Analysis of CoMP for the Management of Interference in LTE

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***Abstract*— The deployment of LTE radio networks, namely in urban scenarios, implies that capacity needs to be maximised, thus, being usual that a "single-frequency" is taken, i.e., all base stations share the same overall available spectrum. However, this approach leads to interference, which can achieve quite high levels, with harmful consequences in the QoS and QoE made available to users. Normally, off-centre users are the ones who suffer more interference. In order to manage this interference, off-centre users use the CoMP technique, more precisely the JT one. A detailed analysis of the CoMP effect on throughput is addressed for the 800, 1800 and 2600 MHz bands in urban scenario in a homogeneous network. The model was implemented in a computational tool to provide a generic study of any scenario. Two versions of the simulator were developed, for static and temporal scenarios. The former analyses network performance at a given time instant, aiming to assess the correct functioning of CoMP. The latter has the capability to do a temporal analysis, with the objective of understanding how CoMP affects network performance. In the second version two separate studies were performed: the low and mid load scenarios. With CoMP in low load scenarios, the off-centre users' throughput presents a gain above 74% in the 2600 MHz band and above 58% in 1800 MHz; in the mid load scenario one achieves a gain around 40% in 2600 MHz.**

Keywords-Coordinated Multipoint; Joint Transmission; LTE; Management of Interference; Quality of Service; Urban Scenarios.

I. INTRODUCTION

Over the years, mobile communication systems became crucial for the people's lives. Currently, mobile phones are very important and with them is possible to do several tasks such as: making phone calls, sending messages and e-mails, watching videos and taking notes. Although the number of consumers recently has not been having an exponential growth, the mobile traffic suffered changes and the data traffic grown unbelievably. According to [1], the growth in data traffic is being driven both by increased smartphone subscriptions and a continued increase in average data volume per subscription, fuelled primarily by more viewing of video content. Data traffic grew 10% quarter-on-quarter and 60% between Q1 2015 and Q1 2016. Nowadays, the LTE-A is the best technology implemented and used in mobile communication systems. Although it has several advantages, also it has some disadvantages. One of them is the interference caused by the capacity that LTE offers, particularly in urban scenarios.

To solve this problem, there are a several techniques, however the technique used in this thesis is the Coordinated Multipoint (CoMP) technology. CoMP was completed in 3GPP Release 11 and uses multi-cell transmission and reception in order to improve the radio communications. The CoMP modes can be identified in Coordinated Scheduling and Beamforming (CS/CB), and Joint Processing (JP). CS/CB requires the least amount of information exchange between eNodeBs since User Equipments (UEs) receive a data transmission from their respective serving cell only, but adjacent cells perform coordinated scheduling and/or transmitter precoding to avoid or reduce the inter-cell interference. JP CoMP aims to provide the UE data for multiple transmission points (eNodeBs) so more than just the serving cell can take part of the transmission for a UE. This requires large bandwidth, very low latency backhaul, in practise, fibre connectivity, between eNodeBs sites. The JP is divided into Dynamic Cell Selection (DCS) and Joint Transmission (JT). DCS the data is sent always from one eNodeB only, based on the UE feedback. In JT CoMP, multiple cells jointly and coherently transmit to one or multiple terminals on the same time and frequency resources [2].

As stated before, the interference is present in mobile communication systems, and the off-centre users are the most affected because usually are covered by more than one BS. The off-centre users' throughput decreases due to this interference, and thus the centre users have usually better Quality of Service (QoS) than the off-centre users. The strategy adopted to combat the off-centre users' problems was to implement the JT. During a LTE connection, there are two different types of air interfaces. One is downlink (DL), from Base Station (BS) to UE, and the other is uplink (UL), from UE to BS. However, in this thesis, it is only considered DL communication.

II. STATE OF THE ART

Several studies addressing the CoMP impact in LTE systems are described in the literature. This section states the work developed by several authors in the area of implementation analysis and performance of CoMP.

In [3], it is studied the performance of DL CoMP in LTE under practical constraints. LTE Release 10 (also called LTE-Advanced) further improves spectral efficiency primarily by providing support for Multi-User MIMO (MU-MIMO) transmissions. Beyond LTE Release 10 the capability to support CoMP transmissions has been prioritized by many cellular operators worldwide as a principal focus area for improving spectral efficiency with LTE Release 11. In order to study CoMP performance under realistic LTE deployment constraints, it was considered two techniques, the DCS and the CoMP JT. The simulation results focus on two deployment scenarios, a macro-only urban scenario with each cell transmitting 46 dBm power and a HetNet where four pico cells transmitting at 30 dBm power each are additionally placed (randomly) within each macro cell area. It was concluded that CoMP transmission primarily benefits cell-edge UEs and can provide a 5%-tile UE throughput gain of up to 30%.

In [4], the Inter-cell Interference is mitigated by Dynamic Point Blanking (DPB), which is a CoMP technology. CoMP DPB allows dynamic point muting in the time and frequency domains. The performance of Single-User MIMO (SU-MIMO) without CoMP is used as the baseline for comparison with CoMP DPB scheme. The evaluated CoMP DPB scheme has coordination within one macro cell and the small cells within its geographical area. SU-MIMO is supported for UE scheduling at each coordinated cell. The maximum number of SU-MIMO data streams per UE is 2, and dynamic rank adaptation is supported. The performance of CoMP DPB with ideal backhaul and coordination within one macro cell and its covered small cells can give 48% cell-edge throughput gain with the cost of 1% cell-average throughput loss compared to SU-MIMO. For macro-cell UEs, there are 1% cell-average throughput gain and 20% cell-edge throughput gain. For small-cell UEs, there is 46% cell-edge throughput gain, at the cost of 1% cell-average throughput loss. It was also done the evaluation results for inter-eNodeB CoMP, with non-ideal backhaul. The evaluated inter-eNodeB CoMP DPB is between one macro cell and small cells within its geographical area. Each coordinated cell uses SU-MIMO for UE scheduling. The non-ideal backhaul configuration transmission delay was done for 4, 8, 12, 16, 20, 40, 60 ms of two-way backhaul delay. CoMP DPB with 4 ms two-way backhaul delay is used as the baseline for performance analysis. There is almost no performance loss with the backhaul delay from 4 ms to 16 ms and only marginal performance degradation for the backhaul delay from 20 ms to 60 ms. These gains are shown to be robust against two-way backhaul delays of up to around 16 ms.

The algorithm described in [5], it is applied in [2], and it shows the gains with DPS both in three-sector macro-cell environment and in HetNet scenario, with ideal backhaul assumed between the baseband units. DPS solution can be implemented with reasonably low backhaul requirements. The cell-edge gain in macro cell is 75% and in HetNet case about 50% which illustrates the power of DPS solution. These results assume a realistic handover margin of 2 dB, and DPS is able to fully overcome the negative effects of handover margin.

In [6], the study used a Dynamic Frequency Reuse (DMFR) and CoMP technique, which are applicable to LTE heterogeneous network (macro-cell/femto-cell) and they are able to enhance both cell edge and adjacent sector transmission performance through adaptive spectrum allocation, interference management and CoMP techniques. DMFR allocates dynamically and reuses spectrum based on the numbers of UEs in adjacent cell sectors and cell edge, and the cell outside surplus spectrum for cell center. The study also implemented the concept of CoMP to assist data transmission for cell edge UEs. CoMP has two operating modes: JP mode and CS/CB mode, respectively. In JP operating mode, data is transmitted from several BSs to the same UE coherently (tight synchronization is needed) or non-coherently (gain obtained from power boost). In CS/CB operating mode, scheduling and beamforming are coordinated among cluster BS. In this study were made two simulations. The simulations assumed an urban area and the UEs are randomly distributed (cell-center, cell-outside or cell-edge). The total bandwidth was 20 MHz with each subcarrier 12 kHz. Each RB was made of 18 sub-carriers within one time slot. Each transmission time interval (TTI) consisted of two time slots and makes 1 ms. The cell layout was composed by 3-sectored hexagonal and 7-cell cluster. Femtocells were uniformly distributed among 7-cell clusters. For the first simulation, the cells were divided into 3 sectors (C, D and E), and it was considered that cell 1, cell 6 and cell 7 were neighbours. The cell 1 of the sector E, the cell 7 of the sector C and the cell 6 sector D became neighbours. If the number of UEs of cell 1 sector E is greater than sum of the numbers of UEs of cell 6 sector D and cell 7 sector C then cell 1 uses CoMP CS/CB method, otherwise uses CoMP JP method. This simulation compared the throughput of both DMFR and FFR, and the results shown that DMFR outperforms FFR by 33.51% in terms of throughput for 7-cell scenario and 78.12% for (1 cell/CS/CB) scenario. In the second simulation, it was compared the 7-cell spectrum utilization of both DMFR and FFR and the results showed that DMFR outperforms FFR by 99.87% for 7-cell scenario and 140.12% for (1 cell, CS/CB) scenario.

III. MODEL DEVELOPMENT

A. Model Parameters

The parameters under study in this work are the received power, the SNR, the SINR and the throughput. The received power is calculated by using the link budget and it is expressed in the following expression [7]:

$$P_{r\,[\mathrm{dBm}]} = P_{Tx\,[\mathrm{dBm}]} - L_{c\,[\mathrm{dB}]} + G_{t\,[\mathrm{dBi}]} + G_{r\,[\mathrm{dBi}]} - L_{p,total\,[\mathrm{dB}]} \quad (1)$$

where:

- G_r: Gain of the receiving antenna;
- $L_{p,tot}$: Path loss;
- P_{Tx}: Transmitter output power;
- L_c: Losses in the cable between the transmitter and the antenna;
- G_t: Gain of the transmitting antenna.

To calculate the path loss is used the COST 231 Walfisch-Ikegami model.

$$L_{p,total[\mathrm{dB}]} = L_{p[\mathrm{dB}]} + M_{FF[\mathrm{dB}]} + M_{SF[\mathrm{dB}]} \quad (2)$$

where:

- L_p: Path loss from the COST 231 Walfisch-Ikegami model;
- M_{FF}: fast fading margin;
- M_{SF}: slow fading margin.

For the calculation of the SNR, noise power needs to be taken into account:

$$N_{[\mathrm{dBm}]} = -174 + 10\log(N_{RB} \times B_{RB[\mathrm{Hz}]}) + F_{[\mathrm{dB}]} \quad (3)$$

where:

- N_{RB}: number of RBs;
- B_{RB}: bandwidth of one RB, which is 180 kHz;
- F: noise figure.

After that, one can finally compute the SNR, by the following relation:

$$\rho_{N[\mathrm{dB}]} = P_{Rx\,[\mathrm{dBm}]} - N_{[\mathrm{dBm}]} \quad (4)$$

where:

- N: Average noise power at the receiver.

Interference being one of the most important parameters in this thesis, it has to be calculated. Since there is communication between BSs and UEs, there is information about RBs distribution and the interference can be calculated. The interference power at the receiver is calculated as the sum of the received power of the signals that are supported in sub-carriers placed in the same frequency as the desired signal, according to the following equation:

$$I_{[\mathrm{mW}]} = \sum_{n=1}^{N_I} I_{i[\mathrm{mW}]} \quad (5)$$

where:

- I_i: interference power coming from transmitter i;
- N_I: number of interfering signals reaching the receiver.

Afterwards, it is calculated the SINR available at each UE's receiver in order to study the impact of interference on system performance. The SINR is given by (6):

$$\rho_{IN[\mathrm{dB}]} = 10\log\left(\frac{P_{Rx[\mathrm{mW}]}}{N_{[\mathrm{mW}]} + I_{[\mathrm{mW}]}}\right) \quad (6)$$

The formula of the relation between throughput and SNR was based on [8]:

$$R_{b\,[\mathrm{bit/s}]} = \frac{A}{B + e^{-C\,\rho_{[\mathrm{dB}]}}} \quad (7)$$

where A, B and C depend on whether QPSK 1/3, 16QAM 1/2 or 64QAM 3/4 is considered. For the coverage calculation, QPSK was picked.

The user throughput is given by (8) being the sum of the throughputs from all RBs allocated to UE [8]. The modulation chosen is the one that enables to achieve the best throughput for one RB.

$$R_{b,user[\mathrm{Mbps}]} = \sum_{i=1}^{N_{RB,user}} R_{b,RB\ i[\mathrm{Mbps}]} \quad (8)$$

where:

- $N_{RB,user}$: number of RBs allocated to UE;
- $R_{b,RB\ i}$: RB i throughput.

The total throughput of a given sector can be obtained from [8]:

$$R_{b,sector[\mathrm{Mbps}]} = \sum_{i=1}^{N_{u,sec}} R_{b,user\ i[\mathrm{Mbps}]} \quad (9)$$

where:

- $N_{u,sec}$: number of users served by the sector.

In order to calculate the CoMP throughput there was the need to assume the scenario as ideal, summing all of the throughputs in all connections as available, whereas in a real scenario may exist losses.

$$R_{b,CoMP[Mbps]} = \sum_{n=1}^{3} R_{b,n[Mbps]} \quad (10)$$

where:

- $R_{b,n}$: the served throughput by BS n.

The received power changes over time due to fading which can be of two kinds: fast fading and slow fading. In the first one, the channel impulse response changes rapidly within symbol duration, whereas for the latter, the impulse response changes much slower than transmitted signal, thus in this thesis only slow fading is considered. The distribution used in slow fading cases and absence of fast fading is Log-normal. The fading margin can be calculated by [7]:

$$M_{F[\mathrm{dB}]}^{p\%} = u(p\%)\sigma_{e[\mathrm{dB}]} \quad (11)$$

where:

- $u(p\%)$: value obtained from the respective percentage value for the normal distribution;
- σ_e: standard deviation of propagation model chosen.

B. Model Algorithms

In this thesis is important to divide the cell in several regions. As can be seen in Figure 1, the cell is divided in cell-centre and cell off-centre. Normally, the cell-centre users have a good QoS and, for that reason, for this thesis only the cell off-centre users need to be concerned, with particular attention to cell-edge users. The cell off-centre users are the most affected by interference, thus the CoMP is used for these users. CoMP technology allows the users to be connected to more than one BS. In a theoretical scenario, one user can be covered by three sectors (middle of three sectors), thus it was defined a maximum of three connections.

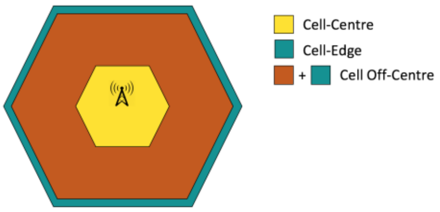

Figure 1 - Cell regions.

During this analysis, the algorithm starts searching for users in each sector. After searching in the three sectors and calculating the received power for each user, the algorithm starts to search for users in other BSs. This analysis stops when all BSs had been analysed. If the received power for a user is equal or higher than the threshold, this user is considered as a cell-centre user and it is served uniquely by one BS, otherwise the user is considered as a cell off-centre and it is served by either one, two or three BSs. During a LTE connection, there are two different types of air interfaces. One is DL (from BS to UE), and the other is UL (from UE to BS). However, in this thesis, it is only considered DL communication. As mentioned above, the concern of this thesis is the cell off-centre users, thus only these users are going to use the CoMP as technique for management of interference, more precisely the JT technique.

The first module, described in Model Implementation, generates a file with users. These users have different geographic coordinates, performing different services. This module is based on modules built in previous works [9], for cases where there is no temporal domain. The approach chosen to counter the problem was to use this module to generate geographic coordinates, which perform different services. The file generated in first module is read by the second module, and thereafter it is done a verification whether it is a service with a duration (video calling, video streaming and music) or a service with a size (e-mail, web browsing and file sharing). The duration of the services and the pauses is generated with the exponential distribution and the size of the services is generated with the log-normal distribution [10]. Hence, the total number of users will no longer be the number of geographic positions, but the number of users which started a service, i.e., the sum of all started services is the total number of users. When the service is terminated, the user is considered as a served user.

Before starting the simulation, it is chosen its duration. Afterwards, all geographic coordinates are analysed, and if there is an active user in this coordinate, it is calculated the user's throughput for each millisecond. When the user finishes its service, that geographic coordinated will be paused during a random interval generated. As soon as the pause has finished, it generates a new user in that geographic position. This process is going to be repeated until the end of the simulation.

C. *Model Implementation*

It was done two version of the model and there are some differences between them. The first version analyses the network performance at a given time instant, taking like a "snapshot" of traffic, with objective to assess the correct functioning of the CoMP. The second version has capability to do a temporal analysis. Another feature included is the variation of received power over time. Therefore, this second version allows to understand how the CoMP affects the network system. Each version is divided into three modules.

In version one, the first module creates a .txt file with users' positioning along the entire city of Lisbon, on the other hand, in version two, the first module of the simulator creates a .txt file with users' positioning along Parque das Nações, which is the area that will be analysed during the temporal simulations.

The second module is the same for both version. It reads the information generated in first module and creates two files, one with information about BSs' location, the sectors each one of them has, and also information about users who are potentially covered by them, including their location, requested service and distance to the BS. The second with information about propagation model parameters, frequency band, bandwidth, antennas' parameters, services' minimum and maximum throughputs, duration of the simulation and the maximum number of BSs that users can be connected.

The third module of the first version has differences in relation with the second version. In version two the second block has a slow fading value oscillating over time, in contrast to the first version that has a fixed slow fading value. The second version also has differences in seventh block, since it has capability to perform temporal simulation. With the modifications realised, the block does the management of the users which can be activated or paused. Consequently, the seventh block of the second version returns different outputs, as can be seen above. This module reads the two files generated by the second module and creates files with information about the CoMP effects in the throughput, SNR, interference, SINR and the capacity of BSs. The third module workflow can be observed in Figure 2.

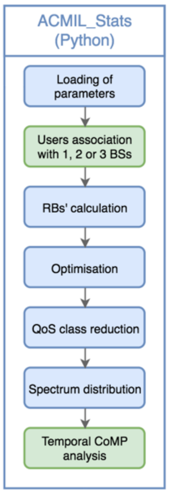

Figure 2 – Third Module Workflow.

IV. RESULTS ANALYSIS

A. *Scenario*

The geographical scenario studied for this thesis is different for the two versions of the simulator. In the first version, all tests are executed in city of Lisbon. On the other hand, the second version considers Parque das Nações, which is an urban environment in the city of Lisbon.

Three different frequency bands associated with their maximum available bandwidths are considered:

- 800 MHz band (with an associated bandwidth of 10 MHz), which provides high coverage, however may suffer more inter-cell interference;
- 1800 MHz band and 2600 MHz (with an associated bandwidth of 20 MHz), designed to offer better

capacity.

The study of each frequency band is done separately, therefore, each sector during a simulation has available the bandwidth and the frequency band previously selected.

Path loss is calculated using the COST-231 Walfisch-Ikegami propagation model and the parameters are shown in Table I [8].

Table I - Parameters for COST-231 Walfisch-Ikegami model.

Parameter Description	Value
Height of the BS antennas (h_b) [m]	25.0
Height of the buildings (H_B) [m]	21.0
Street width (w_s) [m]	30.0
Distance between buildings' centre (w_B) [m]	50.0
Incidence angle (ϕ) [º]	90.0
UE height (h_m) [m]	1.2

The antenna parameters chosen for each frequency band are different. In Table II can be seen these values in more detail [8].

Table II - Antenna parameters.

Parameter Description	Value		
Frequency band [MHz]	**800**	**1800**	**2600**
Maximum bandwidth [MHz]	10.0	20.0	20.0
DL transmission power [dBm]	43.0	42.0	43.0
BS maximum antenna gain [dBi]	16.4	17.8	17.5
Vertical half-power beamwidth [º]	7.4	5.5	4.2
Horizontal half-power beamwidth [º]	65.0	62.0	63.0
Electrical downtilt [º]	12.0	8.0	6.0
Sidelobe attenuation (vertical) [dB]	20.0		
Front-to-back attenuation (horizontal) [dB]	50.0		

Simulations were performed regarding six types of the services: video calling (VC), video streaming (VS), music (MUS), web browsing (WB), file sharing (FS) and e-mail (EM). For this thesis, the voice service was excluded due to several reasons. For the six services chosen, each BS sends packets in each millisecond, which for VoLTE, the packets are sent every 20 ms, therefore, it was decided to remove that service from the work. Another reason was that in this thesis is used CoMP, and the voice users will not benefit from it. Lastly, this simulator is based on previous theses and the VoLTE is not presented there. In future, it can be interesting to include the voice users to observe the network behaviour.

In Table III [1],[8], each service has a QoS priorities, minimum and maximum throughputs in each BSs, a duration or a size and a percentage of service mix. The QoS priorities are used to choose which service receives resources first, in other words, services with lower indexes are served first than with higher indexes (e.g., video calling is the most priority service). The service mix is the number of users, in percentage, that are using each different service.

Table III - Services characteristics.

Service	QoS Priority	Throughput		Dur [s]	Size [MB]	Service Mix [%]
		Min [Mbit/s]	Max [Mbit/s]			
VC	1	0.064	2.000	60	-	8
VS	2	0.500	13.000	300	-	30
MUS	3	0.016	0.320	180	-	20
WB	4	0.400	6.000	-	2.600	20
FS	5	0.400	6.000	-	2.042	12
EM	6	0.400	1.000	-	0.300	10

B. *CoMP Analysis in Static Scenario*

This section presents the CoMP analysis in static scenario, i.e., it presents a "snapshot" of the network and how the CoMP can affect it. The results were obtained from the first version of the simulator, and as has been said, this version performs a simulation in city of Lisbon. Inside of the Lisbon boundaries are deployed 399 users. It was done ten simulations for each frequency band, and the results can be observed in Figure 3 and Figure 4. In Figure 4, it is possible to observe the coverage for each frequency band and how many users are served.

In 800 MHz, as expected, it is the frequency that covers more users which, for this specific case, it covers all users in Lisbon. However, not all are served, because the minimum services' requirements are not ensured. One disadvantage of the CoMP is that the technique affects the capacity, since, if a user is connected to more than one BS, it consumes resources in each BSs. As this frequency band has 10 MHz of the bandwidth, it overloads quicker. In these simulations, when a user is connected to a maximum of two BSs, the number of served users increases and it happens because, when a user is connected to one BS, that BS may have its resources consumed, and without CoMP this user would not be served. On the other hand, when a user is connected to a maximum of three BSs, the number of the users served is affected, due to the priority users connected to the two or three BS.

The 1800 MHz frequency band is an intermediate band, since it has good coverage and it has better capacity than 800 MHz frequency band. This frequency band covers 388 users in the 399 possible. With CoMP, the capacity is a little bit affected, nonetheless the results without it are similar.

Finally, the 2600 MHz frequency band is the best frequency band in terms of capacity, but it is the worst in coverage. In this case, the system with CoMP serves a similar number of users than a system without CoMP, the explanation lies on the fact that the users covered decrease from 399 to 345, and for this reason the system has more capacity for the users connected to more than one BS. In second version of the simulator (temporal simulator), systems with more load are tested and it will be possible to learn more conclusions about this frequency band.

When a user is connected to a maximum of two BSs, the gains are above 30%. If a user is connected to a maximum of three BSs, the gains go beyond 60% in 800 and 1800 MHz frequency band and above 45% in 2600 MHz.

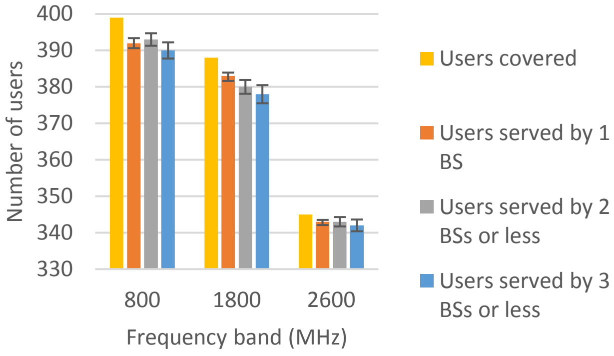

Figure 3 – Number of users covered vs number of users served.

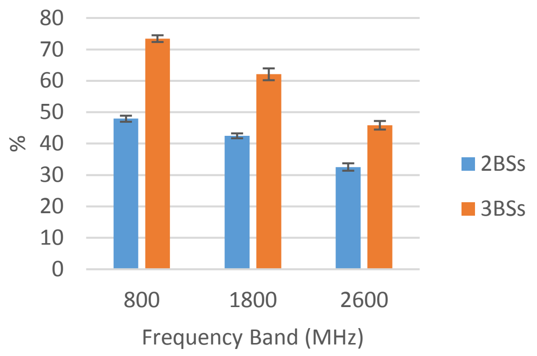

Figure 4 – Throughput Gain.

C. CoMP Low Load Analysis in Temporal Scenario

In this section, a detailed study of the CoMP is performed, followed by the results obtained for the 800, 1800 and 2600 MHz frequency bands. The results were obtained from the second version of the simulator. To simplify the results' description, when is referred CoMP with two BSs, it means that in this system an off-centre user can be connected to a maximum of three BSs and when is referred CoMP with three BSs, it means that in this system an off-centre user can be connected to three BSs maximum.

It was generated 50 geographic coordinates, however 9 of them were generated outside of the map's boundaries, thus the analysis of the low load scenario was performed for 41 geographic coordinates. The services generated in these geographic coordinates may be covered up to six BSs, and this network is set in Parque das Nações.

1) Frequency Band Analysis

This subsection deals with the behaviour of the CoMP with the variation of the frequency band. The variation of the frequency band results in a change in the capacity and coverage. In Table IV, it is presented the maximum number of users' positions covered by each frequency band.

Table IV - Coordinates covered by each frequency band.

Frequency Band [MHz]	Bandwidth [MHz]	Users' Positions Covered
800	10	41
1800	20	40
2600	20	35

As previously mentioned, the interference is harmful to the throughput, and the off-centre users are the most affected. When the simulator executes the algorithm without CoMP, the assumption uttered beforehand is confirmed. In Figure 5, five of the six services (Video Calling, Music, Web Browsing, File Sharing and E-Mail) have worse throughputs in cell off-centre conditions than in cell-centre conditions. This result was obtained with the 2600 MHz band, however for the others frequency bands, in general, the centre users have better throughput than off-centre users.

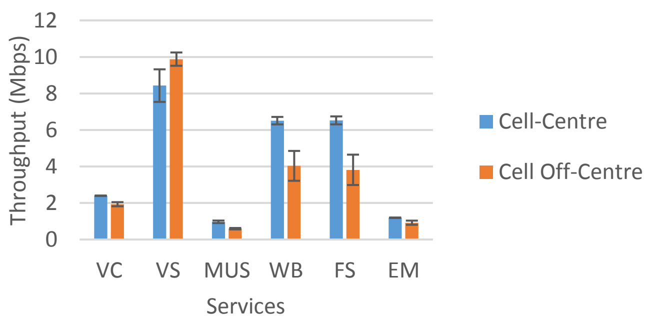

Figure 5 - Centre users vs off-centre users without CoMP for the 2.6 GHz band.

To summarise this subsection, it was created three graphics with throughput gains and losses in each system with the different frequency bands. Analysing firstly the 800 MHz band, there are no advantages of using CoMP with three BSs when compared with two BSs, as can be seen in Figure 6. This bad result is enhanced with the results present in Figure 7 and Figure 8. For systems with CoMP with three BSs the gain for off-centre users that perform CoMP is 16.8%, whereas, the other users (centre users and off-centre users that do not perform CoMP) have losses of 30.2% and 50.1%, respectively. The results for systems with CoMP with two BSs are not better, since the off-centre users that perform CoMP have a gain of 21% comparing with centre users and off-centre users who do not perform CoMP and have losses of 15% and 44.5%, respectively. The explanation for these bad results comes with the fact that this frequency band has less capacity. The 800 MHz band is the frequency band with the smallest bandwidth, 10 MHz. Therefore, this band has less capacity than 1800 MHz and 2600 MHz bands. For the first time, there are losses in the off-centre users that perform CoMP. When it is used the CoMP with three BSs the situation gets worse.

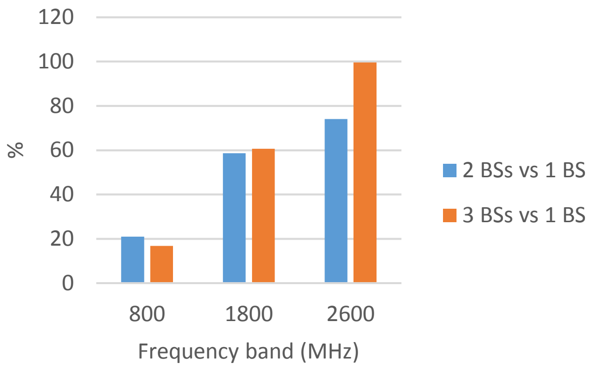

Figure 6 - Throughput gain between off-centre users with CoMP and off-centre users without CoMP.

For 1800 MHz band, in terms of gain, using CoMP with two and three BSs is almost the same, differing from 58.7% against 60.6%. However, the losses in systems with CoMP with three BSs are bigger than with two BSs. With two BSs, the centre users' losses are about 33.4% and in off-centre users that do not perform CoMP are 18.3%. With three BSs, the centre users' losses are 48.6% and in off-centre users that do not perform CoMP are 25.2%. This analysis was done in low load scenarios, therefore in this frequency band, in scenarios with more load, CoMP with three BSs can be harmful.

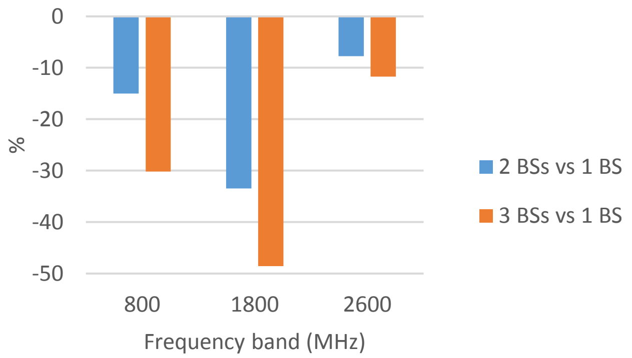

Figure 7 - Throughput loss between centre users in system with CoMP and centre users in system without CoMP.

Finally, the 2600 MHz band presents better results. This frequency band is the band with more capacity and less users are covered, consequently with more RBs available. In this band, the off-centre users that perform CoMP have gains of 74% in systems with CoMP with two BSs and 99.6% in systems with CoMP with three BSs. The centre users have small losses, 7.7% for two BSs and 11.7% for three BSs. The off-centre users that do not perform CoMP have minimal losses. In systems with CoMP with two BSs the losses are 2.7% and with three BSs are 4%. In this frequency band, both systems have excellent results, due to capacity of this band. However, with more load the scenario can change and, for this reason, it was tested a mid load scenario.

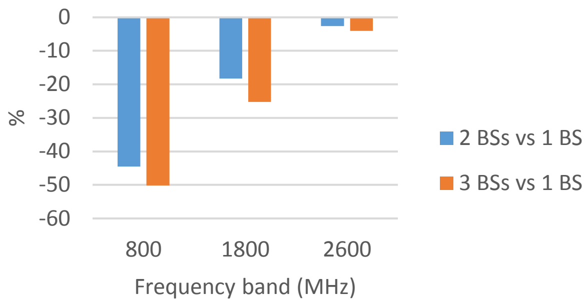

Figure 8 - Throughput loss between off-centre users who do not perform CoMP in system with CoMP and off-centre users in systems without CoMP.

2) *User Classification Analysis*

The users are classified as cell-centre and cell off-centre, and the condition which defines these two types of users is the received power. In reference scenario was defined that all users with a received power above -80 dBm were classified as cell-centre user. In this subsection, the threshold was modified to -100 dBm, therefore only the cell-edge users can use the CoMP technique. When threshold value decreases, there are less users available to perform CoMP, consequently there are less users using resource blocks in different BSs.

In this new scenario, the systems with CoMP with two BSs do not perceived the changes and the results are similar with reference scenario, as shown in Figure 9. However, the systems with CoMP with three BSs, the changes have a positive effect the changes have a positive effect, as can be observed in Figure 10. The off-centre users that perform CoMP in this new scenario have gained 84.2% against the 60.6% of reference scenario. The centre users and off-centre users that do not perform CoMP suffer less losses. In the first ones, the losses are of 38% in new scenario against 48.6% in reference scenario, and the second ones the losses are of 16.2% in new scenario comparing with the 25.2% loss in reference scenario. The changes done in condition to classify the users show in the case of the system does not have the capacity to perform CoMP in all off-centre users, at least the cell-edge users can have a better QoS, with less impact on the network.

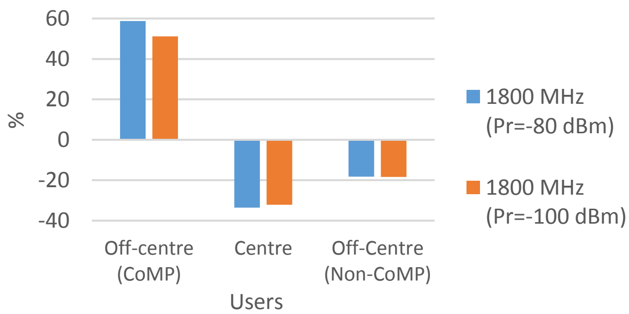

Figure 9 - Throughput gain and loss between a system with CoMP with 2 BSs and a system without CoMP in reference scenario and scenario represented in this subsection.

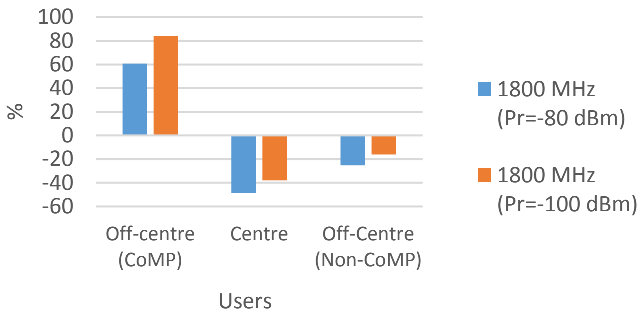

Figure 10 - Throughput gain and loss between a system with CoMP with 3 BSs and a system without CoMP in reference scenario and scenario represented in this subsection.

3) Service Percentage Analysis

In this subsection, a comparison between the reference scenario and a different service profile is performed. This section performs a video centric test, because Video Streaming is one of the most demanding resource services, since it has high priority and maximum throughput, thus it is interesting to observe how the system behaves. In Table V, it is possible to observe the differences between the reference scenario service mix and the new service mix. However, only the 2600 MHz band will be studied, since the simulations are slow.

Table V - Services mix scenarios.

Service	**Scenario [%]**	
	Reference	**Video Centric**
Video Calling	8	8
Video Streaming	30	45
Music	20	9
Web Browsing	20	24
File Sharing	12	9
E-Mail	10	5

The Figure 11 presents an overview of the gains and losses in systems with CoMP against system without CoMP. By looking at the figure, the benefits of CoMP are evident, where the off-centre exhibit gains above 100% and the centre users and off-centre users that do not perform users have losses below 12%. Once again, the CoMP brought considerable benefits, and it shows that, with the concentration of the most demanding service, CoMP can be efficient in a low load scenario.

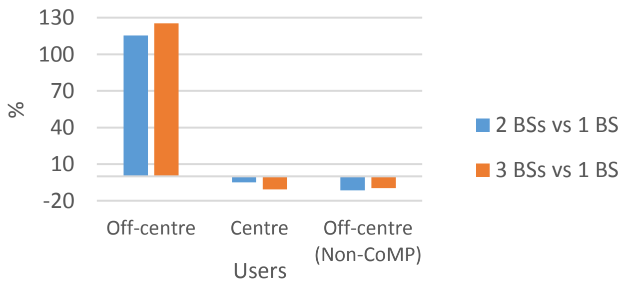

Figure 11 - Throughput gain and loss between systems with CoMP and a system without CoMP in a new service percentage scenario.

D. *CoMP Mid Load Analysis in Temporal Scenario*

In this section, the number of geographic coordinates was increased and subsequently the number of users also increases. It was generated 150 geographic coordinates, however 21 of them were generated outside of the map's boundaries, thus the analysis of the mid load scenario was performed for 129 geographic coordinates. As the simulations are very slow, the increasing of geographic coordinates turns the simulation slower. Thus, the tests for a mid load scenario were done only with one frequency band. The frequency band chose was the 2600 MHz one, because it offers the best capacity. The 2600 MHz band covers 100 geographic coordinates.

In short, with this scenario, the most effective method is the CoMP with two BSs, because presents greater gains than losses. In average, the off-centre users who perform CoMP have gains of 39.7%, the centre users have losses of 17.9% and off-centre users who do not perform CoMP have losses of 20.8% in systems with CoMP with two BSs. In contrast, the system with CoMP with three BSs, the off-centre users who perform CoMP have gains of 32.3%, the centre users have losses of 37.7% and off-centre users who do not perform CoMP have losses of 25.7%. With more load, the CoMP with three BSs is no longer effective, because the system is overload in systems with three BSs. However, the systems with CoMP with two BSs have positive results. These results can be observed in Figure 12.

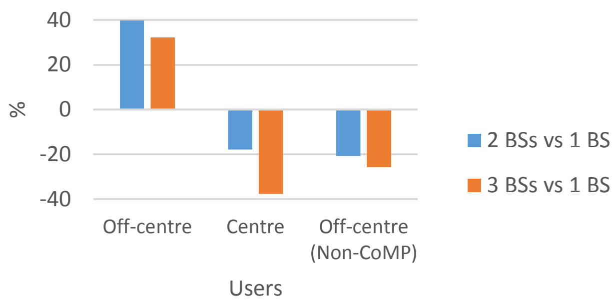

Figure 12 - Throughput gain and loss between systems with CoMP and a system without CoMP in a mid load scenario.

V. CONCLUSIONS

The main goal of this thesis was the study of the CoMP as technique for the management of the interference in off-centre users to improve their QoS. An initial analysis, in the city of Lisbon, was done in static scenario to observe the possible gains of CoMP. Afterwards, it was analysed the CoMP's behaviour in six BSs situated in Parque das Nações with low and mid load.

In the static scenario, for the 800 MHz frequency band, systems with CoMP with two BSs have a gain of 47.8% and with three BSs have a gain of 73.4%. The 1800 MHz frequency band, in systems with CoMP with two BSs have a gain of 42.5% and with three BSs a gain of 62% Finally, the 2600 MHz frequency band, in systems with CoMP with two BSs present a gain of 32.6% and with three BSs a gain of 45.8%. These results show the CoMP capability, even though the scenario is not real, since this scenario is a "snapshot" of the network. Therefore, for results more reliable it was tested a temporal scenario.

The simulations made to test the low load scenario for the different frequency bands presented different results for the each one. Starting by the 800 MHz band, the gain between the off-centre users who perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP, in average, is of 20.9%. The centre users in systems with CoMP with two BSs can suffer losses of 15% when compared with centre users in systems without CoMP. Furthermore, the loss between off-centre users who do not perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP is of 44.5%. The results with CoMP with three BSs are even worse, because the gains are even lower and the losses bigger. The gain for off-centre users who perform CoMP is of 16.8% and the loss for centre users and off-centre users who do not perform CoMP is 30.2% and 50.1% respectively.

The 1800 MHz band presents better results, nonetheless they are not perfect. The gain between the off-centre users who perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP, in average, is of 58.7%. The loss between centre users in systems with CoMP with two BSs and centre users in systems without CoMP is of 33.5%. As for the loss between off-centre users who do not perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP is of 18.3%. For three BSs, the gain for off-centre users who perform CoMP is of 60.6% and the loss for centre users and off-centre users who do not perform CoMP is of 48.6% and 25.2% respectively.

Finally, the 2600 MHz band, is the frequency band with the best capacity and performs the best results in this scenario. The gain between the off-centre users who perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP is of 74%. With three BSs, the gain increases to 99.6%. As stated before, the losses are minimal, in centre users in systems with CoMP with two BSs in comparison with centre users in systems without CoMP the losses are of 7.7%, and in systems with CoMP with three BSs against centre users in systems without CoMP the losses are of 11.7%. The loss between off-centre users who do not perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP is of 2.7%, and in systems with CoMP with three BSs rounds about 4%.

In user classification analysis, with less users to perform CoMP, less resources are used in the network. The results obtained for systems with CoMP with two BSs are similar with the reference scenario, however in systems with three BSs the results are better in this scenario. The gain in off-centre users who perform CoMP in systems with CoMP with two BSs is of 51.2% and with three BSs is of 84.2%. The loss in centre users in systems with CoMP with two BSs is of 32% and with three BSs is of 38%. In off-centre users who do not perform CoMP in systems with CoMP with two BSs, the loss is of 18.4% and with three BSs is of 16.15%. In comparison with the reference scenario, the CoMP with three BSs has less impact in the system and the cell-edge users better QoS.

The last test in the low load scenario was the video centric test. The gain between the off-centre users who perform CoMP in systems with CoMP with two BSs and off-centre users in systems without CoMP is of 115.3%, and with three BSs is of 125.3%. The loss between the centre users in systems with CoMP with two BSs and the centre users in systems without CoMP is of 4.9% and with three BSs is of 10.7%. At last, the loss between the off-centre users who do not perform CoMP in system with CoMP with two BSs and off-centre users in systems without CoMP is of 11.5%, and with three BSs is of 9.6%.

In the end, it was considered a mid load scenario. As expected, with more load the gains decrease and the losses increase. As previously, the gains and losses presented are a comparison between systems with CoMP and systems without CoMP. The off-centre users who perform CoMP have gains of 39.7%, the centre users have losses of 17.9% and off-centre users who do not perform CoMP have losses of 20.8% in systems with CoMP with two BSs. In contrast, the system with CoMP with three BSs, the off-centre users who perform CoMP have gains of 32.3%, the centre users have losses of 37.7% and off-centre users who do not perform CoMP have losses of 25.7%.

To summarise, CoMP in low load scenarios for 2600 MHz frequency band has excellent results in systems with two BSs and three BSs. In the 1800 MHz frequency band, CoMP should be only used with two BSs, because the CoMP with three BSs has some losses. However, if the cell-edge users are the only ones to perform CoMP, the results are good for both cases: CoMP with two BSs and three BSs. In a low load scenario, the only frequency band that should not perform CoMP is the 800 MHz band, since the gains are lower than the losses. In a mid load scenario, the 2600 MHz has a positive performance in systems with CoMP with two BSs. This time, with this frequency band, it is not recommended CoMP with three BSs.

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