the central sector. However, eNBs in the outer tiers also transmit in order to realistically simulate inter-cell interference.

Following the assessment methodology described in [21], femto-cells are deployed according to the dual stripe model. This setup models a dense-urban HeNB deployment, in which each block represents two multi-floor stripes of apartments. An active HeNB may exist in an apartment with probability $p_{active}$. Every apartment that contains an active HeNB also contains exactly one associated femto UE. These are dropped randomly and uniformly within the apartment with a specified minimum separation from the HeNB. In addition to this, as per the user distribution described in [21], every macro UE has a certain probability of lying within one of the apartments. Based on this probability, a macro UE is either randomly dropped outdoors or indoors. Since the method of access is strictly CSG, indoor macro UEs are served by the eNB situated outdoors. In such a situation, these vulnerable macro UEs suffer severely from interference originating from nearby HeNBs.

Three path loss models are used depending on the channel characteristics [21], i.e., whether the HeNB to UE link is purely outdoor, outdoor-to-indoor or purely indoor. Fast fading channels are simulated using the delay profiles for the UMi and InH models provided in [22].

Both macro- and femto-cells utilize the same frequency resources of bandwidth $W$, i.e., co-channel deployment is assumed. The useful received signal power observed by UE $u$ on OFDM symbol $t \in \{1, 2, 3\}$ on RE $n$ is given by

$$Y_n^u = G_n^{v,u} P_x,$$

where $G_n^{v,u}$ is the channel gain between UE $v$ and its serving HeNB or eNB, and $P_x$ represents the transmitted power. The aggregate interference $I_n^u$ seen by UE $u$ is composed of eNB and HeNB interference

$$I_n^u = \sum_{i \in M_{int}} G_{p,i}^{v,u} P_m + \sum_{j \in F_{int}} G_{p,j}^{v,u} P_j,$$

where $G_{p,i}^{v,u}$ accounts for the channel gain between interferer $y$ and UE $u$ on OFDM symbol $t$ and on RE with index $n$. The set of instantaneous eNB and HeNB interferers on symbol $t$ and RE with index $n$ is denoted by $M_{int}$ and $F_{int}$ respectively. Note that the sets $M_{int}$ and $F_{int}$ change from RE to RE due to the PDCCH interleaving and cyclically shifted PCFICH and PHICH locations. The performance gain of maximum ratio combining (MRC) is approximated by simulating $N_a$ individual, uncorrelated receive streams and adding the corresponding signal levels when calculating the signal-to-interference-plus-noise ratio (SINR) [23]. Thus, the SINR observed on RE with index $n$ and OFDM symbol $t$ at UE $u$ therefore amounts to

$$\gamma_n^u = \sum_{a=1}^{N_a} \frac{G_{p,a}^{v,u} P_x}{\eta + I_n^u},$$

where $\eta$ accounts for thermal noise per RE, $N_a$ is the number of receive antennas and $G_{p,a}^{v,u}$ is the gain seen by antenna $a$. In this simulation, for different antennas, $a$, of the same UE, the distance-dependent path loss remains the same, however, the shadowing values may be different since the antennas receive uncorrelated streams. The signals impinging at multiple receive antennas are combined by means of MRC. In order to calculate the effective SINR across all the allocated REs on any of the control channels belonging to UE $u$, a mapping to the capacity-domain is first made and this is then re-translated into the SINR domain as detailed in [24]. Therefore, the effective SINR for UE $u$ on control channel $y$ ($y$ represents the PCFICH...
here) is calculated as
\[ \gamma^u_y = F^{-1}\left( \sum_{p \in N_{RE, y}^u} F(\gamma^u_p) \right), \]  
(8)
where \( N_{RE, y}^u \) is the set of REs allocated to control channel \( y \) of UE \( u \). The spectral efficiency, \( F(\gamma^u_y) \), is calculated using the \textit{attenuated and truncated Shannon bound} [8], where spectral efficiency saturates beyond a certain SINR and is set to zero below a certain SINR. Given a particular SINR, \( \gamma^u_p \), the spectral efficiency on RE \( p \) for UE \( u \), \( F(\gamma^u_p) \), is determined by
\[ F(\gamma^u_p) = \begin{cases} 0 & \text{for } \gamma^u_p < \gamma_{\min}, \\ \alpha S(\gamma^u_p) & \text{for } \gamma_{\min} < \gamma^u_p < \gamma_{\max}, \\ \gamma^u_{\max} & \text{for } \gamma^u_p > \gamma_{\max}, \end{cases} \]  
(9)
where \( S(x) = \log_2(1 + x) \) in [bit/s/Hz] is the Shannon bound, \( \alpha \) is the attenuation factor representing implementation losses and \( \gamma_{\min} \) and \( \gamma_{\max} \) are the minimum and maximum SINRs supported. These parameters are summarized in Table I.

**TABLE I**  
LINK TO SYSTEM MAPPING PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0.6</td>
</tr>
<tr>
<td>( \gamma_{\min} )</td>
<td>-10 dB</td>
</tr>
<tr>
<td>( \gamma_{\max} )</td>
<td>19.5 dB</td>
</tr>
<tr>
<td>( \gamma_{\max}^w )</td>
<td>4.4 bps/Hz</td>
</tr>
</tbody>
</table>

Table II lists the simulation parameters.

**VI. RESULTS**

It is assumed that the control region on the macro layer is always three OFDM symbols long. This, however, is not the case for the femto layer, where the size of the control region depends on the interference management scheme being used, as described in Sections III and IV. When the control region is three OFDM symbols long, the extended PHICH configuration (as detailed in Section II-D) is used. The performances of all interference mitigation techniques described in Sections III and IV are compared against a benchmark system in which the HeNBs transmit power is set to zero. The benchmark system resembles the performance of the macro-cellular network without any femto-cell deployment and therefore serves a lower performance bound.

Fig. 3 shows the cumulative distribution function (CDF) of the effective SINR of the macro UEs. It is clearly seen that the benchmark significantly outperforms all the other schemes, due to the absence of femto-cell interference. On the other hand, the system without any interference coordination experiences the worst SINR distribution. In this setup, the femto control region is limited to the first OFDM symbol with the rest of the subframe used for transmitting data. This means that the femto layer is densely occupied by control channels and CRSs, causing a high probability of collision with the PCFICH of the trapped macro UE. Extending the control region on the femto layer to three OFDM symbols (see Section III-B) significantly boosts the effective SINR of the trapped macro UEs, especially at the low percentiles of the CDF. This is because, compared to the uncoordinated case, the sparseness forced upon the control channel spreads the same number of control REs over thrice the number of available REs, thus reducing the collisions to the PCFICH of the trapped macro UEs. Next, it is seen that inserting ABS at the femto layer improves the effective SINR even further. Due to the lack of control channels with the ABS configuration, the only DL interference seen by the PCFICH of the trapped macro UEs originates from the CRSs belonging to the HeNBs. It must be pointed out, however, that in the ABS configuration case, the HeNBs are assigned PCIs randomly. Therefore, even

**TABLE II**  
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. dual stripes per macro-cell sector</td>
<td>1</td>
</tr>
<tr>
<td>Avg. macro UEs per macro-cell sector</td>
<td>10</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Individual apartment dimensions</td>
<td>10 m x 10 m</td>
</tr>
<tr>
<td>Number of floors per stripe</td>
<td>3</td>
</tr>
<tr>
<td>HeNB activation probability, ( p_{\text{active}} )</td>
<td>0.1</td>
</tr>
<tr>
<td>Percent of macro UEs lying indoors</td>
<td>80%</td>
</tr>
<tr>
<td>Number of REs per RB, ( N_{RB}^{\text{DL}} )</td>
<td>12</td>
</tr>
<tr>
<td>Tot. number of available RBS, ( N_{\text{DL}}^{\text{RL}} )</td>
<td>50</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>eNB transmit power per sector</td>
<td>46 dBm</td>
</tr>
<tr>
<td>HeNB transmit power, ( P_{\text{max}} )</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Sectors per eNB</td>
<td>3</td>
</tr>
<tr>
<td>Min. dist. betw. macro UE and eNB</td>
<td>35 m</td>
</tr>
<tr>
<td>Min. dist. betw. femto UE and HeNB</td>
<td>20 cm</td>
</tr>
<tr>
<td>Number of UE antennas, ( N_a )</td>
<td>2</td>
</tr>
<tr>
<td>Wall penetration loss</td>
<td>20 dB</td>
</tr>
<tr>
<td>Horizontal antenna pattern, ( A(\theta) )</td>
<td>[ \min \left{ \frac{1}{2} \left( \frac{\theta}{\theta_{\text{max}}} \right)^2, A_{\text{m}} \right} ]</td>
</tr>
<tr>
<td>Max. eNB antenna gain, ( A_{\text{m}} )</td>
<td>14 dBi</td>
</tr>
<tr>
<td>3 dB antenna beam width, ( \theta_{\text{max}} )</td>
<td>70°</td>
</tr>
</tbody>
</table>
though there are only 16 REs assigned to the PCFICH, there is a probability that femto CRS to macro UE PCFICH collision occurs. The proposed PCI manipulation carefully chooses the PCI of the HeNBs such that it minimizes the collisions to the PCFICH of the trapped macro UEs. The selection of the PCI takes into account all three control channels and CRS and the latter point is responsible for the improved performance over ABS.

However, the achieved gains of PCI manipulation over ABS come at the cost of increased interference to the CRS of the trapped macro UEs, which may lead to channel estimation errors. There are two approaches to alleviate this problem:

- **CRS interference cancellation could be employed to cancel the CRS interference originating from the nearby HeNB. However, this is not possible with legacy UEs and is therefore only applicable to a subset of macro UEs.**

- **The other option is to allow CRSs to collide with the PCFICH of trapped macro UEs. While this will degrade the performance, it will only degrade it to the level of the ABS performance — which is still acceptable.**

The results presented in Fig. 3 demonstrate that the proposed PCI manipulation procedure combines the advantages of two other state-of-the-art techniques: it enables the femto layer to continue transmitting data (not possible with the ABS configuration) and at the same time, it shows a significant performance improvement over the sparse control region approach.

**VII. Conclusion**

This paper has presented DL femto-to-macro interference management by PCI manipulation to protect the performance of the most important control channel for non-CSG macro UEs that are trapped in the coverage of HeNBs. This technique, which involves manipulating the cell ID of the HeNB, requires no signaling. It was demonstrated by system level simulations that PCI manipulation outperforms the ABS configuration, which involves HeNBs sacrificing a fraction of their subframes in order to protect the trapped macro UEs in their vicinity. What is more, this technique improves the performance of the trapped macro UEs while still allowing the HeNB to transmit data to its own associated femto UEs.

**References**


