Automatic Methods for HetNet Uplink Power Control Optimization Under Fractional Load

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Abstract—In this paper we study uplink open loop power control (OLPC) optimization for co-channel HetNet scenarios with macro and pico cells under fractional load conditions. Two methods for automatic OLPC optimization are proposed, motivated and compared against manual approach. It is found that the OLPC parameters at the pico-layer can be computed as a function of the OLPC parameters at the macro-layer, taking the load at the different cells into account. It is shown that using such a methods results in good overall system level performance. We contribute with in-depth analysis of dependencies between OLPC parameters, cells load, throughput performance and other metrics used to describe network operation on system level.

Keywords - uplink power control; interference mitigation; LTE; Hetnet; small cells; finite buffer

I. INTRODUCTION

Today it is commonly accepted that migration from macro-only to heterogeneous networks (HetNet) with additional small cells is required in order to be able to carry future broadband traffic. Therefore together academia, industry, and standardization bodies are researching on various HetNet topics. To give a few examples of recent LTE-Advanced studies, an overview of 3GPP HetNet studies is provided in [1] while the User Equipments (UE) role in HetNet is addressed in

Further small cell enhancements for coming LTE-Advanced releases are discussed in [3]. Most of the existing HetNet studies have focused on downlink related problems and performance, while only few studies have addressed uplink related challenges [4],[5]. The main topic of this paper is therefore on uplink power optimization for LTE-Advanced HetNet deployments. To further narrow the scope of the paper, we focus on co-channel deployment cases where macro and pico cells are sharing the same carrier frequency. For such a scenario, the standardized Open Loop Power Control (OLPC) scheme is the main inter-cell interference coordination mechanism, so the parameter settings for OLPC have a significant impact on the systems performance. Several studies in the open literature have addressed the problem of OLPC parameter optimization for macro-only scenarios [6]-[10]. Based on these existing studies, we derived an automatic OLPC parameter solution for the considered HetNet scenario. Our priority is to study this topic under realistic conditions, so we assume a time-variant traffic model, and evaluate the performance under different traffic loads. Our study shows that the most promising solution is to use different OLPC parameterization at the macro and pico-layer. A simple, yet efficient, closed form expression for calculating the OLPC parameters at the pico layer as a function of the OLPC parameters at the macro-layer is found to result in good performance. The method ensures that UEs at the macro-pico cell border transmit with equal power spectral density.

The rest of the paper is organized as follows: The system model and problem statement is presented in Section II. The considered methods for OLPC parameter optimization are outlined in Section III. Simulation assumptions and corresponding performance results are presented in Sections IV and V, respectively. Finally, Section VI summarizes the main conclusions from the study.

II. SYSTEM MODEL AND PROBLEM FORMULATION

The system model follows the LTE-Advanced specifications [11], assuming that each UE has one transmit antenna, and base stations have two receive antennas per cell. In order to obtain fairly general conclusions with a high degree of realism, we use commonly accepted random deployment models for pico cells and UEs [12]. In brief: Three-sector macro eNBs are placed in a regular hexagonal grid, assuming 46 dBm transmit power. A constant number of pico cells with 30 dBm are placed randomly for each macro-cell according to a spatial uniform point process, subject to minimum distance constraints to pico and to macros. The UE call arrival is a Poisson point process with average call arrival rate of \( \lambda \) calls/sec, and fixed payload size of \( B \) bits. Thus, the offered traffic for the network equals \( \lambda B \) bits/sec. When a new UE call is generated, the UE is placed following a uniform distribution over cell area with probability 1/3, and with probability 2/3 it is placed near one of the picos, within a radius of 40 meters. Thus, this model represents a case where picos are deployed in hotspot areas with higher traffic density. The serving cell for the UE is determined based on downlink power measurements. Once the UE have successfully transmitted the payload, the UE call is terminated, and the UE is removed from the system. More information on random network models can be found in the recent overview paper [13]. The duration of each UE call naturally depends on multiple factors such as the scheduled bandwidth for the UE, the UEs transmit power, the interference experienced at the base station receiver, etc. Both the uplink experienced signal-to-interference-and-noise-ratio (SINR) and generated other-cell interference, depend significantly on the UE transmit power, and therefore on the configuration of the UEs power control parameters. As will be further demonstrated, the
optimal UE power control parameters also depends on the offered traffic as the importance of controlling the generated other-cell interference becomes less relevant at low offered traffic, where the probability of having simultaneous active UEs in neighboring cells is greatly reduced. Our objective is therefore to have studied how to best configure the UE power control parameters for the considered co-channel HetNet environment in order to obtain good end-user performance. Here the end-user performance is primarily measured by the 5%-ile and 50%-ile UE throughput of the UE call throughput cumulative distribution function (cdf). In order to capture throughput performance with a single metric the geometric mean of UE throughput is chosen as a Key Performance Indicator (KPI). The geometric average of user throughput \( T \) is expressed as:

\[
T = \sqrt[N]{\prod_{u=1}^{N} t_{pu}} = 10^{\frac{\sum_{u=1}^{N} \log_{10}(t_{pu})}{N}},
\]  

where \( u \) is a UE index, \( N \) number of UEs in the system, and \( t_{pu} \) the mean throughput of user \( u \). Note that the well-known Proportional Fair (PF) scheduler also aims at maximizing the utility function that equals the sum of logarithmic throughput of the users [14].

The uplink power control formula for each UE follows the 3GPP specifications [15]. For the sake of simplicity, we only consider the OLPC mechanism in this study, and hence the power control formula reduces to

\[
P = \min\{P_{\text{MAX}}, 10 \log_{10}(M) + P_{0} + \alpha \cdot L\},
\]

where \( M \) is the number of physical resource blocks (PRBs) used by the UE, \( P_{0} \) is the normalized power density, \( \alpha \) is the path loss compensation factor, and \( L \) is the path loss towards the serving cell. Finally, \( P_{\text{MAX}} \) is the maximum transmit power for the UE. The essential parameters to be configured correctly in (2) are therefore \( \alpha \) and \( P_{0} \).

As mentioned, the cell selection for each UE is based on downlink power measurements, more precisely measurements of the reference signal received power (RSRP). Typically, the UE connects to the cell with the highest RSRP. However, as illustrated in Figure 1, this leads to very small coverage area of each pico due to the large transmission power difference between macro and pico.

The effect of cell range extension (CRE) is therefore included in the study as well, where the RSRP measurement from picos is added a CRE offset before comparing against the RSRP measurements from macros. Using a CRE offset equal to 16dB corresponding to the difference in transmit power between macro and pico essentially locates the cell border at the point where there is equal path loss between the cells. Typically, applying high values of the CRE offset is only possible when using techniques like enhanced inter-cell interference coordination (eICIC), as severe downlink interference problems would otherwise occur [16],[17].

### III. POWER CONTROL PARAMETER SETTING METHODS

Three methods for setting the OLPC parameters are studied and compared in this paper.

#### A. Manual

In this method per layer OLPC parameter setting is applied, which means that all UEs served on the same layer uses identical OLPC parameters. The optimal OLPC parameters for the macro layer are obtained by brute-force search over two-dimensional \((\alpha, P_{0})\) parameter space in macro-only network under full-buffer traffic conditions. The optimization target was to maximize the product of 5%-ile and 50%-ile user throughput. After having fixed the OLPC parameters for the macro layer, and second brute force search is performed for \((\alpha, P_{0})\) for the pico-layer. The pico-\(\alpha\) and macro-\(\alpha\) turned out to be the same.

#### B. Equal PSD

As the name of this method indicates, the objective here is to have equal UL power spectral density (PSD) transmitted from UEs at the cell border between macro and pico. The motivation for this approach is to control automatically the interference generated by macro-UEs (MUE) to pico eNBs and by pico-UEs (PUE) to macro-eNBs. The basic principle of Equal PSD is illustrated in Figure 2.

\[
P_{\text{CRE, macro}} = P_{\text{CRE, pico}} + CRE
\]

\[
P_{\text{CRE, macro}} - L_{\text{macro}} = P_{\text{CRE, pico}} - L_{\text{pico}} + CRE
\]

\[
L_{\text{macro}} = P_{\text{CRE, macro}} - P_{\text{CRE, pico}} + CRE
\]

Figure 2. Idea of Equal PSD on the cell border approach. Orange (upper part): the cell border definition. Violet (lower part): UEs on the cell border are transmitting with equal PSD.

The macro-pico cell border is defined as the point where the RSRP from both macro- and pico-eNB (taking into account the effect of CRE offset) is the same, i.e., in logarithmic scale:

\[
P_{\text{CRE, macro}} = P_{\text{CRE, pico}} + CRE
\]

\[
P_{\text{CRE, macro}} - L_{\text{macro}} = P_{\text{CRE, pico}} - L_{\text{pico}} + CRE
\]

\[
L_{\text{macro}} = P_{\text{CRE, macro}} - P_{\text{CRE, pico}} + CRE
\]
where $L_{\text{macro}}$ and $L_{\text{pico}}$ are the UE pathloss to macro- and pico-eNB, respectively, while $P_{TX,\text{macro}}$ and $P_{TX,\text{pico}}$ are the respective maximum Tx powers for macro and pico eNBs. Disregarding $P_{\text{MAX}}$ equal PSD at the cell border then implies:

$$P_{0,\text{macro}} + \alpha_{\text{macro}} L_{\text{macro}} = P_{0,\text{pico}} + \alpha_{\text{pico}} L_{\text{pico}} \quad (6)$$

$$P_{0,\text{macro}} + \alpha_{\text{macro}} (L_{\text{pico}} + P_{TX,\text{macro}} - P_{TX,\text{pico}} - CRE) = P_{0,\text{pico}} + \alpha_{\text{pico}} L_{\text{pico}} \quad (7)$$

$$P_{0,\text{pico}} = P_{0,\text{macro}} + \alpha_{\text{macro}} (P_{TX,\text{macro}} - P_{TX,\text{pico}} - CRE) + L_{\text{pico}} (P_{TX,\text{macro}} - P_{TX,\text{pico}} - CRE) + L_{\text{pico}} (\alpha_{\text{macro}} - \alpha_{\text{pico}}) \quad (8)$$

In order to ensure that $P_{0,\text{pico}}$ is independent from actual UE pathloss towards the eNBs, parameters $\alpha_{\text{macro}}$ and $\alpha_{\text{pico}}$ must have the same value $\alpha$. Under these conditions, $P_{0,\text{pico}}$ can be expressed as follows,

$$P_{0,\text{pico}} = P_{0,\text{macroOnly}} + \alpha (P_{TX,\text{macro}} - P_{TX,\text{pico}} - CRE), \quad (9)$$

where $P_{0,\text{macroOnly}}$ is the $P_{0}$ setting for the macro-layer in a macro-only network (found by brute-force search).

### C. Load Adaptive $P_{0}$ (LAPO)

In [4], it was found that taking the cell load into account when equalizing PSD on the cell border can provide even better performance. Setting OLPC parameters individually, per cell allows accurate adaptation to diverse and dynamic interference environment. Under assumed traffic model, number of users in given cell and average number of MUEs in network are indication of level of interference generated in given cell and received from surrounding cells respectively, thus those metrics drive adaptation used in this method. The Load Adaptive $P_{0}$ (LAPO) procedure for calculation of the OLPC parameters starts with calculation of a $P_{0,\text{macroRef}}$, which can be interpreted as $P_{0}$ in case of one user in the cell. The $P_{0}$ obtained for macro-only network is scaled down according to the average number of macro-UEs in macro-cell $N_{\text{macroAvg}}$:

$$P_{0,\text{macroRef}} = P_{0,\text{macroOnly}} - 10\log_{10}(N_{\text{macroAvg}}). \quad (10)$$

where $N_{\text{macroAvg}}$ is obtained by counting the number of macro users in the timeslot when OLPC parameters update takes place. For simulation purpose it is assumed that both $N_{\text{macroAvg}}$ calculation and OLPC parameters update (based on freshly updated $N_{\text{macroAvg}}$) are done in one timeslot. In order to obtain $P_{0}$ for UEs in the particular macro cell, one needs to scale-up $P_{0,\text{macroRef}}$ according to the actual number of macro UEs $N_{\text{MacroUEs}}$ in the macro cell:

$$P_{0,\text{macro}} = P_{0,\text{macroRef}} + 10\log_{10}(N_{\text{MacroUEs}}). \quad (11)$$

Note that $N_{\text{MacroUEs}}$ in given macro cell may change from subframe to subframe as new UE call are started, or existing UE calls are completed. The starting point for calculating $P_{0,\text{picoRef}}$ is calculated earlier $P_{0,\text{macroRef}}$ which is an input parameter for the PSD equalizing procedure as in (2):

$$P_{0,\text{picoRef}} = P_{0,\text{macroRef}} + \alpha (P_{TX,\text{macro}} - P_{TX,\text{pico}} - CRE) \quad (12)$$

Finally, the $P_{0,\text{pico}}$ is calculated by adjusting $P_{0,\text{picoRef}}$ according to number of UEs in the pico-cell $N_{\text{picoUEs}}$:

$$P_{0,\text{pico}} = P_{0,\text{picoRef}} + 10\log_{10}(N_{\text{picoUEs}}). \quad (13)$$

Compared to Equal PSD method, the LAPO approach does not always result in equal PSD at the macro-pico cell border. As the LAPO method adjusts $P_{0}$ as function of the load, $P_{0}$ is likely to also be different for cells within the same layer.

### IV. SIMULATIONS

In order to further analyze the performance of the outlined methods for setting the OLPC parameters under realistic conditions, extensive multi-cell multi-user simulations have been conducted. The simulations follow the system model in Section II, assuming 4 picos per macro sector area. The propagation model consists of a deterministic distance dependent component, as well as two independent stochastic components for shadow fading and fast fading. Shadow fading is modeled according toeadaptation model [18], while the frequency selective fast fading is Typical Urban. Note that in line with HetNet simulation guidelines in [12], the path loss component and shadow fading standard deviation are different for macro and pico links. The primary simulations parameters are summarized in TABLE I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>System configuration</td>
<td>10 MHz (48 PRBs + 2PRB for signaling), co-channel deployment of macro- and pico-cells</td>
</tr>
<tr>
<td>Transmit powers</td>
<td>macro eNB: 46dBm, pico eNB: 30dBm</td>
</tr>
<tr>
<td>Antenna configuration</td>
<td>Macro eNB: 2Rx, 2Tx, 3 sectors, 3D pattern, 14 dBi gain</td>
</tr>
<tr>
<td></td>
<td>Pico eNB: 2 Rx, 2 Tx, omnidirectional, 5 dBi gain</td>
</tr>
<tr>
<td></td>
<td>UE: 2 Rx, 1 Tx, omnidirectional, 0 dBi gain</td>
</tr>
<tr>
<td>Macro cell deployment</td>
<td>Hexagonal grid, 500m inter-site distance, 7 sites, 3</td>
</tr>
<tr>
<td></td>
<td>sectors each, wrap around</td>
</tr>
<tr>
<td>Pico cell deployment</td>
<td>4 per macro sector area</td>
</tr>
<tr>
<td>User deployment</td>
<td>according to 3GPP scenario 4b for HetNet [36,814]</td>
</tr>
<tr>
<td>Scheduler</td>
<td>Time Domain - Round Robin, Frequency Domain- Proportional Fair with adaptive transmission bandwidth</td>
</tr>
<tr>
<td>Traffic model</td>
<td>Finite buffer, arrival rate 1-15Mbps per macro+4picos</td>
</tr>
<tr>
<td>Fast fading</td>
<td>Typical Urban</td>
</tr>
<tr>
<td>HARQ</td>
<td>Synchronous non-adaptive, 8 channels, 4ms delay</td>
</tr>
<tr>
<td>Penetration loss</td>
<td>20dB (all users indoor)</td>
</tr>
<tr>
<td>BLER target</td>
<td>30% (first transmission)</td>
</tr>
<tr>
<td>Link Adaptation</td>
<td>Fast AMC, LAPO: Po update every 10ms</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>3 runs, each 3s warmup + statistics collection depending on offered traffic: 10-20s</td>
</tr>
</tbody>
</table>

Dynamic link adaptation (selection of modulation and coding scheme) and packet scheduling (selection of which users shall be scheduled on which resources) is conducted every subframe. More details on the assumed link adaptation.
mechanism can be found in [19], while further details for the assumed adaptive transmission bandwidth proportional fair scheduler is available in [20]. Synchronous Hybrid Automatic Repeat request (HARQ) with ideal chase combining is modeled according to the 3GPP specifications as well [11].

V. PERFORMANCE ANALYSIS

TABLE II. summarizes the OLPC parameter settings for the three considered methods under low (1 Mbps) and high (10 Mbps) offered traffic, with/without the use of CRE. Note that since the P_0 settings are time-variant for the LAPO method (depending on number of users), only the average P_0 value is reported for those cases. Similarly, the average number of MUEs is also reported. For the LAPO scheme, there is a clear trend to use lower P_0 values for both macro and pico sectors at higher offered load. This is observed because the average number of users in macro N_{macro} grows above one but in most cases there is only one active user in macro sector and according to (10) P_{0,macro} scale-down is stronger than following scale-up (11). Similarly, for P_{0,pico} we use low P_{0,macro} ref (12) that is not compensated by following PSD scale-up (13).

![Figure 3](image-url) shows the average PRB utilization on the macro and pico layer for the different considered cases.

![Figure 3](image-url) PRB utilization on macro- and pico-layer for CRE=0 and CRE=12dB, Left: Low load (1Mbps), Right: high load (10Mbps)

With CRE=0dB, there is clearly a load imbalance between the macro- and pico-layer, resulting in much higher load in the macro than in case with CRE=12dB. However, by using CRE=12dB, the PRB utilization is better equalized between the two layers, meaning that higher offered traffic can be tolerated before reaching full resource utilization. The three methods for setting the OLPC parameters tend to result in approximately similar PRB utilization despite of their differences.

Figure 4 shows the geometric average throughput for the considered cases as defined in (2). It is observed that the best performance is achieved for the LAPO method for most of the cases. Only for the case without CRE and high load the Equal PSD method brings slightly better performance.

![Figure 4](image-url) Throughput KPI comparisons for cases with and without CRE. Left: Low load (1Mbps), Right: high load (10Mbps)

In order to bring further insight into the achieved performance, Figure 5 shows the cdf of the experienced end-user throughput for the UEs served by the macro- and pico-layer, respectively. Note that the UE throughput is limited to ~20Mbps under the assumption that the highest available modulation is 16QAM with coding of 4/5.

![Figure 5](image-url) Macro (left) and pico (right) UE throughput distribution under high load (10Mbps) without and with CRE=12dB.

It is observed that the LAPO scheme seems to better protect the MUEs when the load is more balanced (case CRE=12dB compared to case CRE=0dB). In general, it provides a higher user throughput when there is an unbalance load between the macro- and pico-layer. The Equal PSD method reduces the pico P_0 when CRE is used, causing a PUE throughput degradation, which is not the case for LAPO method.
In order to better understand the root cause behind the differences in throughput distributions, it is useful to examine the UE transmit power cdf. Figure 6 reports that the MUE transmit power for the LAPO with CRE=12dB is significantly higher than in other cases. When using CRE=12dB, the macro to pico offload frees resources for the MUEs, MUEs use higher P0 and these two factors in the end lead to the higher MUE Tx power when using LAPO. Applying CRE results in using a lower P0 for PUEs according to (9) and (10) for both the LAPO and Equal PSD methods, respectively. In case of LAPO the PUE P0 is increased according to the number of users in the pico cell (which is increased if CRE is used).

When applying CRE=0 dB, the Equal PSD method provides the best performance under medium to high load (more than ~5Mbps). The main advantage over other approaches is caused by efficient transmissions in the pico layer in an aggressive manner. In the study, high load conditions (offered traffic 10Mbps per macro+4picos) were investigated. However this still corresponds to a small number of users simultaneously transmitting in the system. This method takes risk of allowing PUEs to transmit with high power, expecting that there is small probability of causing serious interference to other eNBs. High interference generation probability is decreased by the fact that transmission with high power allows using high MCS which results in higher throughput (average pico call with Equal PSD took ~74% of call with LAPO).

VI. CONCLUSION

Methods for automatic setting of uplink OLPC parameters have been proposed and analyzed in this study. Evaluation under fractional load provided different angle of observation oriented towards understanding of OLPC adaptation methods based on load information. Under various offered traffic conditions, we provided insight into interdependencies between macro-/pico-cell load, OLPC parameters and the throughput performance. The method called Equal PSD is found to be the most attractive method. It provides both automation and throughput performance improvement when compared to manual setting of OLPC. The Equal PSD scheme is simple from implementation point of view as it neither requires new measurements, nor additional signaling between eNBs. The more advanced LAPO method can, for some cases, offer slightly higher performance by explicitly adjusting the OLPC parameters based on the cell load. However, the minor performance benefit of LAPO comes at the cost of higher inter base station signaling overhead for exchange of load information and other information.  

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REFERENCES