Impact of the Use of Beamforming Techniques in 5G Mobile Networks

Tiago Marques Santos

Instituto Superior Técnico, Lisboa, Portugal
tiago.marques.santos@tecnico.ulisboa.pt

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Abstract
The objective of this dissertation is to study the impact that beamforming techniques have on a 5G mobile network, relative to the coverage of a base station. As 5G will be implemented based on a non-standalone topology, for the user to be able to use the network, he also needs 4G network coverage. Thus, it was intended to test the coverage limits between the 5G solution installed in the 3500 MHz band and the installed 4G solution, as well as to forecast the distribution of the beams and the transfer rate of the various users. A coverage simulator was implemented and coverage tests were carried out on the mobile network of the Vodafone operator in order to validate the results obtained. The basis of the simulator is the model developed in the METIS project that takes advantage of the calculation of losses along the path between the base station and the user's terminal.
Keywords: 5G; Coverage; Beamforming; MIMO; Base stations.

1. Introduction

Over the last few years, quite a few changes have happened in mobile wireless communications, affecting people's daily lives and, above all, the economy and development of the various countries, all over the world. In general, they have been endlessly evolving to fulfil increasing demands and higher specification requirements.

With the great technological developments that have arisen in the area of multimedia contents, the increase in video consumption by end users has significantly increased.

Although video encoding become increasingly robust and efficient, with high-resolution video switching to 4K or even 8K resolutions, data volume continues to increase. Thus, it is clear that it is a growing challenge for today's networks support this huge amount of traffic on the network, resulting in the need to create a new standard for mobile networks, the 5G.

On the other hand, the number of subscribers should increase as well. Thus, another key 5G is precisely able to withstand the multitude of devices, being the IoT ones fairly representative.

2. Motivation and Contents

Implementing a mobile network like 5G has a lot of challenges in its way, so it's important to take into account elements such as complexity of implementation, frequency bands, the modulation used, number of antennas in the BS and a MT, etc.

This thesis was developed in collaboration with *Vodafone Portugal – Comunicações Pessoais, S.A.*, which belongs to *Vodafone Group Plc*, a multinational network operator. As a consequence of this partnership with an operator that tries to take advantage of the latest technological solutions in the market, this thesis came from a real-world problem. Since the 5G will initially be supported by a non-standalone technology, it is necessary that the mobile terminals have simultaneous coverage of 4G and 5G to take full advantage of the network.

The main purpose of this thesis is to make a comparison between a 5G New Radio implementation using the 3500 MHz frequency band and an LTE 1800 MHz network solution, mainly in terms of coverage. According to the classical models, being different frequencies, it is expected that the 3500 MHz solution has less reach than the 1800 MHz one. However, with the technological leap from a beam forming technology and a "traditional", doubts arise as to whether it is possible to achieve the same coverage area.

Hence, the predicted main output of this thesis is to confirm if it is possible to serve the same coverage area in various scenarios. Toward this aim, a simulator will be developed to validate the mentioned problem, depending on the variations of its various input parameters.

3. Services and Applications

This section is based on [12], [2], [10] and [7]. According to ITU-R, new services provided by 5G networks in IMT-2020 can be formalised in three important categories for IMT-2020: EMBB, URLLC and MMTC, as shown in the Figure 1.

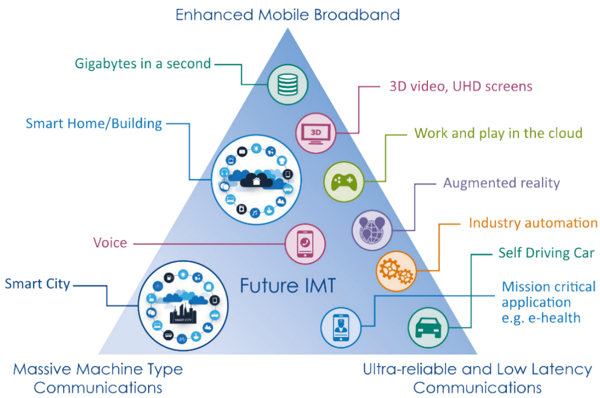

Figure 1: 5G usage scenarios (extracted from [12]).

EMBB addresses the "human-centric" use cases, bringing high-speed mobile broadband to crowded areas, enabling consumers to enjoy high-speed streaming on demand and allowing enterprise collaboration services to evolve. It is also expected to be the primary use case for 5G in its early deployments and should include peak download speeds of at least 20 Gbps.

URLLC allows mission-critical applications, industrial automation, new medical applications, interactive games, augmented reality, communications to/from drones and autonomous vehicles. In this situation, any network latency or loss in signal coverage can have disastrous consequences. There should be sub-1ms latency and very high availability, reliability and security.

MMTC will allow you to support a huge amount of IoT devices (at least one million IoT connections per square kilometre) that usually transmit a relatively low volume of non-delay-sensitive data, with enhanced coverage and long battery life.

As suggested by Figure 1, these three categories encompass multiple day-to-day services and applications, all of them with slightly different requirements.

4. Radio Spectrum

In Europe, it will initially appear at 3.5 GHz band but it will be also present in low (below 1 GHz) and high bands (above 24 GHz). Thus, according to [13] and [4], the 5G spectrum is divided into:

- A low band at 700 MHz: Mainly used for long range, widespread coverage communications and massive IoT.
- A mid-band at 3.5 GHz: This will likely be the key band for 5G, used for EMBB and compromise between coverage and capacity, although since it is at frequencies above those previously used for mobile, it could have some concerns to solve regarding the reduced range.
- A high band above 24 GHz: This might be used for very high throughput services for EMBB, localized deployments and low latency use cases, such as industrial IoT and venues, or for other applications that could require extreme bandwidth values, such as FWA.

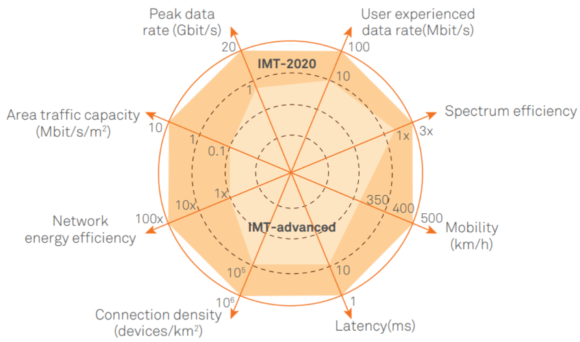

Figure 2: IMT-2020 usage scenarios and key capabilities extracted from [9]).

5. Radio Interface

5.1. MIMO

MIMO is a type of antenna that takes advantage of a set of receivers and transmitters to increase the efficiency of a transmission channel. Using multiple antennas configurations, shown in Figure 3, it is possible to take advantage of spatial multiplexing and spatial diversity.

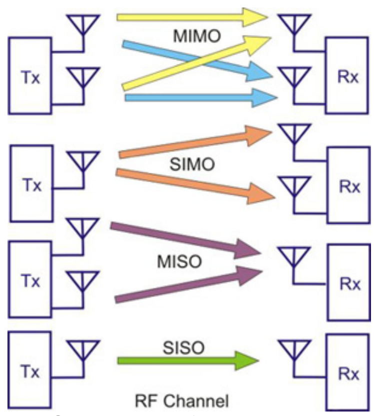

Figure 3: MIMO antenna configuration (extracted from [3]).

The 5G systems are going to employ these techniques in a massive way, using the so-called Massive MIMO.

5.2. Beamforming

Beamforming is a signal processing technique that allows to direct radio energy through the radio channel toward a specific receiver, that is, to orient the various beams of an antenna, and consequently the radiation pattern, as required. In this way, by feeding separately each element of this matrix with different weights in both the horizontal and vertical domains, each beam can be directed in a certain direction. When the phase and amplitude of the transmitted signals is adjusted, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. On the other hand, beamforming also allows to collect the signal energy from a specific transmitter when receiving. So, both uplink and downlink can take advantage of these features. Just as an example, in Figure 4 is presented the system architecture of a 4 × 4 multibeam antenna.

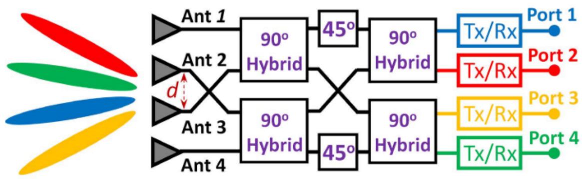

Figure 4: System architecture of a 4 × 4 multibeam antenna (extracted from [8])

Scaling the situation of the Figure 4 to a weighted phased array, spatial processing is allowed to be used in 3D. By controlling the transmission radiation pattern in both the horizontal and vertical planes, the interference can be compressed or avoided, leading to improvements in spectrum efficiency and interference mitigation in cellular mobile communications. By using this technique there is still the advantage that could be not necessary to change the antenna array size of the base station and the antenna number of the terminal.

There are several possible classifications for the various types of beamforming however, one of the possible classifications indicated in [1] is based on signal processing. Presented by Hur et al. (2013) and Bogale and Le (2014), these techniques were classified as:

- Analogue Beamforming - very simple phase shifters but have the advantage of being cheaper compared to digital beamforming. Adopted in Massive MIMO systems.
- Digital Beamforming - are more accurate and rapid foundation results to obtain user signals but suffers from high complexity and an expensive design. Not adopted in Massive MIMO systems.
- Hybrid analogue/digital Beamforming - has been developed for massive MIMO systems to obtain some of the advantages of analogue and digital beamforming.

If users are well spatially distributed, there are even more significant gain improvements that are achieved since there is less interference between them.

According to [6], in order to manage beamforming there are a number of important procedures that are performed:

- Beam sweeping - covering a spatial area with a set of beams transmitted and received according to pre-specified intervals and directions.
- Beam measurement - the evaluation of the received signal at the gNB or at the UE. This can be made by using several metrics such as SINR or the received power.
- Beam determination - the selection of the suitable beam or beams either at the base station or at the UE, according to the measurements obtained with the beam measurement procedure.
- Beam reporting - procedure used by the UE to send beam quality and beam decision information to the Radio Access Network.

In order to estimate coverage it is necessary to consider several parameters, such as test scenario, frequency used and bandwidth allocated. Thus, to have an idea of the covered range it is necessary to use SINR at the receiver side to obtain the acceptable path loss. Using a propagation model that fits in the study case scenario, it is possible to obtain the maximum range where the quality parameters are acceptable and even a throughput approximation.

6. Antenna Specifications

The live network that is currently being used for tests in this area is composed of two 5G base stations, one in the left of the Vodafone building and another in the right, both at the riverside. These locations are marked in the Figure **??**.

The antenna model mounted in the area, in both base stations, takes advantage of advanced state-of-the-art techniques, namely massive MIMO and beamforming, capable to fully utilize radio resources in both azimuth and elevation. Compared to previous macro solutions, the key advantages are changes in: enhanced coverage (high gain adaptive beamforming), enhanced capacity (high-order spatial multiplexing and multi-user MIMO), advanced RAN features (vertical and horizontal beamforming) and improved network performance (low inter-cell interference).

The antenna model that was chosen by Vodafone for this installation can be deployed in three distinct variations: Macro, Hotspot and Highrise. Each of these variations is adapted to a specific scenario. Table 1 provides the vertical and horizontal radiation widths for broadcast beams each setup of the antenna, since each of these variations has different radiation patterns.

	Vertical (°)	Horizontal (°)
Macro	10	65
Hotspot	30	65
Highrise	30	20

Table 1: Radiation widths for broadcast beams in each possible antenna setup.

As a consequence of these different beamwidth for broadcast beams, it is easy to understand that there are different number of traffic beams in each variation. Regarding traffic beams, it was not possible to obtain width of the beams in all directions. Through the manufacturer's specifications, presented in the datasheet, it was only possible to obtain these values for 3 directions. Table 2 provides the vertical and horizontal radiation widths for traffic beams in the 3 mentioned directions.

H(°), V(°)	Vertical (°)	Horizontal (°)
0, 3	9.5	12
5, 3	9.5	22
0, 18	10	12

Table 2: Radiation widths for traffic beams in the 3 mentioned directions.

As the the information presented in Table 2 and this information is quite limited, turns out that it would not be enough to carry out the intended study. So, to overcome the problem of lack of information, the traffic beams of scenario setup was obtained not only from the manufacturer vertical and horizontal radiation beamwidths specifications and the .msi files itself. Thus, a traffic beam was defined whenever the tested gain was inside of the vertical and horizontal radiation beamwidths intervals, stated by the manufacturer.

Thus, each possible antenna setup has a different number of traffic beams and, depending on the UE distribution, is preferably recommended for a particular scenario.

From Table 1 and Table 2, it is easy to understand that:

- If the expected that if the majority of the users are, for example, in a urban scenario with high density buildings (most of the users probably in an indoor environment such as offices and tall residential buildings), it is expected that the chosen setup maximises the number of beams in the vertical plane, that is, Highrise. This solution provides a total of 30 beams.
- If users are placed in a horizontal plane, where there are few (or none) variations of user locations in the vertical plane, it is expected that the setup is chosen according to it. Thus, in this situation the best solution would be a Macro setup since it has a higher horizontal weight compared to the vertical one. This is the typical scenario in a mobile network and this solution provides a total of 26 beams.
- Between the previous solutions, there is also the Hotspot solution that have the vertical width of Highrise and the horizontal width of Macro. This solution would be the smart choice for a scenario with high density of users, such as a special event, where there can be users in a wide area and in various directions. This is the solution that provides the higher number of beams, that is, a total of 78 beams.

Table 3 summarises this informations, presenting the number of traffic beams and the best use scenario for each possible antenna setup.

	Macro	Hotspot	Highrise
N.º Beams	26	78	30
Scenario	Horizontal	Both	Vertical

Table 3: Number of Beams for each possible antenna setup.

7. Simulator Description

This simulator, created in Matlab, use outputs from METIS project [11] and from the previous work done by António Fragoso in his master thesis about "Impact of Massive MIMO antennas on high capacity 5G-NR Networks" [5], also in partnership with Vodafone Portugal. This path was chosen because it is a simulator based on a map, which supports a frequency range up to 100 GHz, a bandwidth up to 10% of the central frequency and allows support for antennas capable of taking advantage of Massive MIMO and beamforming. Although the METIS-based model supports 3D elevation using simplified ray tracing, another approach was initially attempted with true ray-tracing and a real map of the area involved, which would bring more precision and reliability compared to the METIS-based model, however, due to the strong computing requirement that the model was requiring, it made this approach unfeasible.

As in the mentioned studies, in this thesis it is assumed that UE can be in LoS or in Non-LoS. On the other hand, given the location where the UE is located, it can also be in an indoor or outdoor environment.

7.1. Path Loss

As described above, UEs may be in an LoS or Non-LoS situation.

In general, in order to show the simulator's operation in calculating the path losses of all points on the map, the figure 5 presents the value of the losses for each point on the map, at ground level. It appears that the farther the user is from the serving cell, the higher the path loss value and that in an indoor environment the expected increase in the same parameter is also observed.

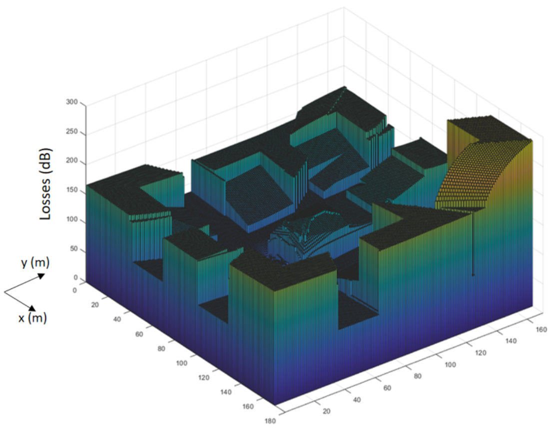

Figure 5: Path loss at the ground floor.

7.2. Which Base Station is Serving Cell?

To make the choice of the base station that serves each UE, it is necessary to perform some calculations. After calculating the path loss value between each base station and each UE location, this value is used to obtain the power value that arrives at each of these locations. Figure 6 present the power received in each location of the map at the ground floor.

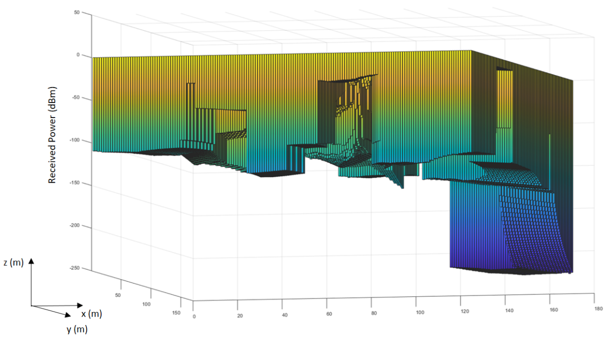

Figure 6: Power received in each location of the map, at the ground floor.

As can be seen from the previous figure, inside buildings there is a lower power in an outdoor environment, which would be expected due to indoor losses. It is also noted that the further away the base is located from the UE, the greater the value of losses and, consequently, the lower the value of received power.

Thus, to obtain the serving cell, the workflow shown in the figure 7 is executed.

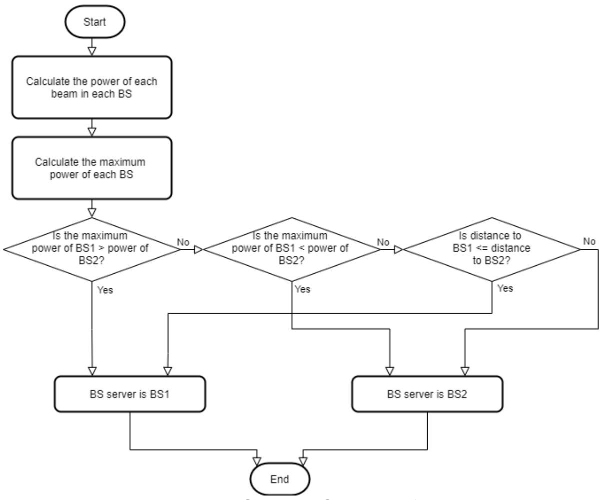

Figure 7: Serving Cell Workflow.

Once this procedure is executed, it is possible to know which base station best suits each location on the map, be it indoor or outdoor. The figure 8 shows the serving cell for floor level locations.

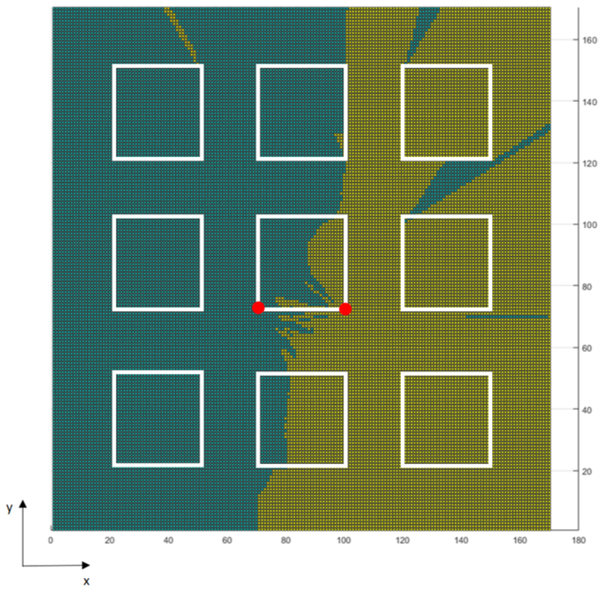

Figure 8: Serving Cell for each location of the map, at the ground floor.

7.3. Beamforming

In order to understand how users are distributed among the various beams, it was calculated the number of admissible beams (that is, with acceptable power) in each position of the map, depending on the base station serving that location. Figure 9 presents the number of acceptable beams in each location, at ground level.

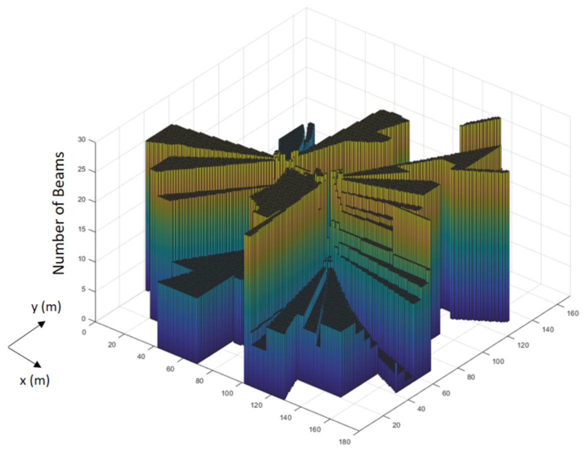

Figure 9: Number of acceptable beams in each location, at ground level.

Based on these calculations, the beam that provides the best quality of service to the end user is then chosen.

7.4. SINR

Once the value of the losses has been obtained and which base station serves each point on the map, it is now important to analyze each user individually. To do this, it is necessary to calculate the SINR of each user to subsequently validate whether or not to activate a new beam to provide service to that particular user.

As an example, as previously done for path loss, an example of the SINR calculation is shown in the figure 10 for all positions on the map (considering that only each position is being served at each moment, that is, without interference), in order to verify that the SNR is much higher at base stations than at cell edge.

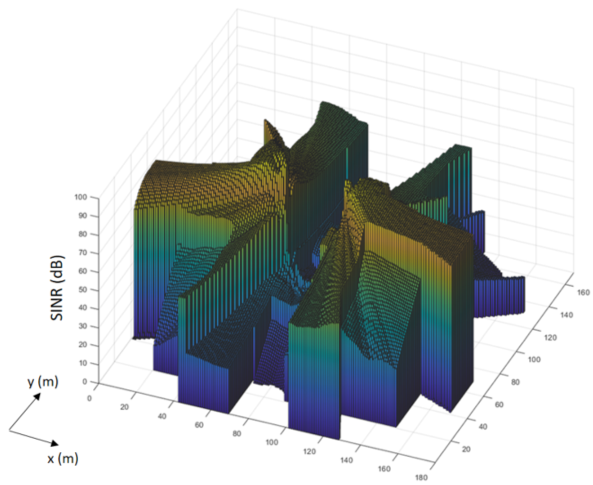

Figure 10: SINR for each location of the map, at the ground floor, without more users in the network.

7.5. Throughput

Using the work developed by [5], the relationship between SINR and throughput have to be considered in 4 different expressions for the downlink, one for each modulation: QPSK, 16-QAM, 64-QAM, and 256-QAM. Each of these expressions is associated with the median value of the coding rate obtained from the CQI reported by the MT. The coding rates for these MCSno are presented in table 4.

Modulation	Target Coding Rate
QPSK	1/3
16-QAM	1/2
64-QAM	3/4
256-QAM	[0.7;0.9]

Table 4: Modulation Coding Scheme and its target coding rate.

Again, taking the work developed by [5], it was possible to obtain normalized curves for each of the modulations, thus adapting to the Vodafone Portugal settings. For a 2x2 MIMO channel and with a numerology 1 - SCS equal to 30 kHz - configuration, comes up:

For QPSK:

$$R_{b[bps]} = \frac{1.69748 \times 10^6}{14.0051 + e^{-0.577897 \cdot \rho_{IN}}} \tag{1}$$

For 16-QAM:

$$R_{b[bps]} = \frac{69019.7}{0.0926275 + e^{-0.295838 \cdot \rho_{IN}}} \tag{2}$$

For 64-QAM:

$$R_{b[bps]} = \frac{57416.6}{0.0220186 + e^{-0.24491 \cdot \rho_{IN}}} \tag{3}$$

For 256-QAM:

$$R_{b[bps]} = \frac{76559.2}{0.0178868 + e^{-0.198952 \cdot \rho_{IN}}} \tag{4}$$

8. Results

To assess the performance of this simulator, this chapter presents an analysis of the data taken from the simulator, as well as the data collected from the Vodafone Portugal live network.

9. Setup Configuration

The phone used to perform some tests in the live network environment was a Xiaomi Mi 10, running Android 10, which supports the following mobile network technologies: 2G, 3G, 4G and 5G.

In the scenario in which the tests were carried out, it was possible to have a slightly more advanced configuration in which a 4G cell could be an anchor cell of several 5G cells and, simultaneously, a 5G cell could have several 4G anchors. Through this process, it was possible to establish

5G connections using 4G anchor cells that were not colocalized.

Each corner of the headquarters building has a 4G sector, as shown in figure 11. The 2 corners of the building that also have a 5G sector are shown in figure 12, on top of the 4G ones. Each of these figures also has the PCI indication of the various cells.

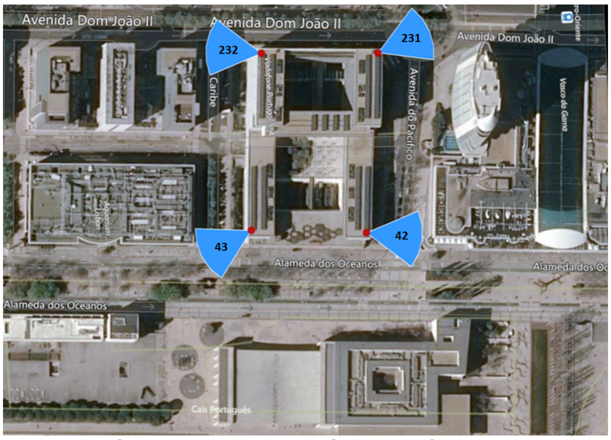

Figure 11: Sector locations and PCI of the 4G the live network

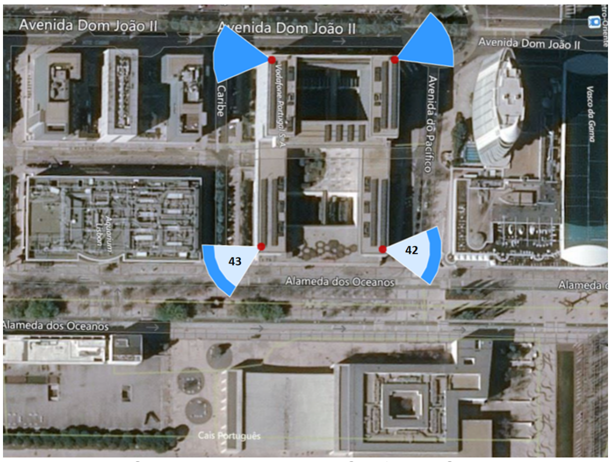

Figure 12: Sector locations and PCI of the 5G live network

10. Walk-test Results and Analysis

The tests on the 5G network were carried out on a summer day in 2020, with clear skies and temperatures around 30 degrees Celsius, in some previously selected locations. The basic criterion for selecting these 59 locations was to try to take advantage of the symmetry that exists in the block, without affecting the number of locations to perform data collection nor negatively impact the collection of the various types of scenarios possible in the area.

Thus, the locations selected to collect data are shown in the figure 13.

As can be seen when comparing the figures 13 and 14, there are locations that in a real environment are outdoor but in the simulator are considered indoor (locations H09 and I09). The H05 location is considered indoor in the simulator but in real life it is an outdoor location with a roof. Finally, the building visible in the lower left corner of the simulator map is actually an outdoor space so any collection and subsequent comparison could be dubious.

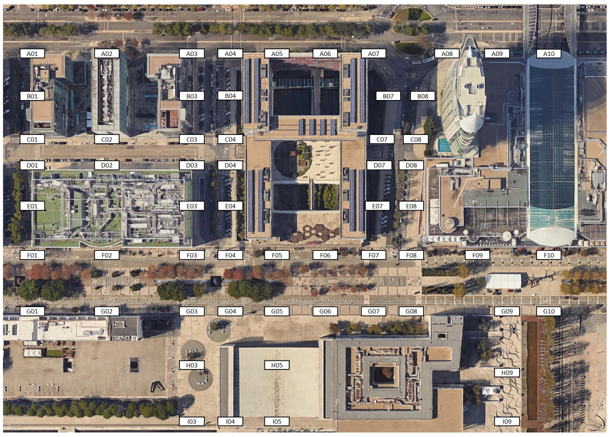

Figure 13: Real map of Vodafone headquarters surroundings with tested locations

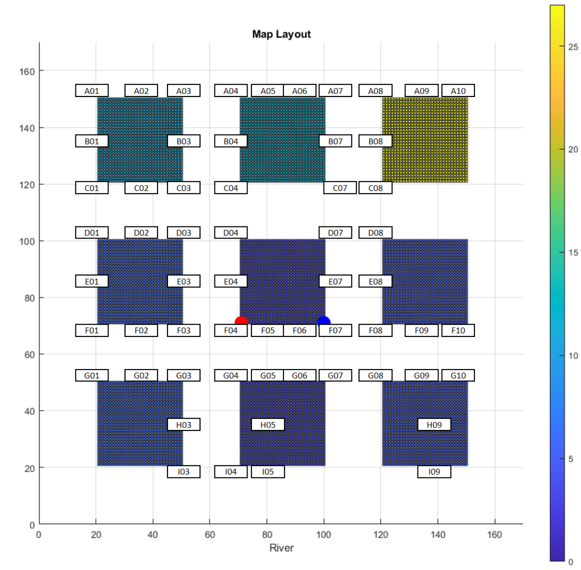

Figure 14: Simulator map of Vodafone headquarters surroundings with tested locations

The simulator considers the existence of the 2 base stations 5G: the base station 1, on the left and in red in the figure 14, and the base station 2, on the right and in blue in the same figure.

Running the simulator for the locations mentioned above, it appears that the distribution of the locations by the base stations is not done equally by the two stations. The figure 15 shows the number of locations covered by each base station.

Thus, according to the simulator, base station 1 is responsible for covering 30 locations, base station 2 for 22 locations and there are 7 locations that do not have coverage for any of the 2 base stations.

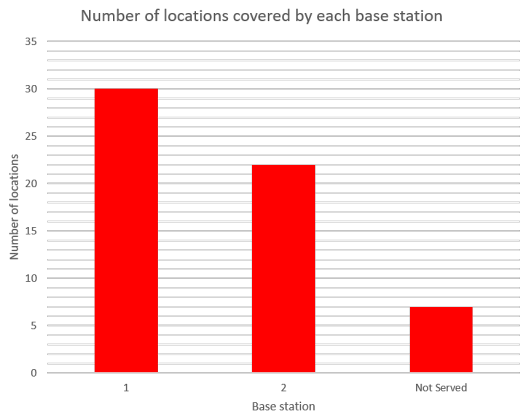

Figure 15: Number of locations covered by each base station

To validate whether this distribution of locations of possible user terminals was adjusted to reality, the PCIs to which the test terminal connected in a real environment at each location were collected. The distribution of 4G and 5G Physical Cell Identities during trials figure 16.

In order to compare the real 5G cells with those of the simulator, the cell with PCI 43 corresponds to base station 1 of the simulator and the cell with PCI 42 corresponds to base station 2.

In addition, the 4G real cells are also presented: cells with PCI 42 and 43 colocalized with 5G and cells with PCI 231 and 232 located at the other end of the building. Two other cells were also detected with PCI 69 and 160 but that were not anchors of any of the two 5G cells under analysis in the study.

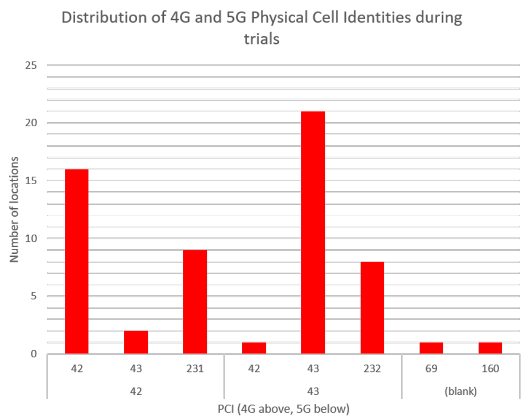

Figure 16: Distribution of 4G and 5G Physical Cell Identities during trials

From the figure 16, it can be seen that most 5G data sessions were anchored by the colocalized 4G cell. In some cases the 4G anchor was one of the other cells that did not have 5G in that sector. As previously mentioned, in the test scenario any of the 4G cells with the PCI 42, 43, 231 and 232 could be anchors of the 5G cells with the PCI 42 and 43. It was found that the handovers between these 4G stations were carried out according to the best coverage conditions, as expected, and without causing problems in the 5G connection. In 2 particular locations it was not possible to do a 5G data session since the 4G cell was not the anchor of any 5G cell.

It should also be noted that, as predicted in the simulator, the 5G base station with PCI 43 (equivalent to base station 1 in the simulator) covers more locations than the base station with PCI 42 (equivalent to base station 2 in the simulator)

After analyzing the group of locations covered by each 5G base station, there is a need to know which beam of each base station covers each location. As mentioned in the previous chapter, the beam of each station covering a given location is chosen based on the value of its gain and its direction. As it was not possible to collect this information from the live network, it is shown in figure 17 the number of locations served by specific beams.

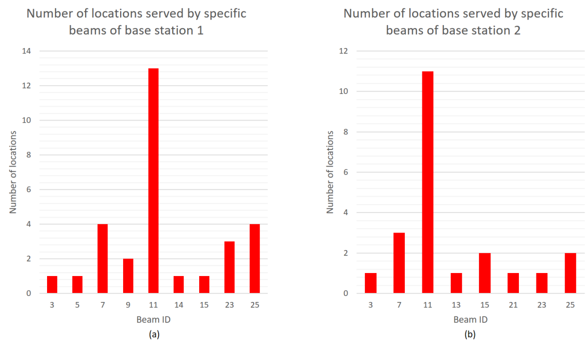

Figure 17: Number of locations served by specific beams of base station 1 (a) and 2 (b)

From the analysis of these figures, the beam with the ID 11 stands out as the beam that covers more locations in both base stations, resulting in 13 locations covered by base station and 11 locations covered by base station 2.

The users, present in the referred locations, are distributed in the simulator by the various beams following the criteria mentioned in the previous chapter. In the real network it is not possible to know how this distribution is made since the provider's algorithm is proprietary, that is, it is not public.

Comparing configurations with a bandwidth of 60 MHz with those of a bandwidth of 100 MHz, it can be seen that the chart behaviour is quite identical. With the exception of the aforementioned limitation, the speeds in the tests are proportional, which would be expected because the propagation conditions were maintained. The figure 18 shows the average speed values obtained in each of the locations served by the two base stations and in each scenario, either with a bandwidth of 60MHz or with a bandwidth of 100 MHz.

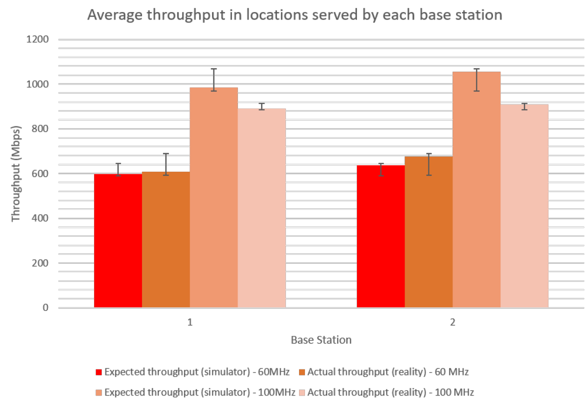

Figure 18: Average throughput in locations by each base station.

It appears that there is some differences between the estimated and actual values. On the one hand, in the case of 60MHz, the average of the actual values is slightly above the average of the values estimated by the simulator. On the other hand, in the case of 100 MHz, the average of the actual values is well below the estimated values due to the limitation already addressed. These differences are also strongly related to the location of the terminals on the map since there are positions that may not be fully mapped due to the irregularities of the surrounding scenario. The figure 19 shows the error values obtained between the measured values and the simulated values.

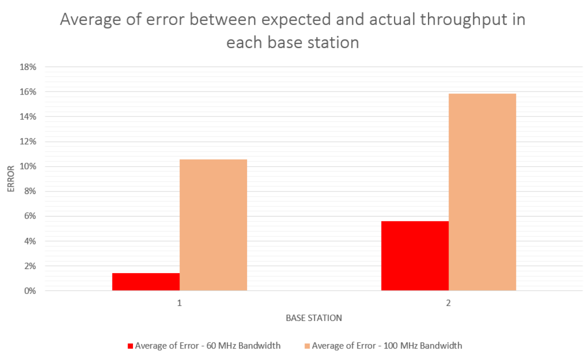

Figure 19: Average of error between expected and actual throughput in each base station.

Despite having some samples with low values for station 1 and others with higher values for station 2, it appears that the error between the simulated values and the real values, compared to the real values, is still a little high. In the case of 60 MHz there is an error of about 1,5% at base station 1 and 5,5% at base station 2. In the case of 100 MHz there is an error of about 10,5% at base station 1 and 15,8% at base station 2.

11. Case with 100 UEs in random locations

This section tests a hypothetical scenario with random locations but with one criterion: 20% of users are in an outdoor environment, on the ground, and 80% are in an indoor environment, spread over the various floors of the buildings.

The figure 20 represents how many beams are active and how many users are served by each of the beams of each base station.

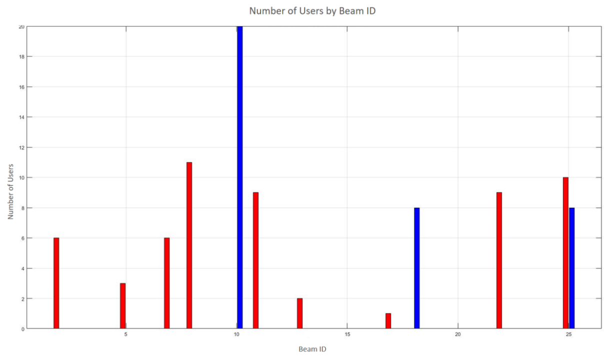

Figure 20: Number of users served by each Beam ID (BS1 in red, BS2 in blue).

Base station 1 is used to serve 51 users and has 9 active beams, while base station 2 is used to serve 28 users and has 3 active beams, as shown below in 5

BS	Beam	PRBs	UEs	PRBs/UE
1	2	162	6	27
1	5	162	3	54
1	7	162	6	27
1	8	160	10	16
1	11	160	8	20
1	13	162	2	81
1	17	162	1	162
1	22	162	9	18
1	25	162	6	27
2	10	154	14	11
2	18	160	8	20
2	25	162	6	27

Table 5: Beam and PRB usage.

In base station 1, the percentage of served users is 86.44 %, the number of PRBs used in BS is 1454 PRBs, the ercentage of PRBS used : 99.72 % and the average number of PRBs per beam : 162 PRBs. In base station 2, the percentage of served users is 68.29 %, the number of PRBs used in BS is 476 PRBs, the percentage of PRBS used is 97.94 % and the average number of PRBs per beam : 159 PRBs PRBs.

12. Conclusions

This paper describes the work developed for the Master Thesis in in Electrical and Computer Engineering. I present an overview of the main theme, 5G, and the motivation that led to the proposed work. Since the main task of this thesis was to study the impact of the beamforming technology in

5G mobile networks, it was crucial to carry out an in-depth study of 3 major themes: LTE, NR and beamforming.

As described in this document, it was possible to implement a simulator that estimates the coverage and capacity of the network environment of the Vodafone Portugal headquarters building. Using the gains of the antenna model used and calculating the path loss between the locations of the serving cell and the various UEs, it was also achievable to create a model that indicates which beam serves each user and present an estimate for the throughput reached.

The main technical problem that was encountered during this project relates to the machine characteristics necessary to run a ray tracing model. Initially it was intended to make a simulator that would take full advantage of 3D cartography and add the various functionalities necessary to achieve the desired result, but as this approach became unworkable due to the required high computing power (such as a few dozen of GB available in RAM and a very good processor), a model based on METIS was the way forward in order to continue the work previously developed with this type of models.

Given the results presented in this document, since the results comparing the simulated values and the real ones are quite similar, this work can contribute to the development of studies in the area. In the walk-tests it was verified that 4G coverage was never a problem to carry out the tests in 5G except in 2 situations in which the UE connected to stations that were not anchor of the 5G network. It was also found that the coverage of the 5G network "stretched" to areas with 4G coverage from non-colocalized cells and, as such, using Beamforming and other techniques such as Massive MIMO, it is possible to increase the coverage area and, in ultimately improve the end-user experience. Moreover, the simulator can predict when the terminal has coverage and which beams serve each user, thus increasing the capacity available on the network.

It is important to note that, given the approach of the type of simulator used and the assumption of the correspondence of the beam concept in the simulator, although it is possible to predict the conditions of the serving network, the distribution of users across the various beams may be different in real life. This is mainly due to the fact that there is no access to all the supplier's information and because the supplier has some freedom in adjusting users to beams using proprietary algorithms.

Thus, this work can contribute to the the development of future applications but it is recommended to change the type of used model to a model that can make these predictions more accurately, reducing the error between, for example, the estimated and the actual speed values.

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