Uplink power control modeling for dense OFDMA-based heterogeneous networks

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***Abstract*—In this paper we propose a novel model for the uplink in heterogeneous cellular networks. Opposed to previous works, we accurately account for the mutual interference caused by other users' connections, and we pose an optimization problem that can be straightforwardly solved to establish the minimum required transmission power that satisfies the minimum Signal-to-Interference-plus-Noise Ratio (SINR) constraint. We assess the validity of the proposed approach by comparing the observed results with those obtained with a traditional closed-loop power control scheme. The main benefit of our solution is that it does not require any iteration to find the transmission power, while legacy approaches usually need a number of steps before finding it. Finally, we study the behavior of the uplink for different access selection strategies, and we compare the SINR and transmission power of open-loop and closed-loop power control solutions.**

***Index Terms*—Uplink power control, LTE, HetNets, optimization, modeling.**

I. Introduction

The relevance of uplink in current and forthcoming cellular communications is believed to increase [1]. In the last years, we are witnessing the appearance of various bi-directional data-based services, such as Mobile Edge Computing (MEC) [2], and, as a consequence, uplink traffic volume is expected to grow. On the other hand, it is known that network densification, and the differences between traditional homogeneous scenarios and heterogeneous networks (HetNets), pose new challenges for network management mechanisms, especially considering inter-cell interference [3]. This becomes even more relevant when new access selection schemes, such as Downlink Uplink Decoupling (DUDe), are exploited.

In this context, leveraging an appropriate power-control mechanism for uplink communications might yield better network performance, inasmuch as the interference would be minimized. At the same time, it could also increase the life-time of User Equipments (UEs), since transmitting with less power reduces the battery drain.

The analysis of different network management techniques in general, and power control in particular, is usually addressed by means of simulations. According to the accuracy objective and the way the network is modeled, we can differentiate three types of simulations [4]: network simulations, link level analysis, and system level approaches.

The first method models real network elements, and it usually requires implementing the whole protocol stack. At the other end, link level simulation focuses on the behavior of the radio link, usually between a single transmitter-receiver pair, considering detailed aspects from the both physical and Medium Access Control (MAC) layers, as well as propagation phenomena at small temporal scales (for instance, symbol duration). Finally, system level simulation aims to characterize the overall behavior of whole systems. Opposed to the link level approach, it looks at the network performance during longer periods of time, and so larger temporal pace is usually considered.

Furthermore, system level simulation is divided into static and dynamic approaches [4], according to its ability to consider the temporal evolution of the network (traffic patterns, user movement, etc.). Static simulation is typically based on *Monte Carlo* analyses, where multiple and independent snapshots are used to analyze the system performance. The objective here is to obtain Key Performance Indicators (KPIs), such as coverage or outage probability. In contrast, dynamic system-level simulation aims to model the system evolution, paying attention to network dynamics. In this case, the way the network changes over time is considered, and the simulation keeps the state between consecutive snapshots (or uses an event-driven methodology). For instance, it allows analyzing aspects like handovers, or including service patterns.

The performance of power control solutions is typically analyzed by means of system-level simulations, either static or dynamic, depending on the particular objectives. In the case of uplink power control of Orthogonal Frequency-Division Multiple Access (OFDMA) based systems, such as Long Term Evolution (LTE), different models for static simulation, or network characterization, have been proposed in the literature, as are discussed in Section II. On the other hand, dynamic system-level simulation is usually simplified by applying open-loop power control, which may lead to inaccurate results. However, when closed-loop power control schemes are used, the analysis requires longer simulation times, to appropriately capture system fluctuations and ensure overall convergence. In turn, these requirements prevent from performing large scale analyses entailing closed-loop power control solutions, together with other techniques happening at a slower pace (e.g. handovers).

In this work, we propose a model for OFDMA-based uplink transmit power, in particular addressing dynamic system level analysis. This model leads to an optimization problem that seeks reducing the overall transmit power of all UEs, while ensuring a certain target Signal to Interference plus Noise Ratio (SINR), so mimicking real systems behavior. This way, the proposed solution is able to find the transmission power that would yield a closed-loop power control scheme with a single-shot, without requiring long simulation times to reach system convergence. In particular, the corresponding formulation boils down to a linear program, which can be thus easily solved. We assess the validity of this solution by comparing it with the results that would have been obtained with a traditional closed-loop power control approach. Afterwards, we exploit such model to analyze different access selection strategies over HetNets, and their impact over the transmission power, and so lifetime, of UEs.

The paper is organized as follows: in Section II we identify the most relevant previous papers, and we highlight the main differences with the work presented herewith. Then, the system model is depicted in Section III, which introduces the linear problem that is used to find the optimum transmission power. Afterwards, in Section IV we use the proposed methodology to evaluate how various access selection schemes impact the uplink transmission power. Finally, Section V concludes the paper, providing an outlook of aspects that we will tackle in our future research.

II. Related work

In spite of the increasing relevance of power control techniques for uplink communications in cellular networks, there has not been much activity on this particular aspect in recent literature. Some earlier works analyzed the differences between open-loop and closed-loop power control solutions in LTE networks [5], [6]. As of late, the authors of [7] compare both power control approaches, and how they impact the system throughput. They conclude that the closed-loop scheme outperforms open-loop based techniques, and that the transmission power obtained when using this latter approach was in fact not always appropriate. However, in most cases the focus is put on open-loop techniques [8], and there exist some works that aim at finding an optimal configuration of the corresponding parameters [9], [10], [11].

Regarding the modeling of uplink power control, previous research has focused on static system analysis or network planning, existing different works that aim to characterize uplink power control mechanisms. For instance, a general model is proposed in [12], while uplink power control schemes used in Wideband Code Division Multiple Access (WCDMA) based systems are studied in [13]. More recently, models for OFDMA-based systems and heterogeneous networks have been also proposed. For example, the impact of Inter-Cell interference (ICI) is considered in [14] to obtain network performance metrics. On the other hand, the authors of [15] exploit stochastic geometry to define a mathematical framework for system-level analysis, which might help in the design of uplink heterogeneous networks. Similarly, Wang et al. [16] analyze the impact of deploying femtocells over uplink power control, looking at cross-tier interference.

On the other hand, very few works have studied the impact that access selection strategies may have over uplink transmission power. The authors of [8] evaluate different configurations of uplink power control in HetNets, using both Reference Signal Received Power (RSRP) based access selection and Cell-Range Extension (CRE). Nevertheless, most of the existing works in the literature assume rather simple selection policies, such as distance-based schemes [17].

As can be observed, most of the proposed models are only suitable for static system-level simulation, while dynamic system-level simulation is carried out either assuming strong simplifications [17] that may yield poor results, or requiring intensive simulation processes [5].

We summarize below the main contributions of this paper:

- We define a model for uplink closed-loop power control in OFDMA-based systems. It is not a proposal for a new power control scheme, but it aims to mimic the behavior of existing ones.
- The model is intended to be used in dynamic system-level simulation. It yields results alike those provided by closed-loop power control schemes, but it just needs a single-shot solution, without the iterations that characterize closed-loop mechanisms.
- The proposed model considers the mutual interference between users at the base station, which is usually overlooked in the related state-of-the-art analyses. Due to the model generic definition, the interference level can be tailored according to the particular system setup.
- The model leads to a linear optimization problem, that can be easily solved with available tools, and it can therefore be easily integrated into existing simulation environments.

III. System Model

In this section we first introduce traditional LTE uplink power control schemes. Afterwards, we depict the proposed analytical model for the closed-loop configuration.

A. Traditional uplink power control mechanisms

We can define the power to be transmitted by a UE, using a closed-loop power control scheme, as follows [18]:

$$P = \min\{P_{\max}, P_0 \cdot N_{RB} \cdot \gamma^{\alpha} \cdot \delta_{\mathrm{mcs}} \cdot f(\Delta)\} \qquad (1)$$

where $P_{\max}$ holds for the maximum power a UE is allowed to transmit, P_0 is a parameter that reflects the expected interference level, N_{RB} is the number of resource blocks allocated to such user, while γ and α correspond to the pathloss and pathloss compensation factor, respectively. The parameter δ_{mcs} indicates a power offset that depends on the current Modulation and Coding Scheme (MCS) configuration, and it is specific to each UE. Finally, $f(\Delta)$ is the closed-loop correction function, which enables transmission power adjustment, according to fast channel variations.

Both P_0 and α are sent by the network to users in a broadcast manner. Furthermore, pathloss is computed by the UE, based on the RSRP. By using these three variables, which correspond to open-loop parameters, the UE can set an initial transmission power without any indication from the serving cell, and it could even compensate slow channel variations.

Afterwards, $f(\Delta)$ is used to vary the transmit power over time (i.e. closed-loop), so that the actual value oscillates around the one obtained with the open-loop parameters, to compensate fast channel variations. The reader may refer to [19] for a thorough explanation of how the closed-loop mechanism operates.

B. System model

We consider a scenario comprising a set of users and LTE cells, $\mathcal{U}$ and $\mathcal{B}$, respectively. Without loss of generality, we assume that cells share the same spectral resources (i.e. single carrier scenario). Hence, all users, but those attached to the same cell, induce interference at the receiving cell of each other. We also assume that resources are modeled as Physical Resource Blocks (PRBs), and that access selection has been already applied, so that users' attachment is known. We will not make any assumption on the specific access selection policy.

We define $\beta(i) \in \mathcal{B}$ as the serving cell of user i, while $\mathcal{U}(k) \subseteq \mathcal{U}$ holds for the set of users attached to cell k, and C_k corresponds to the capacity (number of PRBs) of such cell. In addition, we define γ_{ik} as the pathloss between user i and cell k, being Γ_i the one corresponding to the serving cell of user i, i.e. $\Gamma_i = \gamma_{i,\beta(i)}$. The rest of parameters have the meaning indicated above.

We then define the interference per PRB experienced, at the serving cell, over the resources of user i, I_i, as follows:

$$I_i = \sum_{k \in \mathcal{B}/\beta(i)} \sum_{j \in \mathcal{U}(k)} N_{RB_j} P_0 \, \delta_{\mathrm{mcs}_i} \frac{\gamma_{jk}^{\alpha}}{\gamma_{j\beta(i)}} f(\Delta)_i \; S(C_k, C_{\beta(i)}) \qquad (2)$$

where N_{RB_j} is the amount of resources allocated to the interfering user j. We introduce $S(C_k, C_{\beta(i)})$ to statistically modulate the interference caused by users attached to other cells, as a weighting function that depends on the particular scheduling policy and interference reduction, when coordination between cells or other mitigation techniques are applied. We will assume that access elements are uncoordinated, and that they use a random scheduler, so that $S(C_k, C_{\beta(i)}) = 1/C_k$. Hence, the interference is defined as the normalized summation of the resources allocated to interfering users, $j \in \mathcal{U}(k)$, $k \in \mathcal{B}/\beta(i)$, weighted by the interference at the serving cell, $\beta(i)$.

The power transmitted by user i, P_i, can be defined in terms of its target SINR, St_i, and the corresponding interference, so that $St_i \leq \frac{P_i/\Gamma_i}{\sigma^2+I_i}$, where $P_i = P_0 \Gamma_i^{\alpha} \delta_{\mathrm{mcs}_i} f(\Delta)_i$, and σ^2 is the noise power. Then, if we group all the dependent terms, we can express the SINR of one user as a linear combination of the power transmitted by the remaining ones:

$$P_i - St_i \sum_{k \in \mathcal{B}/\beta(i)} \sum_{j \in \mathcal{U}(k)} \frac{N_{RB_j} P_j \Gamma_i}{C_k \gamma_{j\beta(i)}} \geq St_i \Gamma_i \sigma^2 \qquad (3)$$

If we assume that UEs transmit the minimum required power to ensure that the target SINR is reached, the overall uplink transmission power in the system, when a closed-loop power control scheme is applied, can be modeled as a linear optimization problem, as shown below:

Problem 1 (Uplink power allocation)**.**

$$\textbf{\textit{min}} \quad \sum_{i \in \mathcal{U}} P_i \qquad (4)$$

$$\textbf{\textit{s.t.}} \quad P_i - St_i \sum_{k \in \mathcal{B}/\beta(i)} \sum_{j \in \mathcal{U}(k)} \frac{N_{RB_j} P_j \Gamma_i}{C_k \gamma_{j\beta(i)}} \geq St_i \Gamma_i \sigma^2 \quad \forall i \in \mathcal{U} \qquad (5)$$

$$P_i \geq 0 \quad \forall i \in \mathcal{U} \qquad (6)$$

As can be observed, the mutual interference captured by Problem 1 yields the transmission power that would be obtained once the closed-loop mechanism converges, but in a single-shot evaluation. In addition, the solution, P_i, includes both closed-loop and open-loop parameters, and it would thus depend on the particular configuration. For instance, if we assume fixed values for P_0 and α, the closed-loop parameters (δ_{mcs_i} and $f(\Delta)_i$) could be calculated using: $P_i = P_0 \Gamma_i^{\alpha} \delta_{\mathrm{mcs}_i} f(\Delta)_i$.

It is worth noting that, although fast fading is not included in the model, it is expected to have zero mean within the convergence time of the closed-loop mechanism. In addition, although we assume that all cells use the same spectrum, the model could be easily generalized for multi-carrier and multi-connectivity scenarios, where allocation of resources from different frequencies do not interfere each other. For instance, one may think of a scenario where different carriers are used for macro and small cells, and so inter-tier interference would not need to be considered.

IV. Model validation and evaluation

We have validated the proposed model over a two-tier LTE urban dense scenario. The first tier is made of 7 tri-sector macro eNodeBs, which are deployed following an hexagonal pattern. The second one consists of a number of small-cells (which will be varied during our experiments) randomly placed within the macro-base stations' coverage area. Furthermore, we assume a single carrier situation where all cells share a 20 MHz bandwidth (i.e. 100 PRBs) without any cooperation among them. We deploy 100 users within such network topology, and we assume they are always active, so they are continuously transmitting. Table I summarizes the main configuration parameters of the considered scenario.

Since our interest lies in validating the model, we have used a static snapshot simulation approach. In each iteration users and small-cells are randomly deployed. Then, propagation models are used to estimate received power levels, and access selection strategies are applied, based on the previous estimations. After access selection is completed, the power control mechanism is used to establish the transmission power required by each UE. When we use the proposed model, the resulting optimization problem is solved by means of the GLPK library[1]. In particular, we compare the system performance when the following access selection strategies are used:

- Legacy RSRP based access selection. A user gets attached to the cell from which it receives the strongest reference power. While it is suitable for homogeneous networks, it does not fully exploit the additional capacity brought by small-cells, since it does not consider the differences between access elements' power budget.
- CRE. In order to overcome the limitations of the previous strategy, CRE adds a bias factor to the RSRP from small-cells, to foster attachments to such base stations.
- DUDe. The uplink connection is established to the cell with which the user has the lowest pathloss. On the other hand, the downlink attachment follows the traditional RSRP case.

A. Linear programming model validation

First, we compare the results of the proposed model with those that would be obtained with a traditional closed-loop scheme, to analyze whether it leads to similar system level behavior and so assess its validity. For the sake of simplicity, we carry out this first analysis over a homogeneous scenario, only comprising macro-cells. For the closed-loop mode, we have followed the approach described in [5], where the open-loop component is used at a first step, to establish the initial transmission power. Then, the effective SINR is calculated, and the power level is accordingly corrected for each UE, to reach the required SINR value. This process is repeated until the power levels of all UEs converge. On the other hand, the proposed model is applied in a larger time-scale, so that random independent scenario realizations are used for each problem instance. In order to provide a fair comparison, fading is not considered, so that differences regarding required SINR are only due to the mutual interference that is considered in our model.

Figure 1 depicts the cumulative distribution function (cdf) of the effective SINR, for different values of the target value (i.e. the SINR that needs to be reached). As can be observed, the proposed model always yields the required value, as a consequence of including the mutual interference within the linear program. On the other

[1] https://www.gnu.org/software/glpk/

TABLE I: Scenario characteristics

LTE layout	**20MHz @2.1GHz**
Macro layer	Inter Site Distance (ISD) 500 m, 7 tri-sector sites Max. TX. power 46 dBm, NF 3 dB Antenna Gain 14 dBi, 15^o down-tilt
Small layer	Random Location Max. TX. power 30 dBm, NF 3 dB Omni-antenna, 5.0 dBi
Path Loss (Tables B.1.2.1-1 and B.1.2.1-2 from [20])	Macro-BS $\leftrightarrow$ UE: Urban macro (UMA) Small-BS $\leftrightarrow$ UE: Urban micro (UMi)
UE	Max. transmit power 24 dBm (250 mW) Antenna gain 0 dB
Maximum Allowable Path Loss (MAPL)	140 dB
δ_{mcs}	0 dB, i.e. MCS independent
α	1, i.e. full path compensation

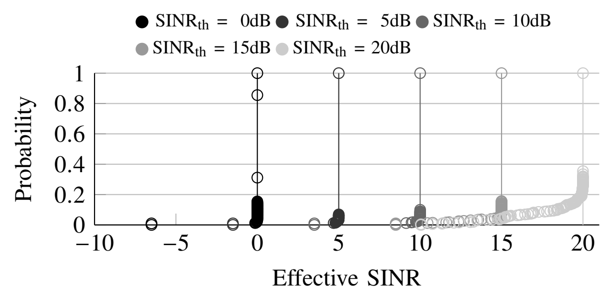


Fig. 1: *cdf* of the effective SINR when using the proposed model (solid lines) and closed-loop (markers)

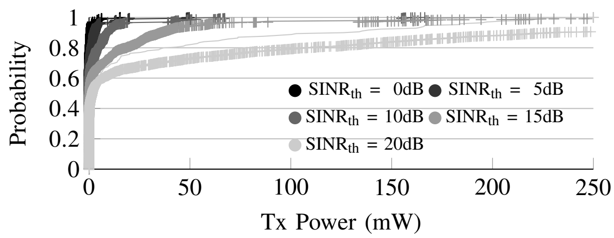


Fig. 2: *cdf* of the transmission power when using linear programming (solid lines) and constant-load (markers) models

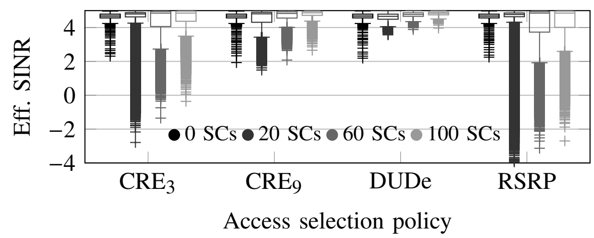


Fig. 3: Distribution of effective SINR when using open-loop power control. The proposed closed-loop model always yields the required value of 5 dB

hand, the closed-loop configuration leads to a slightly more sparse distribution, mainly due to the iterations that are required for the system to converge. In particular, we can observe that for configurations with more stringent SINR requirements, the closed-loop solution needs more time to converge.

Similarly, Figure 2 illustrates the distribution of the transmission power that would be required, when using both a closed-loop configuration and the proposed model, for various target SINR levels. As can be seen, the proposed solution yields a behavior that is rather similar to that exhibited by the closed-loop configuration. In addition, the results evince that the lower the required SINR, the tighter the matching is.

Altogether, the proposed model is able to resemble the system level behavior of the closed-loop scheme in all scenarios, without requiring the additional complexity derived from its convergence time. In particular, for the homogeneous scenarios we have analyzed, we have observed that the legacy closed-loop approach takes between 4 and 12 iterations to converge. We can therefore conclude that the proposed model remarkably reduces the simulation complexity, since it requires between 4 and 12 fewer iterations. In addition, the convergence time for the traditional closed-loop scheme would strongly depend on both network geometry and user density, so more complex network configurations would eventually lead to longer convergence times. However, the proposed model is able to establish the transmission power in a single-shot, and so leverage a notable gain it terms of simulation complexity. An in-depth analysis of the complexity reduction is left for future studies, once the correct behavior of the proposed model has been shown.

B. Access selection strategy analysis

In order to highlight the differences between the closed-loop setup and the widely used open-loop approach, we now compare the performance of both schemes. It is worth noting that the closed-loop results are obtained by exploiting the proposed model, so that both analyses have the same complexity. If traditional closed-loop power control solutions were used, the simulation time would be much longer, due to the system convergence that was discussed above. Unlike the previous analysis, we deploy a heterogenous scenario (see Table I) where small cells are randomly placed on top of the hexagonal deployment of macro-cells. In addition, different access selection policies are studied, to analyze their impact on UE power transmission. In particular, traditional RSRP access selection is compared with two CRE configurations, with 3 and 9 dB bias, and DUDe. The following results are obtained for a target SINR of 5 dB. Similar behaviors were observed for other values.

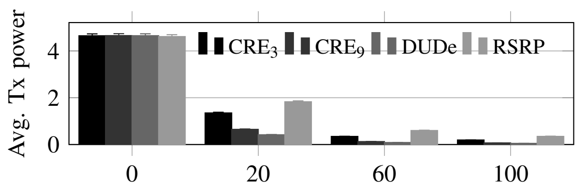
Figure 3 depicts the distribution of the SINR when using the open-loop setup, for different small-cell densities. When using the closed-loop scheme (exploiting the proposed method), the target SINR is always reached, as was shown in Figure1. On the other hand, the results show that the open-loop approach does not always ensure the required SINR, but it actually yields a rather sparse behavior, which depends not only on the number of small-cells, but also on the particular access selection policy. We can indeed see that both RSRP and CRE_3 yield much more sparse performances.

Finally, we compare the required transmission power per PRB when using both the open-loop and closed-loop setups. Although both configurations showed different behaviors in terms of effective SINR, Figure 4 evinces that the required transmission power is alike in both cases. This is a consequence of the proposed optimization for the closed-loop approach, which allows a better power allocation to reduce the mutual interference. It is worth noting that such optimization takes place either with the proposed model by means of the linear program, or when using a legacy closed-loop approach, which would require a more time-consuming simulation.

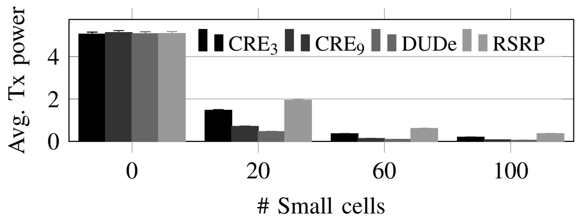
V. Conclusions

The increasing relevance of uplink communications, along with the appearance of novel network topologies and services, call for an appropriate management of uplink resources, which will require accurate simulation models.

We have proposed an analytical model of the closed-loop uplink power control, considering mutual interference, which allows reducing the simulation complexity. We have validated it, comparing its behavior with that



(a) Open-loop power control



(b) Proposed model

Fig. 4: Power allocation per PRB for different configurations

observed when using a legacy simulation approach for closed-loop power control, which requires longer time to converge. The proposed method appropriately mimics its behavior, with a reduction of the simulation complexity.

Furthermore, we have exploited the proposed model to analyze the interplay between different access selection policies and power control schemes, both open and closed-loop. The results show that the overall system performance strongly depends on both aspects, which evince the need to foster accurate models.

In our future work, we will exploit the proposed approach for the system-level analysis of ultra-dense heterogeneous scenarios, in particular those embracing many user devices, which will become more prominent in forthcoming 5G deployments. In addition, we will also fine tune the model to consider advanced scheduling and cooperation techniques.

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