Interference Analysis in a LTE-A HetNet Scenario: Coordination vs. Uncoordination

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Abstract—The electromagnetic spectrum is a scarce resource that needs to be efficiently and effectively reused to allow the provider the necessary conditions to satisfy its costumers increasing demands. It is vital that the reuse of the spectrum does not lead to high interference scenarios. The use of heterogeneous networks (HetNets) allows a better spatial reuse of the spectrum. However it also leads to higher interference scenarios. Thus, it is necessary to create tools that help to mitigate the interference, increasing the effectiveness of spectrum reuse. This paper evaluates interference-coordination algorithms based on game theory for scenarios with different access policies. The results are given in terms of user and cell throughputs. They show that although the use of closed access policies can benefit from the use of cell-driven algorithms, open access policy is preferential to use with user-driven algorithms, in particular for the increase of the service capacity.

Keywords: LTE, Interference, Game Theory, Mitigation, Coordination, HetNet.

I. INTRODUCTION

Following the formal definition of the 3rd-Generation Wireless (3G) by ITU-R in 1997, researchers have focused all their attention on the demanding specifications of the 4th-Generation (4G) of wireless cellular systems. The 4G systems are expected to have peak rates of 100 Mbit/s for high mobility and 1 Gbit/s for low mobility with a good Quality of Service (QoS) [1].

Studies based on the usage of wireless technology indicate that more than 50% of voice calls and 70% of data traffic are originated indoors [2]. This suggests that a large percentage of data traffic and voice calls are originated in HotSpot zones, zones with high population density.

The macro cells (Mcells), already deployed by the operator in the network, do not allow the achievement of such high data rates. The deployment of pico cells (Pcells) is then a necessary step to try to achieve these data rates.

Pcells offer small area coverage, low-power consumption and present a low price. Thereby, these cells can offer better coverage and better data rate services in the zones in which they are deployed, which makes them an interesting technology for the improvement of service in HotSpot zones. Nevertheless, the spectrum is a natural scarce resource that needs to be shared among cells. The reuse of the spectrum can lead to high interference scenarios that need to be dynamically treated, in order to offer a better solution to all network users. Taking all of this information together, the aim of this research work was to create a tool that allows the study of the advantages and drawbacks of different approaches when trying to mitigate the interference in a Heterogeneous Network (HetNet), where Macro Basestations (MBS) and Pico Base Stations (PBS) coexist.

The remainder of the paper is organized as follows. In Section II, an overall view of the state of the art in interference analysis and interference mitigation is presented. This section also focuses on information about LTE/LTE-Advanced. Section III describes the algorithms proposed for the mitigation of the interference. Four algorithms are presented in this section. Numerical results of the algorithms are presented in Section IV. Finally, the conclusions withdrawn from this work and future perspectives are presented in Section V.

II. PROBLEM FORMULATION

The key features for downlink connections presented by the 3rd Generation Partnership Project (3GPP) in the release 8 of the Long Term Evolution (LTE) project were the use of Orthogonal Frequency Division Multiple Access (OFDMA), in order to avoid inter-symbol interference (ISI) provoked by multipath, and Multiple-Input Multiple-Output (MIMO) techniques which are used to increase the spectral efficiency. In December 2009, the first publicly implemented LTE service, was tested by TeliaSonera in Stockholm and Oslo [2]. This LTE service presented great improvements, especially when compared with the previous data rates and QoS achieved. However, the measurements showed that the system did not fully comply with the ITU-R requirements for 4G systems. Due to these problems LTE started to be widely referred in the scientific community as 3.9G. December 2009 was also the time when 3GPP froze the Release 9 of the LTE project, which included minor changes to the previous release and thus it was not seen as the real 4G wireless technology project. Among these minor changes it is important to emphasize the introduction of Pcells and dual-layer beamforming. From this point onwards Pcells started to gain more popularity in the research world.

The real attempt by 3GPP to achieve the ITU-R demands for a 4G system started with the Release 10 of the LTE project, also known as LTE-Advanced. Since LTE already achieved data rates very close to the Shannon limit, the main focus must be in increasing the Signal to Interference and Noise Ratio (SINR) experienced by the user equipments (UEs) and hence provide higher data rates over a larger portion of the cell
[2]. With that purpose the maximum bandwidth was increased from 20 MHz to 100 MHz.

As stated before, the best way of improving the capacity of the systems is to increase the signal-to-interference and noise ratio (SINR). The transmitted signal decays with \( C \cdot d^{-\alpha} \), where \( C \) is a fixed loss, \( d \) is the distance between transmitter and receiver and \( \alpha \) is the path loss exponent, which depends on the radio-environment. Therefore, to maximize the received signal, and consequently the SINR, it is necessary to minimize \( d \) and/or \( \alpha \) [2]. Thus, taking transmitters and receivers closer to each other (minimizing \( d \)) is an important step when trying to increase the capacity of the system. To do so, it is necessary to introduce more basestations (BSs) in the system. These new BSs (PBSs) must have lower coverage area (lower power) than the macro basestations (MBSs) that already exist in the system and must be able to work on a plug-and-play basis.

Another important feature of the PBSs that needs to be analysed is the access policy, which highly depends on “who is the owner of the cell”. If the cell belongs to a private user it is expected that he wants to have all the capacity of the cell to his equipment, this access policy is known as ”closed access”, since it offers a private access to its user. On the other hand, PBSs that are deployed with the intention to serve the users in a public HotSpot area, must have an ”open access” policy.

A. Sources of Interference

The main interference sources in a wireless communication are Inter-Symbol Interference (ISI), Adjacent-Channel Interference (ACI) and Co-Channel Interference (CCI). As stated before, since downlink in LTE/LTE-A is made through the use of OFDMA, ISI can be ignored. OFDMA is also quite robust to ACI, the interference caused by extraneous power in an adjacent channel.

CCI occurs when two transmitters, electromagnetically close to each other, are working with overlapping frequency channels. Hence, to avoid interference problems, MBSs and PBSs must be able to know which resources their neighbouring stations are using in each region of the cell, so that SINR does not decrease to forbidden levels that prevent good QoS.

To help BSs improve each UE receiving capacity, UEs must have the ability to measure the interference it is receiving in each PRB. These values must then be used by the BSs to determine which are the PRBs that better serve each UE.

B. Spectrum Sharing

While sharing the spectrum between Pcells and Mcells, several approaches are possible. In what concerns the analysis of the interference, two extreme approaches exist [1], [3]. Figure 1-A presents an approach where CCI only occurs among cells from the same type, with the drawback of leading to an inefficient reuse of the spectrum. Figure 1-B present the opposite approach, where all the cells share the same spectrum band.

C. Mitigation

There are different approaches that can be taken into account when trying to mitigate the interference in a HetNet. Reinforcement-Learning and Game Theory are the two most used approaches.

In Reinforcement-Learning, as in a Q-Learning strategy [4], [5], the actions of the agents (transmitting equipments) are based on a trial-and-error strategy. The agent needs to discover which actions yield the bigger reward by trying all the possible strategies. The key feature on this approach is the duality between exploring and exploiting. A reinforcement-learning agent must seek the actions that gives it a higher reward, choosing between the actions it previously took and undertaking actions that it has not performed before [6].

In Game Theory, agents are seen as players in a board-game, trying to create strategies that maximize their earnings, based on previous strategies of their opponents [7], [8]. In equation 1, \( a^* \) is the action that maximizes the utility function \( u(a) \) of the player [9].

\[
\alpha^* \in \arg\max_{a \in A} u(a) \tag{1}
\]

D. Coordination

A network with a coordinated architecture allows the exchange of control information among different cells through the X2 interface (wired channel as a digital subscriber line (DSL)). It is expected to offer a more accurate mitigation when compared with an uncoordinated architecture. In an uncoordinated architecture BSs can only rely on what they (and the UEs connected to them) sense, leading to simpler and faster choices with less precision.

The coordinated architecture uses the Inter-cell interference coordination (ICIC) that is sent to the neighbouring BSs through the X2 interface. ICIC is filled with control information measured by the UEs, as the Relative Narrowband Transmitted Power (RNTP), that informs about the PRBs where UEs are sensing a bigger load of interference [10].

III. TECHNICAL APPROACH TO THE SIMULATIONS

The specifications of the network architecture were chosen taking into account the 3GPP Technical Specifications presented in [11] and [12]. Some of the parameters used are listed below:

1) System Bandwidth: 40 MHz
2) Carrier Frequency: 2 GHz
3) Cells Operating Mode: FDD
4) Traffic Model: Full-buffer
5) Scheduling Technique: Proportionally Fair

The physical parameters of the antennas, as well as, the pathloss models used were chosen taking into consideration what is proposed by 3GPP in [13] for HotZones in urban scenarios. The Model 2 was used for the pathloss, that considers...
Line-of-sight (LOS) and Non-LOS (NLOS) conditions with different probabilities of LOS for the different BSs.

To improve the system capacity it is important to guarantee high values of SINR (equation 2):

$$SINR_{c,u}^n = \frac{P_{TX,c,u}^n | h_{c,u}^n |^2}{\sigma^2 + P_{\text{cell},u}^n}$$

Where $u$ is the index of the UE, $c$ the index of the cell and $n$ the index of the PRB, $P_{TX}$ the transmission power, $| h |^2$ the channel gain between transmitter and receiver and $\sigma^2$ is the variance of the Additive White Gaussian Noise (AWGN). $P_{\text{cell},u}$ is the sum of the powers received by the UE, coming from the neighbour PBSs and MBSs, except to the one it is connected to.

The maximum achievable rate can be then calculated as expressed in equation 3:

$$R_u = \sum_n \log_2 \left( 1 + A_{c,u}^n \cdot SINR_{c,u}^n \right)$$

Where $A_{c,u}$ depicts the influence of a Rayleigh Fading Channel. The Rayleigh fading channel is simulated as a random variable that follows an exponential distribution with mean value 1 [14]. In the following sections, $A_{c,u}$ will be omitted in all the equations. Since it represents a channel power gain it can be seen as making part of the channel gain between the user and the cell in the following equations.

### A. Mitigation Technique

It was considered that both uncoordinated and coordinated cell architectures would have small optimization problems to be solved in each cell. Although less accurate than a centralized approach, this approach is more realistic since it asks for less computational power, offering a faster response of the system.

For the coordinated cell architecture a two-ranked hierarchical approach was considered, where cells with higher rank - MBSs - only choose their actions after receiving from the cells with lower rank - PBSs - the information about what actions they are going to perform in the next TTI. Thus, a Stackelberg game approach was considered, as proposed by Bennis et al. in [7].

For the uncoordinated cell architecture it was considered that each cell would act selfishly, working only with the informations sensed by its UEs in the previous TTI. Therefore, a game theory based on Nash Equilibrium was considered, as proposed in the same study [7].

The utility function used for the mitigation of the interference over the $N$ PRBs of cell $c \in \{1, ..., C\}$, in both coordinated and uncoordinated architectures, was:

$$-u(p_c^n) = -\sum_{u=1}^N \log_2 \left( 1 + \frac{p_c^n \cdot | h_c^n |^2}{\sigma^2 + \sum_{j \neq c}^{C} p_j \cdot | h_{u,j} |^2} \right)$$

The difference from one architecture to the other is that $p_j$ is the power used by the neighbouring BSs in the previous TTI for the uncoordinated architecture and for the PBSs in the coordinated architecture. In the case of MBSs - high rank agents - in a coordinated architecture, $p_j$ is the power that the neighbouring PBSs are going to use in each PRB, in the next TTI.

Equation 4 can be easily proven to be convex with the properties presented by Boyd and Vandenberghe in [15].

### B. Algorithms

Algorithms start by scheduling which UE will use each PRB in the next TTI. After the schedule is done, each BS will try to arrange its total transmission power ($\mathcal{T}_c$) among all the frequency channels. It is at this point that the two proposed algorithms differ. The cell-driven algorithm will try to maximize the global throughput of the cell (equation 5 and figure 2). In the user-driven algorithm (equation 8 and figure 3) each user is awarded with a percentage of the total power of the cell. This percentage is equal to the percentage of PRBs it received from the scheduler. Then, the algorithm distributes the power in the way that maximizes the throughput offered to each user.

The utility functions in equation 5 and 8 were derived from equations 2 and 3.

$$\max_{p_c} \sum_{n=1}^N \log_2 \left( 1 + \frac{p_c^n \cdot | h_c^n |^2}{\sigma^2 + \sum_{j \neq c}^{C} p_n \cdot | h_{u,j} |^2} \right)$$

$$s.t. \sum_{n=1}^N p_c^n \leq \mathcal{T}_c$$

$$p_c^n \geq 0$$

As presented in [7] the optimization problem is solvable with the Water-Filling technique [16], obtaining the following solution (equation 6):

$$p_c^n = (K - \lambda_c^n)^+$$

with,

$$\lambda_c^n = \frac{\sigma^2 + \sum_{j \neq c}^{C} p_j \cdot | h_j |^2}{| h_c^n |^2}$$

Where $(x)^+ = \max\{x, 0\}$, $K > 0$ is a constant chosen so that $\sum_{n=1}^N p_c^n \leq \mathcal{T}_c$, which guarantees that all the power of the cell is being used where it is most useful.

In Figure 2 an overview of the cell-driven approach is presented.

**Figure 2.** Cell Driven Algorithm: focus in the overall throughput of the cell.
The optimization problem for the user-driven approach is:

$$\max_{p_{c,u}} \sum_{n=1}^{N_{u,t}} \log_2 \left( 1 + \frac{p_{c,u}^n \cdot |h_{c,u}^n|^2}{\sigma^2 + \sum_{j \neq c}^{N} p_{j}^n \cdot |h_{j}^n|^2} \right)$$

s.t. \( \sum_{n=1}^{N} p_{c,u}^n \leq P_{c,u,t} \) \hspace{1cm} (8)

$$p_{c,u}^n \geq 0$$

Where \( N_{u,t} \) is the number of PRBs allocated to user \( u \) in TTI \( t \) and where \( P_{c,u,t} = N_{u,t} \cdot P_{\text{PerPRB}} \), with \( P_{\text{PerPRB}} = P_{c}/N \).

In Figure 3 an overview of the user-driven approach is presented:

**IV. NUMERICAL RESULTS**

Some tests were performed to the algorithms presented in the previous section. A scenario with only one MBS was used. PBSs and UEUs were placed randomly in the cell area. To get a better analysis, 100 different scenarios with the same characteristics will be considered in each test.

**A. Pcell Density Analysis**

The first test will consider a closed-access policy to test how each algorithm behaves with different densities of PBSs. 10 UEs were placed in each Pcell while 20 UEs were placed all over the Mcell. The UEs were automatically attached to the BSs. The performance of each cell is done through the analysis of the average throughput offered to each user during a period of 100 TTIs.

Figures 4 and 5 show the evolution of the average throughput offered to MUEs and PUEs when the number of PBSs increase in the system.

It was expected that the coordinated algorithms (black and blue triangles) would present better results, since the MBS has access to the PBS future actions. Nevertheless, the strategy of the algorithms (maximize the offered throughput) diverges from the strategy of the PF scheduler (distribute the users over time in a fair way). Thus, simulations show better results when using the uncoordinated algorithms (green circle and red cross).

While in the user-driven algorithms (black triangle and red cross) MUEs and PUEs have a similar average throughput, the cell-driven algorithms (green circle and blue triangle) present much better results for the MUEs and much worse results for the PUEs. It is also observed that the PUEs in the cell-driven algorithms present a big resistance to the increase of the number of PBSs in the system.

**B. Open Access Policies**

In the present subsection of the article the introduction of an open access policy will be studied. While in a closed access policy PBS are deployed to serve some specific users, in an open access policy any UE can connect to any BS. To do so, the UEs must be able to find which of the neighbouring BSs is capable of offering it a better service. Two algorithms were tested with that propose and then compared with the closed access policy (dark blue line in plots 6 and 7).

The first algorithm (distance criterion) will try to avoid scenarios where a MUE is placed in the middle of the PUEs by making the PBSs absorb all the MUEs that are within a fixed distance from the them. In the next plots (6 and 7) this algorithm is represented by purple colour (fixed distance of absorption of 30 meters) and green colour (fixed distance of absorption of 40 meters).

The second algorithm (power ratio criterion) considers that the UE will choose which is the BS it wants to connect to based on the following criterion: the UE must always connect with the MBS if the received power (Rx) from the MBS when compared to the Rx from the nearest PBS is higher than a given threshold value. Otherwise, it must connect to the PBS.

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the network provider does not have any interest in harming its users while protecting the PBS users. The results obtained for the cell-driven algorithm present it as a good candidate to optimize a network with a closed access policy.

The results obtained show that the network can benefit with an open access policy where the attachment criterion is based in the power ratio. An open access policy usually happens when the network provider wants to increase the capacity of the service in a small zone of the network (HotSpot). In that case, the network provider is interested in serving all the users (PUEs and MUEs) the same way. The user-driven algorithm seems to present a good attempt to fulfill this necessity.

Although interesting, the results obtained for the throughput offered to the UEs are quite low when compared with the expected values for a LTE/LTE-Advanced system. The use of a different frequency reuse schemes, without a frequency reuse 1, motivated by the frequency liberation caused by the substitution of the analog television for the digital terrestrial television (DTT) can be an important step into trying to achieve that results.

**REFERENCES**


