LTE radio network deployment design in urban environments under different traffic scenarios

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Abstract— **The focus of this thesis was on the dimensioning of LTE radio access networks and the development of tools for dimensioning purposes. The main purpose is to compute the number of cells needed to cover a given area, taking a specific traffic profile into account. A model taking coverage and capacity planning into account was developed, regarding the 800,1800 and 2600 MHz frequency bands, in three different environments (urban, suburban and rural). The effect of varying parameters regarding user density, geographical area, frequency band and bandwidth, cell edge target throughput, traffic profile, among others, was studied in order to understand the impact of these parameters on the number of cells. For this purpose, a model was implemented, which takes a certain area and user density into consideration and makes the allocation of resources depending on system coverage and available capacity, replicating as close as possible the behaviour of a real network. A significant increase in the total number of cells is verified when the density of users increases. With more users, more resources are needed to fulfil the coverage and capacity requirements. Results show that, for all scenarios, most of the obtained cells are limited by capacity. Thus, the variation of service mix and services throughputs has a particular impact on the required number of cells. The number of urban cells for the voice centric scenario decreases about 12% over the ROM scenario, whereas, for the scenario with lower throughputs, the number of urban cells decreases about 41% over the ROM scenario.**

Keywords- LTE; Dimensioning; Coverage; Capacity; Number of Cells; Lisbon.

I. INTRODUCTION

The growth in mobile data traffic is due to both the rising number of smartphones subscriptions, in particular LTE smartphones, and the increasing data consumption per subscriber. According to [1], there will be a shift from a world dominated by GSM-EDGE-only subscriptions in 2015 to a world dominated by LTE and WCDMA/HSPA-subscriptions in 2021. In fact, LTE subscriptions will make up the largest share of all subscriptions by 2021, totalling 4.1 billion. This will include the deployment of heterogeneous networks, which comprises several types of cells with various sizes, being considered as the most promising approach to enhance network capacity, overall performance, and to increase coverage in a cost effective way.

The vast cost of keeping with demand for mobile data is intensifying the pressure on mobile operators' CAPEX budgets and accelerating their moves to improve their infrastructure cost base. However, the increase in network costs and in the total data traffic will be quite a limitation for mobile operators in the future. The need to reduce networks costs is also driving operators to out-source their whole Radio Access Networks (RANs), and to seek new mechanisms to acquire and manage sites – frequency and channel bandwidth selection strategy, type of technology, service coverage design and architecture structure.

The purpose of dimensioning is to estimate the required number of radio base stations needed to support a specified traffic load in an area, [2]. This number has a fundamental role in cost planning, giving an idea of the economic impacts in the countries under study.

The main scope of this thesis is to study and describe the nominal RAN planning in LTE, and to compute the number of cells needed to cover a given area with all the input parameters that the dimensioning process requires, for different scenarios. Network planning is not a new concept, and has already been addressed and studied for previous technologies, such as 3G. However, the methods, and some considerations implemented, are different, as well as the implementation in different scenarios, generally taking interesting case studies into account, as the Lisbon region with different terrain morphologies and user densities.

Methods and models for coverage and capacity planning are listed and explained in detail, studying mainly the effects of the number of users in the network, different bandwidths, frequency band, service throughputs and traffic profiles on a LTE network scenario with multiple-input multiple-output (MIMO) 2x2. Taking the different traffic profiles used in this work into account, it is possible to determine if cells are limited by coverage or capacity.

The structure of the paper is the following order: Section I – Introduction; Section II - Basic concepts and state of the art of the problem under study; Section III – Theoretical development of the models and its implementation; Section IV – Analysis of results; Section V - Conclusions.

II. BASIC CONCEPTS AND STATE OF THE ART

A. Basic Concepts

LTE-Advanced defined two frame structures; type 1 which makes use of Frequency Division Duplexing (FDD) and type 2 that uses Time Division Duplexing (TDD). Only FDD is considered in this thesis, as it is the widely adopted duplex mode in Europe. LTE radio frames are 10 ms in duration, these are divided into 10 sub-frames, each sub-frame being 1.0 ms long. Each sub-frame is further divided into two slots, each with a duration of 0.5 ms. Dynamically allocating resources in the frequency domain is another of LTE's specifications and DL physical resources can be seen as a time-frequency grid. The basic unit of this grid is the Resource Element (RE) consisting of one sub-carrier during one OFDM symbol. Resource Elements are grouped into Resource Blocks (RBs), each of which consists of a group of 12 sub-carriers, using a total bandwidth of 180 MHz, and 7 OFDM symbols, when CP has normal length, or 6 symbols if the extended CP configuration is used. The larger the transmission bandwidth is, the larger the number of RB that can be used. LTE specifications define bandwidths ranging from 1.4 MHz to 20 MHz, and corresponds respectively to 6 or 100 available RBs.

LTE operates in different arrangements of frequency and bandwidth, depending on the region where it is implemented. In Portugal, through an auction conducted by ANACOM, the Portuguese telecommunications authority, the three frequency bands chosen for LTE were 800 MHz, 1800 MHz and 2600 MHz. Different carrier frequencies originate different path losses and, consequently, different coverage areas, as illustrated in Figure 1. Lower frequencies using the 800 MHz band are used in order to provide larger coverage, while higher frequencies in the 1800 MHz and 2600 MHz bands are useful in providing larger capacities.

Figure 1 - Different carrier frequencies and respective coverage area.

Demand for new services and applications is on the rise. Therefore, these days, users face a huge variety of services and applications with different requirements and purposes. Data services, such as video streaming and web browsing, require more traffic capacity than ever, and pose greater challenges to operators. In order to face these challenges, and especially to provide QoS guarantees, 3GPP proposed four different QoS classes related to the desired type of service and quality: conversational, streaming, interactive and background.

B. State of the Art

Reference [3] focuses on the development of a strategic network planning tool and a set of optimisation algorithms to solve the services distribution problem over a set of technologies, and minimise the total cost of network deployment. The goal of both modules is to provide a set of algorithms capable of performing the dimensioning process of a multi-technological RAN, providing information about the number, type and location of the required base stations in order to satisfy specific coverage and capacity constraints, and the optimisation of the traffic demand's distribution over the different technologies to be deployed. The author has tested the proposed algorithms in a set of different scenarios. In [4], a detailed LTE radio network dimensioning procedure, including frequency, coverage and capacity analysis, has been performed in order to prepare a radio planning guideline considering possible network implementation in the city of Tripoli (Libya). In order to satisfy the traffic requirements of both coverage and capacity, the maximum number of sites obtained from capacity and coverage calculations was chosen. At the end, the link level of the LTE network is simulated for both UL and DL, in order to get a closer view of the impact of the SNR on Bit Error Rate (BER) and Block Error Rate (BLER). From the link level, the authors concluded that, as the BER or BLER increases, the SNR decreases, and vice-versa. It was also verified that the relation BER vs. SNR or BLER vs. SNR varies depending on many parameters, such as modulation scheme, code rate, channel type and antenna configuration. Another conclusion was that receiver diversity affects the SNR. With the increase of MIMO order, an increase on SNR was verified.

Reference [5] indicates the implementation of a dimensioning tool for the LTE planning process that follows the dimensioning algorithms designed by Ericsson. The model considers the concepts and calculations associated with coverage and capacity planning that are essential to the dimensioning process. The tool was developed using C# (C Sharp) programming language and two case studies were analysed. Some parameters were varied in relation to the reference scenario, such as the environment, eNB noise figure and height. The authors concluded that the number of cells increases due to the increase in noise. In addition, areas with dense urban characteristics need more sites to meet the required bitrate, and, in rural areas with fewer users, the number of sites was lower compared to the one obtained for the urban ones. The authors verified that the area type and decreased gain were the primarily responsible elements for the several reduction in the area covered by each site.

III. MODEL DEVELOPMENT

Dimensioning is the initial phase of network planning. It provides the first estimate of the network element count as well as the capacity of these elements, and this process varies from place to place, depending on the dominating factor, which can be capacity or coverage. This is a very important process in network deployment, because it can be modified to fit any needs of any cellular network.

Dimensioning uses relatively simple models and methods that reduce the time required for this process. On the other hand, a dimensioning tool should be accurate enough to provide results with an acceptable level of accuracy, when loaded with subscriber base and expected traffic profile, and a proper set of inputs is vital to yield accurate outputs.

A. Inputs and Outputs of LTE dimensioning

Radio cellular network dimensioning requires some fundamental elements, like geographical area to be covered, frequency band, allocated bandwidth, MIMO order, population density and traffic distribution. Dimension inputs can be divided into three categories, i.e., quality-, coverage- and capacity-related ones. In this thesis, quality-related inputs include the minimum throughput at the cell edge in DL and UL. These inputs are used to compute SINR, but are also connected to the investment that the operator wishes to make, and the quality that it wants to offer to the end-users at the cell edge.

Radio Link Budget (RLB) is of central importance to coverage planning, inputs including transmitter power, transmitter and receiver antenna systems, number and type of antennas, propagation models and their respective parameters, and conventional system gains and losses. Additionally, channel types (Pedestrian, Vehicular) and geographical information, such as area information (urban, suburban, rural) and size of each area type to be covered, are needed to start the coverage dimensioning exercise. Furthermore, the required outdoor and indoor coverage probabilities play a vital role in the determination of cell size.

Capacity planning inputs give the number of subscribers in the network, their demanded services and subscriber usage level. The available channel bandwidth, traffic analysis and data rate to support the available services are also very important for capacity planning.

Regarding dimensioning outputs, the cell radius is the main output of the exercise. Two values of cell radius are obtained, one from coverage evaluation and another from capacity evaluation. Then, the cell radius is used to determine the number of sites. Finally, the average cell throughput is obtained from the capacity evaluation, along with the number of supported active users.

B. Coverage Planning

Coverage planning gives an assessment of the resources needed to cover the area under consideration, without any capacity concern; in other words, there are no QoS concerns involved in this process. The dimensioning process starts with radio link budget calculations, used to determine the maximum path loss. The calculation of the maximum path loss is based on the required SINR at the receiver. The minimum of the link losses in UL and DL is converted into cell radius, by using a propagation model appropriate to the deployment area.

RLB is an important tool for network planning, taking all gains and losses from the transmitter to the receiver into account, allowing one to calculate the maximum path loss. The radio link budget is expressed as:

$$L_{p,max\,[\mathrm{dB}]} = P_{Tx_{[\mathrm{dBm}]}} - L_{c_{[\mathrm{dB}]}} - P_{Rx,min_{[\mathrm{dBm}]}} + G_{r_{[\mathrm{dBi}]}} + G_{t_{[\mathrm{dBi}]}} - I_{m\,[\mathrm{dB}]} + G_{Tx\,[\mathrm{dB}]} + G_{TMA\,[\mathrm{dB}]} \tag{1}$$

where P_{Tx} is the transmitter output power, L_c are the losses in the cable between the transmitter and the antenna, $P_{Rx,min}$ is the receiver sensitivity, G_r is the gain of the receiving antenna , G_t is the gain of transmitting antenna, I_m is the interference margin, G_{Tx} is the diversity gain and G_{TMA} is the tower mounted amplifier (TMA) gain.

Moreover, it is also important to notice that the link budget also varies according to the desired goal of coverage, whether indoor or outdoor, as in each case propagation losses are different. The outdoor and indoor path losses from (2) and (3) are converted into cell radius. The estimation of the outdoor path loss when the UEs are outdoors can be computed using:

$$\overline{L_{p,outdoor}}_{[\mathrm{dB}]} = L_{p,max\,[\mathrm{dB}]} - \overline{\Delta L_{p,out}^{p\%}}_{[\mathrm{dB}]} \tag{2}$$

where $L_{p,max}$ is the maximum path loss and $\overline{\Delta L_{p,out}^{p\%}}$ is the outdoor slow fading margin.

To calculate the indoor path loss when UEs are indoors, an extra attenuation coming from penetration into the buildings must be considered:

$$\overline{L_{p,indoor}}_{[\mathrm{dB}]} = L_{p,max\,[\mathrm{dB}]} - \overline{\Delta L_{p,ind}^{p\%}}_{[\mathrm{dB}]} - \overline{L_{p,outdoor}}_{[\mathrm{dB}]} - \overline{\Delta L_{p,out}^{p\%}}_{[\mathrm{dB}]} \tag{3}$$

where $\overline{\Delta L_{p,ind}^{p\%}}$ is the indoor slow fading margin.

The mean cell radius for each modulation can be calculated using:

$$\overline{r_{cell}}_{[\mathrm{km}]} = p_{ind\,[\%]} \cdot \overline{r_{indoor}}_{[\mathrm{km}]} + p_{out\,[\%]} \cdot \overline{r_{outdoor}}_{[\mathrm{km}]} \tag{4}$$

where r_{indoor} is the maximum indoor radius and $r_{outdoor}$ is the maximum outdoor radius. A percentage of indoor and outdoor users is defined, p_{ind} and p_{out}, in order to get a more realistic approach.

C. Capacity Planning

After the site coverage area is calculated, capacity related issues are analysed. With a rough estimate of the cell size and site count, a verification of coverage analysis is carried out for the required capacity. If the coverage estimate for the given configuration fulfils capacity requirements, then, there is no addition to the previous plan; on the opposite, a suitable number of cell sites is added to achieve capacity targets. After computing the cell range, the number of users inside the cell can be calculated from:

$$N_{u,cell} = \eta_{[\mathrm{users/km^2}]} \cdot S_{[\mathrm{km^2}]} \tag{5}$$

where η is the user density in the target area and S is the maximum area of coverage obtained.

The network dimensioning process is based on the assumption of a uniform distribution of users inside the coverage area. The number of users for each modulation corresponds to a percentage of the obtained total number of covered users, taking the obtained radius for each modulation into account, a validation being done by the following expression:

$$N_{u,cell} = N_{u,QPSK} + N_{u,16QAM} + N_{u,64QAM} \tag{6}$$

where $N_{u,QPSK}$ is the number of users in QPSK, $N_{u,16QAM}$ is the number of users in 16-QAM and $N_{u,64QAM}$ is the number of users in 64-QAM.

Furthermore, another factor that affects capacity requirements is the user traffic demands and the trend of each user type. For this reason, the traffic demand distribution regarding the provided services and certain services at the busies types of the day are factors that are taken into account. Thus, in order to estimate the number of users that a single eNB can support and the average traffic load that it can hold, the information on possible different traffic types and their parameters is essential, i.e., the service mix, or service profile, which is given by the number of active users in a specific service and the total number of active users. Moreover, three different traffic types are considered: Residential, Office and Mixed. As such, the traffic of each user is considered to determine if the maximum permissible network load is exceeded, according to these three traffic profiles.

Then, capacity planning gives an estimate of the radio resources needed for supporting a specific offered traffic with a certain quality, [2]. The available channel bandwidth is very important for capacity planning, because it is directly connected to the capacity of the base station; the higher the bandwidth, the more traffic it can support. Therefore, the average number of required RBs per user for each service and modulation can be obtained from:

$$\overline{N_{RB,user,s}} = \left\lceil \frac{\overline{R_{b,user,s}}_{[\mathrm{Mbps}]}}{\overline{R^n_{b,RB}}_{[\mathrm{Mbps}]}} \right\rceil \tag{7}$$

where $\overline{R_{b,user,s}}$ is the average throughput per user of a service s and $\overline{R^n_{b,RB}}$ is the average throughput per RB of each modulation n.

The number of RBs obtained for each modulation is different, since the average throughput per RB and number of users in each of them is different, therefore, the total number of RBs required for each modulation can be obtained from:

$$\overline{N^n_{RB,required}} = \sum_{service} \overline{N_{RB,user,s}} \cdot N^n_{u,cell} \cdot P_{u,s_{[\%]}} \tag{8}$$

where $N^n_{u,cell}$ is the number of served users by modulation n and $P_{u,s}$ is the subscriber usage percentage of a service s.

Finally, the total number of RBs required for a single cell can be obtained from:

$$\overline{N_{RB,required}} = \overline{N^Q_{RB}} + \overline{N^{16}_{RB}} + \overline{N^{64}_{RB}} \tag{9}$$

where $\overline{N^Q_{RB}}$ is the number of RBs required in QPSK, $\overline{N^{16}_{RB}}$ in 16-QAM, and $\overline{N^{64}_{RB}}$ in 64-QAM.

The number of covered users obtained and number of active (or served) users' needs to be equal when the system is coverage-limited, as all covered users are spending resources in the network in a specific time instance. Thus, $N_{RB,required}$ assumes an important role in capacity planning, because it determines if the system is coverage- or capacity-limited. If $N_{RB,required}$ exceeds the total number of RBs in a cell defined by available channel bandwidth, the network is considered capacity-limited and, consequently, the average throughput per cell and number of active users are reduced.

Regarding the definition of overload, one can use a generic formulation, by dividing the total available resources in a cell by the quantity of required resources. Moreover, the total number of RBs in a cell is fixed, therefore, one can use (9) to determine the respective cell capacity ratio:

$$\eta_{cell} = \frac{N_{RB,cell}}{\overline{N_{RB,required}}} \tag{10}$$

where $N_{RB,cell}$ is the total number of RBs in the respective cell.

This value ranges from 0 to 1, with 1 indicating that a given cell is still limited by coverage. η_{cell} is used only when the total number of RBs in the cell is exceeded. When a cell is not overloaded, i.e,. the total number of RBs required is less than the total number of RBs in a cell, η_{cell} takes a value of 1 in (11).

The total average throughput of a cell can be obtained from:

$$\overline{R_{b,cell}}_{[\mathrm{Mbps}]} = \sum_{service} \overline{R_{b,user,s}}_{[\mathrm{Mbps}]} \cdot N_{u,s} \cdot \eta_{cell} \tag{11}$$

where $N_{u,s}$ is the number of active users in the service s.

D. *Cellular Planning*

The cell structure can be circular or hexagonal. Both are ideal representations, where circular cells give a simple analysis and hexagonal ones give a best fit coverage site without any overlap and gaps. However, no handovers occur between cells taking hexagons' regularity, hence, a percentage for handover has to be defined, which is used to reduce the maximum radius obtained from capacity or coverage evaluations, so that handovers between cells can occur. One assumes a hexagonal cell structure, where the cell area depends on the site configuration, being calculate, for a tri-sectorised site, as:

$$A_{c[\mathrm{km}^2]} = \frac{3}{2} \cdot \sqrt{3} \cdot R^2_{[\mathrm{km}]} \tag{12}$$

where R is the maximum radius from coverage or capacity estimation.

The number of sites to be deployed can be easily calculated from the cell area and the deployment one:

$$N_{sites} = \left\lfloor \frac{A_{D[\mathrm{km}^2]}}{A_{c[\mathrm{km}^2]}} \right\rfloor \tag{13}$$

where A_D is the studied area of deployment.

E. *Model Implementation*

The models described in previous sections were implemented using a simulator developed with the C# (C Sharp) programming language. This dimensioning tool is designed to carry both coverage and capacity calculations. It performs the required calculations, providing the site count on the basis of traffic forecast as the final result. The work previously developed in this simulator considers only LTE, using a snapshot approach, where results refer to the behaviour of the network at a given time instant, being like a “snapshot” of the busy hour traffic. The simulator workflow is presented in Figure 2. After the introduction of all parameters, a preliminary study on coverage is done, where the coverage area for each of the frequency bands is calculated. It is based on a reference minimum throughput, which is translated into a minimum SINR, taking into account that, at the cell edge, QPSK is the modulation scheme being used, as it is the most robust one, enabling realistic throughputs at a relatively low SINR.

The maximum cell distance calculation approach was developed through reverse engineering the appropriate propagation model. As a starting point for this approach, a specific maximum propagation loss allowed between the BS and the UE has to be given as input. This propagation loss is obtained at a first stage by the classic link budget procedure, taking noise power into account where the calculated SINR is translated into a minimum received power, being then possible to extract the maximum cell radius for each modulation and carrier frequency through the reversed model. At this moment, the total number of covered users in a single cell is computed, being uniformly distributed regarding the maximum radius of each modulation. Each cell has a number of RBs dictated by the bandwidth being considered. Users are given all the RBs they need in order to receive the maximum throughput associated with the service they are requesting, if radio channel conditions support it; at this step, system capacity is not taken into account.

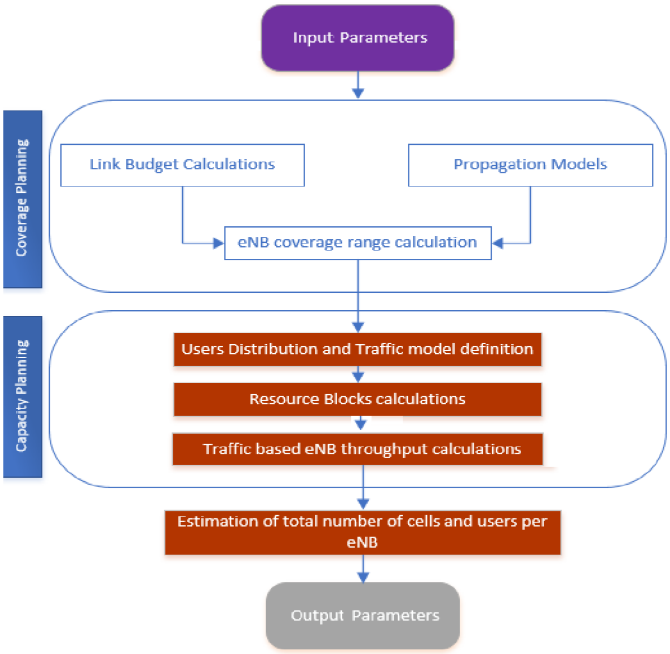

Figure 2 - Simulator Workflow.

In order to able to calculate the number of RBs that a user needs in order to fulfil the desired data rate, the throughput for a single RB is calculated, with an average value for each modulation. Resource allocation is done on an RB basis instead of on a sub-frame one, since the simulator is snapshot based. The user´s desired throughput is divided by the throughput for a single RB (being picked the integer ceiling value), in order to have knowledge, in a first approach, of the number of RBs requested by the user.

The simulator checks if the number of RBs required by users is lower than the maximum number of RBs in a cell, the system being considered coverage-limited in this case, otherwise it is considered capacity-limited. A cell is limited by capacity when the number of RBs used by active users is higher than the maximum of available RBs. After the calculation of RB, based on user´s requested throughput, it is checked if those are coherent with the network capacity; if no reduction has to occur, users are not requesting more resources than the ones the network is able to provide them; if required, a reduction is carried out, where, in a first approach, the requested throughput is decreased until the capacity limit is achieved. At this stage all cells are in their capacity limits. To conclude, when the system is coverage-limited, the cell radius is not initially changed, but only when the handover percentage is multiplied to the obtained radius, with a reduction of the radius being done according to the defined handover percentage (usually around 95%). The number of coverage cells is then calculated by (12). If the number of required RBs for the active users is higher than maximum, a reduction of the number of users in the cell is verified, thus forcing the radius to decrease. The cell radius obtained is divided by the maximum area of coverage (being picked the integer floor value), in order to have knowledge of the number of users supported by single a cell. After the multiplication of the obtained capacity radius by the same handover percentage, the number of capacity cells can be determined. It is important to notice that the obtained number of cells corresponds to the number of sites needed to fulfil all requirements.

IV. RESULTS ANALYSIS

A. *Scenarios Description*

The reference scenario is the city of Lisbon and its surrounding areas. The studied region has an area of approximately 1500 km^2. The total area studied in the simulator is divided into different municipalities with a different variety of users’ density, and amount of generated traffic, meaning that each zone has different coverage and capacity requirements. The model uses a granularity at the level of *districts*, each of the granular areas being classified according to one of the considered geotypes (urban, suburban and rural), which are defined according to the population density of each *district*. The total number of cells of each municipality is obtained from the sum of the number of cells for each of the districts that belong to the municipality. The percentages of urban and suburban scenarios were estimated to be 11% and 26%, respectively, and the remaining 63% for rural. The total number of inhabitants in each district is divided by district area (being picked the integer value), in order to know, in a first approach, the population density in each district. The number of inhabitants for each district were obtained in [6] and the area of each district in [7]. In the reference scenario, the frequency band and respective maximum bandwidth used are 1800 MHz and 20 MHz, respectively.

Table 1 - Parameters for the reference scenario.

Parameter Description	Value
Reference throughput [Mbps]	2.0
Outdoor coverage probability [%]	90.0
Outdoor standard deviation [dB]	6.0 / 8.0
Indoor coverage probability [%]	90.0
Indoor Users [%]	70.0
Outdoor Users [%]	30.0
Penetration Ratio [%]	15.0
Usage Ratio [%]	10.0
Handover percentage [%]	95.0

Simulations were performed for 7 types of services for DL, i.e., voice (VoLTE), video calling, video and music streaming, web browsing, file sharing and e-mail. Each one has minimum, average and maximum throughputs; however, the average throughput per user for the higher throughput services had to be adapted taking into account that the throughput values presented in [8] were too demanding. The service mix was extracted from [8], where the considered device is a smartphone. As one can see in Table 2, video streaming and web browsing use the majority of the resources, since with the current success of smartphones, the different sorts of internet based services incorporated in them, and also the effect of social networks, users are driven to use internet based services such as video and music streaming more often than other services.

Table 2 - Services characteristics.

Service		Service Class	Average Bit Rate [Mbps]	Service Mix [%]
VoLTE		Conversational	0.022	22
Video	Calling	Conversational	0.384	8
	Streaming	Streaming	2	28
Music Streaming		Streaming	0.196	20
Web Browsing		Interactive	2	10
File Sharing		Interactive	2	8
E-mail		Background	1	4

UEs of Category 3 (which are able to support DL throughputs up to 100 Mbps) with a 2x2 MIMO configuration were considered, with an EPA5 channel. As mentioned before, path loss is calculated using the COST 231 Walfish-Ikegami or COST 231 Okumura Hata models, and the parameters shown in Table 3: the former for both urban and suburban scenarios, and the latter for rural ones; the values for the parameters were based on [8] for the urban environment; for the suburban and rural environments, the height of the BS antennas was increased compared to the urban environment, the width of the streets and the distance between the centre of the buildings was reduced for the suburban environment, taking into account the differences of the terrain morphology between urban and suburban environments. The UE height corresponds to the average holding height of the UEs for both data and voice usage.

Table 3 - Configuration of parameters for the propagations models.

Parameter Description	Value		
Environment	Urban	Suburban	Rural
Height of the BS antennas [m]	25.0	28.0	30.0
Height of the buildings [m]	21.0	21.0	-
Street width [m]	30.0	20.0	-
Distance between building centre [m]	50.0	30.0	-
Incidence angle (ϕ) [°]	90		
UE height (h_m) [m]	1.2		

The analysis of the outputs has been done taking the DL scenario into account, considering three different frequency bands associated with their maximum available bandwidths: 800 MHz with a bandwidth of 10 MHz, which provides coverage, and 1800 MHz and 2600 MHz with a bandwidth of 20 MHz, which provide extra capacity.

B. Analysis on the Number of Users

In a first approach, the impact of varying the total number of users on the network performance was studied, regarding the number of active users that is obtained considering the application of the penetration and usage ratios. These ratios are applied to the total number of inhabitants of each district, in order to compute the users' density in each of the districts. For this analysis, as one can see in Table 4, only three different combinations were done. It is easily seen that increasing both ratios lead to an increase of users' density.

Table 4 - Penetration and Usage Ratio for each scenario.

Scenario	Penetration Ratio [%]	Usage Ratio [%]
Reference	15	10
Double	30	20
Triple	45	30

The algorithm provides RBs to users until there are no RBs left to be allocated. If a cell is overloaded, there must be a reduction in the number of RBs down to the limit allowed by the bandwidth. The total number of used RBs depends on the traffic profile of active users: if the traffic profile is heavier, i.e. the average throughput per user established for each of the services is too demanding in terms of capacity, it is seen that by increasing the number of active users in the network, more traffic is generated, thus, more RBs will be used. As previously discussed, a cell is limited by capacity when the number of RBs used by active users is higher than the maximum of available RBs, while, if after fulfilling the capacity requirements for all active users there are still available RBs, one considered that it is coverage-limited. In the reference scenario, the services with the highest percentage of use are web browsing and video streaming. These services have the highest throughput, and therefore consume most of the available resources, thus leading to a higher percentage of cells limited by capacity. Furthermore, increasing the population density means that users' density increases as well, independently of the area, which can be translated into a decrease in the cell radius and in the number of active users if the network is limited by capacity, leading to an increase in the number of cells, as one can see in Figure 3. When the cells of a district are limited by coverage, the cell radius and the number of active users remain constant. For the reference scenario, it is expected that the number of urban cells is higher than for the other two types of environments. Comparing the results from Figure 3, it is concluded that the number of urban cells is higher for the three defined scenarios due to the fact that the urban area presents a higher user density. The number of cells increases proportionally with the number of active users.

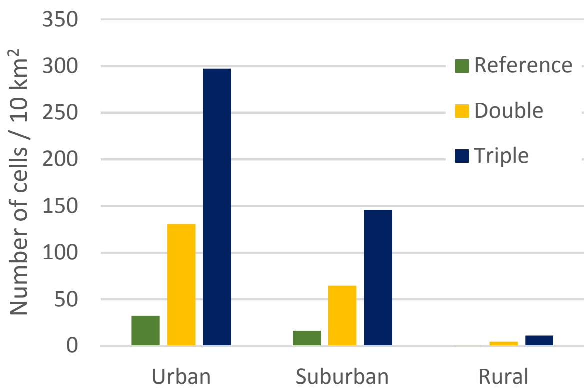

Figure 3 - Number of cells per 10 km^2 for different scenarios taking users' density into account.

C. *Bandwidth and Frequency Band Analysis*

In this section, the behaviour with the variation of the bandwidth in each band is analysed, for each case, the total number of cells required to cover the target area being presented. Varying the frequency band results in a change in the path loss used to calculate the maximum cell radius, resulting in different coverage areas. Considering the propagation models' parameters that depend on the type of environment, the maximum obtained cell radii for urban environments are lower than the ones obtained for suburban and rural environments. For the same environment, the maximum obtained cell radius is higher for the lowest frequency and lower for the highest frequency, as expected, since the 800 MHz band has a lower path loss compared to the others. In terms of capacity, one can distribute the scenarios in ascending order by *All 10 MHz, All 15 MHz, All 20 MHz*, where each frequency is associated with all bandwidths, as can be seen in Figure 4.

Although greater bandwidths correspond to more available resources, and considering that the reference traffic profile is ambitious compared with the service throughputs required by users in reality, most cells remain limited by capacity. With the increase in available bandwidth, the network can provide more resources for services, meaning that the lower the bandwidth, the higher is the required number of cells, as shown in Figure 4, for the same frequency band. When comparing the three bands, it is seen that the number of cells for the highest frequency is higher than the other two, assuming that the bandwidth is equal for all bands. It was expected that, with the increasing frequency, the number of cells would increase. As seen in Figure 4, the number of cells obtained for the 800 MHz band is very similar to the one for 1800 MHz, considering that the bandwidth is equal, which is explained by the fact that capacity is the dominating factor, as less resources are available for these bands and the reference traffic profile is too demanding. However, the number of cells for 1800 MHz is always higher than the 800 MHz one, as expected.

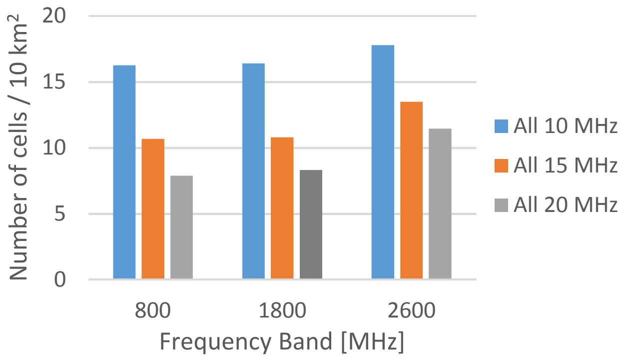

Figure 4 - Number of cells per 10 km^2 for different scenarios (reference scenario in darker grey).

D. *Analysis on Coverage Percentages*

In this section, the main objective is to understand the impact on the number of cells and whether the cells remain limited by the coverage, when the percentages of indoor and outdoor coverage are changed. The analysis is based only on districts that are constituted by cells limited by coverage, because it is possible to better understand the variation of coverage percentages on the required number of cells. When cells are limited by capacity, the obtained number of cells is equal for each one, even when varying the coverage percentages. For reasons of simplicity, the percentages of indoor and outdoor coverage are changed with the same value; these changes were done in the same simulation for each district limited by coverage. With the increase of the percentage of outdoor and indoor coverage, the number of cells increases, as seen in Figure 5. All the districts presented in Figure 5 are constituted by sites limited by coverage for 90% (reference) and 95%; however, it comes down to 85%, some districts have capacity-limited cells, with the reduction of the cell radius. This comes from the fact that the cell radius from coverage estimation is higher for 85%, hence, the number of active users is also higher, so the number of required RBs is higher, exceeding the maximum number of RBs allowed in the cell. The cell radii are higher when both coverage percentages are lower, so when both percentages are higher, more cells are needed in order to fulfil the defined requirements, as seen in Figure 5.

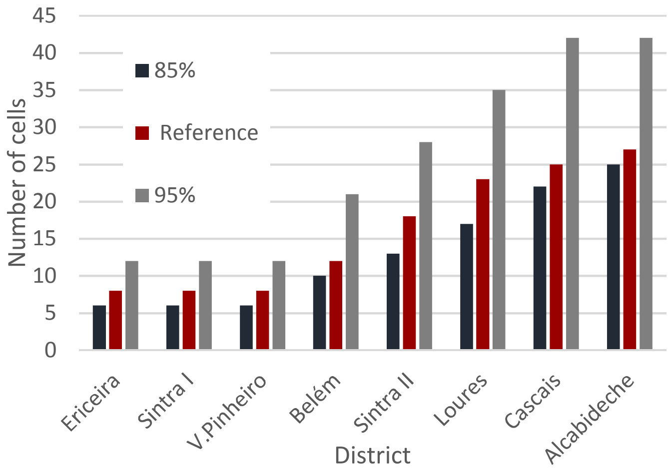

Figure 5 - Number of cells for each district vs. outdoor and indoor coverage percentages.

E. *Traffic Profiles Analysis*

For the analysis of traffic profiles, a scenario was chosen in which users have different traffic profiles. While at the beginning, all users have only one traffic profile, residential, from now on two other types are taken into account, i.e., office and mixed. The percentages for each type of traffic profile were obtained by making an estimate that accounts for the location of hotspots in the urban area of Lisbon. In a real area, there are not only residential users or only business ones, but rather a mixture of the two. In Table 6, it is seen that the number of urban cells is higher in the ROM (Residential, Office and Mix) scenario than in the reference one, because of the introduction of the other two traffic profiles, especially the business traffic profile. It is important to notice that the services throughputs remain constant for each type of user profile, and only the percentages of use of the services change, depending on the environment (residential, office or mix). The only difference between these two scenarios is the introduction of two more types of user profiles (Office and Mix) and, consequently, the percentage of users of each type. All the other parameters defined, for the reference scenario, remain in the ROM scenario.

Table 6 - Total number of urban cells for different traffic profiles.

User Profile	**Scenario [%]**	
	Reference	**ROM**
Residential	100	60
Office	0	30
Mix	0	10
Total urban cells:	539	570

As seen in Table 7, while in the residential profile the service mix remains the reference one, in the service mix for the mixed profile the use percentage of each service corresponds to the average between the percentages of use for the same services in the residential and office profiles. A real network needs to adapt to the new specifications according to different service profiles. It is also important to understand the network utilisation per user profile type, as, for instance, the behaviour of voice calls peak hour might be very different from data ones.

Network traffic is typically a mix of various profiles that are weighted as a function of time and geographical area. As such, two scenarios were established, one focused more on video streaming and another on voice, in order to analyse the impact on the number of cells when the service profile varies and to compare the results obtained with the reference service profile. As seen in Table 8, the traffic profile is changed according to the scenario, and it can be seen that, in the profile focused on video streaming, the percentage is higher than in the ROM reference. As for the profile focused on voice, the percentage is also higher than the one established as reference.

Table 7 - Service mix of each user type profile.

Service		**Scenario [%]**		
		ROM		
		Residential	**Office**	**Mixed**
VoLTE		22	20	21
Video	Calling	8	10	9
	Streaming	28	20	24
Music Streaming		20	10	15
Web Browsing		10	30	20
File Sharing		8	5	6
E-mail		4	5	5

Since video streaming requires more RBs than voice, taking the higher associated average throughput per user into account, it can be concluded that the number of urban cells is greater for the traffic profile where the video is predominant, as seen in Figure 6. Consequently, for the ROM profile, the number of cells is higher than the required number of cells for the profile where voice is predominant, as for the last profile service percentages are less demanding in terms of capacity.

Table 8 - Service mix scenarios.

Service		**Scenario [%]**					
		Video Centric			**Voice Centric**		
		R	**O**	**M**	**R**	**O**	**M**
VoLTE		5	20	12	47.0	20	33
Video	Calling	8	10	9	3.6	10	7
	Streaming	40	20	30	18.0	20	19
Music Streaming		9	10	10	4.3	10	7
Web Browsing		24	30	27	10.0	30	20
File Sharing		9	5	7	8.1	5	7
E-mail		5	5	5	9.0	5	7

Increasing the percentage of the most demanding services in terms of capacity, the number of cells needed to fulfil all requirements increases. It is also verified that substantially increasing the percentage of voice does not result in an increase in the number of cells compared to the ROM scenario, because the services that require more resources suffer a decrease in their percentage of use, reinforcing the previous ideas. A comparison between the reference scenario and the ones proposed by [8] on the traffic profile is performed next. As the average throughput required by the user is too demanding for some of the services considered in this thesis, there was a need to adapt the values for some services, namely for the services with the highest throughput. The remaining services present the throughput values presented in [8].

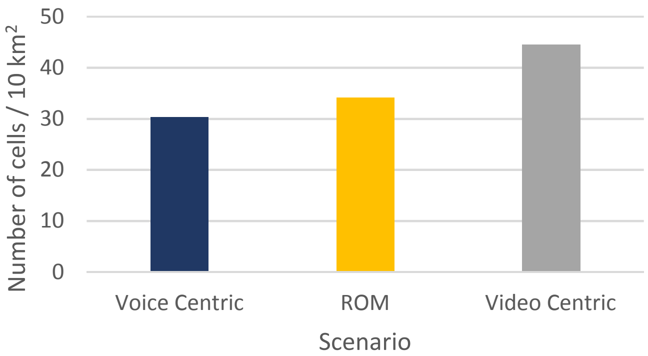

Figure 6 - Number of urban cells per 10 km^2, for different service profiles scenarios.

The main objective is to understand the impact, in terms of the number of cells, when the throughput required by the users for all services is increased or decreased; two traffic profiles have been created, Lower and Higher, in order to make a comparison with the throughputs defined as reference. Previously, it was the service mix that changed depending on the scenario, now it is the throughput that each user requires for each service that changes, maintaining the service mix.

Table 9 - Throughput values for the studied scenarios.

Service		Bit Rate [Mbps]		
		Lower	**Reference**	**Higher**
VoLTE		0.009	0.022	0.036
Video	Calling	0.231	0.384	0.422
	Streaming	1	2	4
Music Streaming		0.176	0.196	0.294
Web Browsing		1	2	4
File Sharing		1	2	4
E-mail		0.819	1	1.5

Figure 7 shows the number of urban cells per 10 km^2 for each of the established scenarios. As expected, it is seen that the scenario with a heavier traffic profile in terms of throughput has more cells, while the scenario with a lighter traffic profile presents fewer cells.

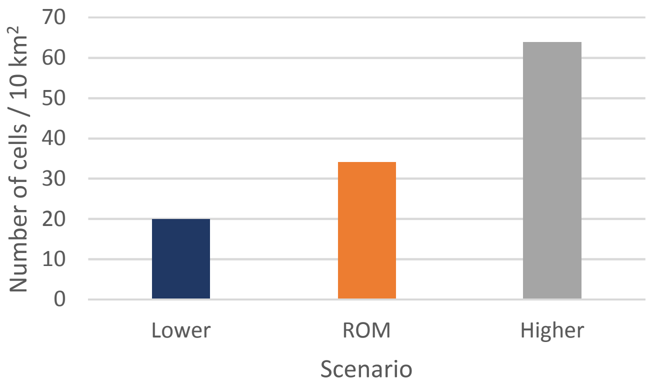

Figure 7 - Number of urban cells per 10 km^2 for each scenario.

The reason for this is also associated with the increase of the required RBs in order to satisfy the higher throughputs requested by users. With a heavier traffic profile, capacity prevails over coverage, and the cells' radius decreases, hence, more cells are needed in order to satisfy capacity requirements.

V. CONCLUSIONS

The main purpose of this thesis was to study the dimensioning and planning processes in an LTE network deployed over different scenarios, in order to understand the impact on the number of cells of the network when some of the input parameters vary. In order to accomplish this goal, a model was developed and several simulations were performed, analysing the impact of different user densities, areas, bandwidths, services throughputs, and the services percentages on the network performance. The region of Lisbon was chosen as a reference scenario, as it presents different municipalities with different varieties of user density. Simulations were done for each district with different number of active users distributed along the network using either typical data download services or VoLTE.

In the analysis of the impact of the number of users on the number of cells, three different combinations of penetration and usage ratios are taken. In the double scenario, both ratios doubled compared to the reference, while in the triple scenario they triple. When the user density increases, the load in cells also increases, as the cell radius and the number of active users follow the opposite trend when the cells are capacity-limited, therefore, it can be concluded that the obtained number of cells increases when the users' density increases. As expected, the obtained number of cells for the reference scenario is lower than for the other scenarios. Varying the bandwidth of each band has impact on the obtained number of cells and cell radius. In terms of cell radius, it is concluded that, for the lower frequency, the associated path loss is lower and, consequently, the maximum cell radius is also higher. As such, in terms of coverage, the required number of cells to cover a given area, for the lowest frequency, is lower. With the increase in available bandwidth, the network can provide more resources for services, meaning that the lower the bandwidth, the higher the required number of cells, for the same frequency band and traffic profile, and vice-versa. For instance, the obtained number of cells for the scenario with the combination (1800 MHz,15 MHz) increases by 33% over the reference scenario. Assuming that the available bandwidth is equal for all frequency bands, it is also verified that, for the higher frequency, the obtained number of cells is higher. In fact, for the scenario with the combination (2600 MHz, 20 MHz), the number of cells increases by 47% over the reference scenario. For the indoor and outdoor coverage probabilities variation test, as expected, the impact is essentially verified in the cell radius. When the coverage probability increases, the obtained cell radius decreases. It is also interesting to verify that, for the lower coverage probability, in some of the coverage-limited cell districts, these limitations switch to capacity ones, while increasing the cell radii. Considering that the increase of the cell radius allows the support of more users, the maximum capacity of the cell is reached, thus, a reduction of the radius is verified.

All of the previous analysis was made considering only residential users for the different environments. However, a distribution of users taking three different user profiles into account was developed in order to have a more realistic approach of the behaviour of a real network. A further analysis considers also this approach, where a percentage of residential, office and mixes users are defined. For simplicity, the urban scenario was the only scenario chosen. The number of urban cells obtained for the ROM scenario is higher than the one for the reference scenario. In fact, the number of cells for the ROM scenario increases by 6% over the reference scenario, given the introduction of two other profiles, especially the office profile, where higher service percentages for the most demanding services is verified.

The reference service profile, with the three user profiles, is compared with the ones proposed by [9] (Video Centric) and [10] (Voice Centric). Video streaming is one of the most demanding resource services, since it has the maximum throughput. Obviously, the required number of cells for the scenario focused more on video service is higher than the one for the other scenarios. The number of cells for the video centric scenario increases by 30% over the ROM scenario. The obtained number of cells for the voice centric scenario is lower than the one obtained for the ROM scenario, as the percentages of the service mix of residential and mixed user profiles are lower for the services with higher throughput. The number of cells for the voice centric scenario decreases about 12% over the ROM scenario. For the services throughputs variation test, two scenarios were proposed in order to compare the number of cells with the one obtained in the ROM scenario. As expected, the required number of cells for the scenario with higher throughputs in all services is higher than the ones for the ROM scenario and for the scenario with lower throughputs in all services. The number of cells for the scenario with higher throughputs increases by 85% over the ROM scenario, whereas, for the scenario with lower throughputs, the number of cells decreases about 41% over the ROM scenario. With higher throughputs, capacity is the dominating factor, leading to a higher number of cells needed to fulfil the users' requirements. Obviously, if services throughputs are not as demanding, the number of cells is lower.

For the analysis of the impact of the required throughput at the cell edge on the number of cells, a scenario with lower throughput was analysed and some limitations regarding the implemented model could be verified. As such only the study for 1Mbps and 2 Mbps (reference throughput) was made. At the beginning, for the scenario with lower throughput, the obtained radii were always lower than the ones obtained for the reference scenarios, in terms of capacity. Consequently, the obtained number of cells for the scenario with lower throughput was higher than the one obtained for the ROM scenario with higher throughput at the cell edge, which is not correct. This comes from the fact of the average throughput per RB is smaller than the reference one, thus, the number of RBs required for each service is higher, leading to a higher overload of the cell. Since it is smaller, more RBs are allocated and, for this reason, the radius is reduced, requiring a higher number of cells. In terms of coverage, the number of cells obtained for the scenario with lower throughput is lower than the one for the ROM scenario, as expected. In order to solve this limitation, the following condition was imposed: when the throughput per RB is less than the maximum defined for QPSK, 200 kbps, and the obtained radius decreases due to capacity, the calculations are made according to the maximum throughput, so that the scenario with the lowest throughput does not present a radius smaller than the one obtained for the ROM scenario. Given this solution, the number of cells for each of the scenarios is equal.

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