Deployment of 5G Radio Networks in Brownfield Scenarios

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***Abstract*— The main objective of this thesis is to develop an evaluation model of the deployment of 5G radio networks, focusing on subjects such as coverage, capacity, and performance parameters, over existing ones from previous generations, i.e., in a brownfield scenario. The proposed model considers coverage and capacity planning characteristics related to 5G-NR, it uses both the 700 and 3 500 MHz, bands. The simulation was conducted in three different types of environments (urban, suburban, and rural). Different traffic profiles were equally considered in order to simulate a mobile communications network that encompasses the new services introduced in 5G NR. The increase in the total number of users influences the number of users served, that is, when the cell capacity is exceeded, some users are deactivated. With the use of other bands and different bandwidths, it is verified that with the increase in the total number of users in the 2.6 GHz band, it is possible to have an addition of 4% in relation to the number of users served when compared to the 0.7 GHz. As for the 3.5 GHz band, with the increase in the total number of users, it was retrieved that it was possible to support a total number of users served 20% higher than the reference band.**

Keywords; 5G-NR, Brownfield, Dimensioning, Coverage, Capacity.

I. INTRODUCTION

Every new generation of wireless networks delivers faster speeds and more functionality to our devices, 4th Generation (4G) delivering the speeds that most users enjoy nowadays. But as more users come online, 4G networks have practically reached their capacity limit. Nowadays, users increasingly want more data for their smartphones and devices, due to the mobile applications' enormous popularity (such as WhatsApp, Facebook, Netflix and Google Drive). It was predicted by [1] that in 2023 the number of internet users will be two-thirds of the total population, which means 5.3 billion internet users, compared to 2018 when there were 3.9 billion users (51% of the population); it is also considered that an increase of about 15% internet users will occur, as can be seen in Figure 1.

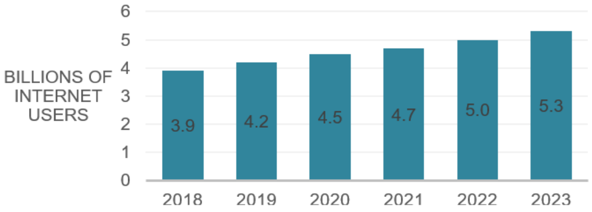


Figure 1. Global Internet user growth (extract from [1]).

Presently, one has the 5th Generation (5G) as the next generation of wireless mobile communications, that will be able to handle a thousand more GB in traffic than previous generations and will be ten times faster than 4G Long Term Evolution (LTE). The fifth generation hit the market by the end of 2018 and will continue to expand at a worldwide level. This evolution will allow the connection of even more devices to the current mobile network, not only the usual devices such as smartphones being considered but also smart TVs, wearables and IoT devices. This means that these devices will be connected to wireless networks instead of using a physical connection, such as the optical fiber used for most devices nowadays.

II. FUNDAMENTAL CONCEPTS AND STATE OF ART

A. *Fundamental Concepts*

A characteristic of the 5G architecture is the novel connectivity to the CN by the Access Network (AN). It can be a connection to a 5G Core Network (5GC infrastructure) or an LTE Core Network, called Evolved Packet Core Network (EPC) infrastructure, which means that 5G can still be dependent on the 4G LTE network, being called the non-standalone (NSA) architecture, represented in Figure 2. The NSA architecture, by having a 4G Core and Radio only supports 4G services. The advantages of using a 5G Radio AN is bigger capacity and lower latency. Furthermore, in the NSA architecture, the evolved Node Bs (eNBs – 4G node) are considered master nodes and the en-gNBs (nodes providing NR user and control planes protocol terminations towards the user equipment (UE)) are secondary nodes in the Evolved Universal Terrestrial Radio Access (E-ULTRA) infrastructure. The connection between E-ULTRA nodes is done by the X2 logical interface that interconnects Radio Access Network (RAN) nodes with a E-UTRA-NR Dual Connectivity (EN-DC) function, which provides the capability of an eNB to request an en-gNB for radio resources for a UE. The other type of connections is between the eNB and en-gNB nodes and the EPC core via the S1 interface. This architecture is considered a step to the full deployment of 5G.

When an operator needs to choose between these two types of architecture, it needs to consider which kind of population they are interacting within the zone where the service will be delivered, more specifically if the studied users are looking mainly for high-speed connectivity, and therefore the NSA architecture should be implemented, or contrarily if it is a community that is looking for new services such as smart cities and smart factories, where the SA architecture should be implemented.

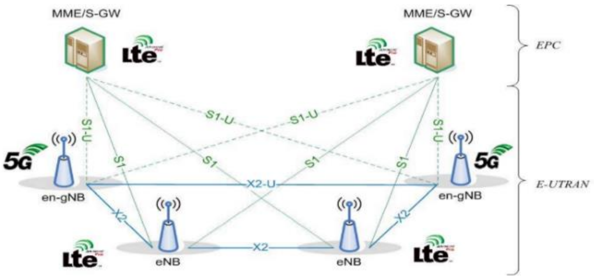


Figure 2. NSA architecture (extracted from [2]).

5G network slicing is a type of architecture that allows multiple virtualized and independent logical networks to be created on top of a common physical infrastructure. The benefit of this architecture is that the network can be divided into multiple parts to create a different slice for each client or a group of clients, which means that resources can be allocated to each slice, turning parameters like throughput, latency, and speed easily managed by the operators. Edge computing is an emerging technology that enables the evolution to 5G by bringing cloud capabilities near to end-users, to overcome the intrinsic problems of the traditional cloud, such as high latency and lack of security.

5G NR supports Orthogonal Frequency Division Multiple Access (OFDMA) with cyclic prefix like in LTE as a radio access method, the difference being that this can be used in UL as well, unlike LTE that uses Single Carrier-FDMA. 5G NR allows different subcarrier spacing (Δf) based on the numerology (μ). The numerology is determined by considering the frequency band that the operator is deploying when using a lower frequency band. The cell size is also important, given that the bigger the cell, the bigger the latency because it has to get to the device and get back again and will take more time if the route is longer, but the numerology will also affect latency, i.e., the larger the symbol the more time is spent until the full symbol reaches the receiver, meaning that higher numerologies that relate to higher frequencies will have lower latencies than lower numerologies, despite this, even changing the numerology, doubling the symbol size will possess no meaning in terms of latency values.

In Portugal, the frequency bands that are available for the development of NR technology are the 700 MHz, 2.6 GHz and 3.6 GHz, with two bands that are considered pioneering for 5G: the 700 MHz band, suitable for transitioning to the next generation of mobile networks and coverage in different areas and the 3.6 GHz one, capable of providing the necessary capacity for services supported on 5G systems. For the 700 MHz band, passive antennas are used and for the 3.6 GHz band active ones are used.

NR introduced an extension of MIMO to Massive MIMO (mMIMO) that will use more antennas in each BS. In terms of coverage, the use of more antennas will make a large coverage cell unnecessary, however, there is a counterpart since there is a higher signal attenuation due to the use of higher frequency bands, the higher frequency signals will suffer from a signal attenuation. These techniques increase coverage and minimize interference, thus, the BS can transmit and receive multiple beams from different directions directed to different users. The primary motivation and drive for 5G is the use cases and, therefore, ITU-R has defined three use scenarios that are part of the IMT recommendation: Enhanced Mobile Broadband (eMBB), this scenario is considered to be the most important since it is a continuous problem. To note the abruptness of this scenario, one can think of two different use cases, for example, the need for a BS for a high user density zone and, on the other hand, the need to cover a considerable area. Ultra-Reliable Low Latency Communication (uRLLC), this scenario is characterized by use cases with strict latency requirements, such as wireless control of industrial equipment or remote medical surgery. And finally, Massive Machine Type Communication (mMTC): As the name implies, it is a use case where there are a large number of connected devices and whose transmissions are limited volumes of data that are usually not sensitive to delays.

B. *State of Art*

A study was conducted by [3] to evaluate the 5G NR against the Key Performance Indicators (KPIs) provided in 2020 by IMT. In this work, each KPI is evaluated based on the three scenarios previously described, i.e., eMBB, URLLC, or mMTC. The KPIs evaluated in this work were bandwidth, peak data rate, peak spectral efficiency, user plane latency, control plane latency, energy efficiency, 5th percentile user spectral efficiency, user experienced data rate, average spectral efficiency, and mobility. The conclusions reached from this study, identify that 5G NR fulfils the IMT-2020 requirements under specific conditions. Interesting values were achieved in this study, for example, 6.4 GHz of bandwidth were reached, therefore enabling a peak data rate of 78.05 Gbps employing the FDD mode, 8 layers, and 1 numerology among other values.

In another KPI measurement study of the implementation of a 5G network in a non-standalone architecture [4], the results were compared with those measured in a current 4G network. The compared KPIs were throughput, latency and packet error rate. It was expected by the authors that the 5G network will have a higher data transmission rate due to the increase in bandwidth, different coding, and the improved modulation used, the results achieved showing that the tested 5G network reached peak rates for DL and UL significantly higher than 4G (a difference of approximately 100 Mbps in the case of DL, and minimum differences around 5 Mbps). It was also expected that the latency will be drastically reduced concerning 4G, and it was proven that the latency of the data transmission is significantly (difference of 8 to 10 ms), the Packet Error Rate (PER) was expected to be detected only in lower layers, where it is not possible to restore the packages, and the results confirmed this view.

III. MODEL OVERVIEW

A. *Inputs and Outputs of 5G Dimensioning*

The model to be developed is based on the concepts studied and consolidated in section II. With these concepts, it is possible to formulate the theme on which the model will focus on. A small representation of the model is shown in the Figure 3.

Regarding the model's input parameters, these were divided into three parts: User parameters, which include the density of network users, what types of services they use, and what areas these services are used on. Services, i.e., users can utilise various types of services such as voice, video, among others, when using each service, their requirements are added, such as minimum transmission rate, among others. Network parameters, which are defined by the operators, are related to the position of the antennas, the frequencies used, the available bandwidth, the number of channels available and the priorities assigned to the different users, among other parameters.

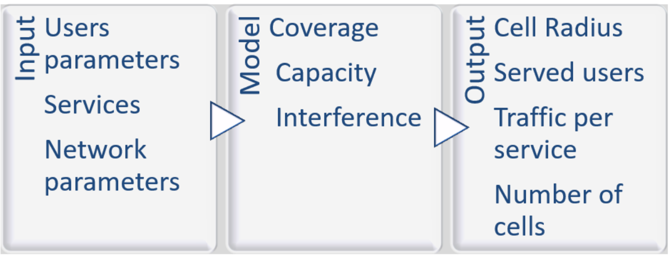


Figure 3 - Model Configuration.

Regarding the model itself, it is equally divided into three parts: Coverage model, which consists of placing the cells in a certain area. This model will include the Link Budget and the path loss among others. Capacity model, which is based on the occupancy rate in the cells by the users and the reassessment of the coverage model considering the QoS, including cell load calculation and cell load adjustment. Interference model, which is composed of a model proportional to the traffic, meaning that, as the traffic increases, the interference also increases at last, this will be added as a margin to the power balance.

As output parameters for the model to be configured, it is expected to obtain results in the three areas of coverage, capacity and interference. For coverage, it is expected to obtain parameters such as cell radius. For the capacity, it is expected to obtain parameters like the number of users per cell, which depends on the services. And finally, for the interference, the carrier to interference ratio is obtained. Table 1 present the propagation models used as well as their requirements.

Table 1 - Propagation models and respective requirements.

Parameters	**Walfisch-Ikegami**	**Okumura-Hata**	**Winner II**
Frequency [GHz]	0.7 – 2	0.15 – 2	2 – 6
Base Station Height [m]	4 – 50	30 – 200	1 – 32
Mobile Height [m]	1 – 3	1 – 10	1 – 5
Distance [km]	0.02 – 5	5 – 20	0.03 – 10

B. *Coverage Planning*

This subsection describes planning in terms of coverage and is based on [5]. In this sense, the objective is to calculate the output parameters of Figure 3, having as main purpose the cell radius calculation, which is defined by the maximum distance between the BS and the UE so that a connection can be established in UL and DL. Coverage planning is divided into the Link Budget calculation, the use of appropriate propagation models so that the maximum distance between the BS and the UE can be calculated and finally, the cell radius. Link Budget is a calculation of all of the power gains and losses that a signal experiences while establishing a communication between receiver and transmitter, including cable and user losses.

The throughput values required, at the maximum distance from the BS, for a given SNR level depend on the modulation, M, in question. For M=4, QPSK modulation with coding rate of 1/3 and MIMO 2x2; for M=16, 16-QAM modulation with coding rate of 1/2 and MIMO 2x2; for M=64, 64-QAM modulation with coding rate of 3/4 and considering MIMO 2x2 and for M=256 256-QAM and MIMO 2x2 the throughput per RB and the corresponding SNR can be given by:

$$R_{b\,[\mathrm{bpsk}]} = 2^{\mu}\frac{N_{MIMO}}{2}\begin{cases} \dfrac{2.34201\times 10^{6}}{14.0051 + e^{-0.577897\ \rho_{IN}}} & M = 4 \\ \dfrac{47613.1}{0.0926275 + e^{-0.295838\ \rho_{IN}}} & M = 16 \\ \dfrac{26405.8}{0.0220186 + e^{-0.24491\ \rho_{IN}}} & M = 64 \\ \dfrac{26407.1}{0.0178868 + e^{-0.198952\ \rho_{IN}}} & M = 256 \end{cases} \quad (1)$$

where: N_{MIMO}: MIMO order. Although, for a connection using MIMO 4x4, the throughput is 2 times the referenced one [6].

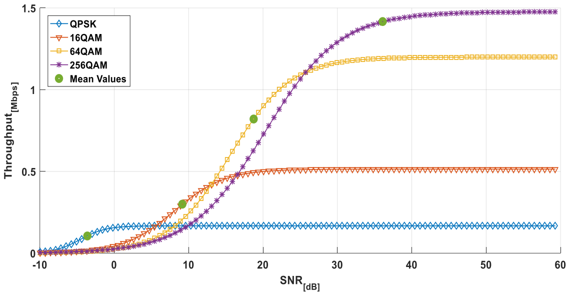


Figure 3: Throughput in function of the SNR, considering MIMO 2x2.

The maximum path loss is given by the system along with the antenna gains. These gains depend on the equipment, at the BS it depends essentially on the antenna type and the number of sectors, while the UE depends on the type of device, essential for the computation of the power feed to the antenna DL and UL. In addition to the user's losses and the ones caused by the cable at the BS between the transmitter and the antenna, the fact that MIMO technology is used in the receiving antenna must also be considered and, for this, its gain must be taken into account. A correlation value between coverage and capacity, the interference margin, which depends on the cell structure, number of active users, and their services, and could take values between 2 dB and 4 dB for coverage limited cells, and between 4 dB and 7 dB for capacity limited ones [Belc18] and finally, there is a gain that reduces the BS noise figure and improves sensitivity, but introduces insertion loss in DL, the Tower Mounted Amplifier (TMA) gain.

The path loss can be summarized by:

$$\begin{aligned} L_{p_{max}} = {} & P_{t_{[dBm]}} + G_{r_{[dBi]}} + G_{t_{[dBi]}} - P_{r,min_{[dBm]}} \\ & - L_{c_{[dB]}} - L_{u_{[dB]}} - I_{m_{[dB]}} \\ & + G_{div_{[dB]}} + G_{TMA_{[dB]}} \end{aligned} \quad (2)$$

where: I_m is the interference margin,G_{div} is the diversity gain; and G_{TMA} is the TMA gain.

By measuring the Link Budget and using the propagation models, mentioned above in Table 1, the maximum distance that the user can be from the BS is calculated. For the communication using the 0.7 GHz band, the most suitable models are the Okumura-Hata and the Walfisch-Ikegami depending on the user's distance from the base station, and the 3.6 GHz using the Winner II model.

C. *Capacity Planning*

This subsection describes planning in terms of capacity, having as purpose calculate the number of users that a cell can accommodate for each service. The capacity model takes advantage of the cell area, A_{cell} ,that is the subject of the coverage model's response, and the number of users per kilometer, η, to calculate the number of users within each cell. This can be calculated with the following expression:

$$N_{users,cell} = \eta_{[\text{users/km}^2]} \times A_{cell[\text{km}^2]} \tag{3}$$

In the use of active antennas, in terms of available throughput levels to users, this will be dependent on the occupation of each beam, that is, if the UEs are in the same restricted area they can be covered by the same beam and its level throughput will be lower because of having to share resources with other users, otherwise, each UE is entitled to one beam and the available throughput level will be higher. Having access to the number of users that will be accommodated in a cell, it is relevant to perceive how they are distributed throughout the service area, since that the closer to the base station, the greater the modulation used.

$$N_{u,cell}^{M} = \begin{cases} \dfrac{R_Q^2 - R_{16}^2}{R_Q^2}\, N_{u,cell} & M = 4 \\ \dfrac{R_{16}^2 - R_{64}^2}{R_Q^2}\, N_{u,cell} & M = 16 \\ \dfrac{R_{64}^2 - R_{256}^2}{R_Q^2}\, N_{u,cell} & M = 64 \\ \dfrac{R_{256}^2}{R_Q^2}\, N_{u,cell} & M = 256 \end{cases} \tag{4}$$

It is essential to consider the available bandwidth, as the greater the bandwidth available by the BS, the greater the traffic capacity accommodated by it. For this, the number of RBs allocated in the BS for a user for a specific service will be calculated:

$$\overline{N_{RB,users,s}} = \frac{\overline{R_{b,users,s}}_{[\text{Mbps}]}}{\overline{R_{b,RB}^{M}}_{[\text{Mbps}]}} \tag{5}$$

where $\overline{R_{b,users,s}}$ represents the average throughput per user of a service s and $\overline{R_{b,RB}^{M}}$ the average throughput per RB of each modulation M. The average throughput per RB of each modulation M, therefore, having the number of RBs per user, it is possible to allocate them in a cell, dividing them by the different modulations, thus calculating the total number of RBs for a modulation and the total number of RBs in a single cell is given by:

$$\overline{N_{RB}^{M}} = \sum_{service} \overline{N_{RB,users,s}}\, N_{u,cell}^{M}\, P_{u,s[\%]} \tag{6}$$

where $N_{u,cell}^{M}$ represents the number of served users by modulation M, $P_{u,s}$ is the subscriber usage percentage of a service *s*.

$$\overline{N_{RB,required}^{M}} = \sum_{M} \overline{N_{RB}^{M}} \tag{7}$$

where $\overline{N_{RB}^{M}}$ represents number of RBs required in modulation M.

With the calculations presented above, it is possible to determine if the system is limited in terms of coverage or capacity. In case it is limited in terms of coverage, the value of $\overline{N_{RB}^{M}}$ will be greater than the total value of RBs accommodated in a single cell, and in this case, there is an overuse of the available resources which it is considered good in terms of QoS but bad in terms of costs for the service provider. In the case of being limited in terms of capacity, users will have lower throughput levels, which implies that each user has less RB to use a service than what would be expected, $N_{RB,users,s}$. It will be possible to evaluate the overload of a cell in the following equation:

$$\eta_{cell[\%]} = \frac{\overline{N_{RB,required}}}{N_{RB,cell}}\, 100 \tag{8}$$

where $\overline{N_{RB,required}}$ is the total number of required RBs in the respective cell and $N_{RB,cell}$ represents the total number of RBs in the respective cell. To continue the cell capacity study, the average user consumption in all services can be determined, meaning the total average throughput of a cell, through the sum of the average throughput per user for each service multiplied by the number of users who enjoy this same service.

$$\overline{R_{b,cell}}_{[\text{Mbps}]} = \sum_{services} \overline{R_{b,users,s}}_{[\text{Mbps}]}\, N_{u,s[\text{users}]} \tag{9}$$

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

To obtain more detailed information about the services that are used in the cells, that is, what type of traffic exists and what percentage of cell users use a particular service, it is possible to calculate the percentage of traffic for each service, as well as the percentage of active served users:

$$p_{traffic,s[\%]} = \frac{\overline{R_{b,user,s}}\, N_{u,s}\, \eta_{cell}}{\overline{R_{b,cell}}_{[\text{Mbps}]}} \tag{10}$$

$$\eta_{u,cell[\%]} = \frac{N_{u,cell[\text{users}]}}{N_{u,cell[\text{users}]}^{M}} \tag{11}$$

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

D. *Interference Planning*

Interference may lead to deterioration of the received signal and for this reason cause throughput reduction. In this way, interference limits network capacity and makes the throughput received by the users not enough for the services desired. As a result, the increase in interference leads to cell radius degradation which necessarily leads to data rates reduction.

For this model, two situations will be considered, using a BS and a reference radius obtained from the previous models, from which the interference will be calculated for a given user. In the first case, the user is at the extreme of the area covered by the BS, that is, he is at a distance from the reference radius, which is the worst case, as he is subject to greater interference from the surrounding BS. In the second case, the user is in the same position as the BS, this being the best case, because the user is as far away as possible from the surrounding BS. It will also be considered that all neighbouring BS are positioned at twice the coverage radius of the owner and that they have the same powers and gains as the owner. Although both cases are not physically realistic, they are the worst and the best interference estimate. For these two cases, the expression can be simplified using the radius of coverage of the BS, thus, for the best-case scenario:

$$\rho_{IN_{best}[\mathrm{dB}]} = 10log\left(\frac{P_{t[\mathrm{mW}]}\, G_t G_r 100^{-\beta}_{[\mathrm{m}]}}{6P_{t[\mathrm{mW}]}\, G_t G_r\, (2r)^{-\beta}_{[\mathrm{m}]}}\right) \tag{12}$$

where r is the coverage radius of the donor BS.

E. Model implementation

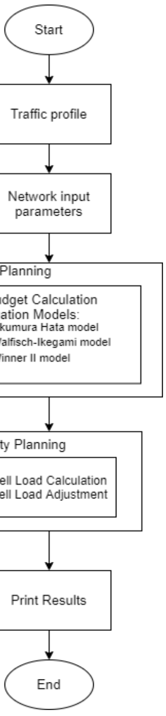


Figure 5 - Model flowchart.

It starts by choosing a scenario, in this case where the BS is located as well as its surrounding environment, which will define, among others, the most suitable propagation model. In addition, other parameters inherent to the users' profile and the services used must also be defined. Once the scenarios are defined, the program moves to coverage planning, which involve the Link Budget and the propagation models, this block that has the purpose of calculating the maximum distance that the user can be situated from the BS, this being also influenced by the modulation in use. Subsequently, the capacity planning is followed, this model has the particularity of making a readjustment to the dimensioning of the cell resources in case the system is limited. The Print Results block aims to collect all the results obtained in the previous blocks and create a results file as well as a set of graphs which will subsequently be used in the results analysis phase in order to simplify it. The system may be limited in terms of capacity and in that case, adjustments must be made to the cell load. Starting by removing RB from users who are using values higher than the minimum QoS value required to utilize the service, which can solve the system problem. If the reduction in the number of RB is not enough, the following step is to remove users, thus, reducing the number of active users in the cell, with the objective of achieving the maximum capacity of the cell.

IV. RESULTS ANALYSIS

A. Scenario Description

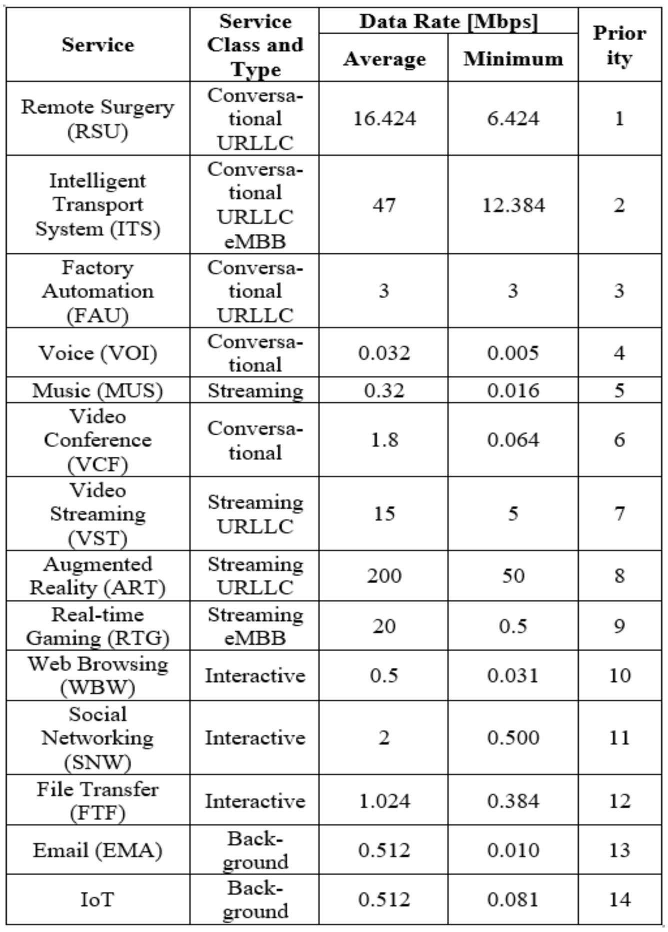
As previously described in the model overview, parameters that describe the users are required, such as their geographic spread, the used services description, Table 2, and also the network description Services are classified by their type, eMBB, URLLC or mMTC, their data rate, express in Mbps, and their class, that can be, Chat services such as voice calls and multimedia communications demand lower latencies due to the bidirectional flow of data. Streaming Services, which represent an alternative to downloading data, consist of performing activities that crave real-time data transfer, like listening to music or watching videos. Interactive Services comprise services where the user can directly interact with the application, such as online games and web browsing. Background services are typically distinguished as the process of sending and receiving data in the background, requiring no user interface. Some instances of this class of resources are Short Message Service (SMS), email, and information download. Regarding the Remote Surgery (RSU), Intelligent Transport System (ITS) and Factory Automation (FAU) services, these are composed of a set of sub-services, that is, only when they work simultaneously is it possible to perform these three services. Table 3 shows the reference values that will be used to calculate the Link Budget.

One of the study scenarios will include 3 clusters that will cover 3 different environments, urban environment composed by 5 sites, suburban environments composed by 9 sites and rural environment composed by 7 sites. For these three clusters, an analysis will be performed of how this area can be covered including the 5 bands.

Table 3 was constructed with the aim of studying different percentages of use of services depending on usage scenarios.

Throughout this section, multiple service mix scenarios will be used, which will vary according to the scenario under study, the expected evolution of the population over the years and a greater use of new technologies. Table 4 aims to investigate the urban, suburban and rural scenarios and the behaviour of the system when there is an underload of RSU, ITS and FAU services, which are the highest priority services.

Table 2 - Services classes and demanded data rates.



Service	Service Class and Type	Data Rate [Mbps]		Priority
		Average	Minimum	
Remote Surgery (RSU)	Conversational URLLC	16.424	6.424	1
Intelligent Transport System (ITS)	Conversational URLLC eMBB	47	12.384	2
Factory Automation (FAU)	Conversational URLLC	3	3	3
Voice (VOI)	Conversational	0.032	0.005	4
Music (MUS)	Streaming	0.32	0.016	5
Video Conference (VCF)	Conversational	1.8	0.064	6
Video Streaming (VST)	Streaming URLLC	15	5	7
Augmented Reality (ART)	Streaming URLLC	200	50	8
Real-time Gaming (RTG)	Streaming eMBB	20	0.5	9
Web Browsing (WBW)	Interactive	0.5	0.031	10
Social Networking (SNW)	Interactive	2	0.500	11
File Transfer (FTF)	Interactive	1.024	0.384	12
Email (EMA)	Background	0.512	0.010	13
IoT	Background	0.512	0.081	14

Table 3 - Reference values for the Link Budget parameters.

Parameter	NR700 L800	L1800 L2600	NR3600
Slow-Fading Margin [dB]	5	6	7
Interference Margin [dB]	2	4	6
Cable Losses [dB]	2	2	0
SCS [kHz]	15	15	30
Number of RBs	50	100	273
Bandwidth [MHz]	10	20	100
MT Height [m]	1.5		
BS Height [m]	42.0		
MT Antenna Gain [dBi]	3.0		
MT Losses [dB]	3.0		
MT Noise Figure [dB]	7.0		
Coverage Probability [%]	90.0		
Output Power per Carrier/MIMO Element [W]	40	42	5
Maximum Antenna Gain [dBi]	15.2	17.8	23.8
Number of MIMO Elements	2	2	32

Table 4 - Service mix variation.

Service	Urban Service mix 1 [%]	Urban Service mix 2 [%]	Urban Service mix 3 [%]	Suburban Service mix [%]	Rural Service mix [%]
RSU	12	4	4	0	0
ITS	9	18	4	12	17
FAU	3	2	16	6	0
VOI	39	39	39	38	37
MUS	1	1	1	2	2
VCF	4	4	4	2	0
VST	5	5	5	2	1
ART	1	1	1	2	2
RTG	2	2	2	1	1
WBW	5	5	5	11	17
SNW	10	10	10	10	10
FTF	4	4	4	2	2
EMA	3	3	3	10	10
IoT	2	2	2	2	1

Table 5 - Evolutive urban scenarios.

Year	Total number of users	LTE traffic [%]	NR traffic [%]	Scenario 1 (without Refarming)	Scenario 2 (with Refarming)
2022	500	20	20	NR7 + L8 + L18 + L26 + NR35	NR7 + L8 + L18 + L26 + NR35
2023	500	35	30	NR7 + L8 + L18 + L26 + NR35	NR7 + L8 + L18 + L26 + NR35
2024	500	40	40	NR7 + L8 + L18 + L26 + NR35	NR7 + L8 + L18 + NR26 + NR35
2025	725	55	90	NR7 + L8 + L18 + L26 + NR35	NR7 + L8 + L18 + NR26 + NR35
2026	900	60	120	NR7 + L8 + L18 + L26 + NR35	NR7 + L8 + NR18 + NR26 + NR35
2027	1300	80	180	NR7 + L8 + L18 + L26 + NR35	NR7 + L8 + NR18 + NR26 + NR35

In order for the model to involve realistic values for the areas being studied, real values will be used, taken from the censuses for the load of inhabitants in the study areas.

Table 5 aims to study the evolution over the years of mobile networks and the various transitions in the use of different bands and technologies, for that, two scenarios were built, one that aims to include LTE and NR bands without refarming and the other one with refarming.

B. Cell Radius

In these figures, there will be variations of the urban, suburban, and rural scenarios, of the propagation models, Okumura-Hata (OH), Walfisch-Ikegami (WI), and Winner II (Win II), and of the 0.7 GHz, 1.8 GHz, 2.6 GHz, and 3.6 GHz.

Figure 6, Figure 7, and Figure 8 show the cell radius for the throughput levels of 1 Mbps, 5 Mbps, and 10 Mbps, respectively.

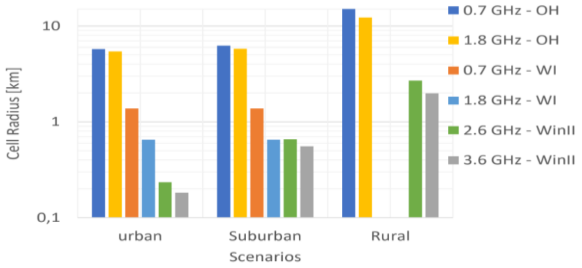


Figure 6 - Cell radius for different scenarios and models for 1Mbps.

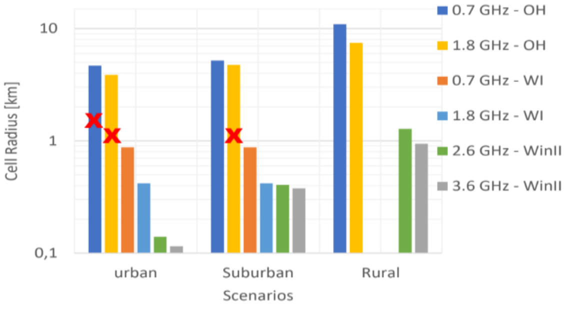


Figure 7 - Cell radius for different scenarios and models for 5Mbps.

With the required value at the cell end increased, to 5Mbps, in this case, the Okumura-Hata model is not valid for distances less than 5 km, and therefore, these are found marked with “X” the columns for which this happens, that is, for urban environments with frequencies 0.7 GHz and 1.8 GHz and for suburban environments with frequencies 1.8 GHz.

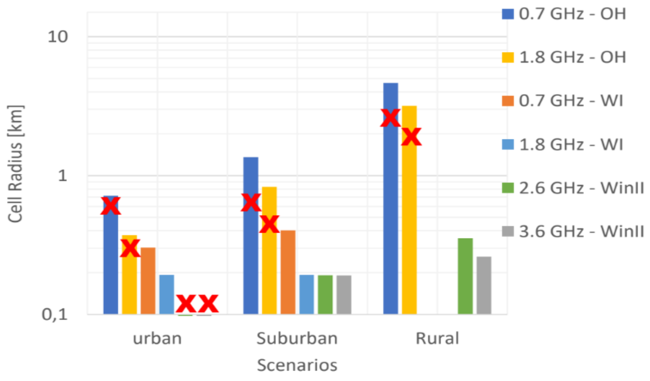


Figure 8 - Cell radius for different scenarios and models for 10 Mbps.

In the Figures 7 and 8, it is possible to verify that the radius of the cell increases, with the change of the scenario from urban to suburban and from suburban to rural, it can also be confirmed that the radius decreases with increasing frequency. it can be seen that with the increase of the required throughput at the end of the cell, the radius of the cell decreases and for cases where the required throughput is high, the cell radius saturates, as can be seen for the urban scenario for 3.6 GHz frequency. In the event that the services that are to be performed have throughputs higher than the levels available at the end of the cell, they can be used more RB, that is, in case the throughput available at the end of the cell is 1 Mbps, it is possible to perform a service that requires 2 Mbps using 2 RB.

C. Influence of Frequency

In this subsection, the analysis of results is presented regarding the influence of the frequency used, depending on the number of users in the cell, between 100 and 300 users, taking into account the urban service mix in Table 4. The frequencies used for this evaluation will be 2.6 GHz for 4G technology and 0.7 GHz and 3.6 GHz for 5G technology.

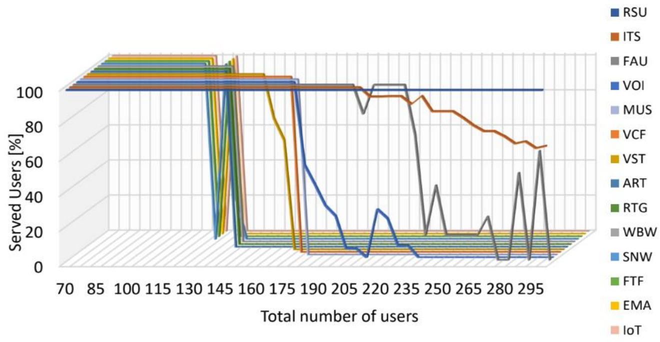


Figure 9 - Percentage of served users per number of users for 0.7 GHz.

Comparing Figure 9 with Figure 8, it can be seen that due to the increase in bandwidth from 10 MHz to 100 MHz the system can guarantee capacity for more users until the maximum load of the cell is reached, for 0.7 GHz it is up to 120 users and for 2.6 GHz it is up to 125 users.

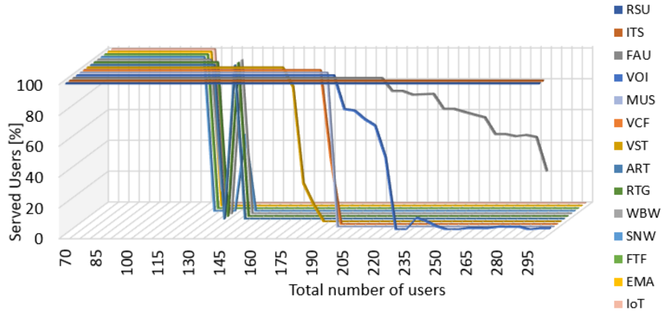


Figure 10 - Percentage of served users per number of users for 2.6 GHz.

Analyzing Figure 11, it is possible to conclude that up to a combined number of users equal to 145, it is possible to guarantee that all services are served at 100%, that is, with the increase in bandwidth, the cell capacity also increased, as would be expected.

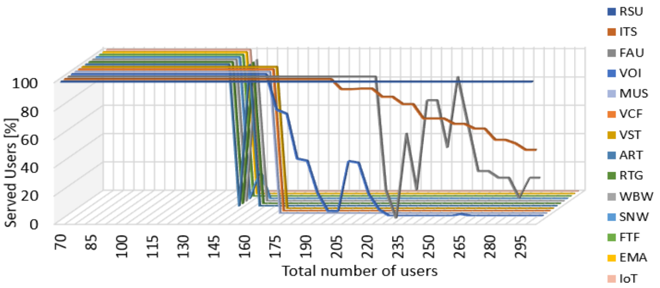


Figure 11 - Percentage of served users per number of users for 3.6 GHz.

D. *Influence of the Scenario*

This subsection will analyse the percentage of traffic per service, taking into account the aggregate number of users in the cell, as well as the number of users served in terms of the total number of users in the cell, excluding the reference service mix and keeping the frequency of 3.6 GHz. The same load of users in the cell were used as in the previous section, between 70 users and 300 users. The figures are grouped in pairs, each referring to the urban setting, subsequently suburban and rural.

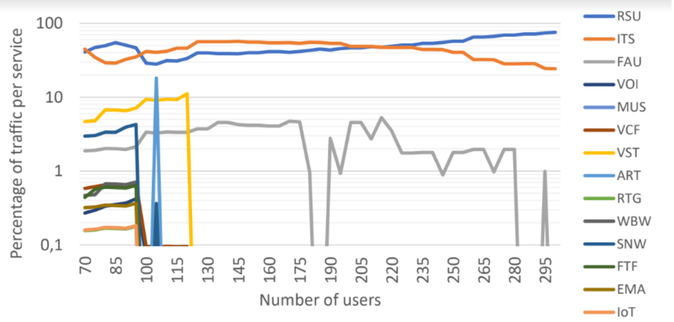


Figure 12 - Percentage of traffic per service to urban scenario.

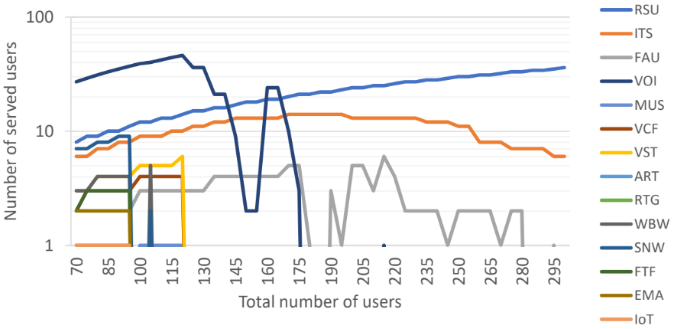


Figure 13 - Number of users served per service to urban scenario.

By evaluating Figures 12 and 13, regarding the urban scenario, it is possible to verify that the percentage of traffic from all services increases until achieving a total of 90 users in the cell. It can still be verified that the VOI service, despite the considerable number of users corresponding to 39% of the total cell load, this is not the service with the highest percentage of traffic due to its data rate. For the total load of 75 users in the cell, 29 utilize the VOI service. This service represents 0.3% of traffic, on the other hand the RSU service, which for the equivalent total number of users in the cell, only 9 use the VOI, it represents 47% of the percentage of traffic generated. When the aggregate number of users reaches 220, the combined number of served users no longer varies greatly, being always between 41 and 43 users, justified by the fact that most services are no longer being served by the cell, leaving only 3, which require elevated levels of data rate.

From the evaluation of Figures 14 and 15, it is possible to verify the RSU and FAU services are not represented, as would be expected and that due to the absence of these services, the VOI service has a vaster number of active users as the total number of users in the cell. Regarding the number of users served, from the total value of 210 users, it varies between 35 and 42, which is higher than the suburban environment (27 users served) and when at most it fits the values of the urban environment (between 41 and 43 active users). It is possible to verify that from the total value of 120 users it is only possible to carry out ITS and VOI services.

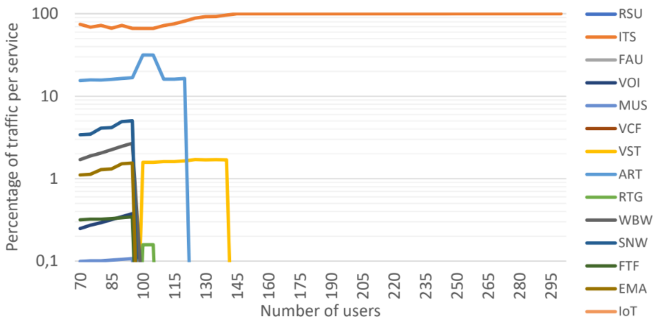


Figure 14 - Percentage of traffic per service to rural scenario.

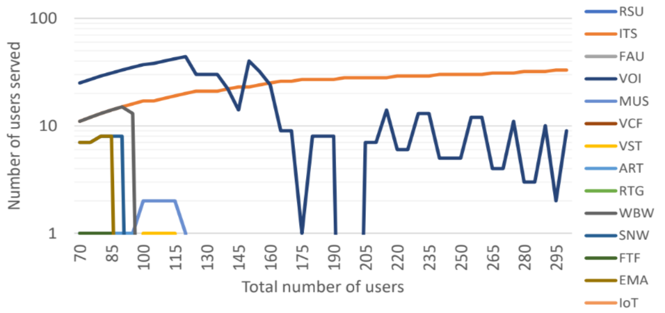


Figure 15 - Number of users served per service to rural scenario.

E. *Influence of the Service Mix*

In this subsection, an analysis will be developed of the number of users served according to the total number of users of the cell, maintaining the urban scenario and the frequency of 3.6 GHz and only varying the service mix for 3 services, RSU, ITS and FAU according to Table 4.

In Figure 16, there is an increase in the percentage of the RSU service in the service mix, and it can be seen that the number of users served remains at 100% up to 145 total network users. It is also possible to see that despite the ITS service being more prioritized than the FAU service, the users who perform this service are no longer 100% when 205 users are reached, while the FAU service is no longer 100% served at 220 users, that this is due to the fact that the ITS service has a high data rate and when users of this service are deactivated, it will be possible to occupy the vacant bandwidth with a less priority service with a data rate lower than the ITS service and that does not exceed the cell capacity.

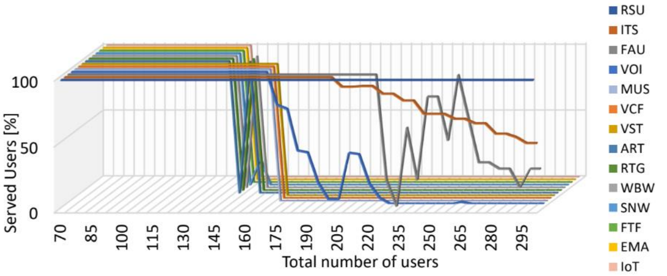


Figure 16: Number of users served per service to urban service mix 1.

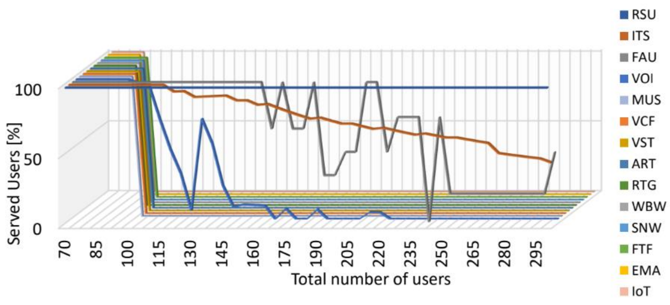


Figure 17 - Users served per service to urban service mix 2.

In Figure 17, there is an increase in the percentage of the ITS service in the service mix, which, as had been seen in the variation of scenarios, leads to the deactivation of most users who perform services of lesser priority when it achieves the total value of 95 users in the cell, not returning these services to have active users unlike service mix 1.

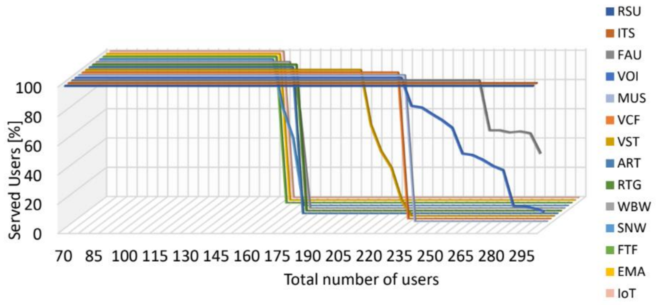


Figure 18- Users served per service to urban service mix 3.

In Figure 18, there is an increase in the percentage of the FAU service in the service mix, as this service has a lower data rate than the other two, it can be perceived that the number of users served per service remains at 100 % for a greater total number of users than in the other two service mix. It can equally be noted that for urban service mix 3, the three highest priority services remain with 100% active users, up to a total of 270 users. With this, it can be concluded that if the services with the highest percentage of users are services with lower data rates, it will allow more users to be active when the total number of users increases.

F. *Deployment Analysis*

Taking into account all the analysis carried out previously in terms of cell radius, as well as the number of users served and traffic generated, it is possible to develop an analysis regarding the three clusters and on how the three different scenarios can be covered. The cell radius was calculated for the various scenarios and for the different frequency bands through the Link Budget. Subsequently, the maximum capacity in which the cell guarantees that all cell users are served was calculated. Then, with the maximum value obtained, the number of cells necessary to guarantee that users for the various environments are covered by the radio network was calculated. For the urban scenario, eight cells of the 0.7 GHz frequency are necessary so that it is possible to cover the entire area and to have capacity for 866 users, for the case of the 2.6 GHz band, seven cells would be necessary to have capacity for 866 users and for 3.6 GHz, 6 cells would be needed, this considerable number of cells would be caused by the traffic exerted on the network and not by the area that it is necessary to cover. For the suburban scenario, due to the intensification of the ITS service traffic, a service with the most demanding data rate, the system continues to require a significant number of cells due to the traffic exerted.

The limitation in this scenario is caused by the 10 km2 area that needs to be covered. For the analysis over the years, it will be considered that in 2022 the total traffic will represent 500 users and that the services will be distributed by the bands as follows the FAU, VST and RTG services will merely be carried out in the 0.7 GHz frequency band using NR technology. The VOI, MUS, VCF, WBW, SNW, FTF, EMA and IoT services will be carried out in the 0.8 GHz, 1.8 GHz and 2.6 GHz bands with identical percentages using LTE technology. Also, the RSU, ITS and ART services will only take place in the 3.5 GHz frequency band using NR technology.

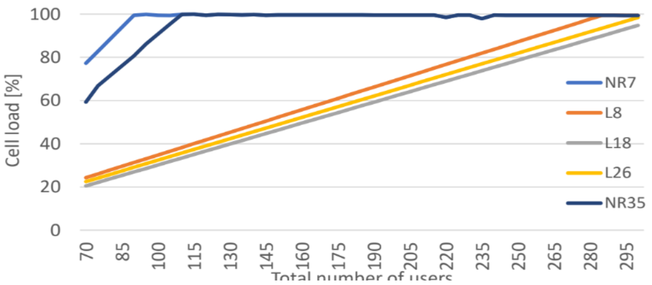


Figure 19 - Cell load (without refarming).

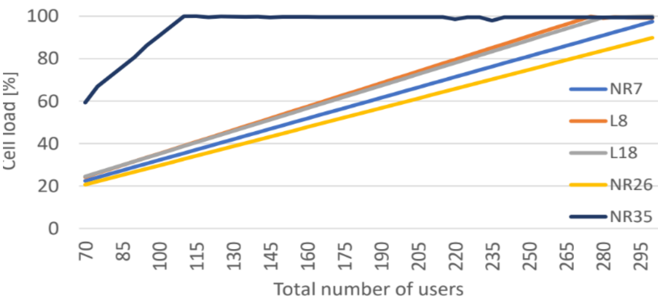


Figure 20 - Cell load (with refarming of 2.6 GHz band).

The increase in traffic is not uniform for all services, taking into account Table 5. Although the 3.5 GHz band is only occupied by three services, these are services with high data rates, which leads to users who perform the ART service being unable to be served by the same cell from 2023 onwards, due to having exceeded the capacity thereof. The same occurs for the IT service from 2025 onwards.

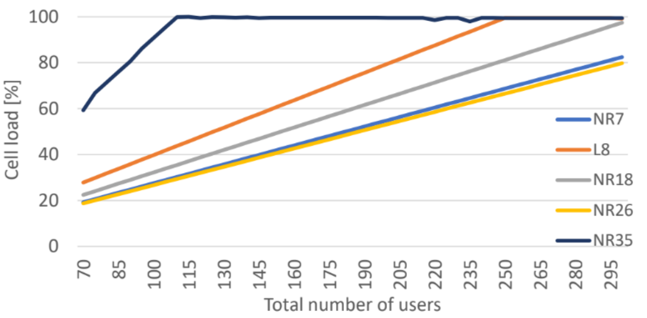


Figure 21 - Cell load (with refarming of 1.8 and 2.6 GHz band).

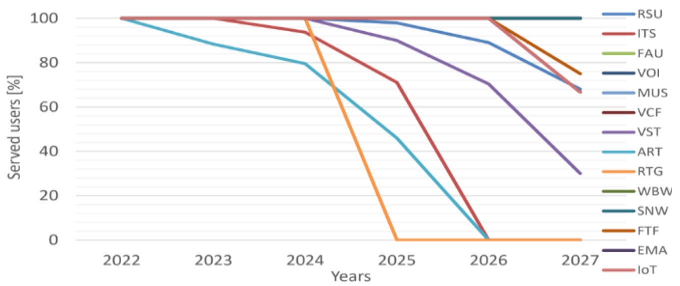


Figure 22 - Percentage of users served during the years for scenario 1 (without refarming).

With the use of 2.6 GHz band refarming in 2024 and the 1.8 GHz band in 2026, the traffic of VOI, MUS, VCF, WBW, SNW, FTF, EMA and IoT services became limited to only two bands and subsequently to one band, limiting the available capacity for this type of service. Since there was no transition of traffic to the NR bands, and traffic from these services continues to increase, in 2025 users who perform the IoT service will be deactivated and in 2026 the WBW and SNW services will be deactivated. The refarming of the two bands was carried out in such a way that the traffic of services carried out in the 0.7 GHz band would be executed in 3 bands, concluding users who perform these services can always be served 100% over the years.

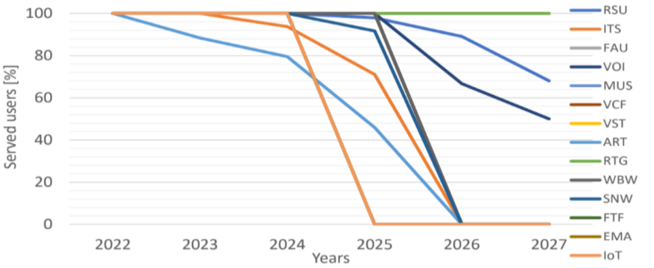


Figure 23 - Percentage of users served during the years for scenario 2 (with refarming).

V. CONCLUSIONS

The primary objective of this thesis is to study a 5G network implementation in a brownfield scenario, that is, on an existing network. This implementation will help grasp the advantages and disadvantages in terms of coverage and capacity that this network offers. In order to achieve this, there is a need to develop a model that can be used to analyze the coverage and capacity variations by varying the input parameters according to the kind of scenario in question. As the name implies, the input parameters operated are deemed to simulate the regular behavior of a 5G network. This model will additionally allow to understand the importance of user density, traffic profiles among others on the network's coverage and capacity. As the name indicates, the input parameters are deemed to simulate the regular behavior of a 5G network insert in a brownfield. bands.

In the cell radius evaluation, it was concluded that the increase of the data rate at the extreme of the cell decreases the cell radius, and some of the propagation models became invalid. The frequency band analysis concluded that 3.6 GHz allows more 20% of served users than the 0.7 GHz band, due to the bandwidth increase from 10 MHz to 100 MHz. In the analysis of different service mixes, for services with more demanding data rates such as the Intelligent transportation system, the radio network saturates with fewer users than the other two services with fewer demanding data rates. Regarding the deployment analysis, it was concluded that the refarming increased the band for FAU, VST, and RTG services, being all the users from these services served, and decreased the band for the VOI, MUS, VCF, WBW, SNW, FTF, EMA and IoT services, which, due to the increase of the number of users over the years, deactivate users from these services.

In the future it would be interesting to consider and improve the interference among cells of this network, since in this simulator the interference is equal both for users in the center of the cell and at the edge and that is not a realistic assumption, also other considerations about carrier aggregation can be accessed in the future since that could produce results with the greater bandwidths accessible for the 3.5 GHz band. It would be useful for future work to consider a percentage deactivation of users, that is, due to the priority levels, the system completely deactivates the users of lower priority, as soon as the capacity saturates due to the underload of users. If the lowest priority service has a high data rate, these users will never be able to perform the same again, unless the number of cell users decreases. For this, a percentage deactivation in accordance with the priority would be more suitable.

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