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Research Article

Analytical Model for Estimating the Impact of Changing the Nominal Power Parameter in LTE

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UpLink Power Control (ULPC) is a key radio resource management procedure in mobile networks. In this paper, an analytical model for estimating the impact of increasing the nominal power parameter in the ULPC algorithm for the Physical Uplink Shared CHannel (PUSCH) in Long Term Evolution (LTE) is presented. The aim of the model is to predict the effect of changing the nominal power parameter in a cell on the interference and Signal-to-Interference-plus-Noise Ratio (SINR) of that cell and its neighbors from network statistics. Model assessment is carried out by means of a field trial where the nominal power parameter is increased in some cells of a live LTE network. Results show that the proposed model achieves reasonable estimation accuracy, provided uplink traffic does not change significantly.

1. Introduction

Coverage and Capacity Optimization (CCO) has been identified by mobile network operators as a relevant use case of self-organizing networks [1–3]. The aim of CCO is to ensure an adequate trade-off between capacity and coverage during network operation. For this purpose, CCO algorithms adjust key radio network parameters, such as antenna configuration [4–8] or power settings in downlink [9–14] and uplink [15–25].

One of the most promising, albeit challenging, techniques for CCO in Long Term Evolution (LTE) is adjusting UpLink Power Control (ULPC) parameters. ULPC determines user transmit power for different uplink physical channels. It was conceived to avoid the near-far effect and to adjust received signal level to the limited dynamic range at the receiver. Without power control, far users would receive excessive intracell interference from close users in the same cell, as Single Carrier Frequency Division Multiple Access (SC-FDMA) is not totally orthogonal and it causes Inter Carrier Interference (ICI). Thus, far users with weak signal could be drowned out by strong signals from close users due to the limited quantization resolution of the Analog-to-Digital Coverter (ADC) at receiver. By regulating user transmit power, ULPC also improves system capacity and coverage, ensuring Quality-of-Service (QoS) requirements, minimizing UL interference to other cells, and reducing user battery consumption.

In the literature, most studies have focused on the design and characterization of effective ULPC algorithms based on simulations. Due to its benefits, the fractional ULPC (FPC) algorithm has been standardized for LTE [26]. The behavior of FPC is controlled by two parameters, namely, the nominal power parameter and the path loss compensation factor. The impact of these parameters on the performance of FPC in interference and noise limited scenarios is evaluated by means of simulation in [27]. In [28], an analytical model is proposed for computing UL cell loads and blocking probabilities from the values of the nominal power parameter and the path loss compensation factor in a simulator designed for network planning purposes. In [29], a theoretical framework for modeling FPC in a computationally-efficient simulator is proposed for validating self-organizing algorithms. All these models are based on propagation, traffic, and radio link quality predictions. However, to the authors' knowledge, no analytical model has been proposed to predict the impact of changing the referred parameters in an existing LTE scenario.

In this work, a novel analytical model for estimating the impact of increasing the nominal received power parameter in the FPC algorithm for the Physical Uplink Shared CHannel (PUSCH) in LTE is presented. Unlike previous models, the proposed model is conceived for network optimization purposes. Thus, the model is designed as an incremental model, whose aim is to estimate the change in the UL interference level and Signal-to-Interference-plus-Noise ratio (SINR) caused by modifying the current configuration of the nominal power parameter on a cell-by-cell basis. Therefore, it would be a predictive model that would allow the algorithm to react faster (i.e., in one shot) and more accurately (i.e., no unnecessary changes and subsequent reversion) than working iteratively. The predictive approach is very demanded in the current algorithms, both for optimization and for self-healing. Although this model has been conceived for optimization phase, it could also be used during self-healing phase in order to compensate cells in outage, ensuring minimum UL SINR. Moreover, the model can be easily adjusted to any particular scenario based on available network performance statistics. Model assessment is carried out by means of a field trial where P_0 is increased in some cells of a live LTE network. The rest of the paper is organized as follows: Section 2 outlines the FPC algorithm for PUSCH in LTE. Section 3 presents the proposed estimation model. Section 4 shows the results of the model in a live network, and Section 5 summarizes the main conclusions.

2. FPC Algorithm for PUSCH

FPC defines the transmit power of each User Equipment (UE), which is dynamically adapted to the changing radio propagation conditions and fluctuations of interference from users in neighbor cells. The equation defining the value of UE transmit power, P (in dBm), in each PUSCH subframe is

$$P = \min\left\{P_{\max},\ \underbrace{P_0 + \alpha \mathrm{PL}}_{\text{open loop}} + \underbrace{\Delta_{\mathrm{TF}} + f\left(\Delta_{\mathrm{TPC}}\right)}_{\text{closed loop}} + \underbrace{10 \cdot \log_{10} M}_{\text{bandwidth factor}}\right\}, \tag{1}$$

where $P_{\max}$ is the maximum user transmit power, P_0 is the target received power per Physical Resource Block (PRB) at the eNodeB, α is the path loss compensation factor parameter, PL is the estimated user path loss, M is the number of PRBs assigned to the user by the scheduler at the eNodeB, and $\Delta_{\mathrm{TF}} + f(\Delta_{\mathrm{TPC}})$ is a dynamic offset defined on a per-connection basis dependent of the modulation/coding scheme and closed-loop compensation [26]. P_0 consists of a cell-specific power level, common for all UEs in the cell, referred to as nominal power parameter, and a UE-specific offset, used to correct for systematic offsets in a UE's transmission power setting (3GPP TS 36.213). In this work, only the nominal power parameter is considered, which can be adjusted on a cell-by-cell basis. Likewise, full path loss compensation is assumed (i.e., $\alpha = 1$), as it is still a common setting and the default value in today's LTE networks, being also used in the analyzed network during the field trial. The maximum value of M assigned by the scheduler to a user is limited by the system bandwidth and the power headroom of the user (i.e., the ratio between the maximum user transmit power and the UE transmit power per each PUSCH subframe, given by (1)) [30]. Therefore, in this paper, it is assumed a specific UL scheduler implementation that stops allocating PRBs to a user if it estimates based on UE power headroom reports [31] that UE has reached its maximum transmit power.

3. Analytical Model

The analytical model proposed here estimates the impact on interference and connection quality statistics caused by changing P_0 in one or more cells in a live LTE system from statistics in the Network Management System (NMS). For this purpose, the change in the average UL interference level in a cell is first computed, and the change in the average SINR in the cell is derived later.

To quantify such changes, UL cell coupling is quantified that was utilized previously for congestion relief algorithm in Subway Areas by tuning Uplink Power Control in LTE [32]. A pair of cells (i, j) is strongly coupled when P_0 changes in cell j affect significantly the interference in cell i. For this to happen, several conditions must be satisfied: (a) the interfering cell must be closed in electrical terms (i.e., small path loss between the interfering users), (b) the load of the interfering cell must be high, and (c) interference generated by users must be above the noise floor. In the absence of a precise propagation model for the live network, in this work, proximity between cells i and j is estimated by the ratio between the number of handovers from i to j compared to the total number of handovers of source cell i (i.e., more handovers means more overlapping between cells). Thus, the proportion of the UL interference in cell i coming from users in a specific neighbor cell n, hereafter referred to as *Interference Contribution Ratio* (ICR), can be computed as

$$\mathrm{ICR}(i, n) = \frac{I(i)}{I(i) + N_0(i)} \cdot \frac{\mathrm{HO}(n, i) \cdot L(n) \cdot P_0(n)}{\sum_{\forall j \in N(i)} \mathrm{HO}(j, i) \cdot L(j) \cdot P_0(j)}, \tag{2}$$

where $I(i) + N_0(i)$ is the total received interference level in the cell under study i, $I(i)$ is the sum of the interference generated by users in neighbor cells, $N_0(i)$ is the noise floor plus external interference from other systems (and hence the dependence of N_0 of the specific cell i), $N(i)$ is the set of cells neighboring cell i, $\mathrm{HO}(n, i)$ is the number of outgoing handovers from cell i to neighbor cell n, $L(n)$ is the load of neighbor n, and $P_0(n)$ is the nominal power of the neighbor

n (the contribution is greater if more transmit power). In the formula, P_0 and interference and noise levels are in linear units (mW) and cell load is given by the PRB utilization ratio (i.e., $L(n) \in [0, 1]$).

ICR has been created in a heuristic way from the knowledge of what parameters have an effect on received UL interference. The first term in the product shows the ratio of the total undesired signal level due to users in surrounding cells, while the second term shows the ratio of interference due to a particular neighbor.

A cell i is considered a potential victim of the interference generated by a source cell n if the interference contribution ratio is above 0.28 (i.e., ICR > 0.28). Conversely, a cell n whose maximum interference contribution ratio to its neighbor i, $\mathrm{ICR}(i, n)$, is below 0.28 should be able to increase its P_0 without causing interference problems in surrounding cells. This criterion has been considered in the algorithm for selecting which cells should increase P_0.

In a real LTE network, noise plus external interference level on a cell basis can be inferred from the lowest bin in the histogram of Received Strength Signal Indicator (RSSI), and $P_0(n)$ value is obtained from configuration file. Likewise, $\mathrm{HO}(n, i)$ and $L(n)$ are NMS statistics. For consistency, the ratio of UL interference in cell i not coming from its neighbors, $\mathrm{ICR}_{N_0(i)}$, is given by

$$\mathrm{ICR}_{N_0(i)} = 1 - \sum_{\forall j \in N(i)} \mathrm{ICR}(i, j). \quad (3)$$

Once ICRs are obtained, the change in average UL SINR in a cell i is computed from the change in the average received desired signal level ($\Delta S(i)$) and received interference level ($\Delta I(i)$) in that cell, as

$$\begin{aligned}\Delta\widehat{\mathrm{SINR}}(i) &= \Delta\widehat{S(i)} - \Delta\widehat{I(i)} \\ &= \Delta P_0(i) \cdot (1 - P\mathrm{lim}(i)) - \Delta\widehat{I(i)} \text{ (dB)},\end{aligned} \quad (4)$$

where $\Delta P_0(i)$ is the P_0 increase (in dB) in cell i and $P\mathrm{lim}(i)$ is the ratio of power-limited users in cell i, which is available in the NMS. The equation reflects that the change in received desired signal level is only due to non-power-limited users in the cell under study [33].

The change in the average interference level in cell i due to P_0 changes in neighbor cells, $\Delta\widehat{I(i)}$ (in dB), is computed as

$$\Delta\widehat{I(i)} = 10\log_{10}\left(\mathrm{ICR}_{N_0(i)} + \sum_{\forall j \in N(i)} \mathrm{ICR}(i, j) \cdot \frac{\widehat{L'(j)}}{L(j)} \cdot 10^{\Delta\widehat{S(j)}/10}\right) \text{ (dB)}, \quad (5)$$

where $L(j)$ and $L'(j)$ are the load before and after increasing P_0, respectively, and $\Delta\widehat{S(j)} = \Delta P_0(j)(1 - P\mathrm{lim}(j))$, being $\Delta P_0(j)$ the P_0 change (increase or decrease, in dB) in the neighbor cell j. Briefly, for the case of increasing P_0, the increase of interference in a cell i is larger when cell coupling, $\mathrm{ICR}(i, j)$, is larger, the increase of P_0, $\Delta P_0(j)$, is larger, the power-limited user ratio, $P\mathrm{lim}(j)$, is smaller, and the after/before load ratio is higher. In contrast, interference does not change when $\mathrm{ICR}(i, j) = 0\ \forall j$ (note that, in this case, the term in the parenthesis is 1, from (3)).

The only term in (5) that cannot be directly taken from network statistics is the cell load ratio, $L'(j)/L(j)$, which is computed here as

$$\widehat{L'(n)} = L(n) \cdot \frac{\mathrm{RLE}(n)}{\widehat{\mathrm{RLE}'(n)}}, \quad (6)$$

where $\mathrm{RLE}(n)$ is the average radio link efficiency in the neighbor cell n before changing P_0 and $\widehat{\mathrm{RLE}'(n)}$ is the estimate of the same indicator when P_0 has changed. Note that (6) considers that traffic does not change, so that load changes are only due to changes in radio link efficiency. $\mathrm{RLE}(n)$ and $\widehat{\mathrm{RLE}'(n)}$ are computed from the average SINR values using Shannon–Hartley theorem [34] as

$$\mathrm{RLE}(n) = \log_2\left(1 + 10^{(\mathrm{SINR}(n)/10)}\right) \text{ (bps/Hz)}, \quad (7)$$

$$\widehat{\mathrm{RLE}'(n)} = \log_2\left(1 + 10^{(\mathrm{SINR}(n) + \Delta\widehat{\mathrm{SINR}(n)}/10)}\right) \text{ (bps/Hz)}, \quad (8)$$

where $\mathrm{SINR}(n)$ is the average SINR in cell n and $\Delta\widehat{\mathrm{SINR}(n)}$ is the estimated SINR change. The former is included in NMS statistics, but the latter must still be calculated from (4). To break the loop in the use of equations (4)–(8), $\Delta\widehat{I(i)}$ and $\Delta\widehat{\mathrm{SINR}(i)}$ are computed in several steps. An initial estimate $\Delta\widehat{I(i)}$ is computed with (5) by assuming that P_0 changes do not affect cell loads (i.e., $L'(j)/L(j) = 1$). Then, a preliminary estimate $\Delta\widehat{\mathrm{SINR}}(i)$ is obtained with (4), from which $\widehat{\mathrm{RLE}'(n)}$ is obtained. Later, $\Delta\widehat{I(i)}$ is updated with changes in cell loads, from which the final value of $\Delta\widehat{\mathrm{SINR}}(i)$ is obtained.

4. Model Assessment

A field trial was conducted to check the impact of changing P_0 in some cells of a live LTE network. Model assessment is carried out by comparing network performance measurements with estimates from the model.

4.1. Assessment Setup. The trial area comprises 124 outdoor cells in a densely populated urban scenario covering 10 km^2. The network includes a single carrier frequency at 2 GHz with 10 MHz bandwidth. UL antenna configuration is 1 transmit antenna in the UE and 2 receive antennas in the base station. Initially, P_0 is set to −106 dBm in all cells of the scenario.

The rules used to select cells increasing P_0 are heuristic criteria that take both cell capacity and connection quality performance into account. Cells increasing P_0 improve their spectral efficiency, but they have to be carefully selected to avoid deteriorating connection quality of neighbors significantly due to excessive interference. Note that this improvement is only achieved if the dynamic range at receiver is not violated. In another case, a cell increasing P_0 will degrade greatly its own cell edge users. In this study, UL signal level received at base station is always inside dynamic range at receiver due to adequate power configuration. Therefore, for this purpose of improvement in spectral efficiency taking special care in the neighbors, a cell is chosen for increasing P_0 if (a) it experiences low UL SINR values and, at the same time, neighbor cells do not suffer from UL interference problems or (b) the cell is not strongly coupled to any neighbor cell, so that users can increase their transmit power without affecting any neighbor. Cell coupling is obtained from initial P_0 value, handover, load, interference, and RSSI statistics with (2). With these criteria, 14 cells in the scenario are selected for increasing P_0 from −106 to −102 dBm. This conservative value of 4 dB is selected as a tradeoff between observability and safety. The larger the magnitude of changes, the larger the impact on network performance indicators and the easier the analysis, but, at the same time, large parameter changes might cause unnecessary network degradation or instability. In this sense, it is worth noting that network usage is still very low in current LTE networks, especially in the UL. This causes large traffic fluctuations between hours and days in a cell, which make the analysis complicated when introducing small network parameter changes.

The analyzed key performance indicators are the average UL PRB utilization ratio (%), average UL interference level (dBm/PRB), and average UL SINR (dB). All these indicators are collected on a per-cell basis in 4 office days before and after changing P_0 settings. Busy hour (BH) measurements are considered, since network load is still small in the trial area, and hence interference is relatively low. A single value of these indicators is obtained for the before and after periods, which are then subtracted to obtain the difference.

Network measurements $\Delta\text{SINR}(i)$, $\Delta I(i)$, and $L'(j)$ are compared with model estimates $\Delta\widehat{\text{SINR}}(i)$, $\Delta\widehat{I(i)}$, and $\widehat{L'(j)}$ by means of linear regression analysis. Goodness of fit is evaluated by checking the regression equation and the coefficient of determination, R^2. To avoid border effects, results are presented only for nonborder cells, whose neighbors are all inside the cluster of cells where statistics are collected.

During the trial, unexpected changes of UL traffic demand took place in some cells between the before and after periods. These changes were due to the low traffic demand in the trial area, where the average PRB utilization ratio in the UL during the BH is less than 4%. To include these uncontrollable changes of traffic in the model, a correction factor is introduced in (6) on a cell basis. This factor is the ratio between the traffic in the after and before period. Moreover, these traffic variations cause that UEs connect from different positions in the cell, which means that the number of power-limited users might change significantly. Consequently, all nonborder cells will not be analyzed, both the interference and the SINR.

To reduce the impact of these fluctuations in the traffic and power-limited users on the analysis, and thus isolate the effect of P_0 changes, the median value of both indicators has been calculated for each nonborder cell in before and after periods. In the case of the interference, a nonborder cell is filtered from the study when any relevant neighbor (HO > 10%) suffers from significant traffic or power-limited users variations (greater than 20% for traffic and 30% for power-limited users). These variations are calculated as the relative variation of the median value in after and before periods on the median value in the before period. In the case of the SINR, a nonborder cell is filtered by 2 reasons: (a) traffic or power-limited users variations in relevant neighbors that cause received interference level variations in the cell under study, as detailed above, and (b) power-limited users variations (greater than 30%) in the cell under study, which can change the received signal level.

4.2. Results. The analysis is first focused on changes of cell load caused by P_0 changes. Only for this indicator, both border and nonborder cells are considered, since it is necessary to have the load of all cells in the cluster which act as neighbors to others. To calculate the load of border cells, which have a lot of neighbors out of cluster, it has been assumed that the load in these neighbors is the average of the load for the rest of their neighbors in the cluster. Furthermore, it is supposed that these cells out of cluster have not load and P_0 variation. Results show in Figure 1 that the coefficient of determination is $R^2 = 0.92$ with a slope of 1.16 and an offset of −0.004 (i.e., $\widehat{L'(j)} = 1.16 \cdot L'(j) - 0.004$). All these parameters (i.e., 0.92, 1.16, and −0.004) have been obtained from the linear correlation between real UL load, $L'(j)$, and estimated UL load, $\widehat{L'(j)}$ (using (6)) after P_0 changes using real data.

The analysis is then focused on changes in interference levels. Figure 2 plots measurements and estimates of UL interference variations (i.e., $\Delta I(i)$ and $\Delta\widehat{I(i)}$, resp.). Each dot in the figure represents a nonborder cell that does not fulfill the criterion for being filtered from the analysis. It is observed that the slope of the regression equation is close to 1 (i.e., 0.73) and the coefficient of determination is reasonable (i.e., $R^2 = 0.57$). Note that, in the figure, some cells experience a smaller UL interference (i.e., negative change), which is not possible if P_0 has increased. This unexpected result might be due to changes in the spatial traffic distribution inside each cell, mentioned previously, which have been detected from the comparison of power-limited ratios in the before and after periods in cells not changing P_0. The change in the position of UEs between periods is again a consequence of the low traffic in the UL.

The following analysis is focused on changes in connection quality. Figure 3 shows measurements and estimates of UL SINR variations (i.e., $\Delta\text{SINR}(i)$ and $\Delta\widehat{\text{SINR}}(i)$, resp.) for nonborder cells that do not fulfill the criteria for being eliminated from the study. It is observed that the regression equation is $\Delta\widehat{\text{SINR}}(i) = 0.94 \cdot \Delta\text{SINR}(i) + 0.25$ with $R^2 = 0.38$. Dots in the upper-right of the figure correspond to cells increasing P_0, which experience larger increases in UL SINR. However, not all cells increasing P_0 experience a significant improvement in UL SINR, but only those with a small ratio of power-limited users [33]. Note that a P_0 increase leads to a higher transmit power only for users that are not power limited (for which $P < P_{\max}$, typically close to the base station). A closer analysis shows that some cells increasing P_0 experience worse UL SINR. This is explained by the negative effect of increasing P_0 on distant users in the same cell (i.e., cell-edge users), which tend to be power limited ($P = P_{\max}$). For these distant users, an increase of P_0 is not translated into a higher transmit power, while interference from other cells could be increased due to P_0 increase in those neighbor cells. As a result, cell-edge users

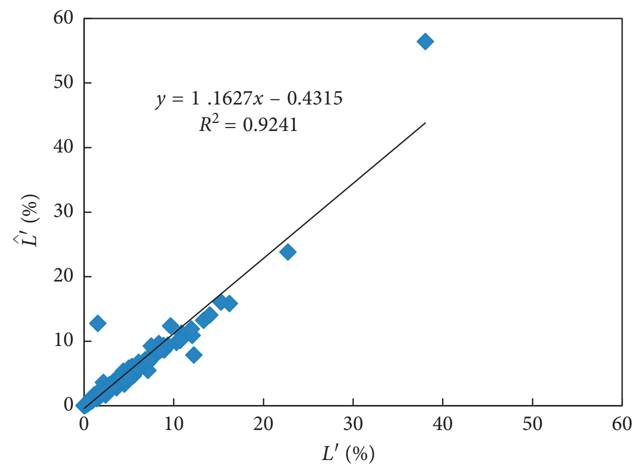

Figure 1: Correlation of UL load after P0 changes.

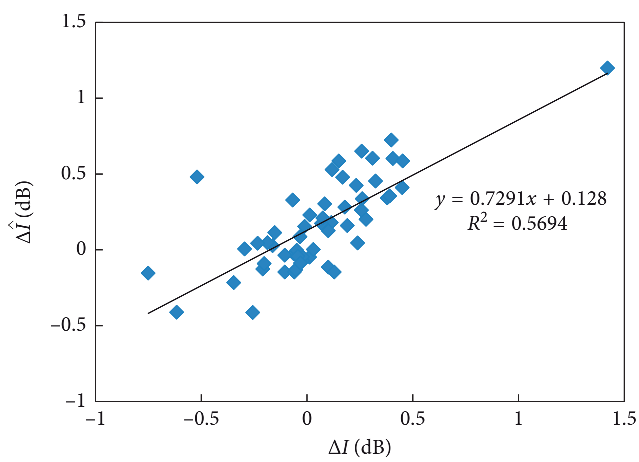

Figure 2: Correlation of UL interference variations.

experience a lower UL SINR. Whether UL SINR in a cell is increased or decreased depends on the ratio of power-limited and non-power-limited users, as included in the model by the Plim parameter. The rest of the dots in the lower-left of the figure correspond to neighbor cells of those increasing P_0, which experience a decrease in UL SINR.

The impact on 95%-ile UL SINR should be larger than on average UL SINR; however, for optimization purposes, it is usually more convenient to work with average values. Nevertheless, it will depend on the final goal. Thus, if the optimization objective is an average improvement of the cell, average SINR will be the parameter used. Conversely, if the aim is to improve, for example, the coverage, 95%-ile SINR should be taken into account. In this work, the optimization is based on the average cell level, so the average SINR is analyzed in the model.

Finally, Table 1 compares measurements and estimates aggregated in a cluster level, considering all cells for the load and only nonborder cells that are not filtered by any exposed criterion for interference and SINR. In the table, it is shown that the average real change in interference level and SINR is 65% less than the estimated values. It is expected

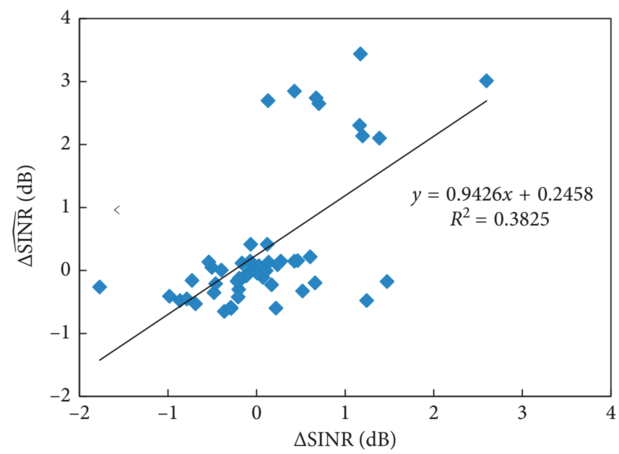

Figure 3: Correlation of UL SINR variations.

Table 1: Modeled and measured variations of network KPIs after the increase of P_0.

Key performance indicators	Real	Estimate
Average of UL radio utilization variation (%)	0.03	0.19
Average of UL interference variation (dB)	0.06	0.17
Average of UL SINR variation (dB)	0.11	0.35

that these differences between model estimates and real network measurements reduce as UL traffic increases in LTE networks.

During field trial, cells changing P_0 were decided intelligently based on different rules explained in Section 4.1. Unfortunately, the experiment where all cells changed their P_0 could not be checked to compare results with the analyzed experiment as it was not part of the optimization process. Nonetheless, if all cells increased P_0 without using any criterion of cell selection, the following behaviors could be observed:

(i) Cells increasing their P_0 could be improved insignificantly in terms of UL SINR due to many power-limited users (only close users would be improved).

(ii) Degradation in neighbor cells in terms of UL interference due to high UL coupling between cells or initial interference problem that would be worsened when P_0 is increased in other nearby cells despite not having high UL coupling.

This basic approach would give way to not consider the tradeoff between benefit (i.e., more UL signal) and degradation (i.e., more UL interference), leading to possible situations where the degradation is greater than the benefit. With the proposed model, the impact on UL SINR and UL interference could be estimated in advance and to avoid unwanted effects.

5. Conclusions

In this work, an analytical model for estimating the change in interference level and SINR caused by modifying the nominal power parameter in the uplink power control scheme of a live LTE network has been proposed. The model can be easily adjusted to any particular scenario based on P_0 parameter (configuration), handover, RSSI, SINR, load, and power-limited user statistics available in the network management system. Model assessment has been carried out in a field trial where the nominal power parameter is increased in some cells of a live LTE network. Results show that the performance of the proposed model is reasonable, provided that uplink traffic demand is stable in the network. The flexibility and low computational load of the model makes it ideal for integration into self-tuning algorithms for the nominal power parameter.

More specifically, this analytical model could be used in both optimization and self-healing phases (i.e., compensation of cells in outage) as it would allow to predict variations on certain KPIs when P_0 is modified. With optimization algorithms, P_0 is normally modified iteratively until reaching a goal for these KPIs. However, this process could be carried out in one shot using the proposed model. Nowadays, an important objective is to get algorithms capable of reacting very fast using, for example, a predictive model, especially when they are working on self-healing phase. Moreover, iterative processes involve many times unnecessary changes and subsequent reversion that wastes time and resources. It is proposed as future work to extend the model to high-level KPIs such as UL throughput and to test it on an LTE network with more UL load.

Data Availability

The underlying customer data is not publicly available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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